# Sustainable PV manufacturing solutions for relaunching the European PV manufacturing industry

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## Abstract

To embrace the terawatt-scale challenge of the PV market growth, a low-carbon and resource-efficient pathway has to be guaranteed. An approach for doing this is to enable market mechanisms that account for the greenhouse gases emissions, and their associated costs, from PV systems and components. Under such conditions, it is expected that different technological options and solutions will have to be considered for the development and deployment of PV power plants and systems. In this paper, the economic competitiveness and environmental performance of the production of PV systems in Europe and China are assessed. Results are presented for the currently dominant recharged Czochralski (Cz) wafer technology, and for the less energy-intensive seed manipulation for artificially controlled defect technique (SMART) cast-mono (CM) technology. The analysis shows that SMART technology can be used to produce mono PERC systems with a climate change impact of just 21.63g CO2-eq/kWh, while a Cz PERC system produced in China will entail an emission of 43.32g CO2-eq/kWh. Around 45% of this reduction is achieved by having the production located in Europe. SMART technology yields a reduction potential of 9% of the associated global warming potential (GWP), when compared with the more energy-intensive Cz growth technology. Both Cz and SMART technologies can be produced at a competitive cost in Europe when carbon-associated costs are taken into consideration, leading to total costs of ownership of 21.5 and 21.6€ct/Wp respectively.

## Motivation

The PV market is expected to grow from about 740GW total installed capacity worldwide in 2020 to about 2,840GW in 2030 [1]. For this deployment it is assumed that the market share of mono-Si wafer-based PV will remain at around 95%, which represents a demand of approximately 2,000GW of PV capacity over the next 10 years. The associated environmental impacts of this development with respect to emissions of greenhouse gases and total energy consumption, along with other impacts on the biosphere and on human health, must be considered in order to follow a sustainable development path. This is especially true for energy-intensive processes in the PV value chain, such as the production of polysilicon, the crystal growth process of silicon and the production of balance-of-system (BoS) components.

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According to the principles of the European Green Deal [2], it is essential that the growth of the PV market is achieved as cleanly as possible and that resources are used with an ever-increasing efficiency. Adhering to these principles, along with satisfying the economic competitiveness, represents both a challenge and an opportunity for the relaunch of the European PV manufacturing industry.

Major Tier 1 PV producers – such as Jinko Solar, First Solar and LONGi – have already made public statements with regard to sourcing 100% renewable electricity for their global operations between the years 2025 and 2028 [3]. This positive news shows how relevant a product sustainability strategy has become to market-leading companies, but clearly this strategy faces its own implementation and operational costs. The establishment of a sound compliance system and chain of custody along the companies' value chains is challenging and may prove difficult if the scope of their commitments includes the production of the energy-intensive aluminium frames, glasses and BoS components. It is also challenging to demonstrate that these efforts generate net greenhouse gas emission savings for the economy and not just a virtual effect where other products and consumers are fed with a slightly more carbon-intensive electricity than before. Additionally, the environmental hazard potentials of raw materials extraction and production should also be addressed by the industry with the same priority that is given to carbon footprints [4].

In this paper the cost competitiveness and environmental performance of the production of PV systems and their components in the European Union and China are assessed. Results are presented for the currently dominant recharged Czochralski (Cz) wafer technology and for the less energy-intensive SMART (seed manipulation for artificially controlled defect technique) cast-mono (CM) wafer technology. Both wafer types are processed into passivated emitter and rear contact (PERC) solar cells, as these are the mainstream solar cell product. Modules with half-cut PERC cells and multi-busbar interconnection technology are then considered.

