Photovoltaics Equipment

International Technology Roadmap for Photovoltaics (ITRPV)

2024 Results

16. Edition, May 2025

International Technology Roadmap for Photovoltaics (ITRPV)

Results 2024

Sixteenth Edition, April 2025

Content

1. Executive Summary

The photovoltaic (PV) industry needs to provide power generation products that can compete with both conventional energy sources and other renewable energy technologies. An international technology roadmap can help to identify trends and to define requirements for necessary improvements. The aim of the International Technology Roadmap for Photovoltaics (ITRPV) is to inform suppliers and customers about anticipated technological trends in the crystalline silicon (c-Si) based PV industry and to stimulate discussions on required improvements and standards. The objective of the roadmap is not to recommend detailed technical solutions for identified areas which need improvement, but instead to emphasize to the PV community the need for improvement, to formulate requirements to meet and to encourage in this way the development of comprehensive solutions. The present sixteenth edition of the ITRPV was jointly prepared by 49 leading international poly-Si producers, wafer suppliers, c-Si solar cell manufacturers, module manufacturers, PV equipment suppliers, and production material providers, as well as research institutes and consultants. The present publication covers the entire c-Si PV value chain from crystallization, wafering, cell manufacturing to module manufacturing, and PV systems. Significant parameters set out in earlier editions are reviewed along with some new ones, outdated parameters are omitted and discussions about emerging trends in the PV industry are reported. This year's publication is the 16th edition of the report, demonstrating 16 years of successful service to the PV community. For the first time, data surveying from contributors, analysis, and result generation is performed by a new developed digital platform that automates the process. Apart from increasing productivity of the process, it provides exclusive interactive user experience features for contributors and VDMA members companies. The roadmap is still offered in its traditional format as a document available for download.

The global c-Si cell and PV module production capacity at the end of 2024 is assumed to have further increased to levels above 1,500 GWp due to continued capacity expansions [1]; a market share of about 98% for the c-Si and about 2% for thin-film technologies is considered [2]. The PV module market in 2024 showed again an unprecedented growth of around 703 GWp [3].

The c-Si module market finally shifts completely to mono-Si. The implementation of innumerable new module products, dominated by M10, and G12 wafer formats with their rectangular variants together with bifacial module technology, continued. The weighted average spot market price of c-Si modules at year end 2024 dropped by 33% compared to the end of 2023. Considering year on year rate, the price reduction is even 35% [4]. This tremendous price drop is largely as a result of market conditions of overcapacity in the module market, despite technological development that also plays a role. Almost all c-Si based products experienced price reductions and price premiums for high power, bifacial or n-type modules are gone.

Efficiency improvements in the fast rolled out n-type based tunneling oxide passivated contacts (TOPCon) products, and the deployment of rectangular and larger wafers in larger modules resulted in higher average module efficiency values. The use of larger wafers in G12 format enabled module power classes of up to 720 W [5]. Construction of new cell and module capacities in 2024 continued the shift from passivated emitter and rear side (PERC) to the n-type based TOPCon and silicon heterojunction (SHJ) devices. For the first time TOPCon market share exceeded that of PERC. All new plants can process large cell formats just from the beginning. The price experience curve continued with its historic learning; the new calculated learning rate (LR) is 25.6%. Maintaining the LR up over the next years requires cost reduction measures and implementation of cell perfections, with improved wafer material, improved cell front and rear sides, refined layouts, the intensive deployment of bifacial cell concepts, improved module technologies as well as with the introduction of new cell technologies. Different cell formats contribute to PV system cost reduction. Improvements in all fields will result in module area efficiency increase: today's n-type based modules with TOPCon, SHJ, or interdigitated back contact (IBC) technologies show module efficiencies of 23.2%, 23.6% and 23.8% respectively. Also, p-type mono-Si based PERC modules reach efficiencies of up to 21.7%. In the upcoming 10 years, module efficiency is expected to increase up to 26% for single junction cell technology based modules. Si-based tandem cells can enable to go even beyond this value. Tandem cells and modules are expected to enter mass production around 2027, starting with module efficiencies of about 26.9%. The combination of optimized manufacturing costs and increased cell and module performance will support the reduction of PV system costs and thus ensure the long-term competitiveness of PV power generation. We experience nowadays that the PV industry is growing into a multi-TW market as projected by previously discussed scenarios in former editions. All those aspects are again discussed in this revision of the ITRPV.

In its 16th edition VDMA Photovoltaics Equipment sector group continues the roadmap activity, and updated information will be published annually to ensure comprehensive communication between manufacturers, suppliers, R&D institutes and consultants throughout the value chain. The scope of the topics is redefined in discussion with the steering committee leading to a more compact version by updating the presented core parameters. More information about the roadmap and the new digital interactive product access our webpage itrpv.vdma.org.

2. Approach

The main c-Si technology value chain elements wafer, cell, and module are discussed in three areas: materials, processes, and products. Data was collected from the participating companies and processed anonymously by VDMA. The participating companies jointly agreed that the aggregated results are reported in this roadmap publication. Plotted data points of the parameters reported are median values generated from the input data of all contributors if not separately indicated otherwise. For a few designated topics, the input of GW-scale manufacturers only is considered, mainly due to the impact of these companies on respective market shares. In addition to the discussion of parameters linked to crystallization, wafers, cells, modules, we look at the impact and trends for PV systems. For the first time the data collection, analysis and publication are also done using a digital interactive product with additional user experience features with exclusive use for contributors and VDMA member companies.

2.1. Materials

The requirements and trends concerning raw materials and consumables used for wafer, cell, and module manufacturing are described in these subsections. Reducing the consumption or substitution of some materials will be necessary to ensure availability, avoid environmental risks, reduce costs, and increase efficiency. Price development plays a major role in making PV-generated electricity competitive with other renewable and fossil fuel-based sources of energy.

2.2. Processes

New technologies, new materials, and highly productive manufacturing equipment are required to reduce production costs. Information about key production technologies is provided with discussions about process parameters to optimize the wafer production, to increase cell and module efficiency as well as module power output. This roadmap constitutes a guide to new developments and aims to support their progress. The subsections on processes identify manufacturing and technology issues for each segment of the value chain. Manufacturing topics center on raising productivity, while technological developments aim to ensure higher cell and module efficiencies.

2.3. Products

Each PV value chain element contributes to final products. The products subsections therefore discuss the anticipated development of the value chain elements ingot, wafer, crystalline silicon solar cell, and module over the upcoming years.

3. PV Learning Curve

It is obvious that cost reductions in PV production processes will also result in price reductions [6]. Fig. 1 shows the price experience curve for PV modules, displaying the average module sales prices - at the end of the corresponding period - (in 2024 US$/Wp) as a function of cumulative module shipments from 1976 to 12/2024 (in MWp) [3, 7]. Displayed on a log-log scale, the plot changes to an approximately linear line until the shipment value of 3.1 GWp (shipments at the end of 2003), despite bends at around 100 MWp. This indicates that for every doubling of cumulative PV module shipment, the average selling price decreases according to the learning rate.

Considering all data points from 1976 until 2024 we found an LR of about 25.8%, again an increase compared to the 24.9% in the 15th edition. The large deviations from this LR plot in Fig. 1. are caused by market fluctuations between 2003 and 2012 as well as in 2016 and 2018. Particularly in 2023 but also 2024 a strong drop of price is observed.

Learning curve for module price as a function of cumulative shipments

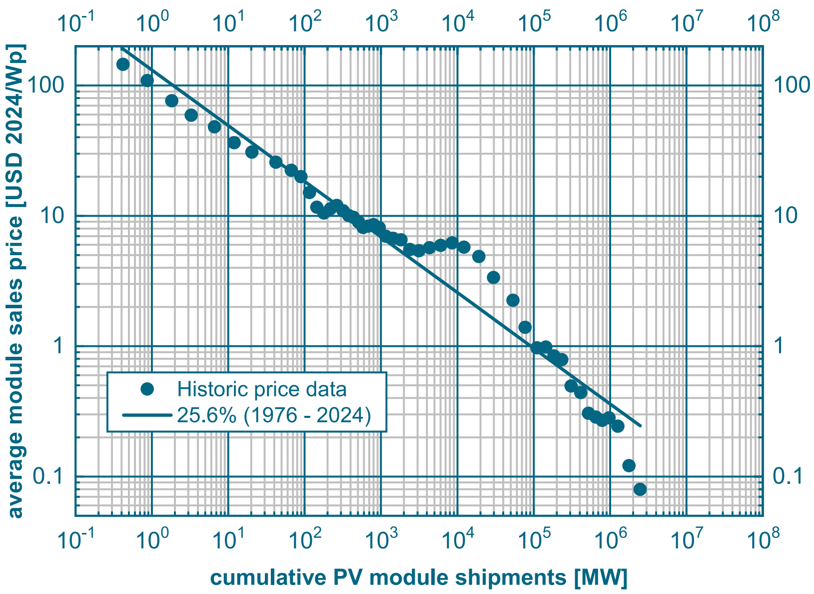

Fig. 1: Learning curve for module spot market price as a function of cumulative PV module shipments.

The last data point indicates the module shipment volume and average spot market price at the end of 2024. The 2024 shipment volume was calculated to be 703 GWp - Installation of 566 GWp plus 137 GWp not yet installed (i.e. in warehouses, at customers, and in transit) until year end. Estimated oversupply alone in Europe is assumed to be about 60 GW [8]. Based on this data the cumulative shipped module power at the end of 2024 was calculated to be 2,472 GWp. The corresponding worldwide installed cumulative module power by the end of 2024 is 2,176 GWp after 1,610 GWp in 2023 [3]. The calculated average module spot market price at the end of 2024 is 0.08 US$/Wp, a drop from 0.118 US$/Wp at year end 2023.

Module production capacity at the end of 2024 is assumed to be about 1,600 GWp due to continued capacity expansions [1]. So, the PV module market showed again unprecedented growth to 703 GW. All crystalline silicon -based products experienced a price reduction and price premiums for high power, bifacial and n-type modules are nearly gone.

Publicly available price data report mono-Si standard module prices, prices for poly-Si, cells, and modules for different wafer formats M10 and G12 including bifacial modules (both for p-type and n-type devices). Based on this data for c-Si technology based modules, nearly no clear price difference between PERC and TOPCon as well as M10 and G12 wafer size base modules respectively is visible anymore.

The average module prices are calculated based on the year end values of 2024 in [9]. So, we calculated 0.0795 US$/Wp as weighted average spot market price for c-Si modules at year end of 2024.

The non-silicon module manufacturing costs are mainly driven by consumables and materials as discussed in the c-Si PV module cost analysis in the 3rd edition of the ITRPV [10]. The prices also stayed high in 2024. Achieving cost reductions in high price consumables like silver, aluminum, and other non-silicon pre-cursor materials will remain challenging but must be continued. Improving productivity, product performance, focusing on innovation, cost optimization, and rigorous quality assurance will be key for the inevitable success of the PV industry [8].

The known three strategies, emphasized in former ITRPV editions, help to address this challenge:

- Improve module area efficiency without significantly increasing the processing cost.
- Continue the cost optimization per piece along the entire value chain by increasing the Overall Equipment Efficiency (OEE) of the installed production capacity. This takes place by implementing upgrades and new production capacities to use silicon and non-silicon materials more efficiently and ensuring higher OEE.
- Introduce specialized module products for different market applications (i.e., tradeoff between cost-optimized, highest volume products and highest efficiency, higher price end-customer applications or even fully customized niche products).

The first point implies that continuous cell efficiency improvements need to be implemented not only with creative wafer formats but in parallel with new module concepts to further improve the module area efficiency. To enable cost-efficient manufacturing this must be implemented with lean processes to optimize capital expenditure. Introducing totally new, immature technologies that do not show potential reductions of the cost per Wp from the beginning will remain challenging.

4. Results of 2024 | Crystallization and Wafering

4.1. Materials

Polysilicon (Poly-Si) is the most expensive material of c-Si solar cells. According to the results, Siemens is expected to keep today's mainstream position as a silicon feedstock technology.
Fluidized Bed Reactor (FBR) process will remain the second technology of choice to produce poly-Si as for today's projections. Other technologies with a more direct method of purification have no significant role in market share.

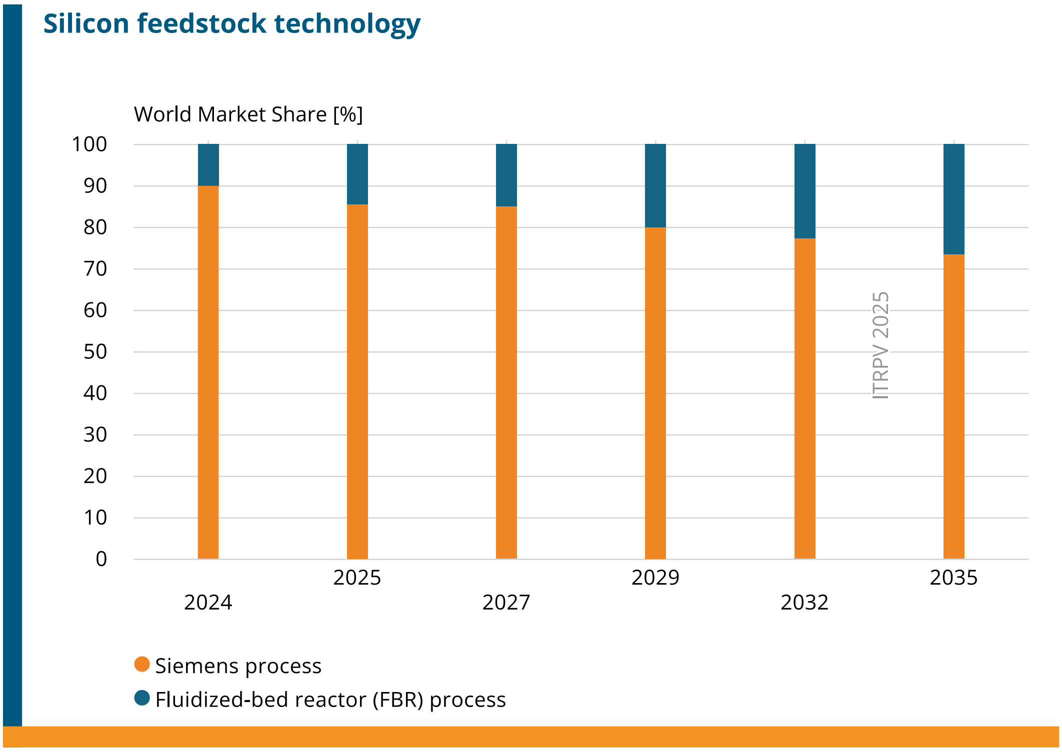

Fig. 2: Expected world market share of poly-Si feedstock technology.

Based on our results, the market share of FBR poly-Si was about 10% in 2024 as shown in Fig. 2. This share is expected to increase to around 26% within the next 10 years against the mature and further optimized Siemens process. This is close to the findings in [11].

Fig. 3 shows the average consumption of poly-Si to produce silicon wafers. It is projected that all wafer formats will consume significantly less silicon within the next 10 years. Expected reductions are in the range of 24% for M10 and about 27% for G12, respectively. This reduction will be realized by improving the yields in crystallization and wafering, by further reduction of kerf loss, and, most importantly, by further thickness reduction as shown in Fig.6 and Fig.7.

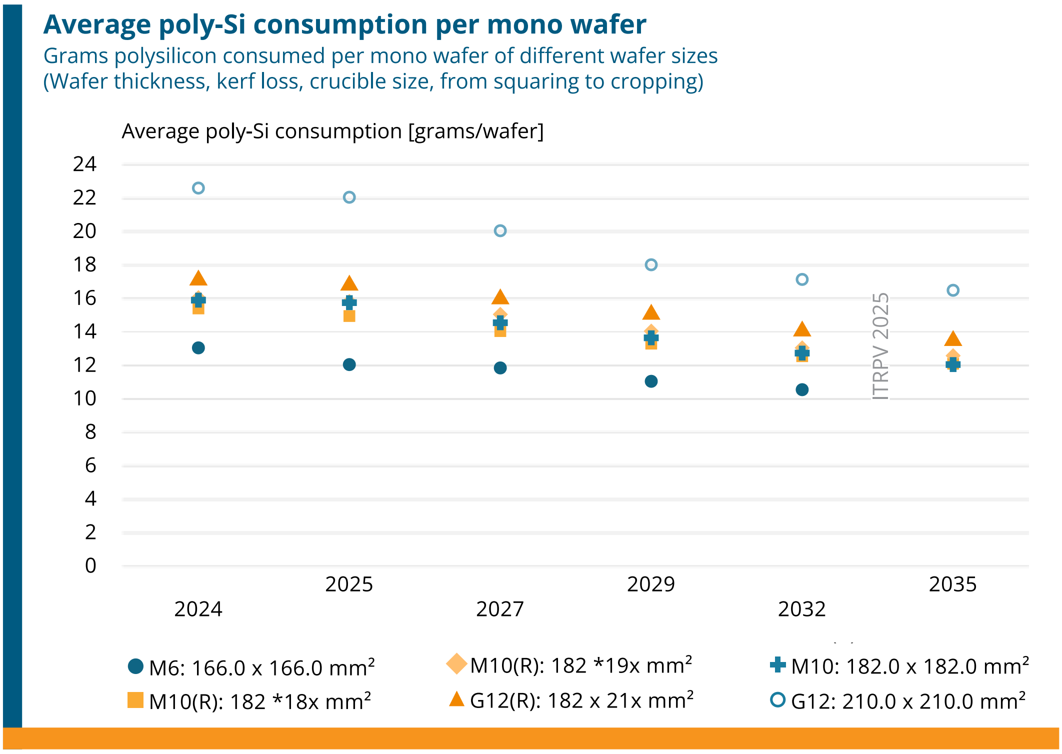

Fig. 3: Average poly-Si consumption for mono-Si wafers with different wafer formats.

Fig. 4 shows the poly-Si consumption per Wp of n-type wafers for TOPCon cells of the corresponding wafer sizes.

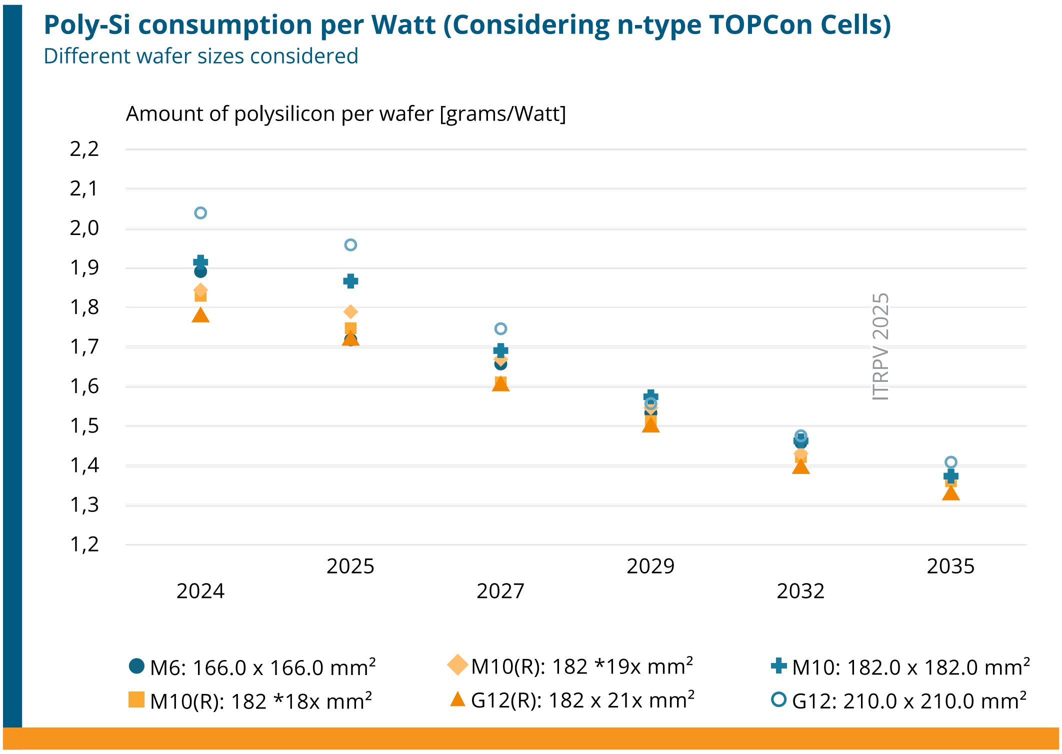

Fig. 4: Average poly-Si consumption per Wp for mono-Si wafers with different wafer formats.

Cell power is calculated according to the cell efficiency trend for TOPCon cells in this report as shown in Fig. 43. Consider the dominant wafer formats M10 *(R)* and G12 *(R)*, the trend in Fig *4*. shows that, based on current assumptions, M10 wafers consume lower poly-Si per generated power than G12 and G12 *(R)* is found to have the lowest consumption per Wp. Anyhow, the difference between all formats is expected to be reduced with time. This emphasizes that larger formats can realize their benefits not only in levelized cost of electricity (LCoE) but also on a module cost per Wp level. In 10 years, the poly-Si consumption will be around on average 1.41 g/W for the G12, 1.37 g/W for M10, and 1.32g/W for G12 (*R)* respectively.

4.2. Processes

4.2.1. Crystallization

It is possible to increase the throughput of the crystallization process by changing the common sizes of the ingots and by growing more crystals with the same crucible. The trends to larger ingot mass as discussed in former ITRPV editions continue. Czochralski (Cz) growth with recharging is the main-stream technology in crystallization.

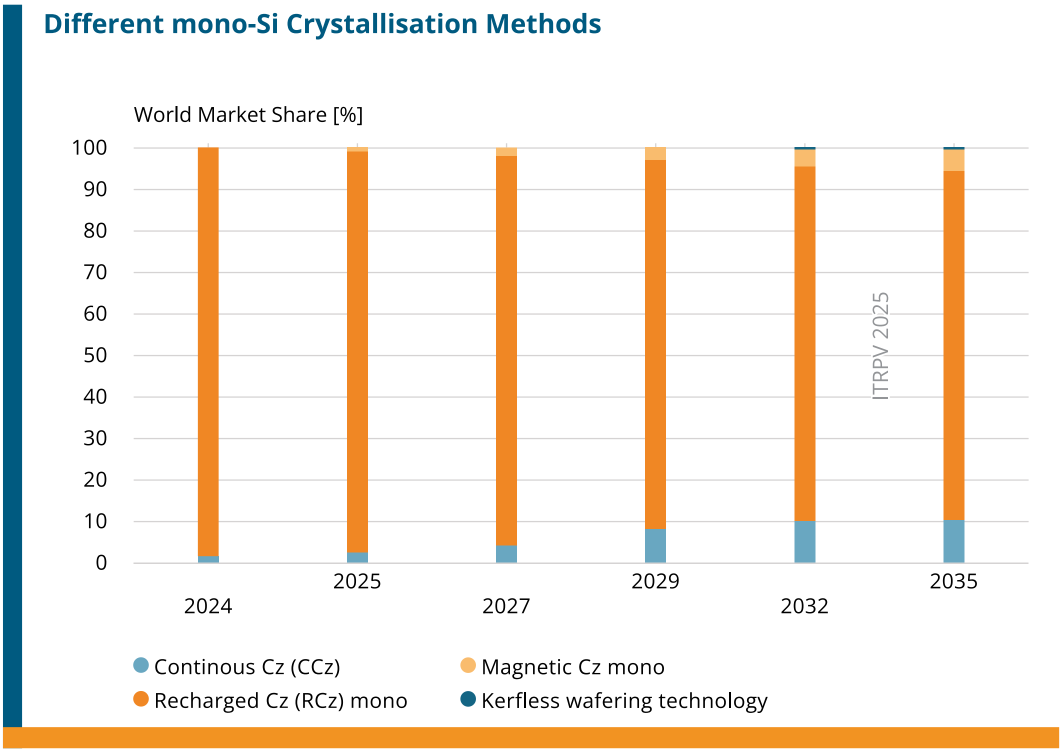

Fig. 5: Different mono-Si Crystallization methods.