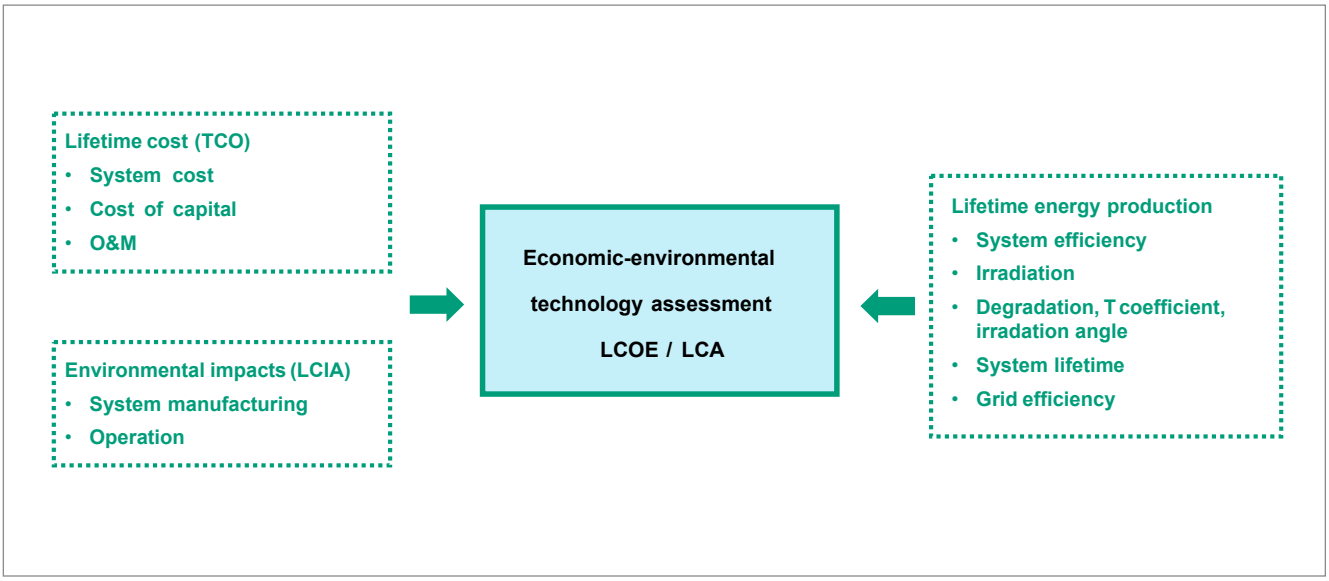


**Figure 1. Structure of the technology assessment based on life cycle assessment (LCA) and total cost of ownership (TCO).**

## Approach

For new technologies, a technology assessment based on total cost of ownership (TCO) is not sufficient, since the cost uncertainty often dominates the cost advantage between technology options. Moreover, a singular view on the environmental impacts has limited predictive power for rational technology decisions. What is obvious is that an environmentally friendly module cannot achieve a significant market share without economic competitiveness.

Fig. 1 shows the general structure of the integrated assessment. The approach follows Norris' proposals for integrating full life cycle costing (LCC) and full life cycle assessment (LCA) [5].

An LCA was carried out using Umberto LCA+ version 10.0 software and the Ecoinvent version 3.6 database. In compliance with the ISO standards 14040/4 for the general LCA procedure, in this assessment the IEA PVPS guidelines on LCA for PV and the European Product Environmental Footprint Category Rules for PV were considered [6–8].

The goal of this analysis is to assess 1) the environmental impacts of PV electricity with selected impact categories, 2) the corresponding levelized cost of electricity, and 3) the effects of carbon pricing at selected production locations in China and the European Union. The selection of the impact categories is carried out according to the status of available and modelled production data of a PERC module production process.

The LCA part of this study is an attributional assessment; in other words, no recycling bonus/waste treatment process of the PV modules and BoS components is included. The functional units are 1Wp of module power, rated under standard test conditions (STC) and 1kWh of electricity generated by the PV system.

The scope of assessing two different crystallization and cell concepts, and the corresponding production processes, includes mg-Si and poly-Si, and wafer, cell and module production (see Fig. 2). The data for BoS components (excluding inverter) and background processes are derived from the Ecoinvent 3.6 database. It is assumed that the whole PV system, including BoS components, is manufactured in a single production location, namely either China or the EU. Therefore, transportation is modelled for the whole PV system from the production site to the location where the PV system is installed. As the focus is on final PV installations in Europe, the cost of shipping modules from China to Europe is therefore included.

To derive the inputs used in the life cycle assessment and cost-of-ownership economic assessment, the SCost model of Nold et al. (2012) is used. The core of SCost is a detailed bottom-up model of the whole PV value chain based on the widespread SEMI standard composed of several layers to accurately represent production activities, process steps, and wafer, cell and module production processes [9,10].

The cast-mono technology data used in this work are based both on experimental data for the growth of CM-Si via the SMART seeding approach [11] and on industry information about equipment and process parameters. In order to study the potential of CM-Si technology for the next decade, data from state-of-the-art G8 furnace concepts (SCU 1500, ALD Vacuum Technologies) were used for the analysis. For the material quality distribution, data from growth experiments

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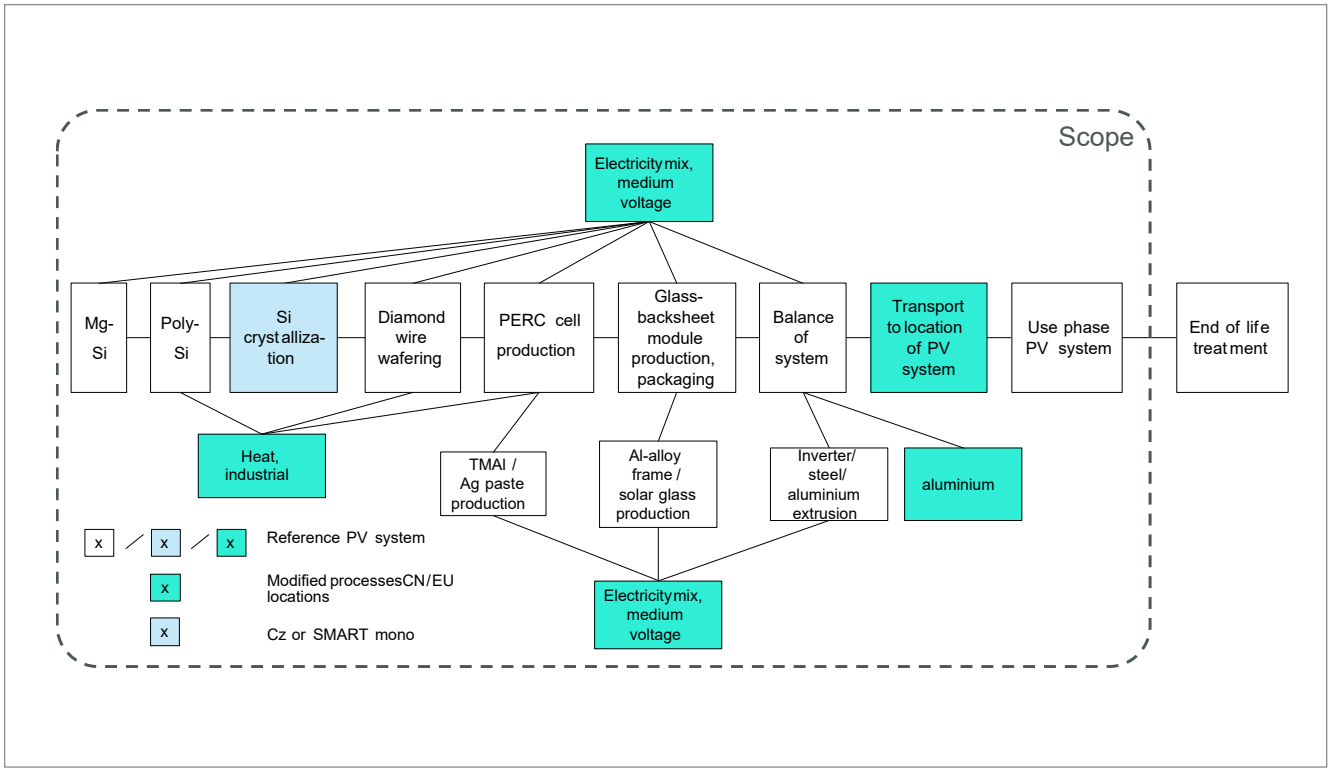