Fig. 5 shows the market share of different methods for mono-Si ingot crystallization. There is a clear market dominance of recharged Cz ingot crystallization. The continuous Cz process is expected to gain market share reaching around 10% in 2035. Magnetic Cz is introduced in mass production starting from 2025. With its potential to eliminate further impurities and potential of longer crucible lifetimes, it is expected to gain gradually market share, reaching around 5% in 2035. It is however clear that continuous Cz, with the particular RCz will dominate the market share. It is also worth mentioning that according to the survey by 2032 kerfless wafering technology will be a niche application in the market with about 0.5% market share.

4.2.2. Wafering

The advancements of diamond wire sawing (DWS) for mono-Si wafering, guaranteed a significant improvement in terms of wafering process stability and cost reduction. So DWS is mainstream in wafer slicing. Since its introduction, DWS has enabled significant reductions of the kerf width and contributed therefore to the improved usage of poly-Si, as discussed in chapter 4.1.

The shift was enabled by the fast improvement of appropriate wet chemical processes for saw damage removal and texturing. Based on the results of our report, kerfless wafering technologies are still not seen to contribute to the market share significantly. DWS is the mature technology.

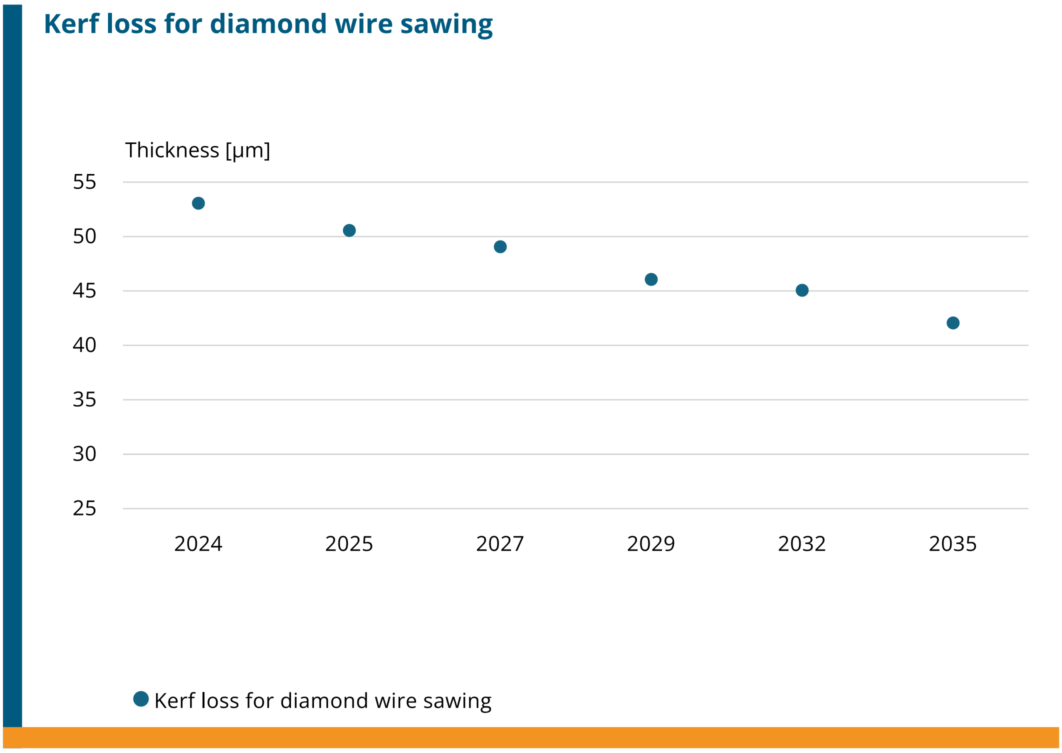

Fig. 6: Trend of Kerf loss in diamond wire sawing (DWS) for of all wafer formats.

Fig. 6 and Fig. 7 describe the trend for kerf loss and for Total Thickness Variation (TTV) respectively for larger than M10 and less than or equal to G12 wafer format. In 2024 a kerf loss of 53 µm was observed. Large wafer formats also benefit from this trend. The kerf loss is predicted to decline down to 42 µm within the next 10 years. TTV of 10 µm in 2025 is expected to be reduced to 7.5 µm until 2035.

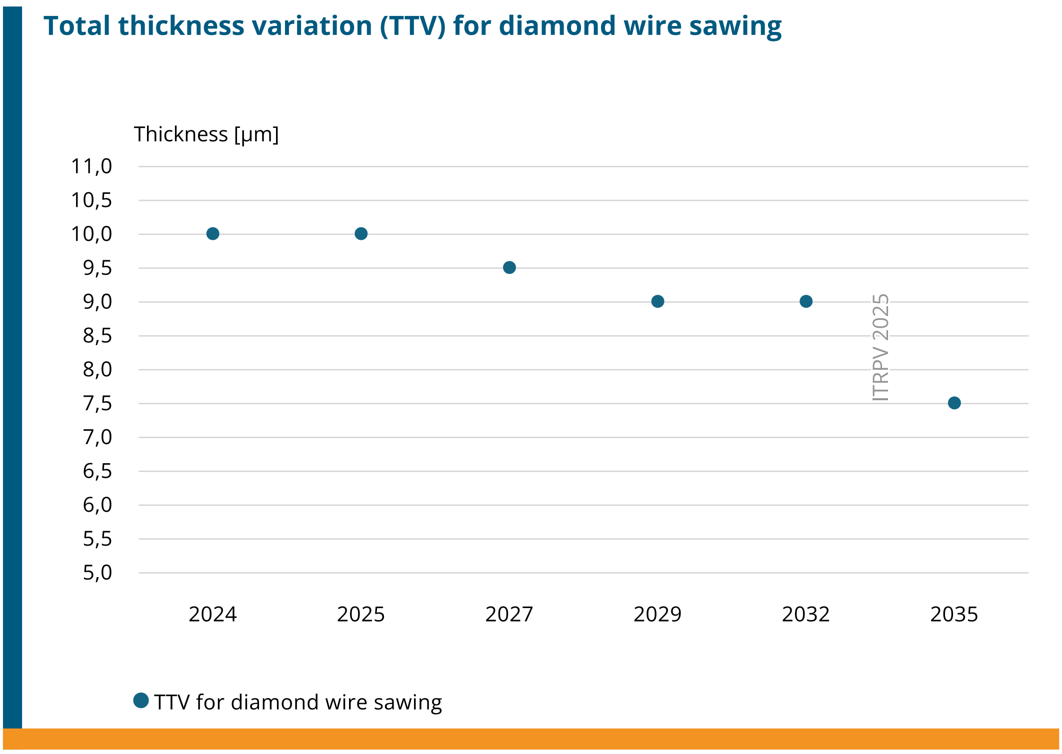

Fig. 7: Trend of Total Thickness Variation (TTV) in diamond wire sawing (DWS) for of all wafer formats.

Thinner wafers, reducing kerf loss, increasing recycling rates, and reducing the cost of consumables, will yield in cost savings. Wire diameters will be reduced continuously and there will be more recycling of silicon and diamond wire over the next years. Increased tool throughput is expected to improve productivity in crystallization and wafering on top of the yield enhancements by reduced kerf loss. This contributes to further total cost optimization. All technologies are expected to realize between 10% and 30% throughput increase within the next 10 years. Kerfless wafer manufacturing approaches are are not expected in mass production before 2032 as shown in Fig. 5.

4.3. Products

Using poly-Si as efficient as possible has been key for further cost reduction for c-Si cells and modules especially during phases of high prices as for example in 2021. Although this is not the situation currently with the extremely low poly-Si prices these days, reducing the as-cut wafer thickness is still a main method to save costs.

Fig. 8 shows the expected trend for minimum as cut wafer thickness for p- and n-type as cut mono-Si wafers for different wafer sizes and expected cell technologies. Since 2020 we have been watching that mono-Si wafer thickness reduction is going further, even ahead of the trend shown in the 12^{th} edition of the ITRPV. In 2024, a wafer thickness of 145 - 150 µm was the standard for p-type mono wafers of all wafer dimension. A minimum wafer thickness of 95 µm is expected for SHJ wafers in 2035. For n-type TOPCon cells the thickness expected in 2035 is between 110 and 115 µm, as shown in Fig. 8.

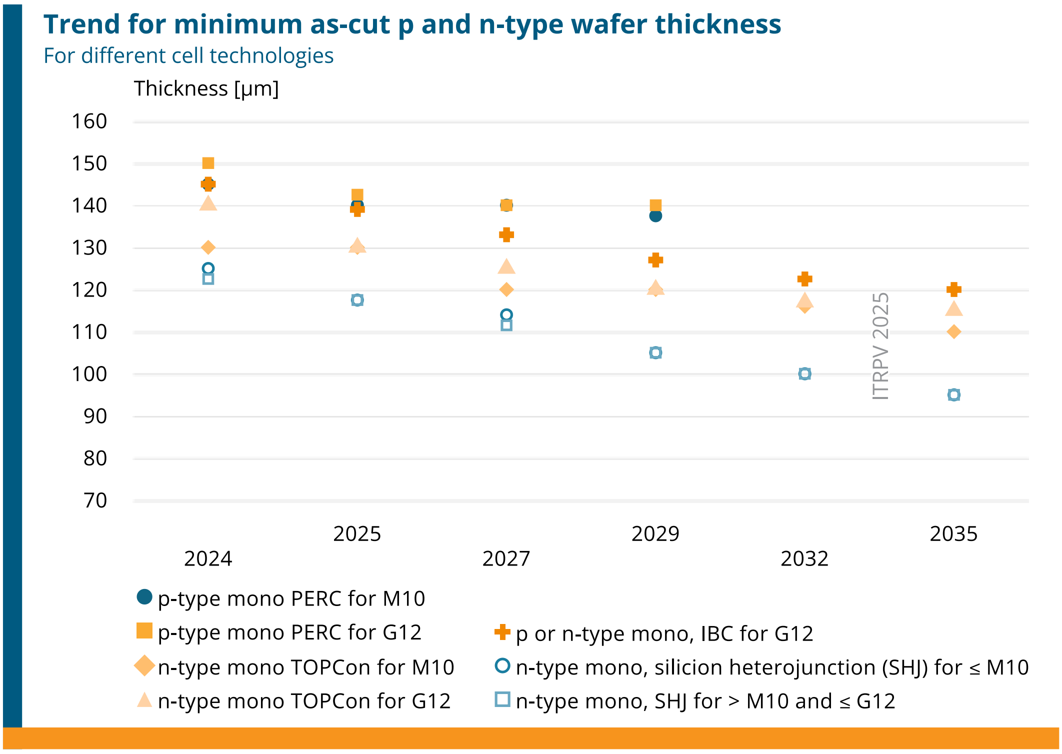

Fig. 8: Predicted trend for minimum as-cut wafer thickness for p- and n-type c-Si wafers for different technologies and wafer formats.

Based on the data analyzed, there is no difference anymore between the n-type wafers thickness of M10 and G12. The corresponding cell thickness limit trend in module technology is discussed in chapter 5.

G12 IBC wafers are expected to reach a wafer thickness of 120 µm. P-type wafers are expected to disappear from the market by 2032. SHJ can use lowest wafer thickness: 122 µm in 2024 are expected to be reduced to 95 µm in 2035.

In general, SHJ leads the wafer thickness reduction rate going towards also the thinnest wafers, however with the reduction of wafer thickness topics of bending and handling have to be practically dealt with.

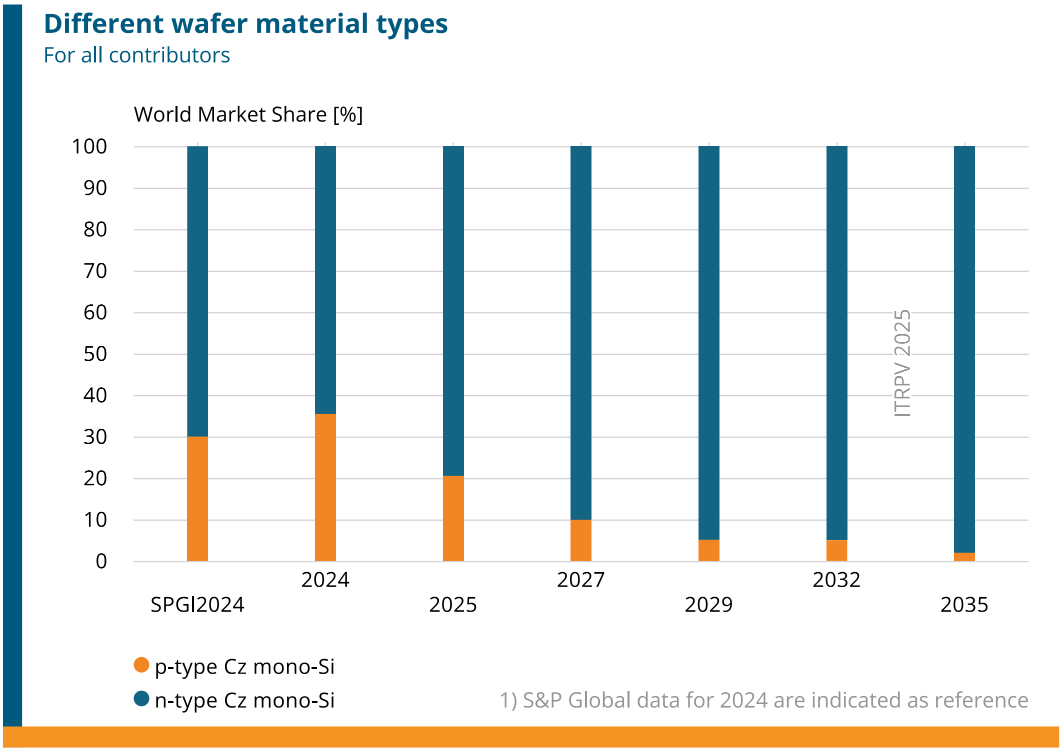

Fig. 9: Market share for different wafer types S&P Global (SPGI) data are indicated for 2024 as reference, [14]. This is a result of the data from all contributors.

Fig. 9 shows the results of the expected market trend for different wafer types from the data collected from all contributors, meanwhile Fig. 10. shows the result from the data of only GW-scale device and equipment manufacturers.

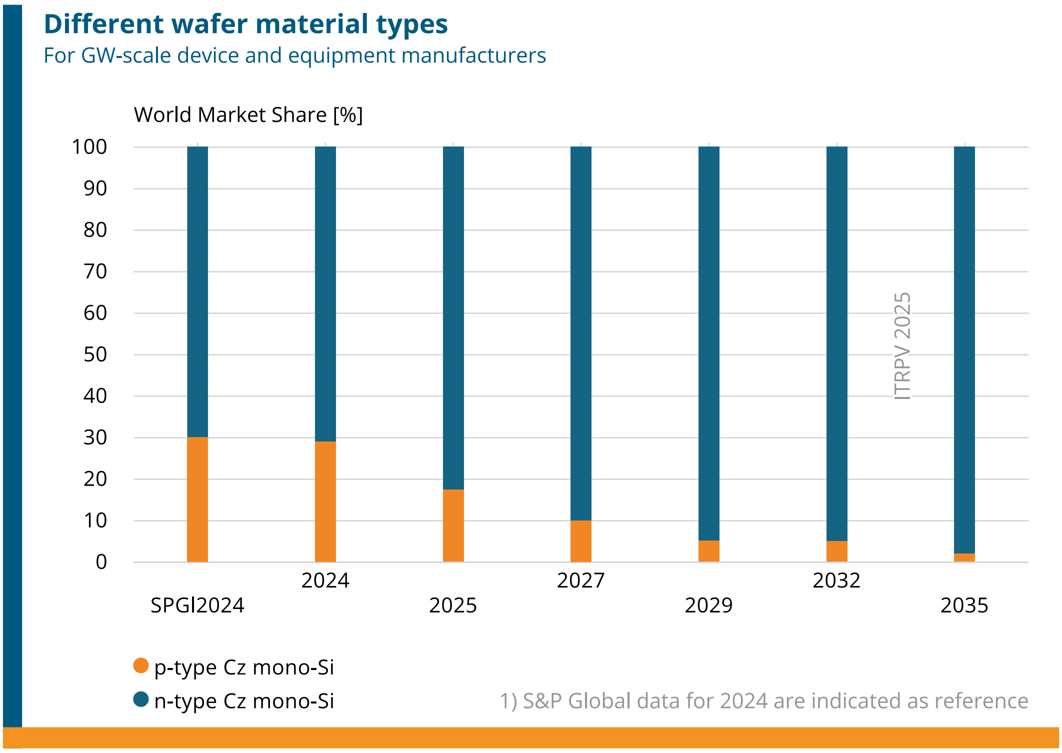

Fig. 10: Market share for different wafer material types S&P Global (SPGI) data are indicated for 2024 as reference, [14]. This is a result of the data only from GW-scale manufacturers.

In 2024, Cz-mono-Si materials only are present in the market, casted materials do not exist anymore. The plotted analysis of S&P Global for 2024 as a comparison shows, that the ITRPV result is close to it. Looking at the data analyzed from GW-scale manufacturers it is even more accordant with the S&P Global analysis [12].

The mono-Si market splits into n- and p-type. The n-type material dominates the market in 2024 with about 70% as predicted in the 15th edition of the ITRPV [13]. That dominance was driven by the very fast transition towards TOPCon. The n-type mono-Si market share is expected to grow to 98% within the next 10 years.

Fig. 11 shows the share of different dimensions for mono wafers. Wafer formats M6 expected to rapidly phase out in 2026. M10 and G12 formats are present in the market with especially rectangular formats, that fit best for rooftop modules, projected to gain shares in the future. Wafers larger than G12 will be present from 2027 onwards according to the results.

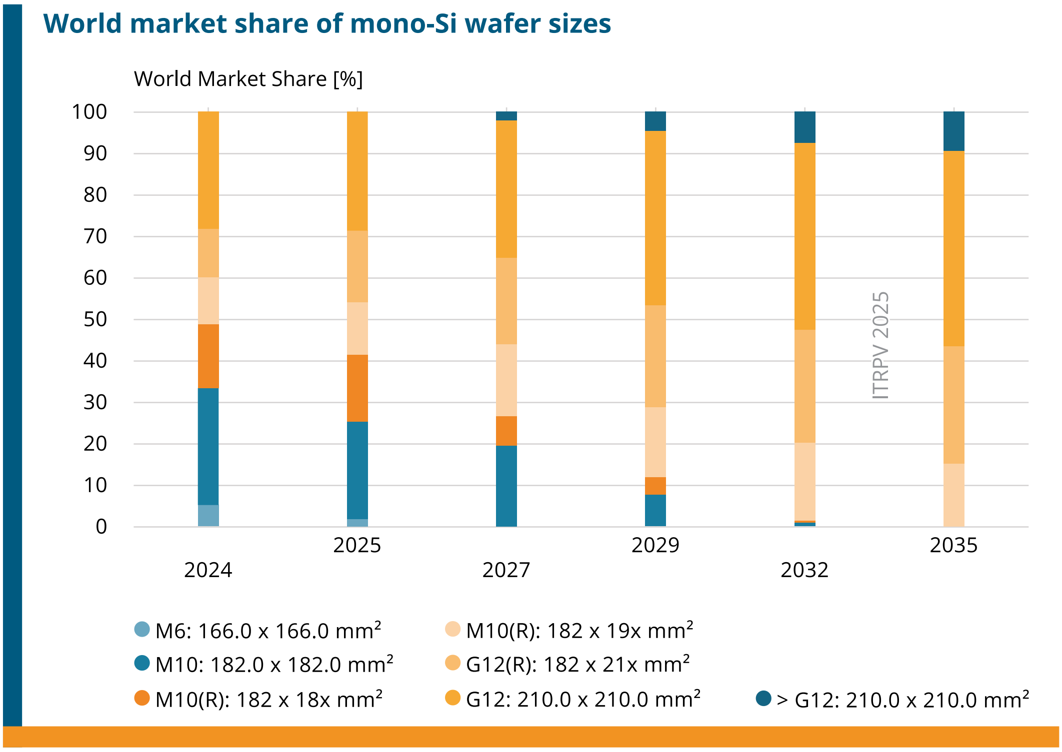

Fig. 11: Expected trend of Cz-mono-Si wafer formats in mass production.

G12 and G12 (R) are expected to cover about 75% of the market by 2035, >G12 format will reach close to 10% and a rectangular M10 format will stay at about 15%. So new built cell lines will be ready for those formats and have to be prepared for even >G12 formats.
The standardization of the different wafer formats is important to enable availability of appropriate production machines and materials like glass and foils for cost-efficient manufacturing of modules. SEMI published a specification for Silicon Wafers for Use in Photovoltaic Solar Cells [14]. In addition, there are activities at IEC for a new wafer standard [15]. M10 based modules have now a standard width of 1134 mm, which facilitates product comparison.

5. Result of 2024 | Cell

5.1. Materials

Metallization pastes containing silver (Ag) and aluminum (Al) are the most process-critical and most expensive non-silicon materials used in current c-Si cell technologies. Paste consumption therefore needs to be reduced.

Fig. 12 shows the report's expectation regarding the future reduction of the silver that remains on 182.0 x 182.0 mm² (M10) cells of different p- and n-type cell concepts after processing.

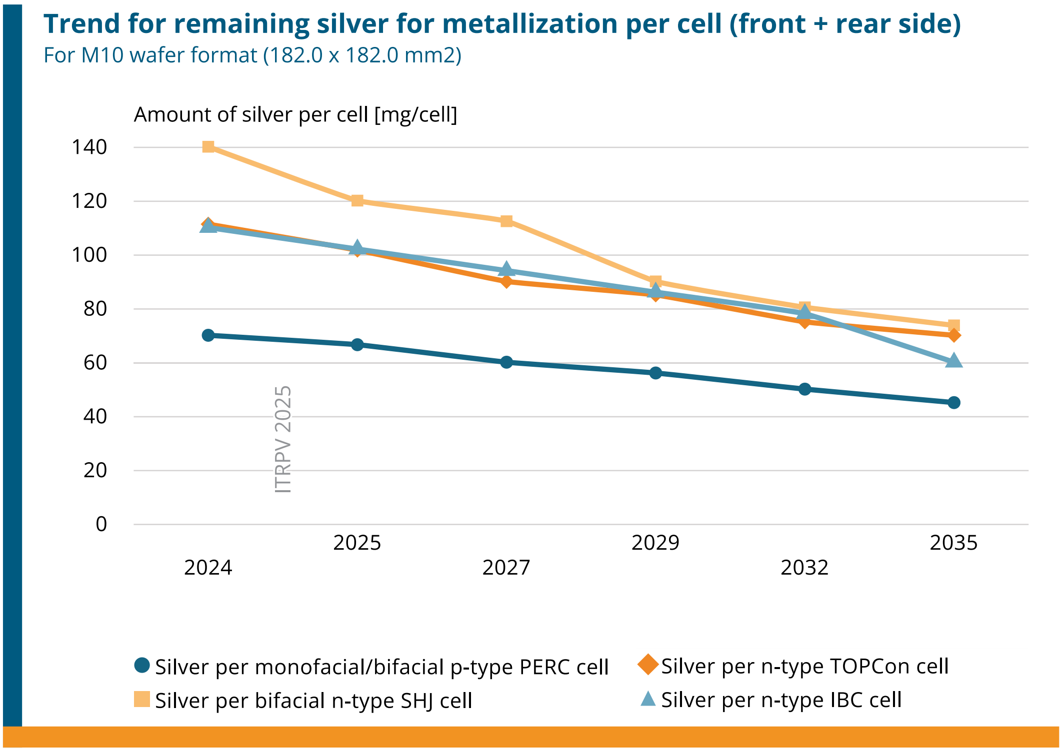

Fig. 12: Trend for remaining silver per cell for different cell concepts in M10 wafer format (182.0 x 182.0 mm²).

The n-type cell concepts have an expected higher silver consumption than p-type PERC. In 2024 PERC on M10 format consumed about 70 mg/cell, TOPCon and IBC consumed around 110 mg/cell and SHJ used about 140 mg/cell. The higher consumption is due to the use of silver for front and rear side metallization in these n-type concepts. The difference between TOPCon and SHJ silver consumption is expected to fade away in the upcoming 10 years.