**Figure 2. Scope of regional assessment. The modifications to the processes indicated in green enable a regional assessment of the environmental impacts of PV systems produced in Europe (EU, RER) and China (CN).**

| Parameter | Value |
|---|---|
| Feedstock charge [kg] | 1,500 |
| Seed height [mm] | 20 |
| Ingot side length [mm] | 1,420 |
| Brick side length [mm] | 166 |
| Number of bricks | 64 |
| Growth velocity [mm/h] | 12 |

**Table 1. Input data for CM-Si growth process (M6 wafer size).**

| Parameter | Value |
|---|---|
| Feedstock charge [kg] | 360 |
| Ingot height [m] | 4 |
| Ingot diameter [mm] | 226 |
| Pulling speed [mm/min] | 1.7 |

**Table 2. Input data for Cz-Si growth process (M6 wafer size).**

utilizing laboratory processes with G2-sized ingots, equivalent to 75kg of Si feedstock, and G6-sized industrial processes, with 650kg of Si feedstock and SMART seeding concept, were evaluated. On the basis of these results, the main assumptions for material quality distribution, and thus potential yield, were derived for a G8 system with crucible sizes adapted to an optimal ingot side length for M6 wafer production. An overall electricity consumption of 6.8kWh/kg of crystallized silicon is assumed [12].

Additional input values for the CM-Si process model are shown in Table 1.

A general width of 30mm for ingot side cuts and a 1mm grinding loss per brick were accounted for. After cropping the top and bottom of the brick including the seed, a maximum usable brick height of 85% of total ingot height was calculated for all bricks. The brick yield – defined as the brick mass that meets the required material quality after squaring and polishing – strongly depends on the quality assumptions of the investigated growth process and the material requirements of the subsequent cell process. In order to model a more realistic yield for CM-Si material that meets the quality requirements for further cell production, a usability of 70% of the outer brick material and 80% of the inner was calculated, resulting in overall brick yield values of 53.1% for the M6 process.

For the Cz-Si growth model, the input data are based on an industrial Cz furnace including a recharging unit, a 36" crucible and a receiving chamber of more than 4m in height and an average of 4.5 pulls of 4m-long ingots per crucible. An overall energy consumption of 30kWh/kg of crystallized silicon was assumed [12]. Additional input values for the Cz-Si process model are shown in Table 2.

A maximum ingot usability of 85% after the cutting of seed, shoulder and end cone is assumed for all ingots, without taking into account any remelting processes. The usable brick mass considering the geometric constraints of creating a square wafer from a round ingot was thus calculated to be 58.8% for the M6 format.

As regards the following steps, the input data were mostly the same for both CM-Si and Cz-Si wafers, with the exception of the cell efficiency, and subsequently the module power. A PERC solar cell process was assumed to have an average efficiency of 22.3% for the CM-Si material, compared with 22.5% for the Cz-Si. Prior to module manufacturing, all cells were cut into half cells for the M6 format. The modules were modelled as glass–backsheet modules with 120 half cells. The average module power for Cz-Si material was thus calculated to be 372Wp; in the case of CM-Si, this worked out to be 371Wp for analogue modules. A summary of all relevant parameters is given in Table 3.