Fig. 13 shows the reduction trend for silver expected for 210.0 x 210.0 mm² (G12) formats. The cell area increase compared to former editions of the ITRPV does not influence the trend but only the absolute value of the silver amount in mg/cell.

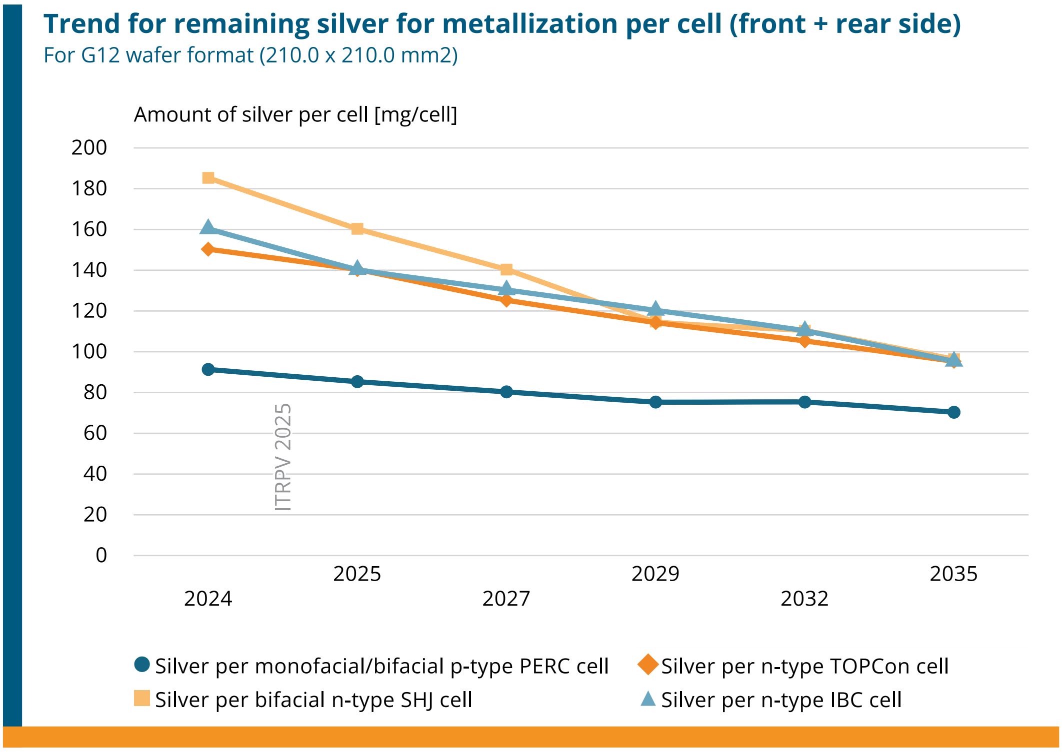

Fig. 13: Trend for remaining silver per cell for different cell concepts in G12 wafer format (210.0 x 210.0 mm²).

To get a better understanding of the Ag consumption, Fig. 14 shows the corresponding average cell level silver consumption per Wp calculated with the expected cell efficiencies according to Fig.43. Values in the unit of mg/Wp is equal to the unit of t/GWp.

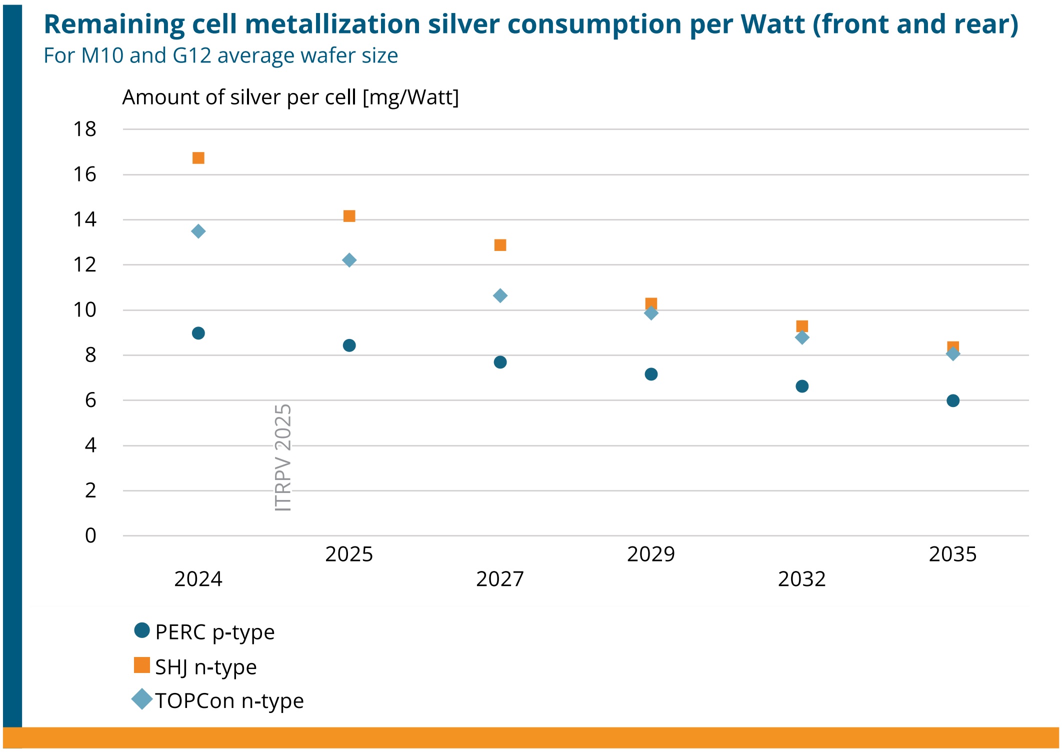

Fig. 14: Remaining silver per Watt cell (values in units of mg/Wp are equal to units of t/GWp).

The reduction of remaining silver per cell will continue during the next years as it plays a strong role in the cost of the cell. The current study found about 9 mg/W on cell level as the median value in 2024 standard PERC monofacial and bifacial cells as average of M10, and G12 format. 13.5 mg/W and 16.7 mg/W are the corresponding values for TOPCon and SHJ respectively.
Moreover, a reduction down to values: 8 mg/W for TOPCon and 6 mg/W for SHJ, respectively is expected to be reached within the next 10 years. New developments in pastes and screens will support this reduction, and this emphasizes again the necessity of a close collaboration between suppliers and cell manufacturers to tackle this challenge.

The silver price is known to fluctuate frequently, which has a direct impact on the cost of pastes and cells. For instance, the silver price in February 2025: 1044.9 US$/kg [16] corresponds to around 1.27 $cent/W per cell. In Spring 2024, the price was around 850 US$/kg.

Because silver will remain cost critical due to the world market dependency, it is extremely important to continue all efforts to lower silver consumption as a means of achieving further cost reductions. 703 GW modules shipped in 2024 contained cells that consumed about 8,616.7 tons of silver, assuming 9 mg/W for PERC, 13.5 mg/W for TOPCon, and 16.7 mg/W for SHJ respectively (assuming a share PERC:TOPCon:SHJ of 35:56:9). This corresponds to about 27.6% of world silver supply in 2024 and a marginally higher than the expected value for 2024 (23%) in the World Silver Survey 2024 edition [17]. So TOPCon consumes still about 50% more than PERC but overall, a reduction was realized, compared to the findings in the ITRPV 15th edition [13]. However, the continued reduction in silver consumption is essential to meet future production and cost targets for c-Si PV and also decoupling to a certain extent from the silver price fluctuations.

On top of a continuous reduction of silver consumption at the cell manufacturing level, silver replacement is still on the agenda. Copper (Cu), as less expensive material, applied with plating technologies or even with silver coated copper as another approach is of high interest. The latter is mainly targeting the SHJ cell concepts. Plating is still not introduced in a significant mass production market share. In general, copper is already being used in SHJ more in the form of adapted pastes. For particularly SHJ solar cells we will see an increase in market share of copper-containing metallization, based on our results as shown in Fig 15.

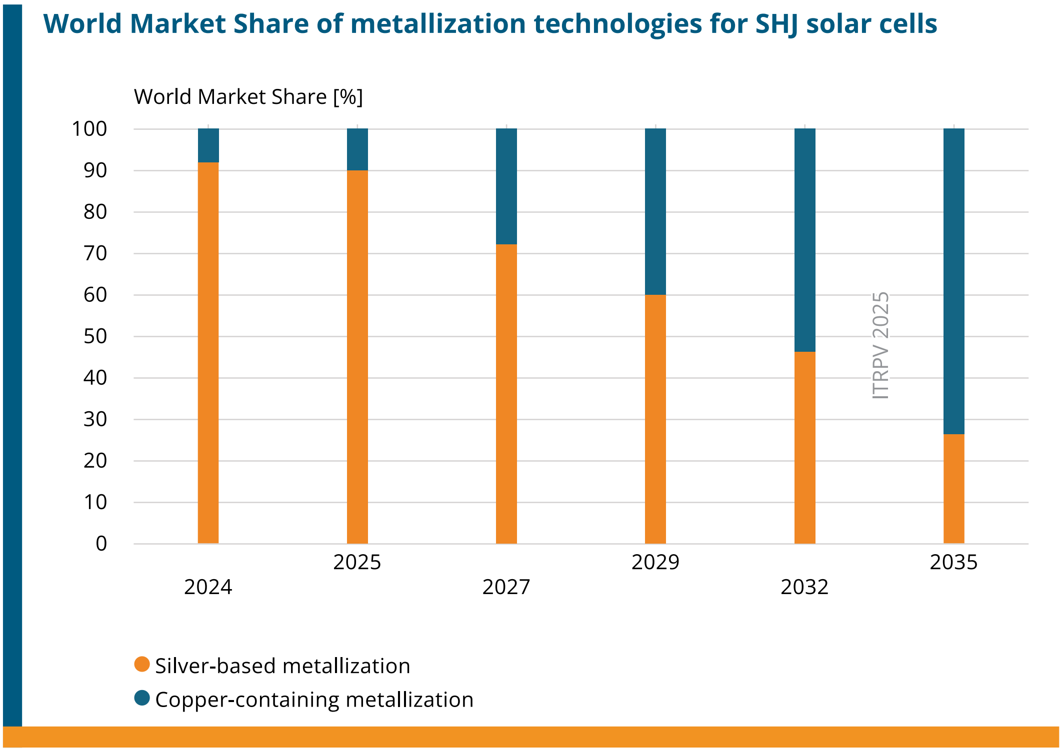

Fig. 15: Market share of metallization for SHJ solar cells.

SHJ cells already use lead free pastes. As shown in Fig. 16, lead free pastes are expected to increase in the mass production share of non SHJ c-Si cells as well.

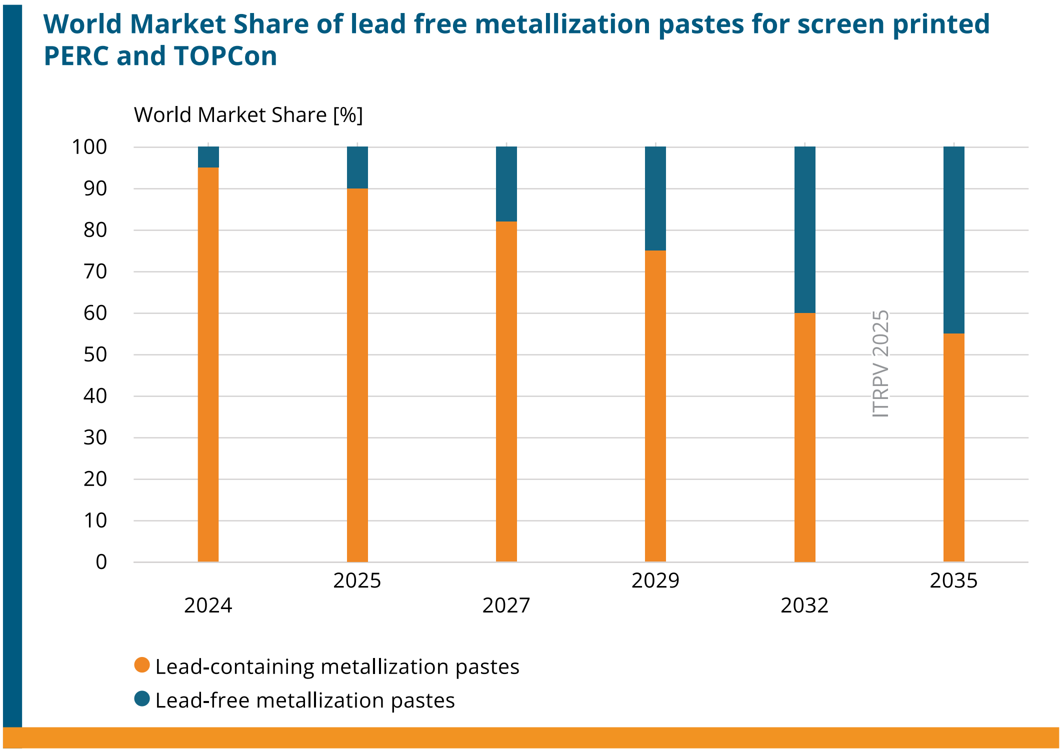

Fig. 16: World Market Share of lead free metallization pastes for PERC and TOPCon cells.

5.2. Processes

The first production process in cell manufacturing is texturing. Reducing reflectivity is mandatory to optimize cell efficiency. Mono-Si cell texturing is done with alkaline etching using KOH with additives. This technology is reliable with high throughput batch processing tools.
Solar cell recombination losses on the front and rear sides of the cell, as well as recombination losses in the c-Si bulk material, must be reduced in line with high-efficiency cell concepts. The recombination currents J0bulk, J0front, J0rear, indicating the dark saturation current density values in the volume, on the cell's front and rear side respectively, are a reasonable way to describe recombination losses, leading to efficiency losses. Fig. 17 and Fig. 18 show the expected recombination current trends for p-type and n-type materials, respectively. The values are in line with the assumptions of former ITRPV editions. Recombination currents can be measured as described in literature [18], or they can be extracted from the I-V-curve if the other J0 components are known.

Dark saturation current density for p-type

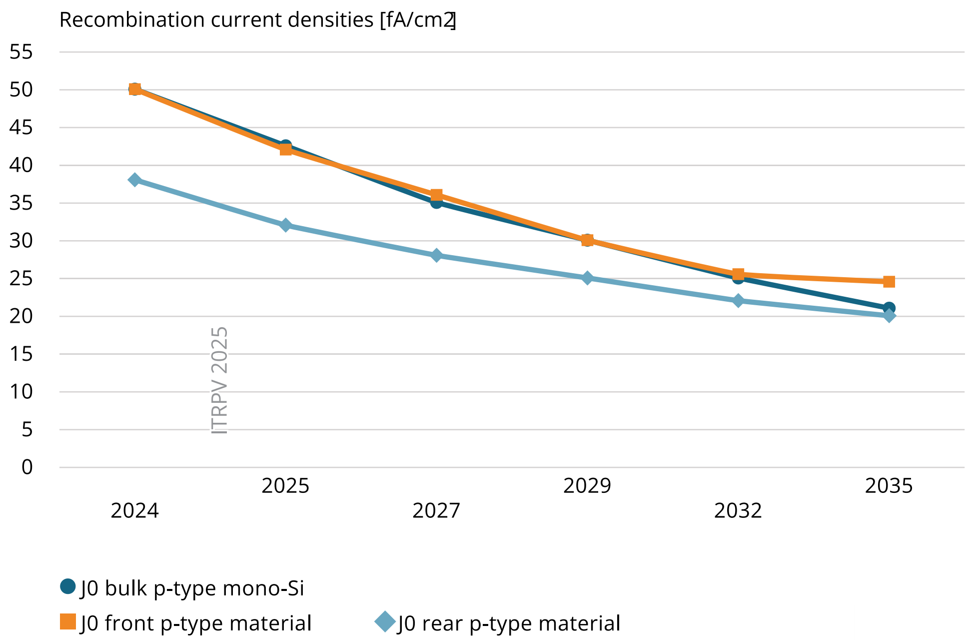

Fig. 17: Predicted trend for recombination currents J0bulk, J0front, J0rear for p-type cell concepts.

As shown in Fig. 17, the improvement of the p-type mono silicon material quality will continue. J0bulk for p-type mono-Si is expected to reach about 21 fA/cm² within the next 10 years. Reductions of J0bulk will result from further improvements of the crystallization process. J0front and J0rear are expected to improve similar in p-type mono-Si to well below 25 fA/cm² in 2035. As n-type cell concepts start to gain market share, it is of interest to check the expected recombination losses, it is even of more interest in comparison to the p-type cell losses.

Dark saturation current density for n-type

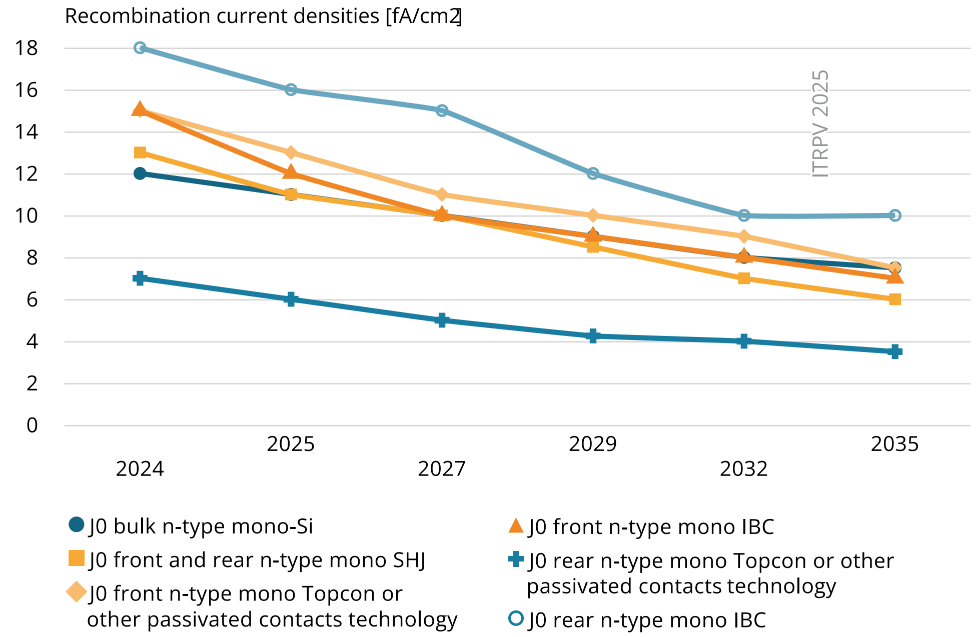

Fig. 18: Predicted trend for recombination currents J0bulk, J0front, J0rear for n-type cell concepts.

Fig. 18 shows that today's n-type mono-Si wafers have J0bulk values of ≈12 fA/cm² much lower than the 50 fA/cm² p-type J0bulk value. J0front and J0rear are also lower for n-type concepts emphasizing the potential for higher cell efficiencies. It is expected that all values will be further reduced to below 10 fA/cm² within the next 10 years. J0rear improvements are linked closely to cell concepts with passivated rear side.

J0front improvements cover all relevant front side parameters (emitter, surface, contacts). A parameter that influences recombination losses on the front surface for cell concepts with diffused pn junctions is the so-called emitter sheet resistance. A high sheet resistance is beneficial for low J0front. Sheet resistances well above 180 Ohm/square can be realized with selective emitters. If a selective emitter is used, sheet resistance values refer only to the lower doped region.

Phosphorous is used as dopant to form the pn junction in p-type cell concepts. Fig. 19 shows the current situation for homogenous and selective phosphorous doping: today's sheet resistance of homogenous doped p-type emitters is around 130 Ohm/square and it is expected to increase to around 180 Ohm/square. Selective doping allows higher sheet resistances: 180 Ohm/square were standard in 2024. An increase is expected up to 200 Ohm/square within the next years. It is important to mention that all PERC solar cells have selective emitters formed with a laser doping process after diffusion.

Emitter sheet resistance for phosphorous doping of cells for p-type

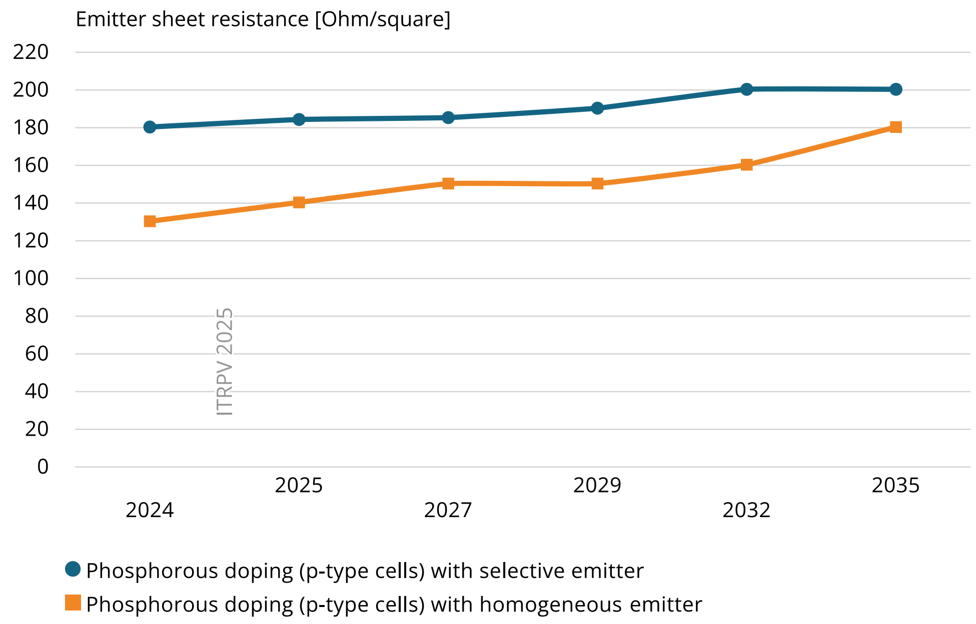

Fig. 19: Expected trend for emitter sheet resistance of phosphorous doped emitters for p-type cell concepts. In case of selective emitter the sheet resistance value refers only to the lower doped region.

Applied after standard POCl3 gas phase diffusion, laser based selective emitter processes enable the contacting of lowest phosphorous concentrations with standard metallization pastes. Therefore, selective emitter diffusion techniques are mainstream with a 100% market share in 2025 and will dominate the remaining future of p-type cells. Laser doped selective emitters are the technology of choice.

Emitter sheet resistance for boron doping of cells for n-type

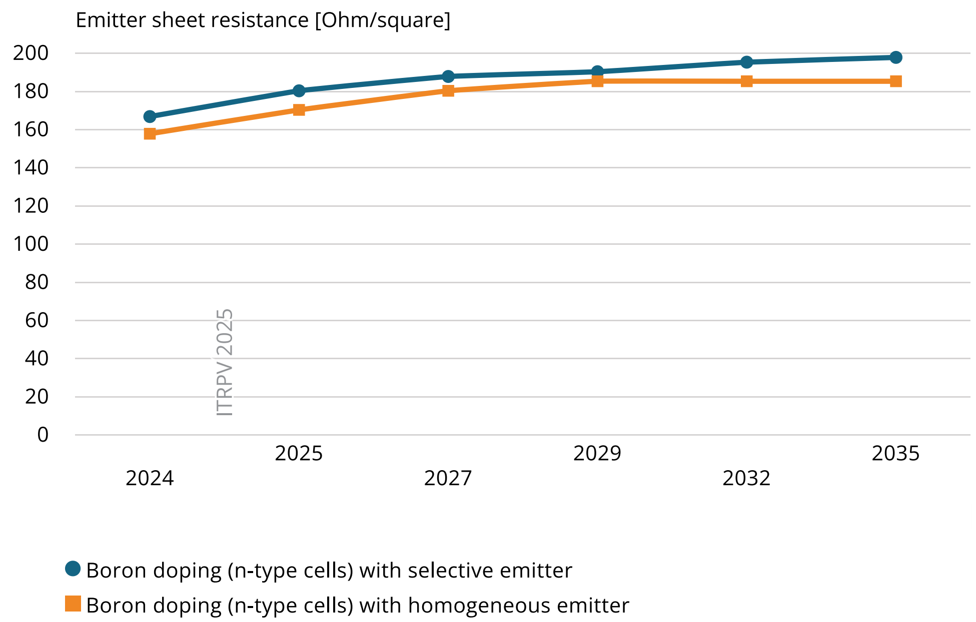

Fig. 20: Expected trend for emitter sheet resistance for boron doping for n-type cell concepts.

Boron is the dopant to form the pn junction in n-type diffused cell concepts. The predicted trend for n-type emitters is shown in Fig. 20. For Boron diffusion we also distinguish between homogenous and selective doping. An emitter sheet resistance of ≈ 160 Ohm/square is mostly used in 2024 lower-doped region. An increase to 185 Ohm/square is expected. Selective emitters categorized by a highly-doped region show in 2024 ≈ 170 Ohm/square. This value will reach ≈200 Ohm/square until 2035.

Boron doping for n-type cells in 2024 is about 95% done with the BCl_3 thermal diffusion technique. 5% of the current market share goes to BBr_3 diffusion technique. However, BBr_3 based diffusion is expected to phase out after 2027. Alternative processes are not expected to have significant market shares so far.

Market Share of emitters for n-type base TOPCon cells

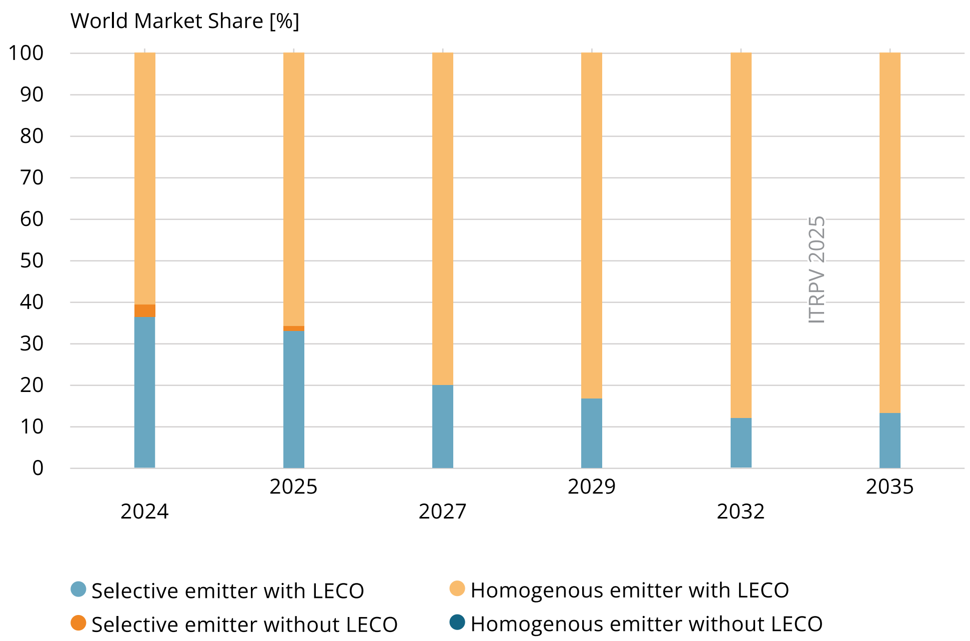

Fig. 21: Market Share of emitters for n-type base TOPCon cells.

Fig. 21 shows the market share of homogenous and selective emitter with or without Laser enhanced contact optimization (LECO) for n-type TOPCon cells. Homogenous emitter with LECO led the market with around 60% in 2024 and will gradually increase market share up to almost 87% in the coming 10 years. Selective emitter will lose importance over the years declining from around 39% in 2024 to only 13% by 2035. It is also worth mentioning that selective emitter without LECO are in the market in 2024, with only 3% but will disappear from the market by 2027. So, the use of LECO process is standard in the market for homogenous as well as selective emitters.

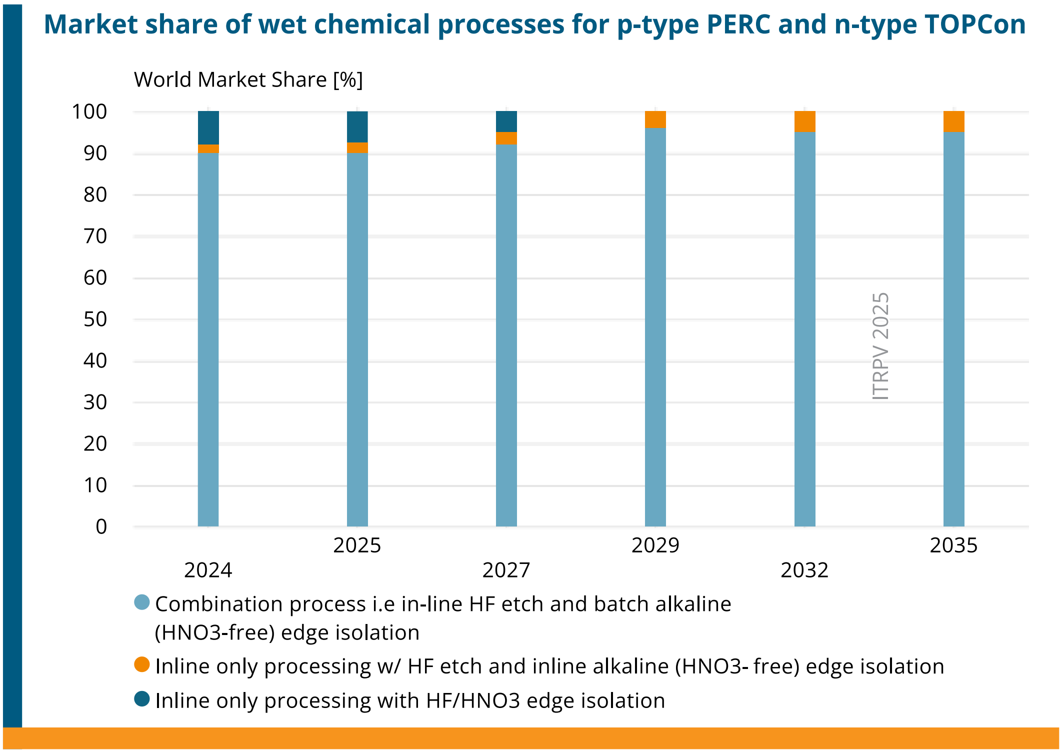

Fig. 22: Market share of wet chemical processes.

To separate the pn junction from bulk, an edge isolation is required. Wet chemical edge isolation is performed in manufacturing lines. Fig. 22 shows the market share of wet chemical processes for p-type PERC and n-type TOPCon. In-line processing with HF/HNO_3 has been the mainstream technology in the past. However, HNO_3 free processing is mainstream nowadays. The dominant process flow is the in-line HF oxide etching and batch KOH (alkaline) silicon removal. This approach dominates around 90% of the market. It is expected that the dominance continues until 2035. Also, we found that the share of HNO_3 free in-line based approach with an inline alkaline approach will gradually have a market share reaching 5% in 2035, according to our surveying results. Benefits of KOH based edge isolation are the substitution of expensive HNO_3 and a less expensive process exhaust gas treatment due to the elimination of nitrous fumes. So Inline edge isolation with HF and HNO_3 will disappear from the market after 2027.

Cleaning processes are mandatory for high efficiency cell production lines. H_2O_2 based cleaning was mostly used in the past, experiencing an ongoing decline in market significance.

Market share of cleaning processes for n-type SHJ

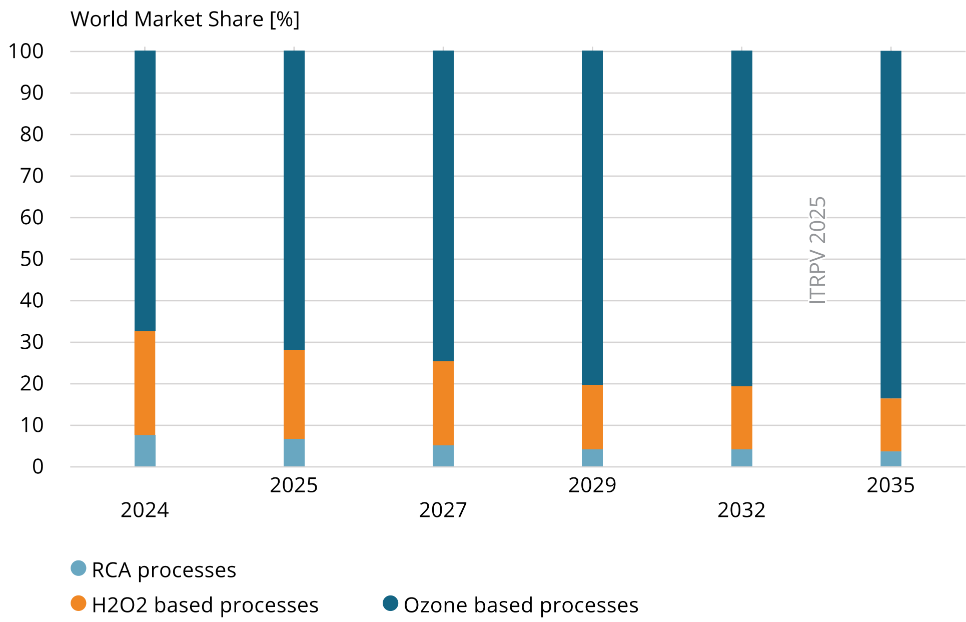

Fig. 23: Market trend of cleaning processes for n-type SHJ.

Fig. 23 and Fig. 24 show that ozone-based cleaning processes are already mainstream for SHJ and PERC/TOPCon cells, respectively. Ozone-based cleaning will continue gaining market share in the upcoming years. In the case of SHJ solar cells, RCA processes will stay niche with market shares slightly decreasing from 8% to 4% throughout the decade.

Market share of cleaning processes for p-type PERC and n-type TOPCon

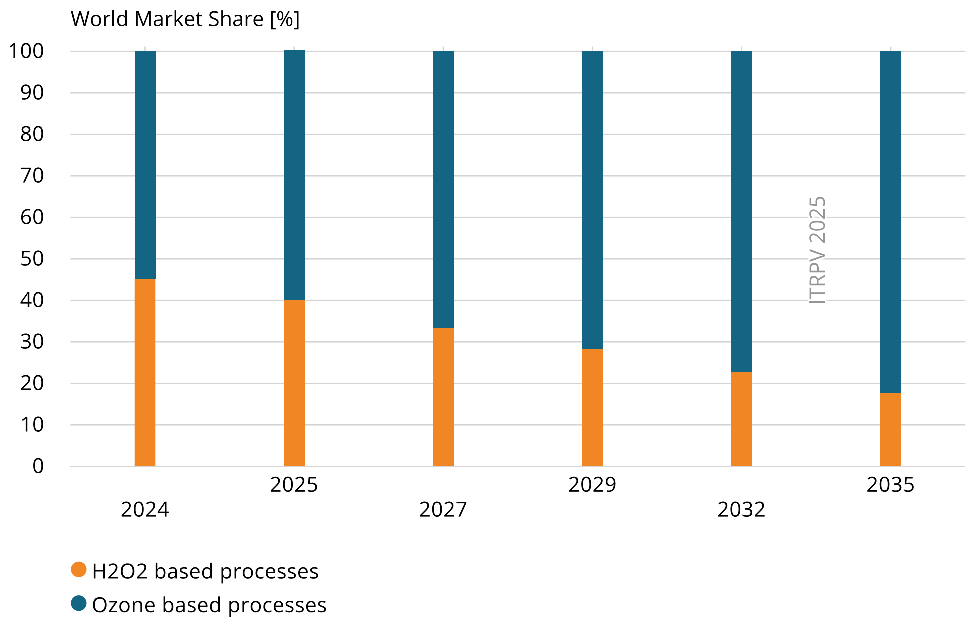

Fig. 24: Market trend of cleaning processes for p-type PERC and n-type TOPCon.

Since 2013, cell concepts using passivation with dielectric layer stacks have been in mass production starting with PERC technology and are mainstream today in c-Si PV.

PERC on p-type has been using aluminum oxide (Al_2O_3) as rear side passivation layer since the beginning. Additionally, for n-type TOPCon solar cell front side, the dielectric Al_2O_3 passivation is also used. Fig. 25 shows the expected market shares of different technologies for the deposition of Al_2O_3 passivation layers on the rear side of p-type PERC cell concepts and the n-type TOPCon front side. The market share of remote plasma PECVD Al_2O_3 in combination with a capping layer will disappear after 2025. In 2024, the main Al_2O_3 passivation process is direct plasma PECVD Al_2O_3 with integrated capping layer deposition, reaching a market share of almost 43%. However, this technology is expected to lose share in the upcoming decade. This comes hand-in-hand with the increase of the TOPCon cell structure in comparison to PERC. Batch ALD is expected to dominate the market from 2025 onwards.

Forming electrical contact via tunneling of electrons instead of forming ohmic contacts to the bulk silicon is used for rear side contacting in TOPCon cell concepts. This technique further reduces the forming of recombination centers at the interface and eliminates recombination current losses at resistive bulk contact. In other words, offers higher efficiency potentials.

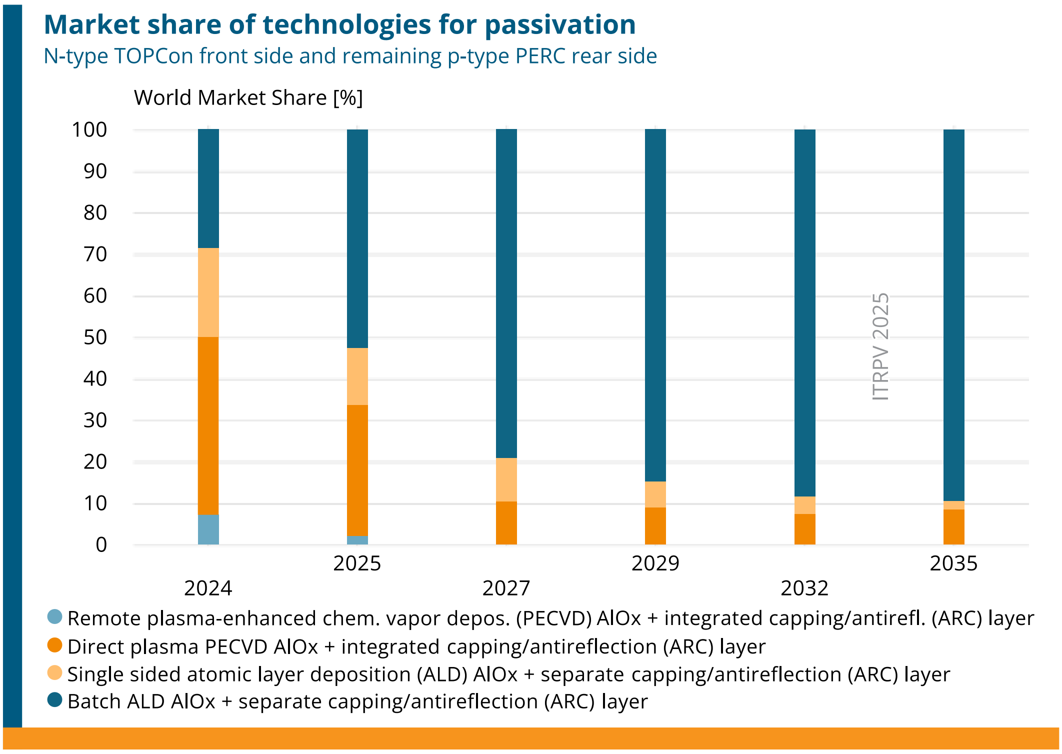

Fig. 25: Market share of technologies for passivation.

Insitu doping of the poly-Si layer and exsitu doping with POCL3 are the two mainstream technologies, sharing 50 % each, equally in 2025. Until 2035, insitu doped layer will be slightly more preferred reaching up to 60% market share, as seen in Fig. 26.

World Market share for the doping of poly-Si

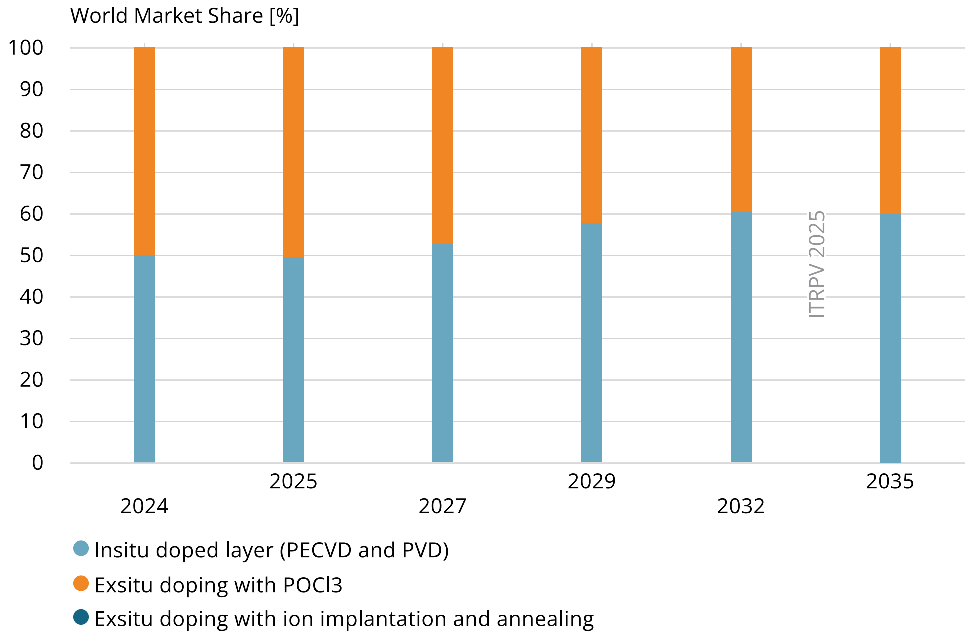

Fig. 26: Expected trend of the doping process of poly-Si layer for TOPCon solar cells.

Considering the deposition processes of poly-Si for TOPCon cells, PECVD and LPCVD seem to hold significant market share. Fig. 27 shows the market share of different deposition techniques for the poly-Si layer.

Different deposition technologies for TOPCon polysilicon

For all contributors

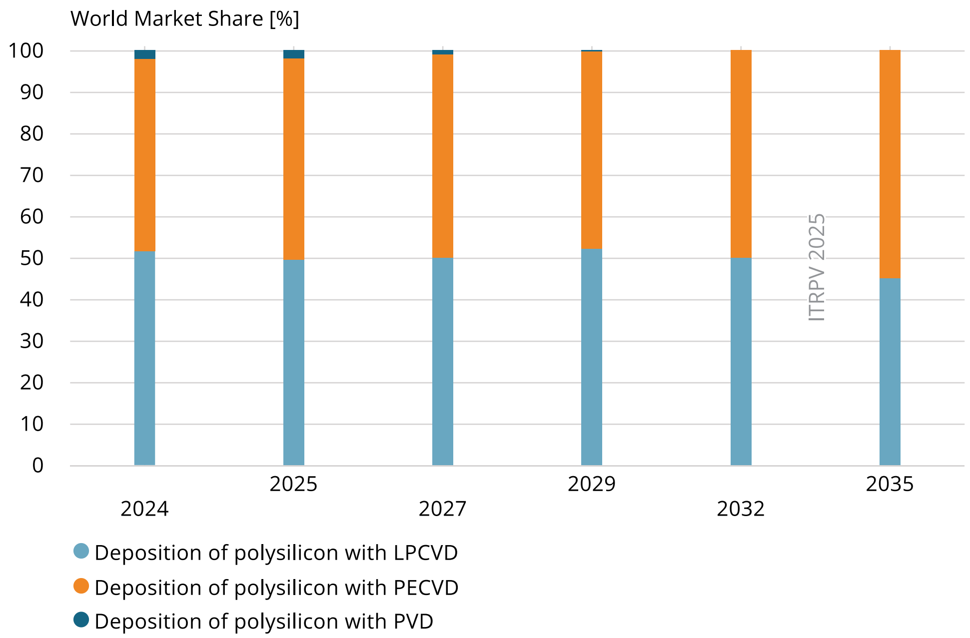

Fig. 27: Expected trend of forming the polysilicon layer of TOPCon contacts.

Considering the data of all contributors, it seems like the main technologies of choice are PECVD and LPCVD, with a slight market share of around 2% for PVD technology. It is expected that PECVD, and LPCVD remain the main dominating technologies and PVD have limited market share in the upcoming years. GW-scale manufacturers expect similar trends with PVD staying niche over the upcoming decade as shown in Fig. 28.

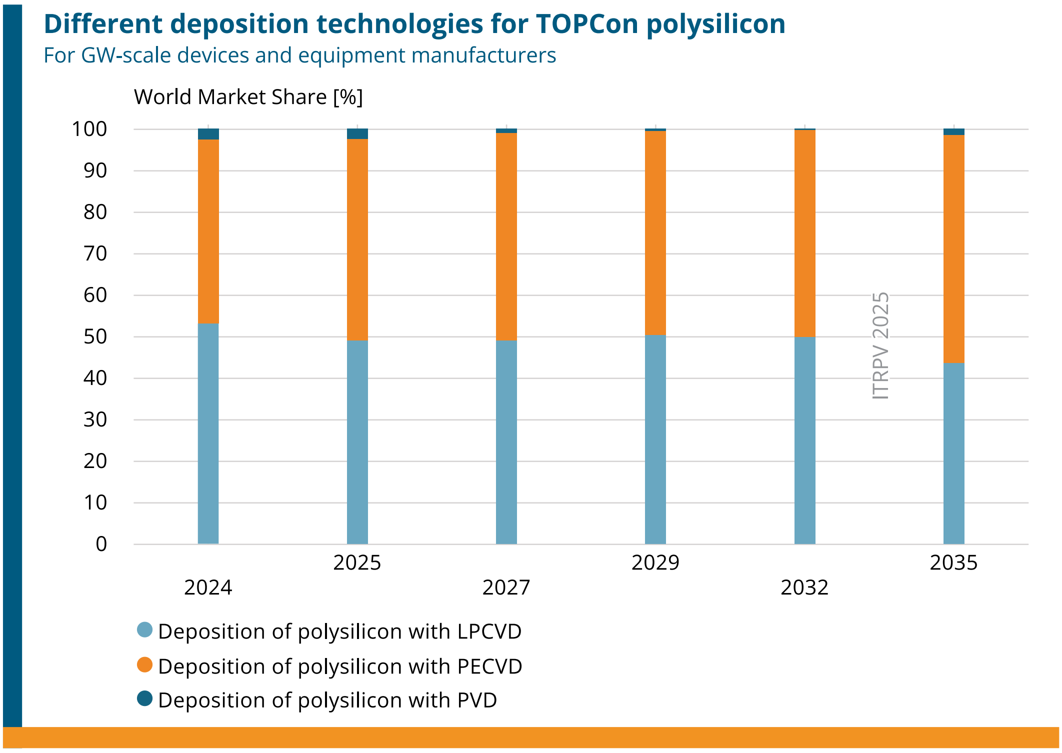

Fig. 28: Expected trend of forming the polysilicon layer of TOPCon contacts (Only data from GW-scale manufacturers).

For LPCVD processes, the loading process is also of interest. In 2024 the market was divided in half by single and double loading processes. However, the single loading process is expected to lose market share towards higher productivity with a double loading process. In 10 years double loading process is expected to have a 95% market share, as shown in Fig. 29.