The modules are combined with the necessary electronic and roof-mounting equipment to form a residential rooftop PV system with a rated power of 15kWp at an average European location. An average annual global tilted irradiation of 1,331kWh/m² and a degradation of 0.7% are considered for a system lifetime of 30 years.

| Cell type | Cz | | SMART mono |
|---|---|---|---|
| **Ingot/wafer** | | | |
| Wafer area (M6) [cm²] | 274.2 | | 275.6 |
| Wafer thickness [µm] | | 170 | |
| Kerf loss (wafer slicing) [µm] | | 80 | |
| **Cell** | | | |
| Cell area (half cell) [cm²] | 137.1 | | 137.8 |
| Cell efficiency (STC) [%] | 22.50 | | 22.30 |
| **Module** | | | |
| Module area [m²] | | 1.85 | |
| Half cells per module | | 120 | |
| Module efficiency [%] | 20.11 | | 20.04 |
| Module power [Wp] | 372.3 | | 370.9 |

**Table 3. Performance parameters for the selected technologies.**

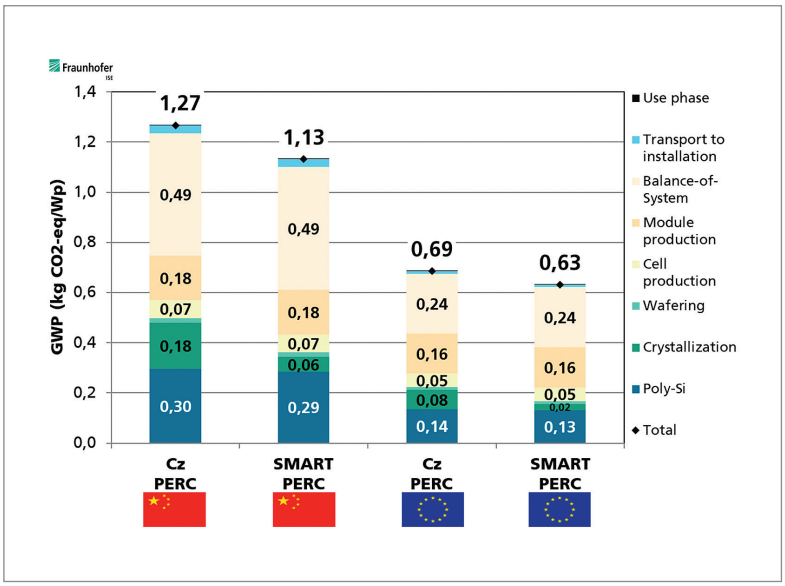


**Figure 3. Global warming potential (GWP) of 15kWp Cz and SMART mono PERC systems, produced in CN and the EU, and installed on a rooftop in an average European location. GWP is calculated with IPCC 2013, 100 years.**

## Carbon footprint

The resulting carbon footprint of the production of PV systems and their components was significantly smaller in the EU than in China (see details in Fig. 3); this holds true for both Cz and SMART cast-mono PERC technologies. The main driver for this smaller carbon footprint lies in the electricity grid mix which powers the chemical vapour deposition (CVD) Siemens bell reactors for poly-Si production, the ingot pullers for Cz-Si crystallization, and the production of inverter components, electrical installation, and aluminium and steel mounting structures. SMART technology provides a smaller carbon footprint than with Cz for both regions.

The GWP results for PV electricity (Fig. 4) range from 21.63g $CO_2$-eq/kWh for the SMART mono PERC system produced in the EU to 43.32g $CO_2$-eq/kWh for the Cz PERC system produced in China. The GWP advantage of SMART crystallization is a potential reduction of around 9% compared with the established Cz technology for the EU and China regions. Another 45% GWP reduction can be realized by producing the PV systems in the EU instead of China.

## Effects of a carbon pricing

Up to now, there have been at least 45 countries worldwide that have implemented a national carbon tax and/or an emissions trading system (ETS) initiative [13]. European countries were the first to establish such practices, and now the EU commission is discussing the introduction of a broad border carbon tax for the whole region [14].

As the EU's PV industry cost structure and prices already take into consideration carbon allowances, the introduction of a border carbon tax is expected to have a maximum effect on imported goods from China. In Fig. 5 the effect of a varying carbon price on the differential $CO_2$-eq costs of a PV module is shown for both cases – a Cz system as well as a SMART mono PERC system.