Market share of single or double loading for LPCVD

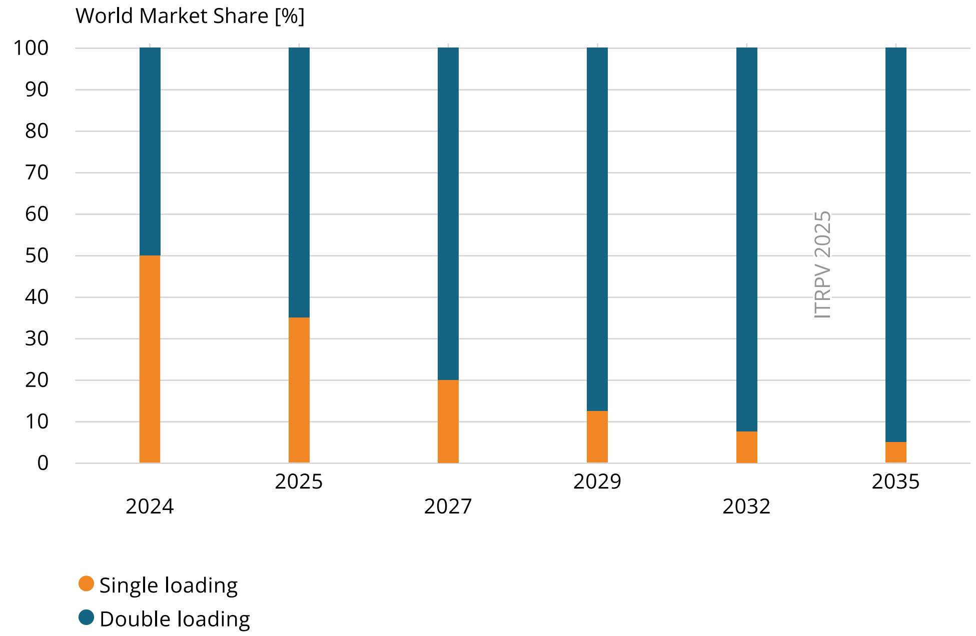

Fig. 29: Market share of single or double loading for LPCVD.

Fig. 30 shows the market share of exsitu and insitu poly-Si doping. A slight trend is observed to insitu technologies, however a considerable market share for exsitu of around 40% is still expected in 10 years. Developments in this topic have to be carefully observed.

World Market Share of doping method of polysilicon

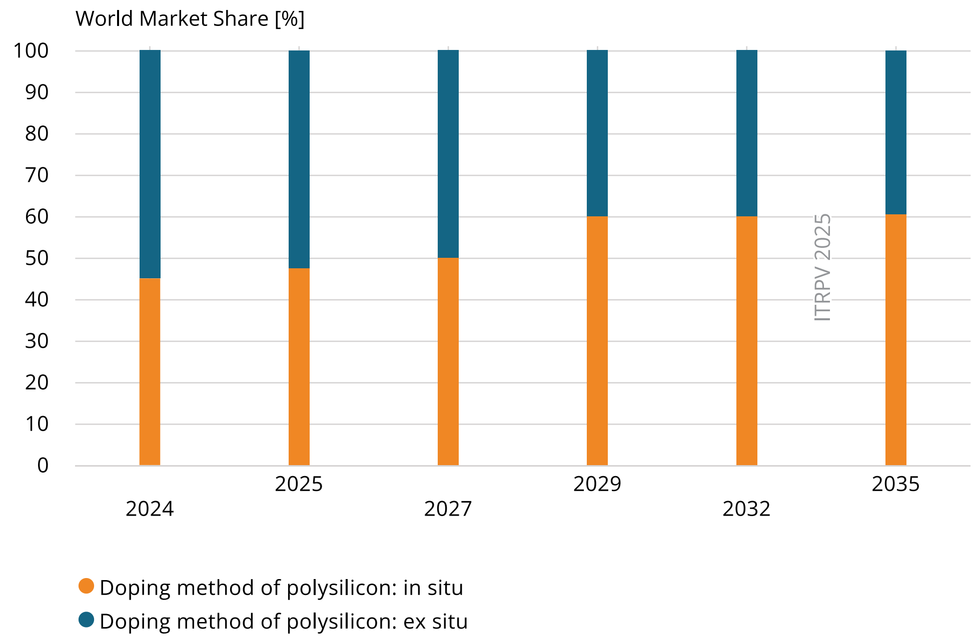

Fig. 30: World Market Share of doping method of polysilicon.

Fig. 31 shows the anticipated thickness trend of the poly-Si layer deposited for TOPCon concepts. The 115 nm in 2024 will be reduced to around 70 nm in 10 years.

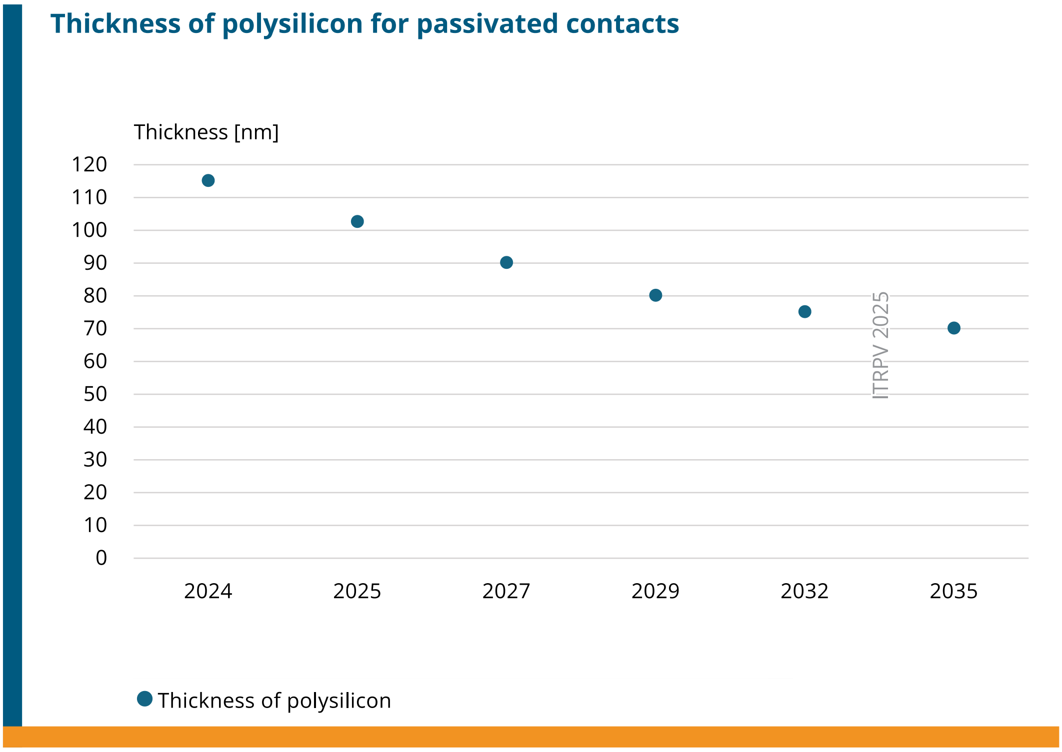

Fig. 31: Expected trend of polysilicon thickness for TOPCon layer stack formation.

Contacting the emitter and the rear side of the solar cell is the final processing sequence in solar cell manufacturing and a key process regarding cost, efficiency, and quality.

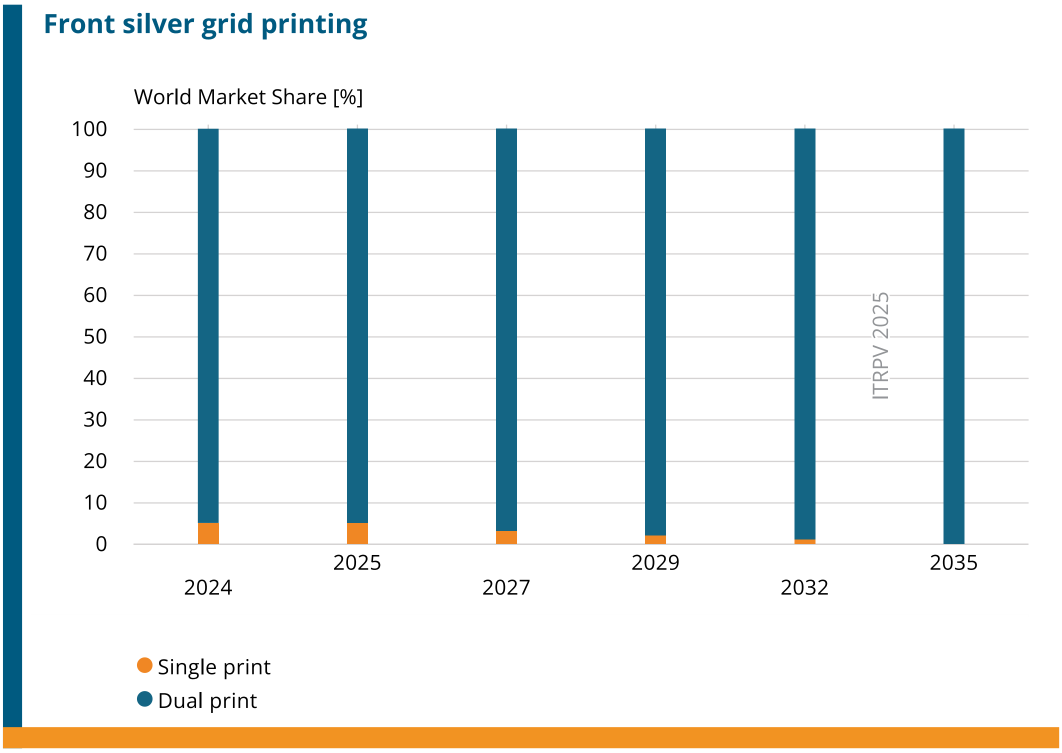

Fig. 32: Expected market share of different front side printing techniques.

Screen printing has been the technology of choice for front and rear side metallization since the beginning of c-Si solar cell mass production. We see screen printing also in the future as the mainstream metallization technology. Plating is still considered to be present as rear side metallization technology with market shares around 1% after 2025. Other technologies are so far not reported to be in the mass manufacturing market, yet.

Three different approaches for high quality front side print exist. Fig. 32 summarizes the available technologies and their estimated market share during the next 10 years. New front side metallization pastes in combination with LECO enable the contacting of the previously discussed low doped emitters without any significant reduction in printing process quality. Dual printing is mainstream today with around 95% in 2024 and will be the only technology in the market by 2035. Single print is expected to continue losing market share, with a disappearance in the upcoming decade. Double prints already disappeared from the market in 2024.

As of 2024 screen-printing takes up 100% of the market and will stay dominant over the decade. Stencil printing and plating on seed layer will gain a small market share until 2035 as shown in Fig. 33.

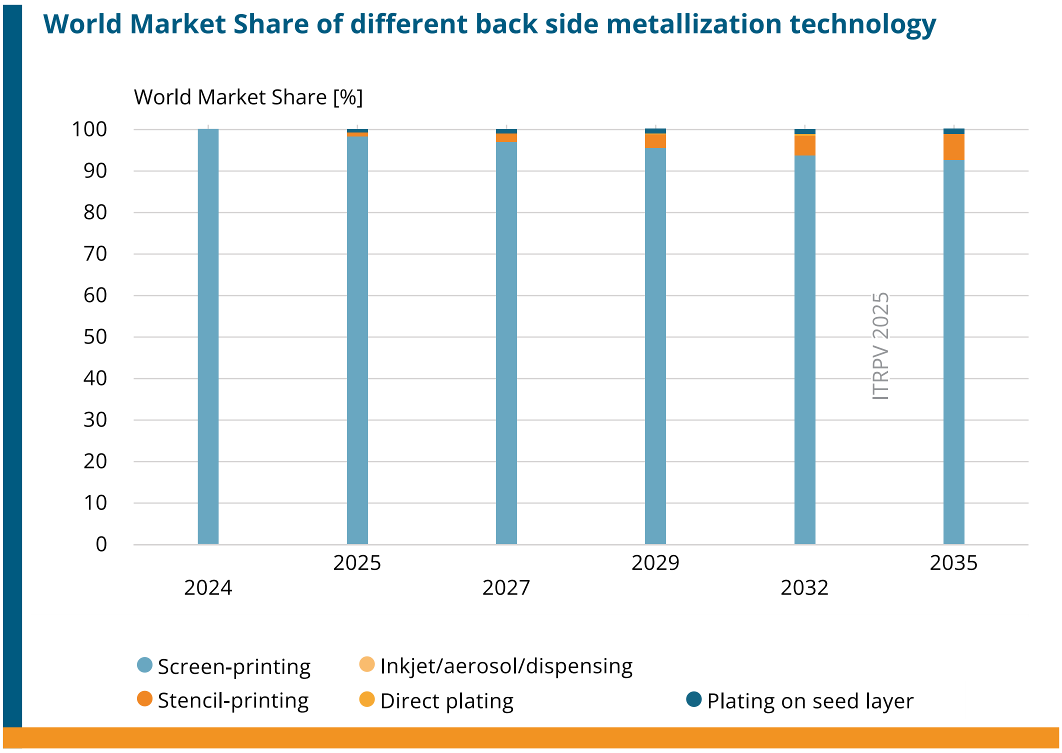

Fig. 33: Expected market share of different back side printing techniques.

A reduction in finger width is one method yielding efficiency gain and cost reduction, but only if it is applied without significantly increasing finger resistance. Furthermore, contact with a shallow emitter needs to be established reliably. One possible way to achieve these goals is to use selective emitter technologies, preferably without significantly increasing processing costs.
Reduction of finger width reduces shadowing, which leads to an increase in the generated current of the cell. To maintain conductivity a trade-off has to be made, if the roadmap for silver reduction, as discussed in chapter 5.1. will be executed. Finger widths of about 25 µm were standard in 2024 as shown in Fig. 34.

A further reduction down to 12 µm over the next 10 years is expected. Even ultra fine line screen printing is currently discussed which could possibly reach a finger width of around 7 µm [19].

Front side metallization parameters

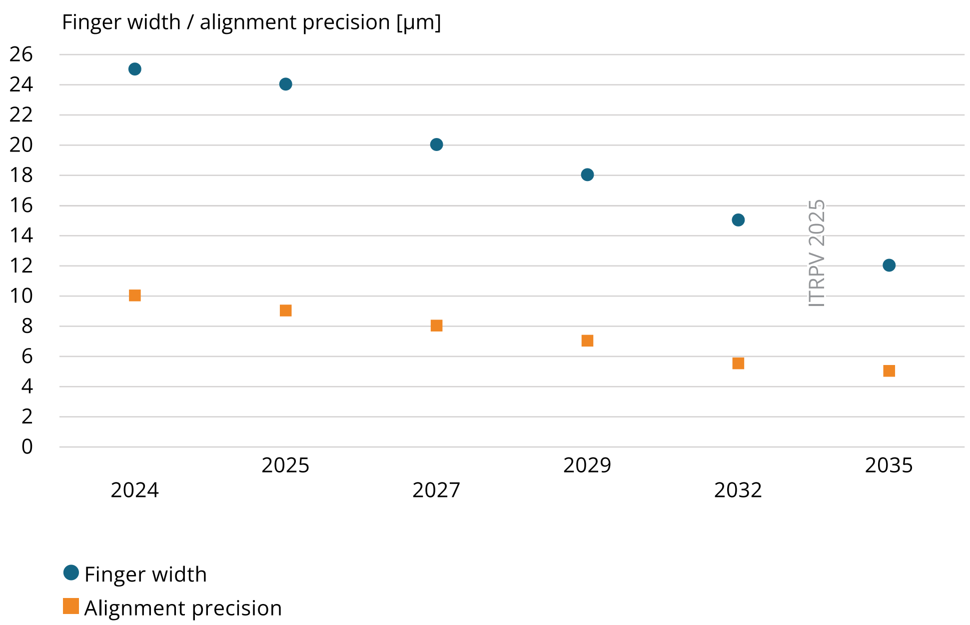

Fig. 34: Predicted trend for finger width and alignment precision in screen-printing. Finger width needs to be reduced without any significant reduction in conductivity.

Besides the reduction of finger width, the printing alignment accuracy requirements are of increasing importance. Dual print separates the fingerprint from the busbar (BB) print, enabling the use of special busbar pastes with less silver but excellent soldering capabilities. Busbarless cell interconnect techniques can even omit the busbars completely. For reliable module interconnection and for bifacial cells, a good alignment accuracy in metallization is also mandatory - an alignment accuracy of down to 5 µm (@+/- 3 sigma) will be required in the future as Fig.34 shows. This will be necessary especially regarding an improved alignment to subjacent structures as in the case of selective emitter structures.

For half cut cells edge passivation is not yet commonly used. In 2024 only 5% of the cells were edge passivated by atomic layer deposition (ALD) or plasma-enhanced chemical vapor deposition (PECVD). Edge passivation technologies will gain importance and will dominate the market by 2035 with up to 91% market share.

The trend towards edge passivation in more than half cut cells, such as third, quarter and shingle cells, will go through a similar trend, with edge passivation technologies reaching almost 95% market share by 2035 as shown in Fig. 35.

World Market Share of edge passivation of post metallization separated more then half cut solar cells in mass production (third, quarter and shingle cells)

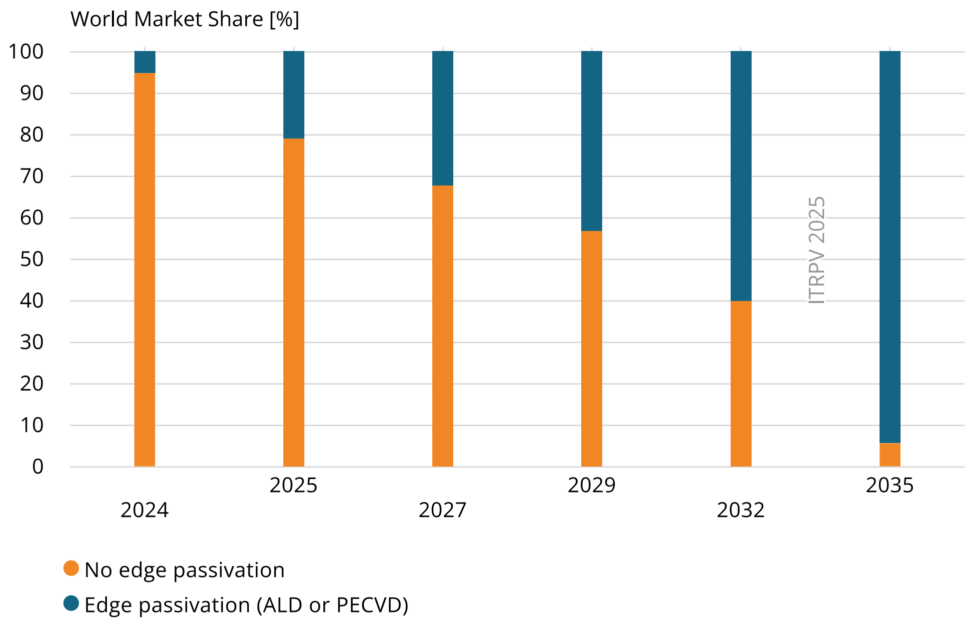

Fig. 35: World market share of edge passivation of third and quarter cut cells and shingle cells in mass production.

Reducing finger width is going in parallel with increasing the number of busbars. Fig. 36 shows details on this metallization trend for cells. Busbar layouts with ≤ 12 led the market with 49% in 2024. The transition however to busbar layouts between 13 – 18 busbars as well as layouts with more than 18 busbars and busbarless formats is ongoing. In 2035, only 6% of the market share is expected to be covered by 12 busbar or less metallization layouts. It is very interesting to see the trend towards busbarless layouts, which are expected to cover around 47% of the market in 2035. Nevertheless, BB-less layouts will require new interconnection technologies in module manufacturing that - in best case - should be implemented by upgrading of existing stringing tools.

Optimizing productivity is essential to be cost competitive. Increasing the throughput of the equipment in order to achieve maximum output is therefore a suitable way to reduce tool related costs per cell and hence per Wp. To optimize the throughput in a cell production line, both front-end (chemical and thermal processes) and back-end (metallization and classification) processes should have equal capacity. We currently see that wafer formats ≥ M10 are mainstream. New tools will be capable of processing all those formats.

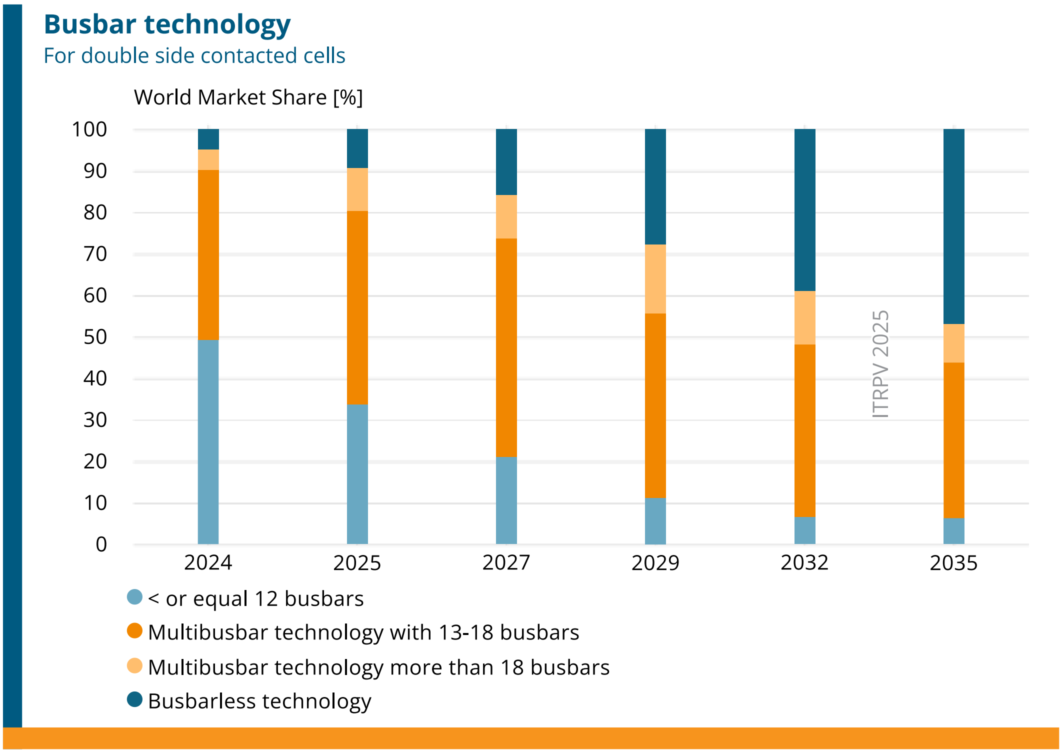

Fig. 36: Market share for different busbar technologies.

In Fig. 37, Fig. 38, and Fig. 39 we summarize the expected throughput trends of new tools capable for processing cell formats greater or equal to M10.

Fig. 37 shows the expected throughput trend in chemical processing and pure thermal processing: diffusion, oxidation, and annealing. Chemical processing tools are leading the throughput list with about 12,000 wafers/h for 2024 in batch processing (for e.g. texturing). This throughput is expected to increase to 17,000 in the upcoming decade.

Boron diffusion requires long process times and therefore the throughput is limited to about 6,000 wafers/h in 2024. Throughput for B-diffusion is expected to increase to above 9,000 wafers/h within the next 10 years.

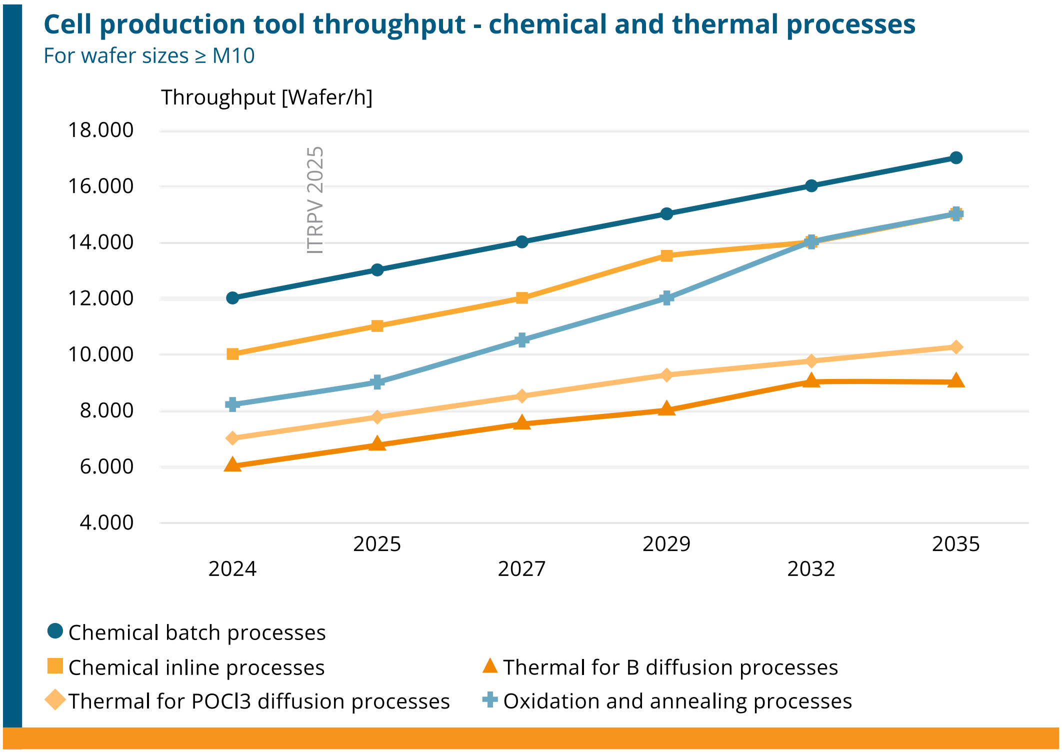

Fig. 37: Predicted trend for throughput per tool of cell production equipment in the frontend.

Fig. 38 shows the expected throughput trends for layer deposition tools. ALD is leading in this process field with 12,000 wafers/h in 2024 and expected 18,000 wafers/h in 2035.

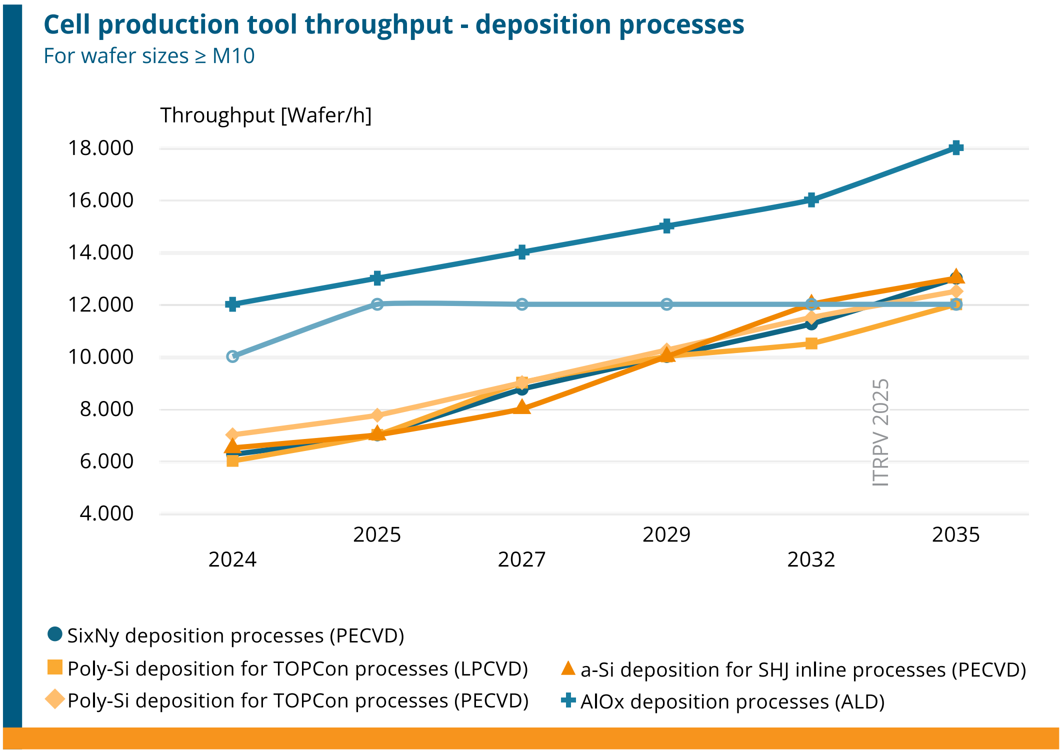

Fig. 38: Predicted trend for throughput per tool of cell production equipment for layer deposition.

The throughput trend in cell processing backend is shown in Fig. 39. Screen printing tools with throughputs of around 8,000 M10 wafers/h are available on the market in 2024. Laser contact opening before printing, as well as firing and testing after screen printing are installed in line in contemporary cell production lines, meeting the same throughput figures. Further improvements in this field will depend strongly on the progress made with the screen-printing technology that currently focuses on narrower line finger width and lower paste consumption. The trend towards further enhancing the throughput in the upcoming decade.

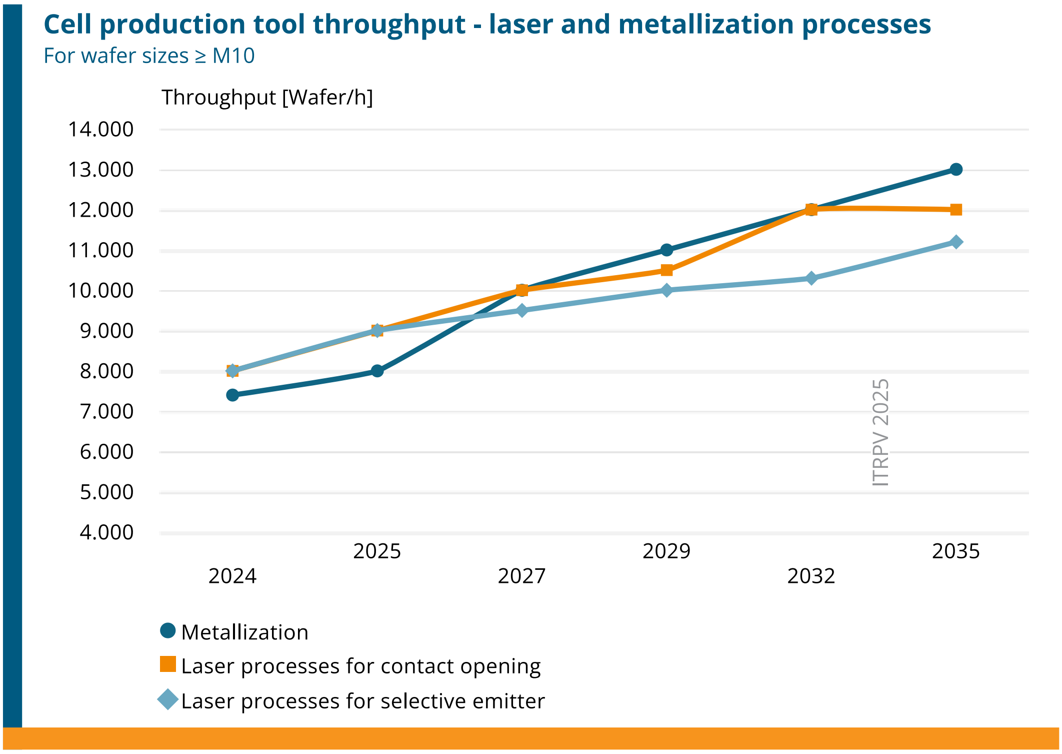

Fig. 39 Predicted trend for throughput per tool of cell production equipment in backend processing.

5.3. Products

According to our findings, the aluminum BSF cell concept disappeared completely in the market. Nevertheless, the matured concept of diffused and passivated pn junctions will be further used in the mainstream with different other rear side passivation technologies (PERC /TOPCon). The most dominant cell technology in 2024 was the TOPCon double sided contact cell. The phase out of the PERC cells concepts started: PERC occupied 35% of the market in 2024 and is expected to disappear over the next 10 years. Fig. 40 and Fig. 41 show the expected market share of cell technologies of all contributors and of GW-scale manufacturers, respectively.

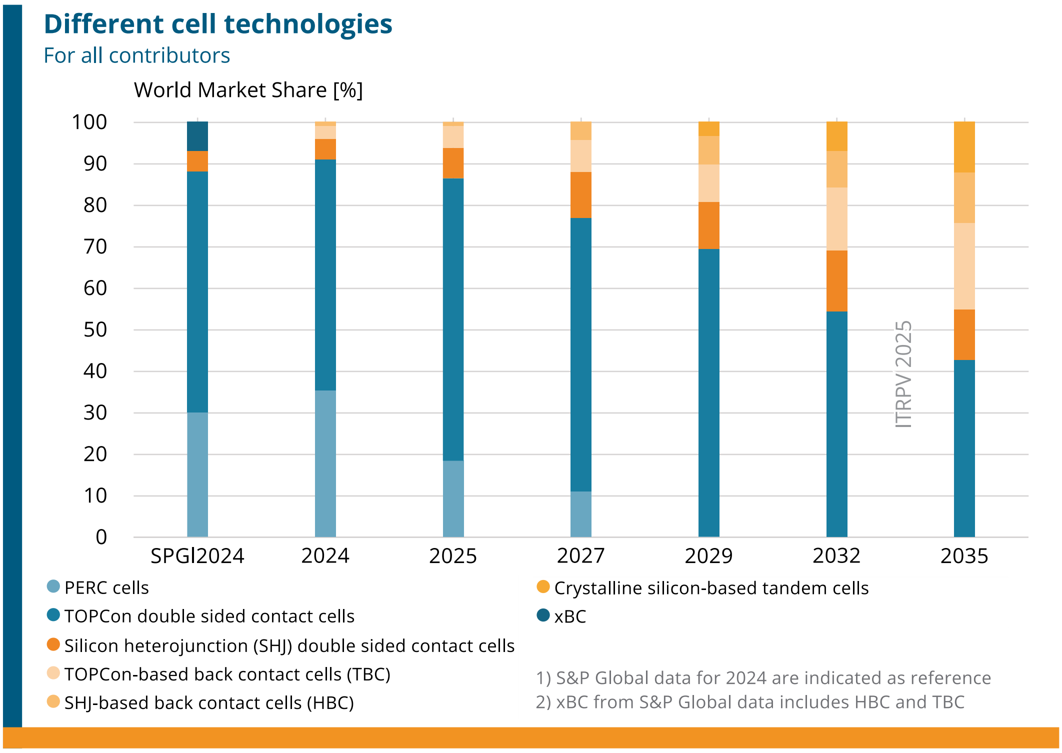

Fig. 40: Market shares for different cell technologies. S&P Global (SPGI) data for 2024 are indicated as reference [12].

If we consider the data of only GW-scale manufacturers, as shown in Fig. 41, the transition towards n-type concepts is more progressive. The data from all contributors show a more conservative approach.

The first pillar in Fig. 40 and Fig. 41 shows, that our findings for 2024 are in line with the SPGI analysis [12]. SPGI data results shows back contact cell concepts (xBC) at this stage without further distinguishing between TBC and HBC. So xBC is the combination of all back contact cells (including TBC and HBC).

There is still a clear market dominance of double-sided contact cell concepts. Back contact cell concepts are expected to get a market share of up to 33%. TOPCon based back contact (TBC) is expected to be more popular than SHJ based back contact concepts (HBC).

Silicon-based tandem cells are expected to appear in the market after 2025 and will increase their market share to over 10% in 2035.

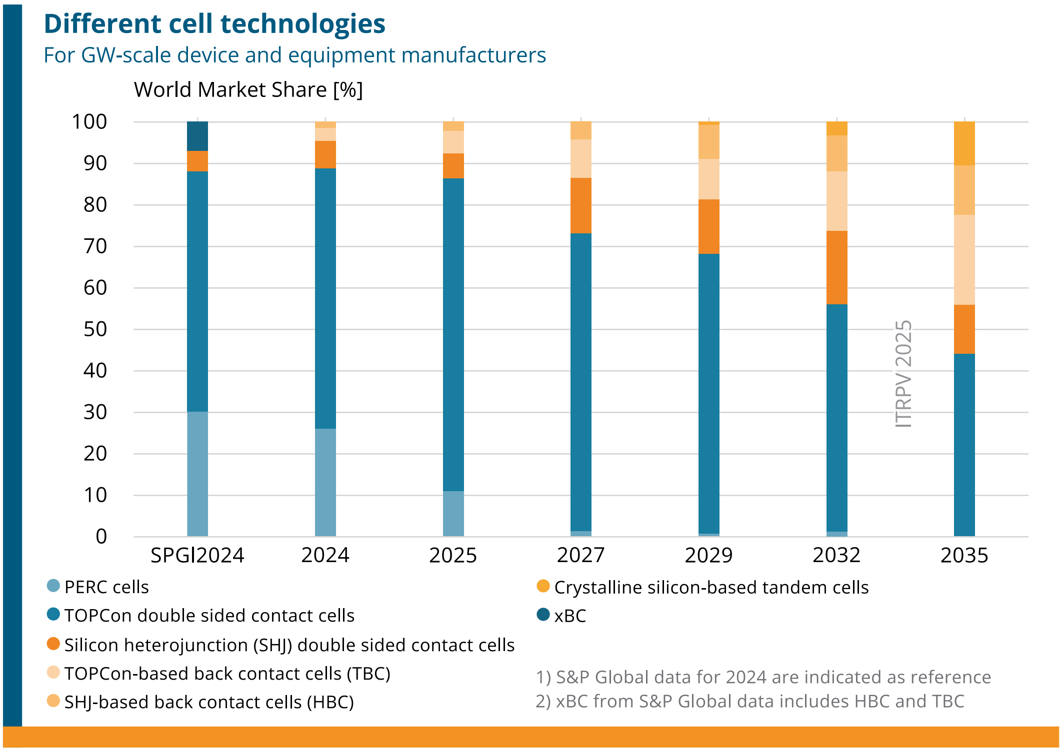

Fig. 41: Market shares for different cell technologies from GW-scale manufacturers. S&P Global (SPGI) data for 2024 are indicated as reference [14].

Double-side contacted PERC, TOPCon, SHJ, and more sophisticated back contact cell concepts can capture the light from the front and from the rear side if the electrical contacts are designed accordingly. These cell types can therefore be perfectly used for bifacial light capturing.

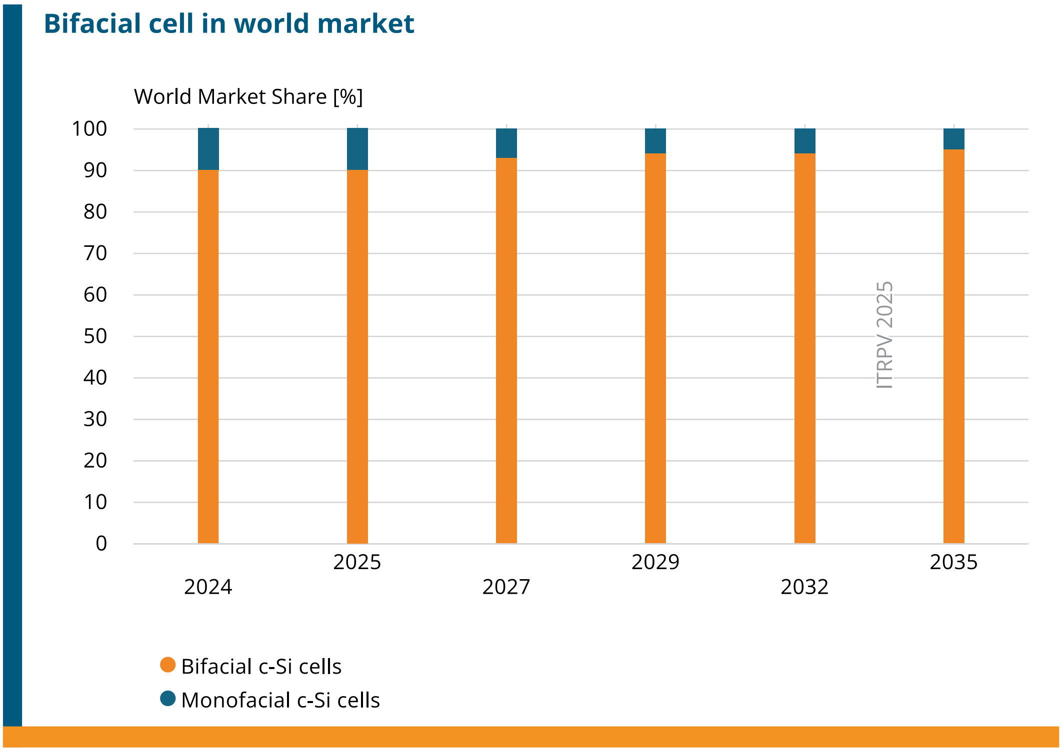

Fig. 42: Market share for bifacial cell technology.

Fig. 42 shows the expected market trend for bifacial cells. The market share of 90% in 2025 is expected to remain stable, with a slight increase to 95%, within the next 10 years. Bifacial cells can be used in conventional, monofacial modules or in bifacial modules with transparent rear sides.

Average stabilized efficiency values for Si solar cells in mass production
Measured with busbars (no BB-less measurement) and front side STC

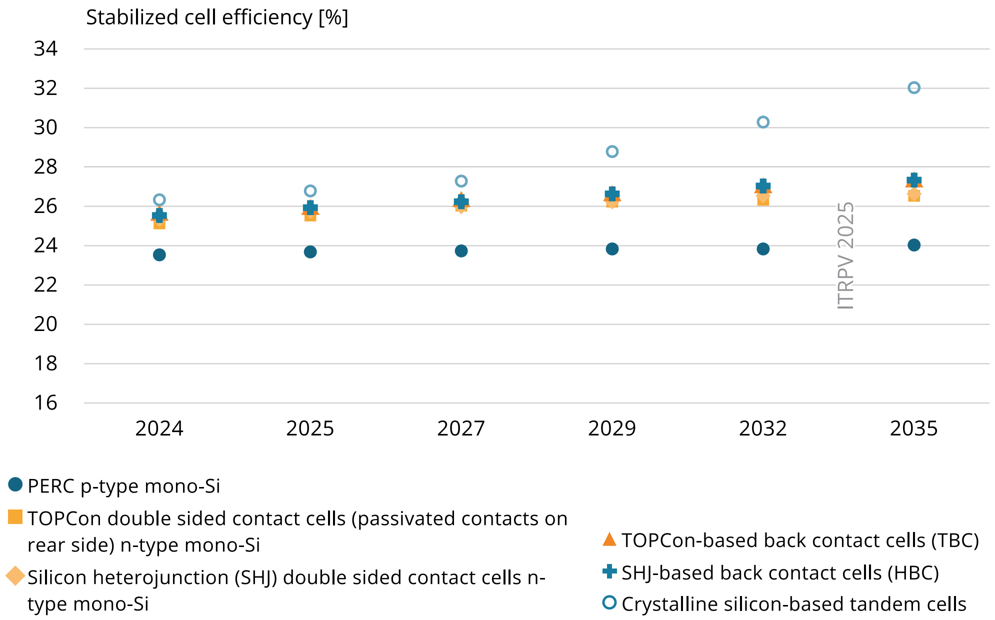

Fig. 43: Average stabilized efficiency values of c-Si solar cells in mass production.

Fig. 43 illustrates the expected average stabilized front-side cell efficiencies of state-of-the-art mass production lines for double-sided contact and rear-contact cells on different wafer materials. The plot shows that there is potential for all technologies to improve their performance.

Cells using crystalline silicon-based tandem material show the highest efficiency potential of today's cell technology concepts, which will further increase in the future. We found that TBC and HBC will attain efficiency values reaching up to 27% respectively in the next 10 years. Cells on n-type using tunnel oxide passivated contacts at the rear side show higher efficiencies than all p-type cell concepts. Other n-type-based cell concepts like SHJ and back-contact cells, will reach higher efficiencies of up to 26.6% in mass production until 2035. We nevertheless see that the Si-based single junction cell concepts are converging to a practical efficiency limit of about 27%, close to the theoretical upper limit of around 30% [20]. Tandem cells will overcome this limit with 32% in 2035. Mass production cell efficiencies of Si based tandem cells concepts will start at about 26%. It was extremely difficult to predict the start of tandem mass production in the past.

Fig. 44 shows the expected V_{OC} trend for different cell technologies. For the measured V_{OC} in mass production p-type mono PERC has the lowest value, with 695 mV in 2024 and will reach a maximum of 700 mV. For n-type concepts a V_{OC} of 735 mV is standard, with SHJ reaching the highest amount of 750 mV. All concepts will see a slight increase over the years with TOPCon and IBC reaching around 750 mV by 2035.

Cell results Voc measured value in mass production (highest efficiency class in production)

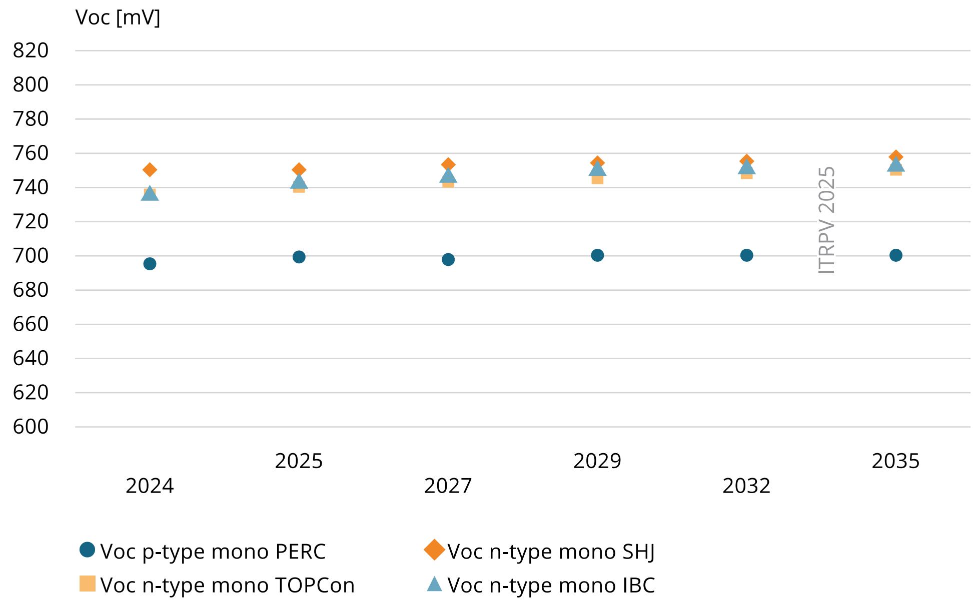

Fig. 44: V_{OC} values of different cell concepts in mass production (for highest efficiency class in production).

Fig. 45 shows the expected market shares of different tandem cell concepts. By 2027 perovskite - n-type Si tandem solar cells will cover almost 99% of the market, while perovskite-perovskite cells will cover the remaining 1%. Over the next decade perovskite-perovskite tandems will gain more importance, covering around 11% of the market by 2035.

World Market Share tandem solar cells

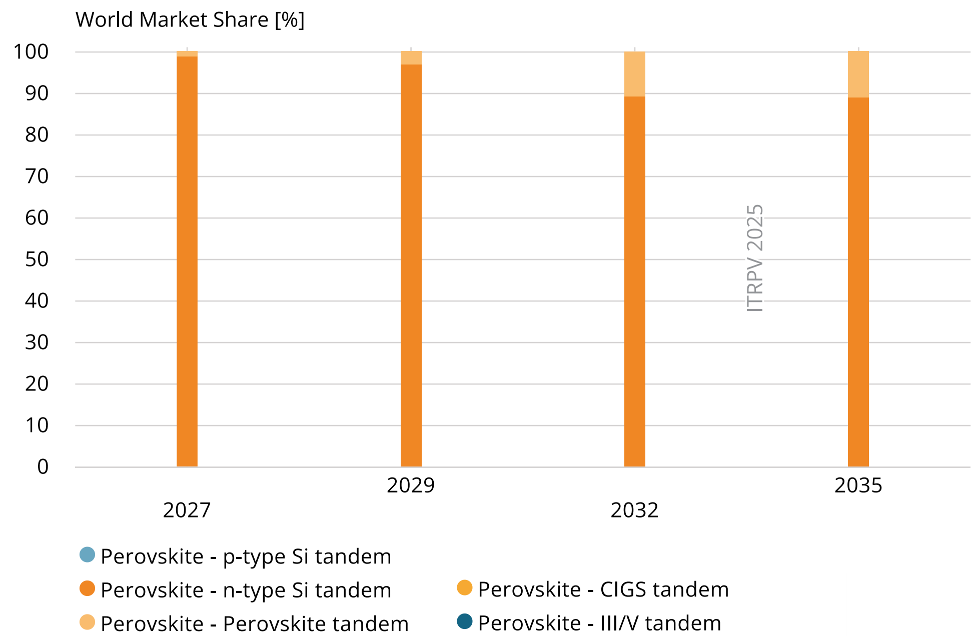

Fig. 45: Expected market share of tandem cell technologies.