A border carbon tax introduced by the EU will certainly help as a ground leveller for local PV manufacturers. Goods produced by energy-intensive industries in the EU have already been facing 'carbon taxes' since 2005 by the cap-and-trade EU emissions trading system (EU ETS) [15], where they need to acquire emission allowances

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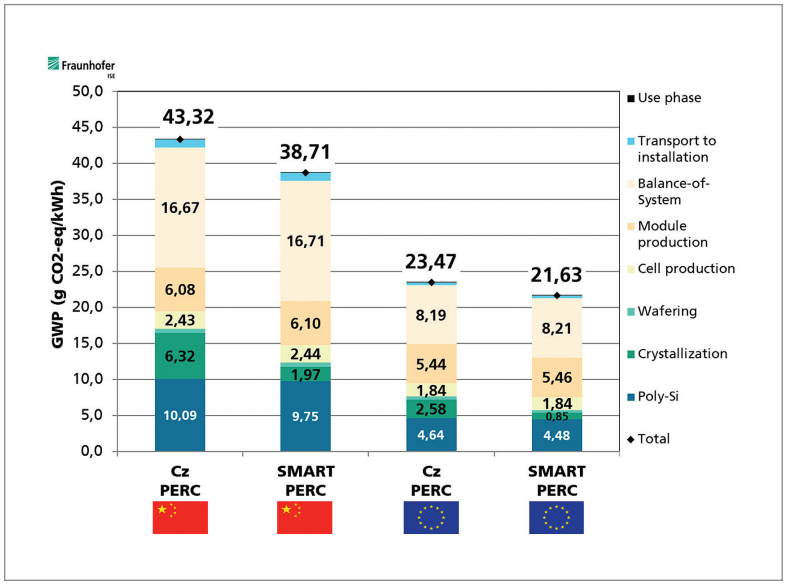


**Figure 4. Global warming potential (GWP) of PV electricity generated by 15kWp Cz and SMART mono PERC systems, produced in CN and the EU, and installed on a rooftop in an average European location with a 30-year lifetime and 29.25MWp lifetime electricity generation. GWP is calculated with IPCC 2013, 100 years.**

"The introduction of a border carbon tax is expected to have a maximum effect on imported goods from China."

for a current market price of ~€34/kg³ $CO_2$-eq [16,17] (which will increase in future years). On the other hand, goods imported into the EU enjoy the luxury of being sold without assuming any carbon levy if this has not already been imposed by the country of origin of the goods and components production.

As China is already in the process of establishing a national ETS [18], a compensation system between the EU and China will have to be designed in the near future.

## TCO assessment

The TCO results presented account for all fixed, operational, maintenance and yield loss costs over the life of the range of equipment needed to produce the PV systems and their components for the selected regions. As can be seen in Fig. 6, the net costs of modules from China, including shipping costs to Europe, are lower than the costs of those from the EU by ~1.9€ct/Wp, for both Cz and SMART. The competitive advantages behind this are to be found in the economies of scale for consumables, electricity prices, labour costs and non-carbon-related levies. Wider differences are found in the wafer and module production step costs. The costs of PV modules with SMART technology are slightly higher than the ones with Cz; this is explained by a net increase in costs due to labour costs versus electricity saving costs.

If we now consider and implement a carbon border tax for PV modules imported into Europe similar to the already existing EU emission trading system, and assume a future carbon price of around €100/10³kg, the differential costs of these two taxes need to be paid on top for the Chinese modules. In reality, the carbon border tax needs to be paid for the full carbon-equivalent emissions of the Chinese module and the full carbon-equivalent emissions of the European module.