Fig. 46 shows that new built cell production facilities will make use of the economy of scale by increasing their annual production capacity. Planned factories larger than or equal to 5 GW capacity will dominate the manufacturing landscape in 2025. It is expected that the trend continues, such that in 2035 around 56% of to be planned fabs have an annual cell production capacity higher than 10 GW. These factories will dominate the production landscape for new cell production capacities on the long run. Nevertheless, there will always be room for new factories that are rated to be less than 5 GW capacity, even lower than 1 GW. It is expected that these factories would mainly serve local markets and in some cases niche products.

Market share for size of cell production fabs

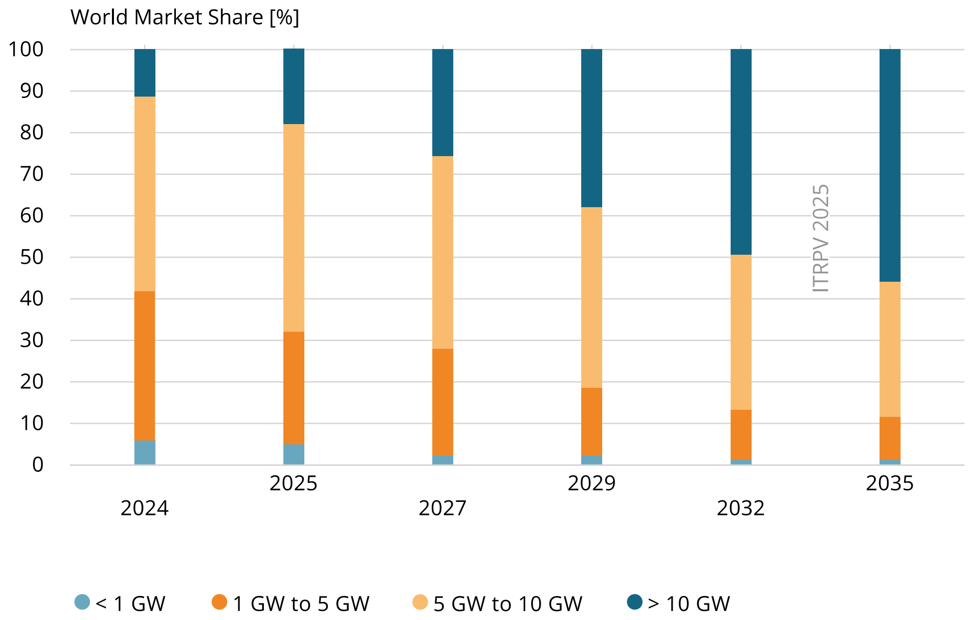

Fig. 46: Trend for name plate capacity of cell manufacturing fabs.

6. Results of 2024 | Module

6.1. Materials

The module related non-cell cost share contributes with 40% to 45% to the module manufacturing cost [21]. Cells are still the most expensive individual part of the module's bill of materials (BOM). The introduction of larger cell formats M10 and G12 as well as their rectangular variants enables higher module powers and advantages in module efficiency at the expense of increased module size. Module conversion costs are dominated by material costs. Improvements of the module performance and of material costs are therefore mandatory to reduce module costs. Approaches for increasing performance like the reduction of optical losses (e.g., further reduced reflection of front cover glass), reduction of resistive losses, and the reduction of interconnection losses will be discussed in chapter 8.2. Approaches for reducing material costs include:

- Reducing material volume, e.g., material thickness,
- Replacing (substituting) expensive materials,
- Reducing waste of material.

All key non-cell module materials contribute to module manufacturing cost with a similar portion. Glass is the heaviest material of a module. It determines weight and light transmission properties. The thickness is also important for the mechanical stability and hail persistence of the module. Glass is used in standard modules as front side cover, in glass-glass modules (especially for bifacial applications) it is used as front as well as back side cover.

Fig. 47 and Fig. 48 summarize the trend of front side glass thickness for glass-glass and glass-foil modules respectively.

A thickness between 2 and 3 mm is mainstream for glass-glass modules today. It is expected that glass with a thickness lower than 2 mm will gain some market share over the next years. A thickness below 2 mm is seen in the market with a share close to 8% in 2025 and is expected to increase share over the next years reaching almost 15% in 2035. The dominance of the thickness between 2 and 3 mm will however remain. The stability of the glass is not a topic of compromise particularly for heavy load and hail conditions.

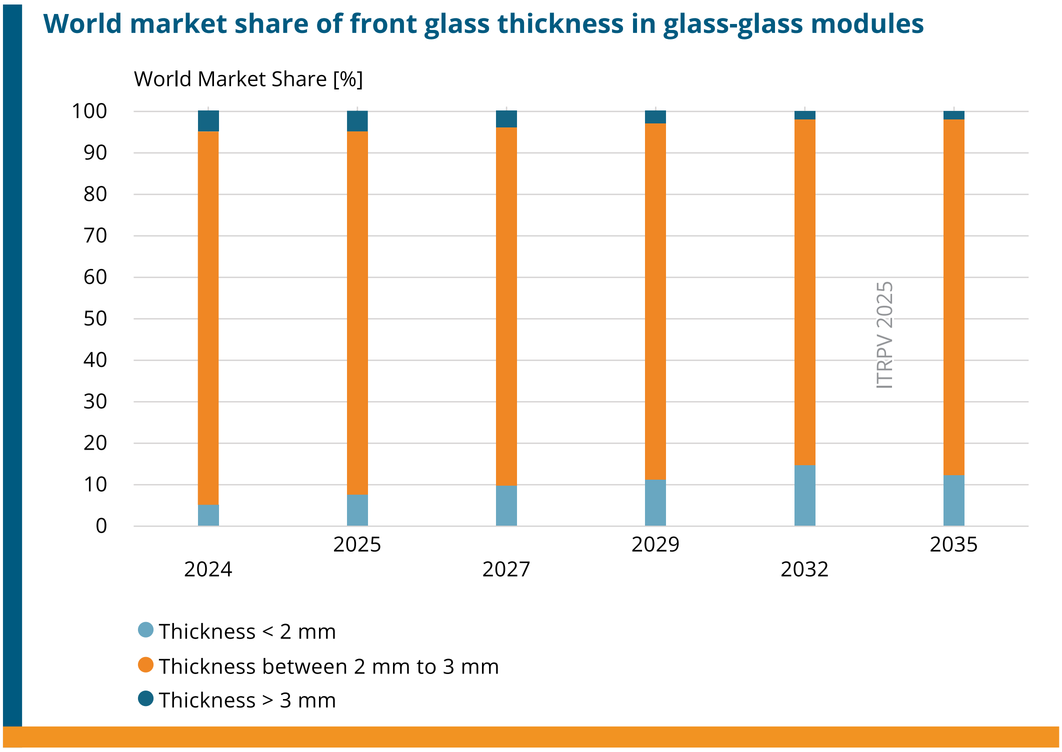

Fig. 47: Expected trend of front glass thickness in c-Si modules.

For glass-foil modules a thickness over 3 mm is mainstream today, which is expected to remain, with small decreases, quite constant over the next years. A thickness between 2 mm to 3 mm will have increases to 14% by 2035.

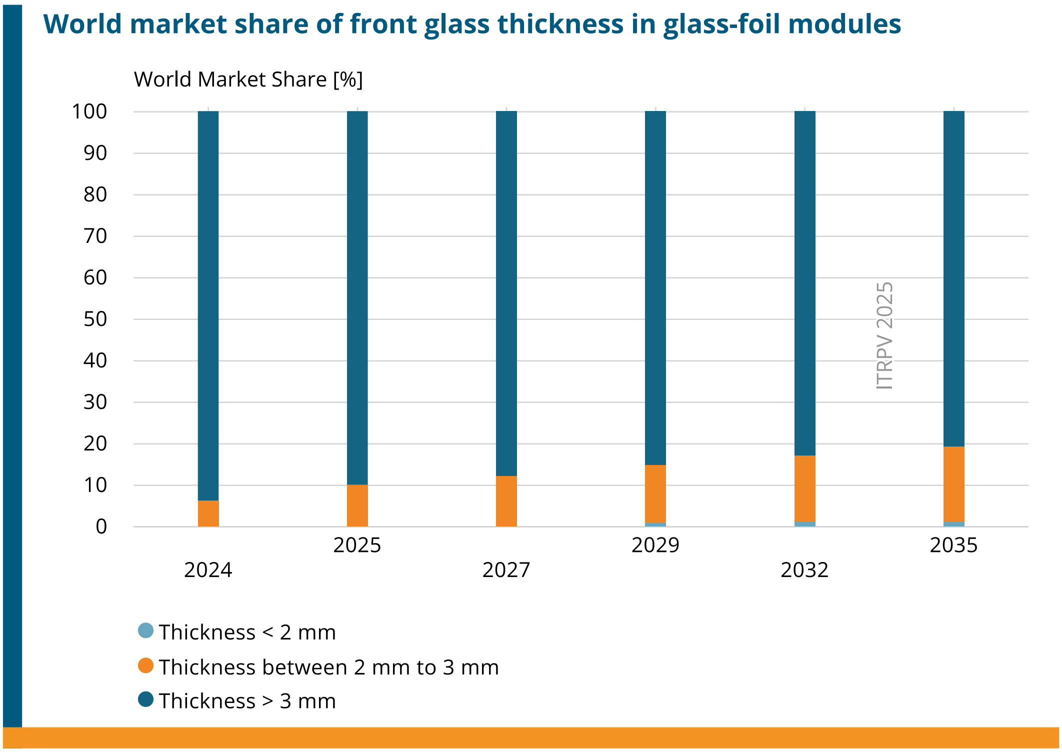

Fig. 48: Thickness of front glasses in glass-foil module.

Fig. 49 shows that antimony-free glass is starting to gain more market share over the next decade, reaching around 18% market share by 2035. Antimony-containing will still keep market dominance.

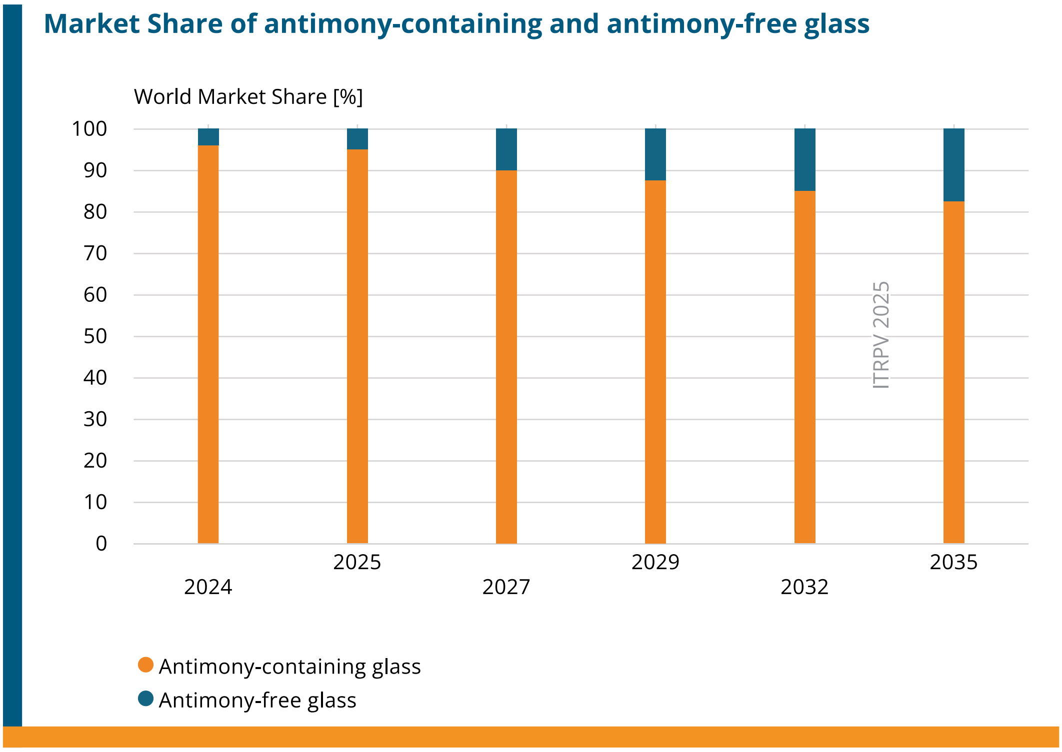

Fig. 49: Market share of Antimony containing glass.

Rolled/structured glass is mainly used in today's module manufacturing. The float glass market share of 3% in 2024 will grow to about 8% within the next 10 years as shown in Fig. 50.

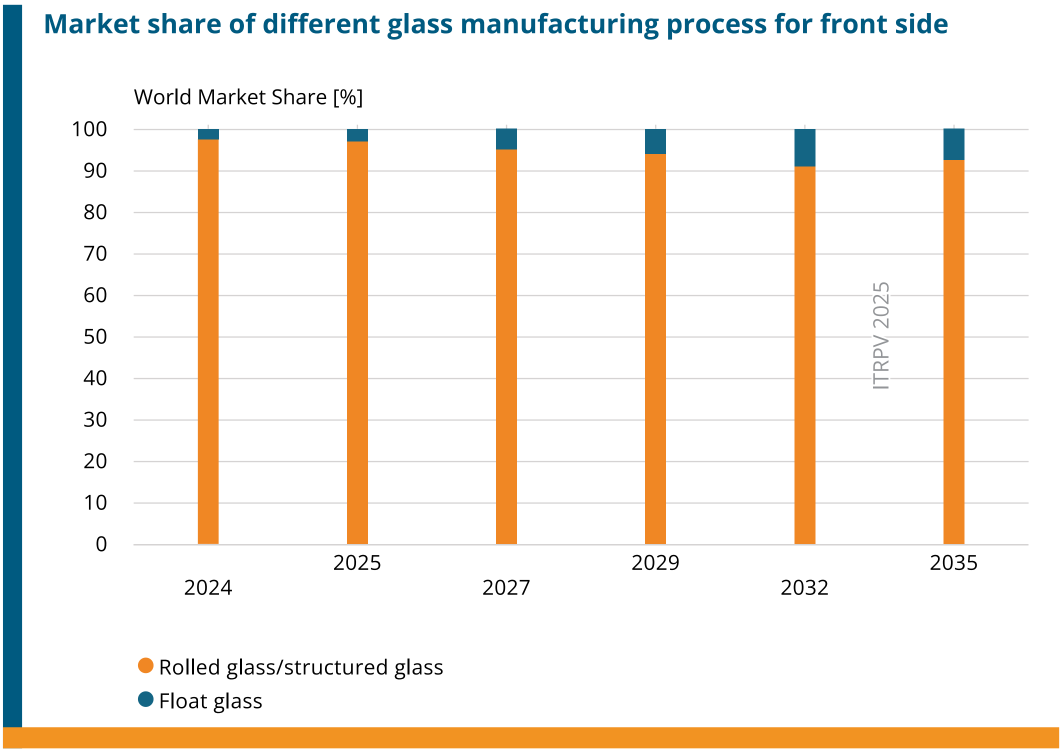

Fig. 50: Trend of front glass material market share.

Back side glass thickness is similar to front side glass, in some cases it is thinner.

World market share of back side glass thickness in bifacial modules

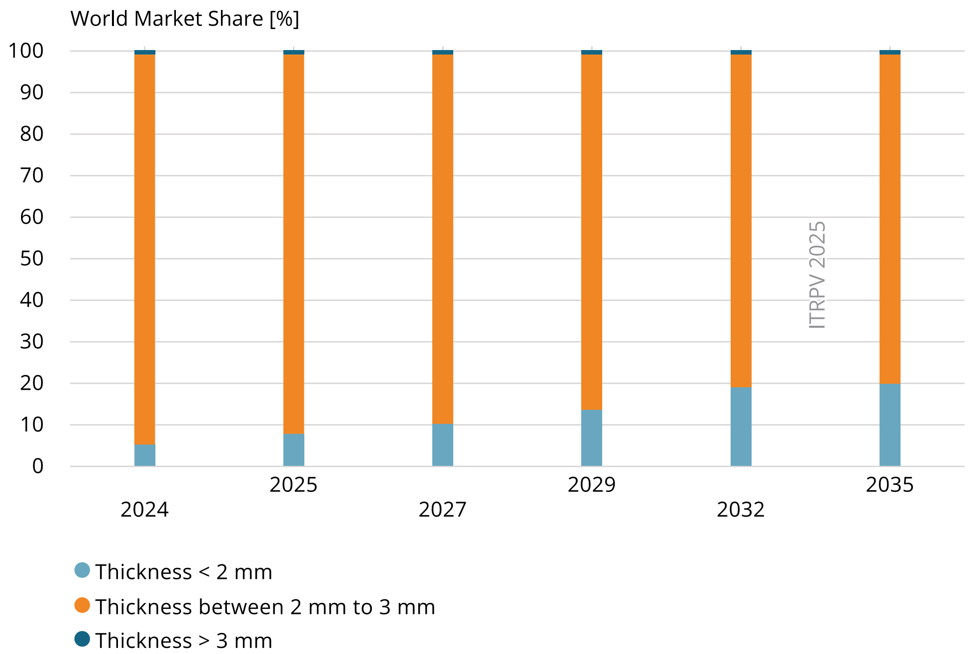

Fig. 51: Expected trend of back side glass thickness in bifacial modules.

Mainstream thickness is between 2 mm and 3 mm. Thickness below 2 mm has been in the market since 2022 and the market share is expected to increase in the upcoming years to almost 20% in 2035, shown in Fig. 51.

World Market Share of different glass manufacturing process for back side

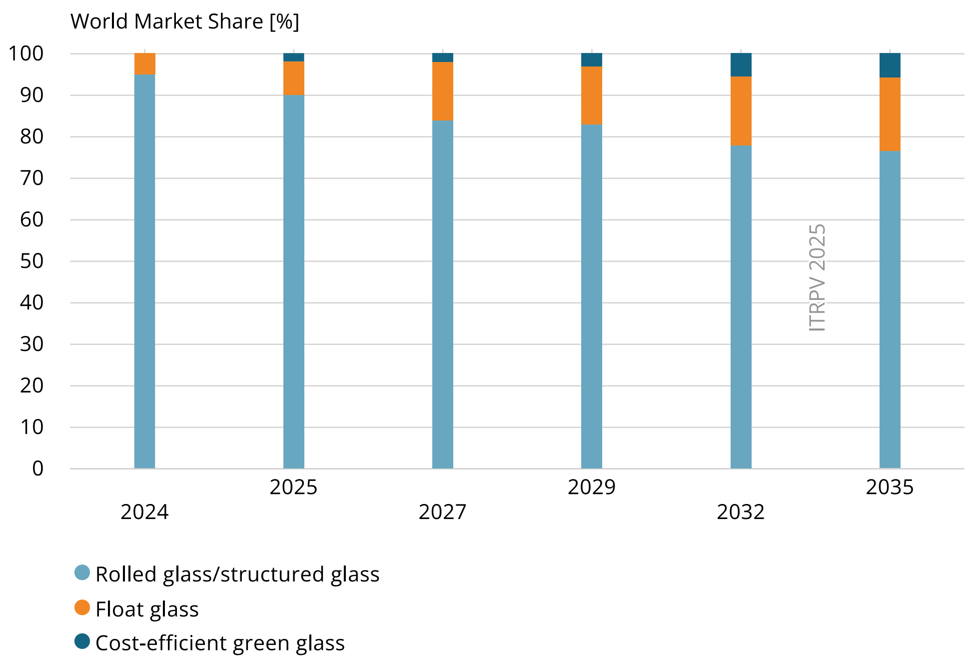

Fig. 52: Trend of back side glass market share.

Rolled/structured glass is dominating the back side glass market today, but it is expected that more float glass will be used in the future with a share of about 18% in 2035, as shown in Fig. 52. Also some market share will be covered by relatively cost-effective architectural grade glass reaching around 6% in 2035, according to the analysis in this report's edition.

The use of antireflective (AR) coatings has become standard to improve the transmission of the front cover glass. AR-coated glass will remain the dominant front cover material for c-Si PV modules in the future.

Since AR-coated glass will be the most used front cover, it is important that the AR coating remains effective and stable under various outdoor conditions during the entire operational life of the module. Fig. 53 shows that all AR coatings on the market today meet an average lifetime of at least 15 years, and there is a clear trend indicating that the average service life of these coatings will improve to > 25 years already by 2032.

Expected Lifetime of AR-coating on Module Front Glass

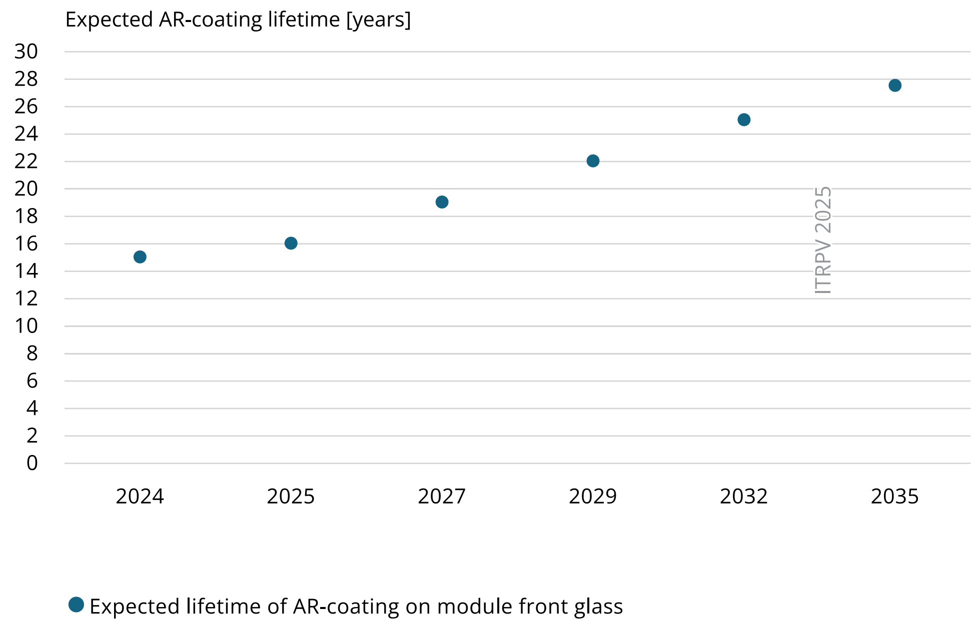

Fig. 53: Expected Lifetime of AR-coating on Module Front Glass.

Today, lead containing solders are used as the mature standard technology for reliable and cost-efficient interconnection of double-sided contact Si solar cells and interconnection of strings in the module manufacturing process. Lead-free interconnection alternatives exist for special applications and for SHJ cells and IBC cell concepts.

Fig. 54 and Fig. 55 show the expected market trends of different technologies for cell interconnection and for string interconnection in the module, respectively.

Lead containing soldering is the expected mainstream technology for the next 10 years. Electrically conductive adhesives (ECA) for cell interconnection are expected to gain market share from almost 3% in 2024 to about 15% within the next 10 years, in 2035. Lead free soldering for cell interconnection is expected to gain market share from 5% in 2024 to 31% in 2035. Some other technologies such as taping and other back contact-related solutions are expected to come up with a low market share too, according to the data collected. The trends for string interconnection technologies in Fig. 55 show similar tendencies with slightly different market share values.