The corresponding additional cost of PV modules will increase the net production costs of

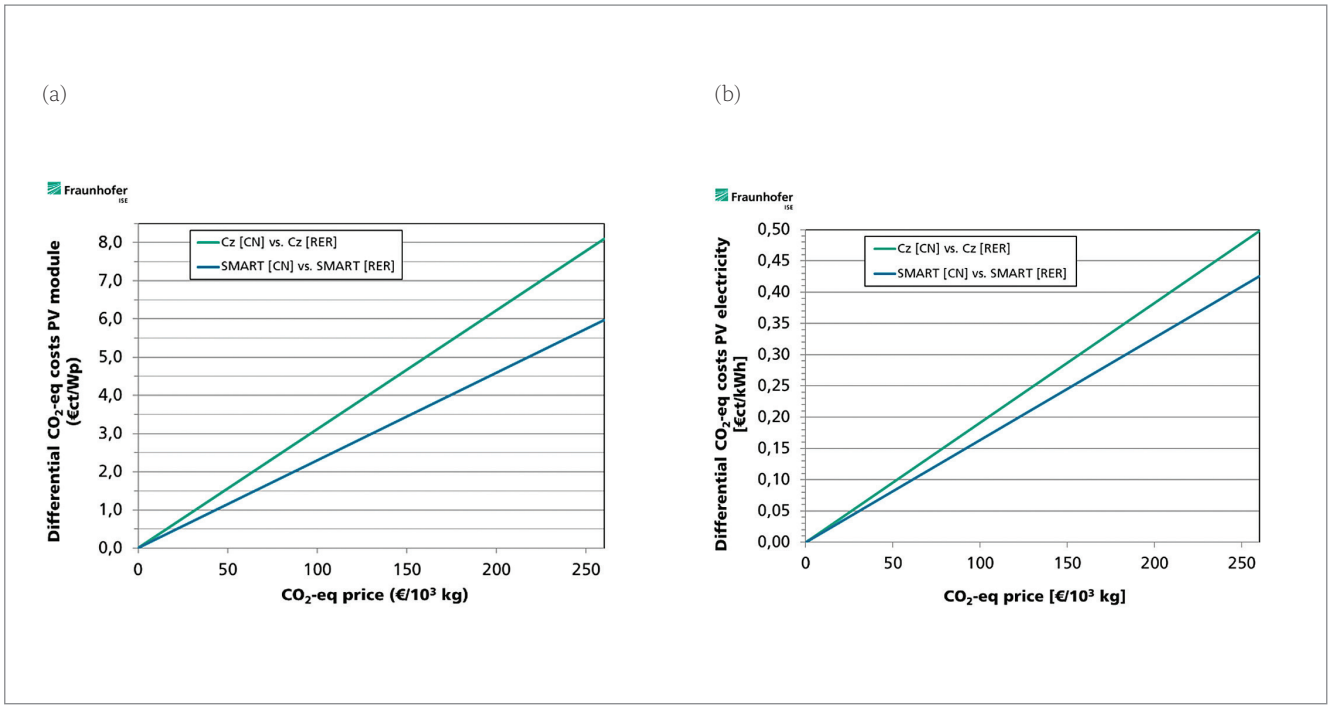


**Figure 5. Cost difference of (a) PV modules and (b) PV electricity generated by PV systems produced in CN and the EU (RER) and installed in an average European location, taking a carbon pricing of the EU into account.**

Cz PERC and SMART PERC modules from China by 15% and 11%, respectively, and will certainly level the competitive playing field for European producers (see Fig. 7).

## Conclusion and outlook

The enormous PV market growth expected for the next decade will consume high amounts of raw materials and energy in the production process. It is therefore preferable to achieve this growth with an environmental impact and energy consumption as low as possible in order to achieve a rapid decarbonization of the energy sector in accordance with the Paris Climate Agreement.

The main driver for a smaller carbon footprint lies in the electricity grid mix, especially within the energy-intensive production steps such as poly-Si and ingot manufacturing. The environmental advantage of producing a PV system in Europe is highlighted by a 45% GWP reduction compared with a PV system made in China.

Furthermore, with the right technology choice, the carbon footprint of the production chain can even be improved by using SMART cast-mono silicon wafers in comparison to Cz silicon wafers for the production of PERC solar cells. With SMART crystallization, an additional GWP benefit of a potential reduction of around 9% compared with the established Cz technology for both the EU and China regions can be realized.

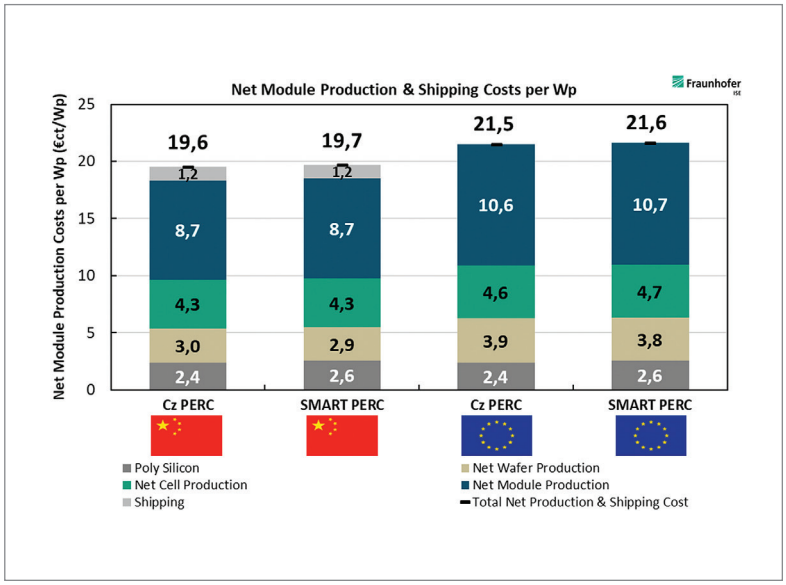


**Figure 6. Net module production costs for Cz and SMART mono PERC PV modules produced in CN and the EU. Shipping costs from China to Europe for the whole module are 1.2€ct/Wp. Production processes are modelled bottom up for a total production capacity of 5GW and assessed using a total-cost-of-ownership (TCO) approach. Polysilicon costs are modelled with an average world market price of €10/kg.**

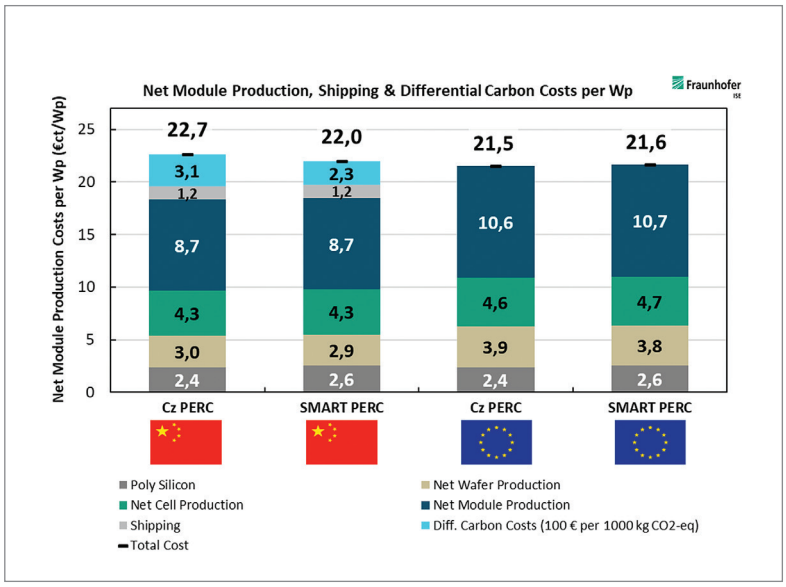


**Figure 7. Net module production costs for Cz and SMART mono PERC PV modules produced in CN and the EU, including a differential carbon cost for a future carbon price of €100/10$^3$kg.**

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