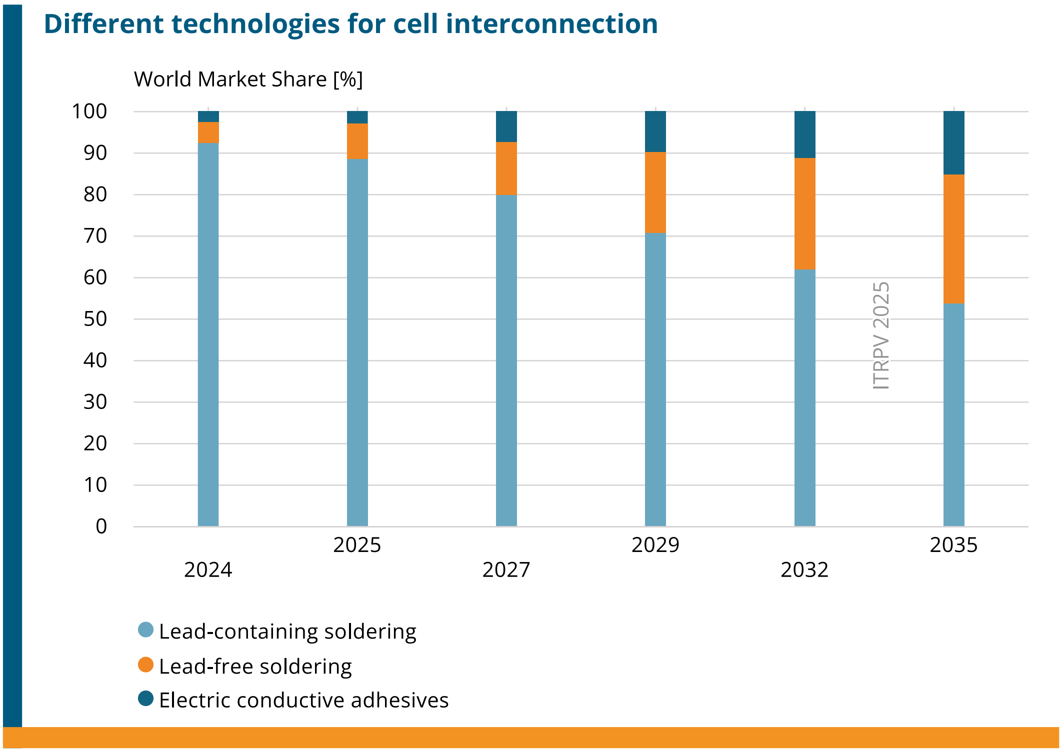

Fig. 54: Expected market share for different cell interconnection technologies.

Materials containing lead are restricted in accordance with legislation that went into effect in 2011 under the EU Directive on the Restriction of Use of Hazardous Substances (RoHS 2) [22]. This restriction affects the use of lead and other substances in Electric and Electronic Equipment (EEE) on the EU market. It also applies to components used in equipment that fall within the scope of the Directive. PV modules are excluded from RoHS 2, meaning that they may contain lead and do not have to comply with the maximum weight concentration thresholds of 0.1% as set out in the directive.[1] PV's exclusion and the thresholds will remain in effect.[2]

Cell and module manufacturers should act carefully, especially, as the exclusion to the defined threshold in question is limited to PV panels installed in a defined location for permanent use (i.e., power plants, rooftops, building integration etc.). Should the component in question (the module) also be useable in other equipment that is not excluded from RoHS 2 (e.g., mobile charging applications), then the component must comply with the Directive's provisions at this stage.

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[1] Article 2(i) of the RoHS Directive [2011/65/EU] excludes from the scope of the Directive "photovoltaic panels intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications."

[2] Article 24 of the RoHS Directive [2011/65/EU] requires an evaluation and possible revision of the Directive, including its scope, by July 2021. The REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS concluded that a major overhaul of the Directive is not considered as necessary [23].

Different technologies for module (string) interconnect

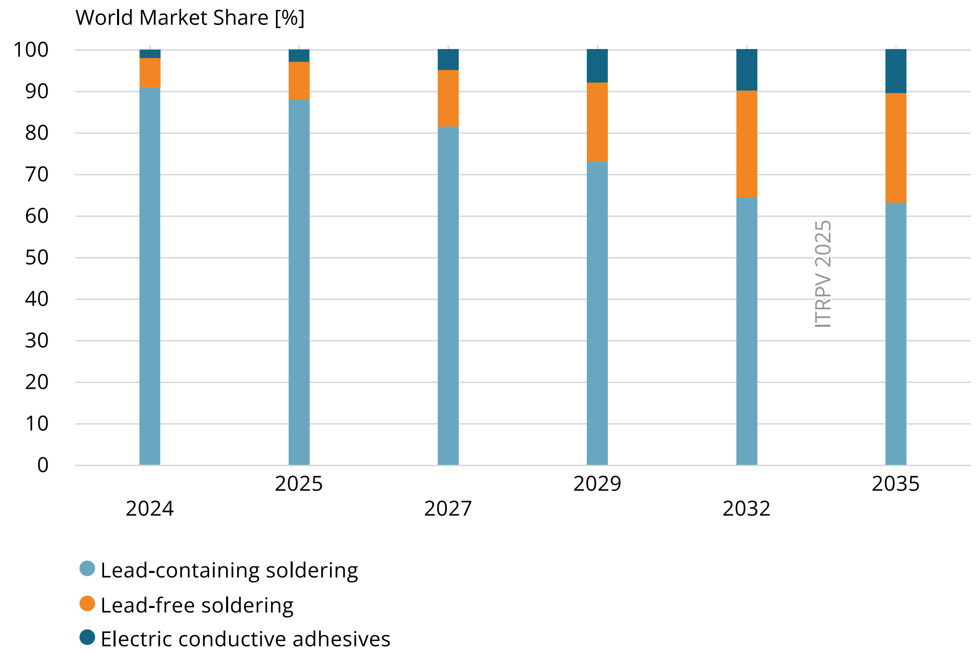

Fig. 55: Expected market share for different module interconnection technologies (i.e., for string interconnection).

Fig. 56 shows that copper wires, introduced some years ago for half-cell technology, will remain the dominating cell interconnection material within the next 10 years, with around 90% market share. Copper ribbons are expected to stay as niche technology in the market. Within the next 10 years, overlapping interconnection technologies and structured foils will gain market share to about 5% and 8%.

Different cell interconnection materials

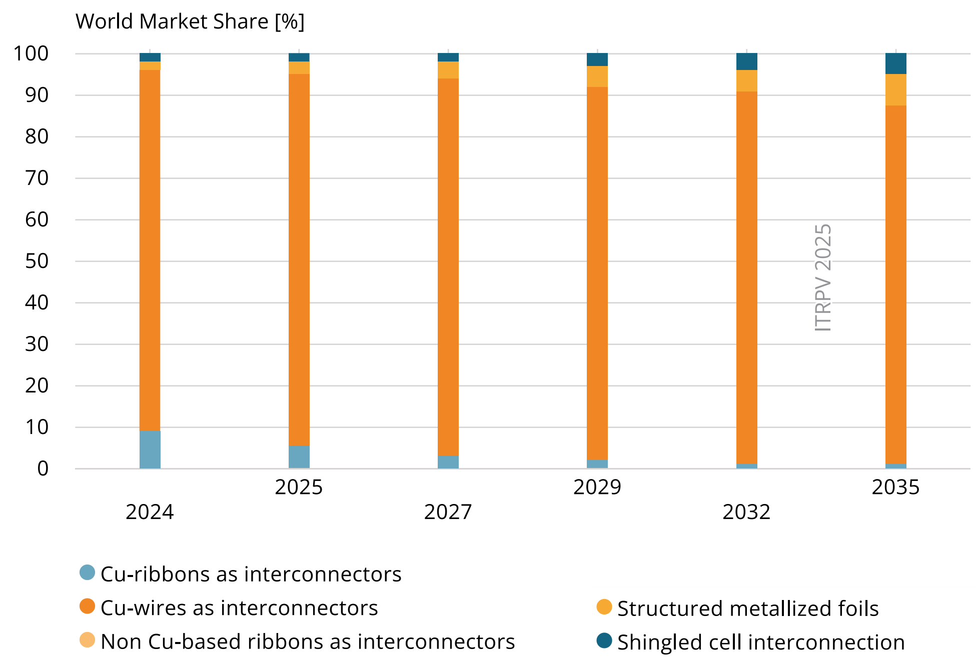

Fig. 56: Expected market shares for different cell interconnection materials.

Cu-ribbons as module (string) interconnect materials will sustain market dominance throughout the next decade.

The expected trend of the diameter of copper wires for cell interconnection is shown in Fig.57. The standard in 2024 is 260 µm. The diameter will be further reduced to 200 µm until 2035.

It is important to note that the existing and upcoming interconnection technologies will need to be compatible with all cell formats and the reducing cell thickness as well as with upcoming cell technologies. In this respect, low-temperature approaches using conductive adhesives or wire-based connections have an inherent advantage due to the lower thermal stresses associated with them.

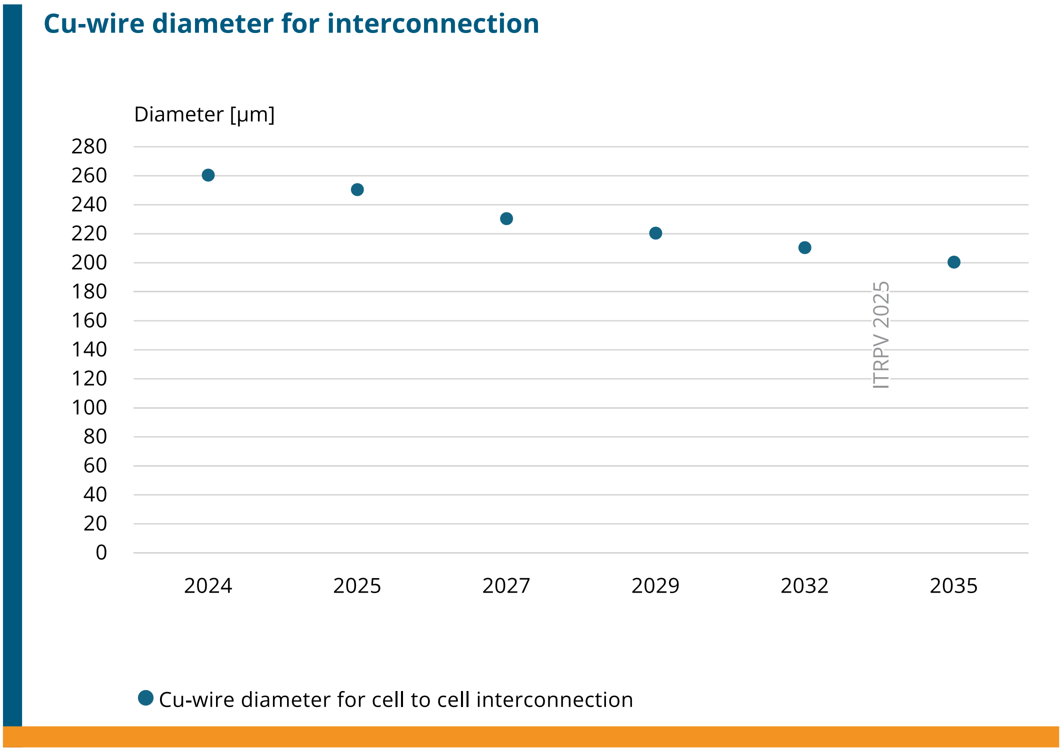

Fig. 57: Expected copper wire diameter for cell interconnection.

In Fig. 58 and Fig. 59 we see how module technology will be capable of processing thin cells as discussed in chapter 5.3 for smaller or equal to M10 and larger than M10 but smaller or equal to G12 formats respectively.

Limit of cell thickness in module technology for different cell types for wafer size ≤ M10

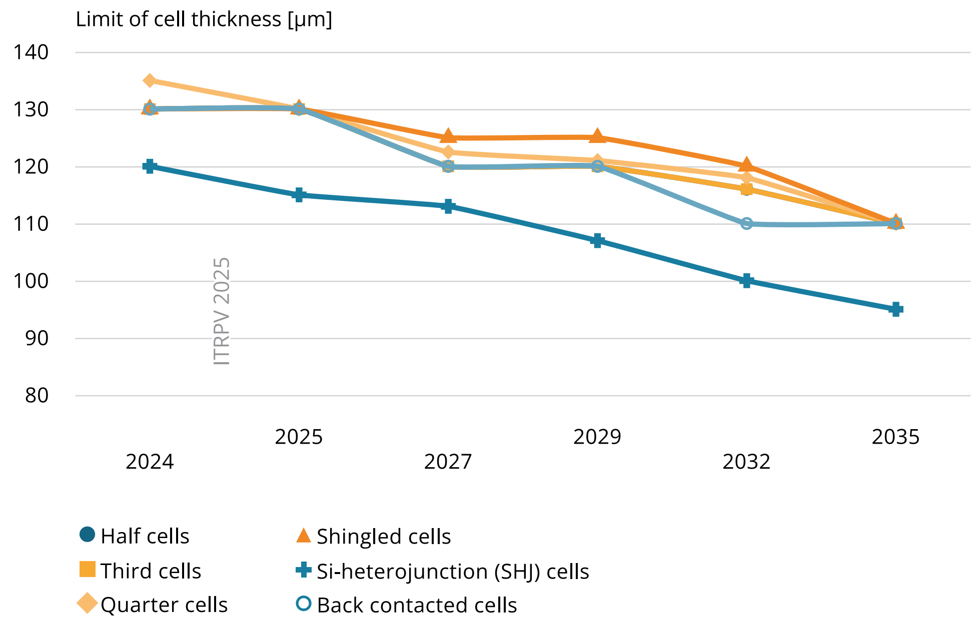

Fig. 58: Predicted trend of average cell thickness limit in different module technologies for wafer sizes ≤ 182.0 x 182.0 mm².

Cell thickness reductions will not be limited by module technology. So, silicon material savings have to and will contribute to future Wp cost reductions.

Limit of cell thickness in module technology for different cell types for wafer size > M10 and ≤ G12

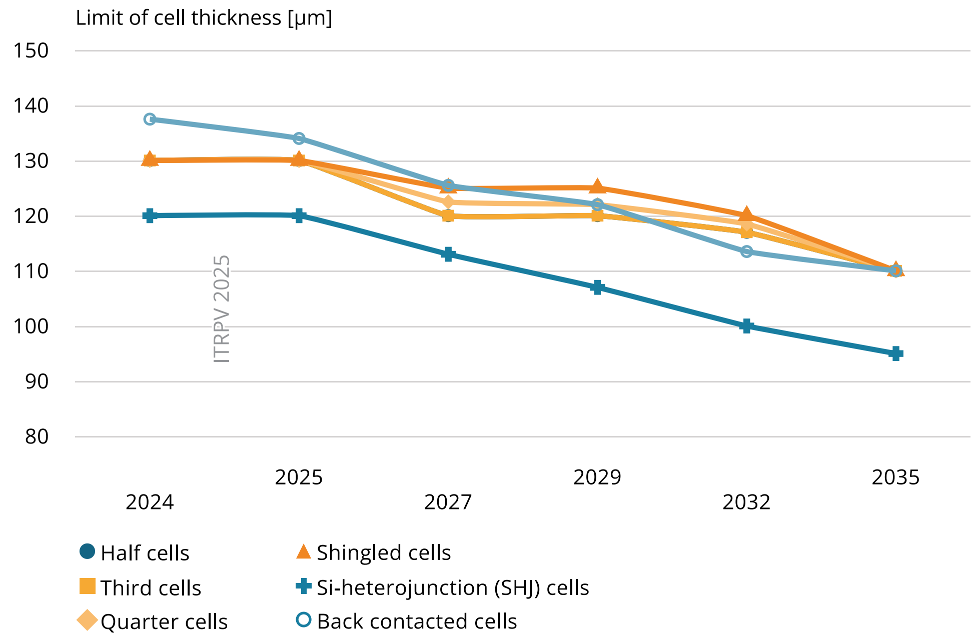

Fig. 59: Predicted trend of average cell thickness limit in different module technologies for wafer sizes ≤ 210 x 210 mm² and > 182.0 x 182.0 mm².

The encapsulation material and the back sheet/ back cover materials are key module components to ensure long time stability. Both are also major cost contributors in module manufacturing. Intensive development efforts have been made to optimize these components regarding performance and cost. Improving the properties of these key components is mandatory to ensure the module service lifetime.

Different encapsulation material

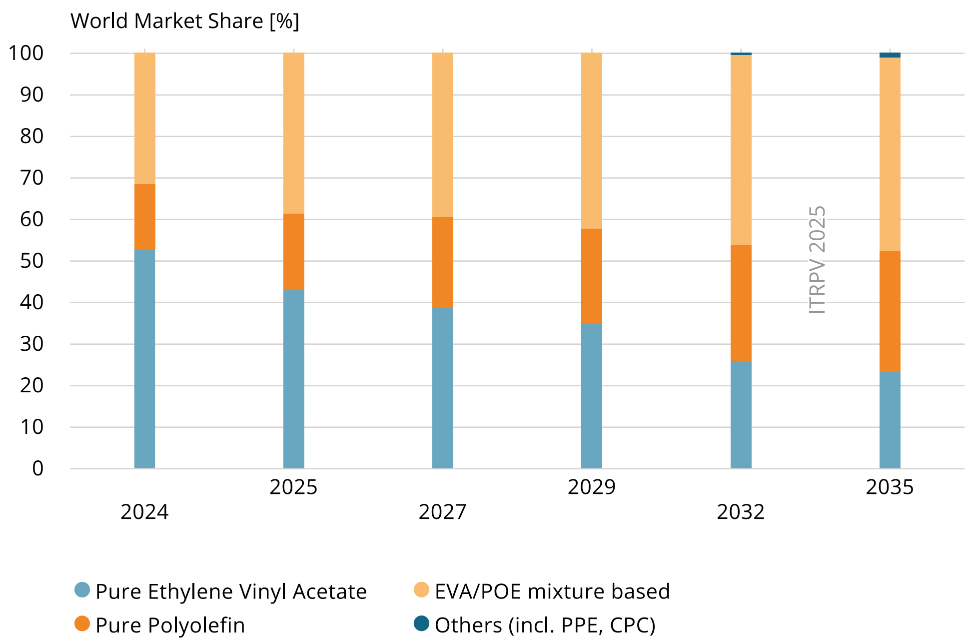

Fig. 60: Market share for different encapsulation materials.

Fig. 60 shows that EVA, has still considerable market share due to its cost efficiency. Pure Polyolefins (POE) and EVA/POE mix materials will dominate the market in the future due to the higher reliability [23]. Other materials are expected to occupy low market share for future niche applications.

Glass will become the dominant back cover material within the next years as shown in Fig. 61. The combination of front glass with foils as back cover material will reduce its market share to below 20% within the next 10 years. Flexible foil-foil modules will stay a niche.

Market share of different front and back cover materials

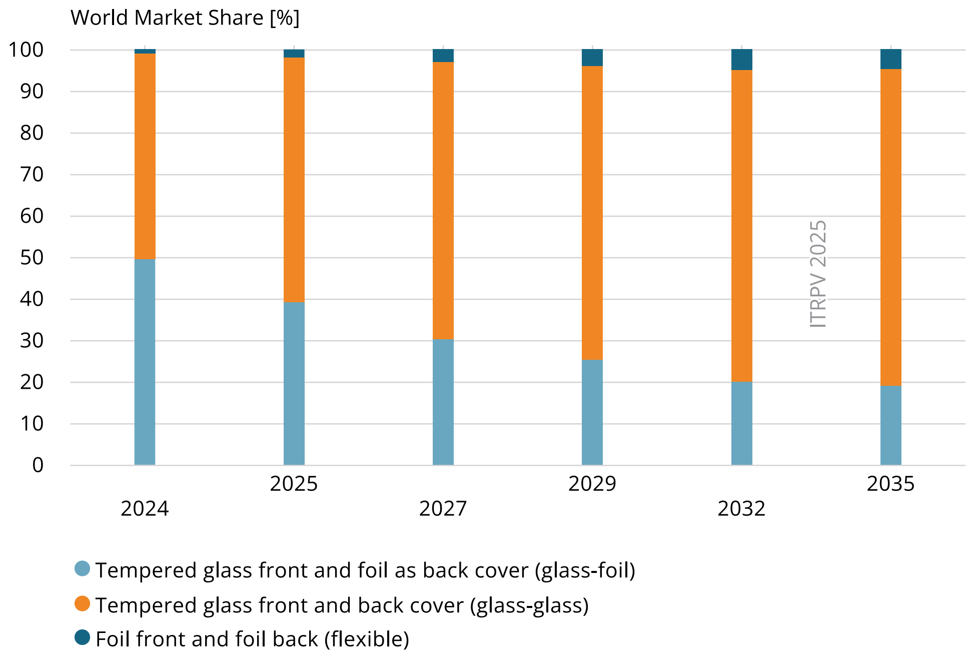

Fig. 61: Market share of glass and foil as front and back cover.

The most common backsheet foil materials are Kynar-based materials with around 44% market share in 2025, staying in the same range until 2035. Tedlar-based and Polyolefin-core-based materials have a small market share which will be reduced to 3% and 4% by 2035. Until 2035, other, fluorine free materials will gain high importance covering around 51% of the market as shown in Fig. 62.

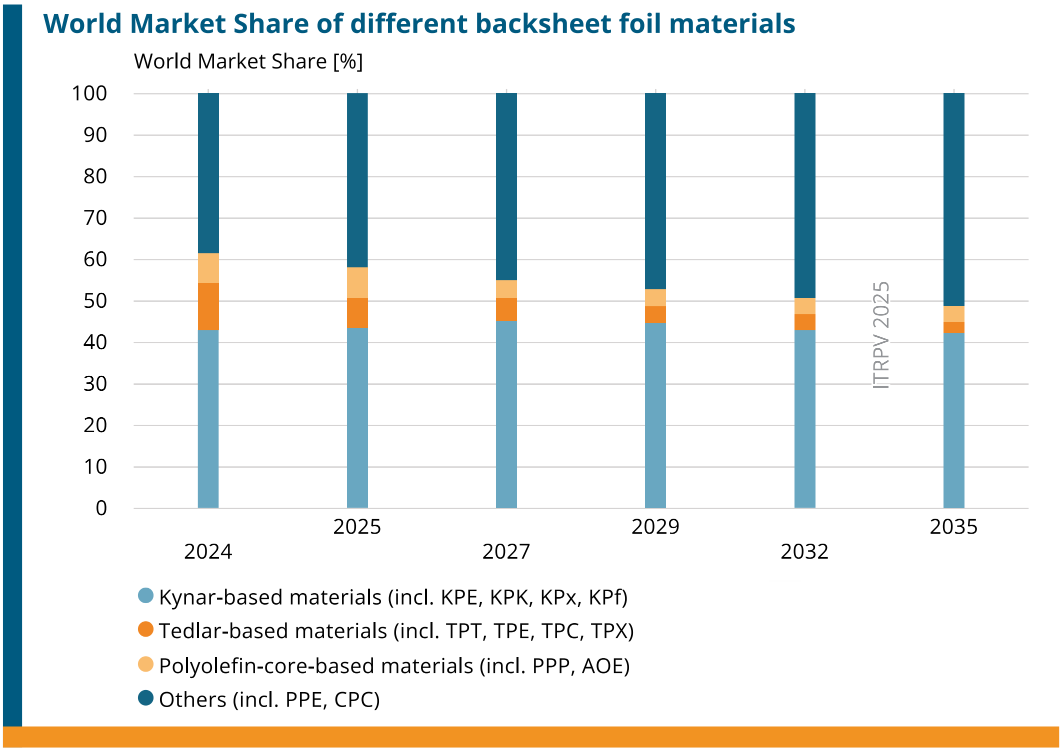

Fig. 62: Market share of different backsheets foil materials.

For bifacial modules, patterned transparent backsheets dominate over 77% of the market in 2025 but unpatterned, transparent backsheets will gain market share in the future, Fig. 63 shows.

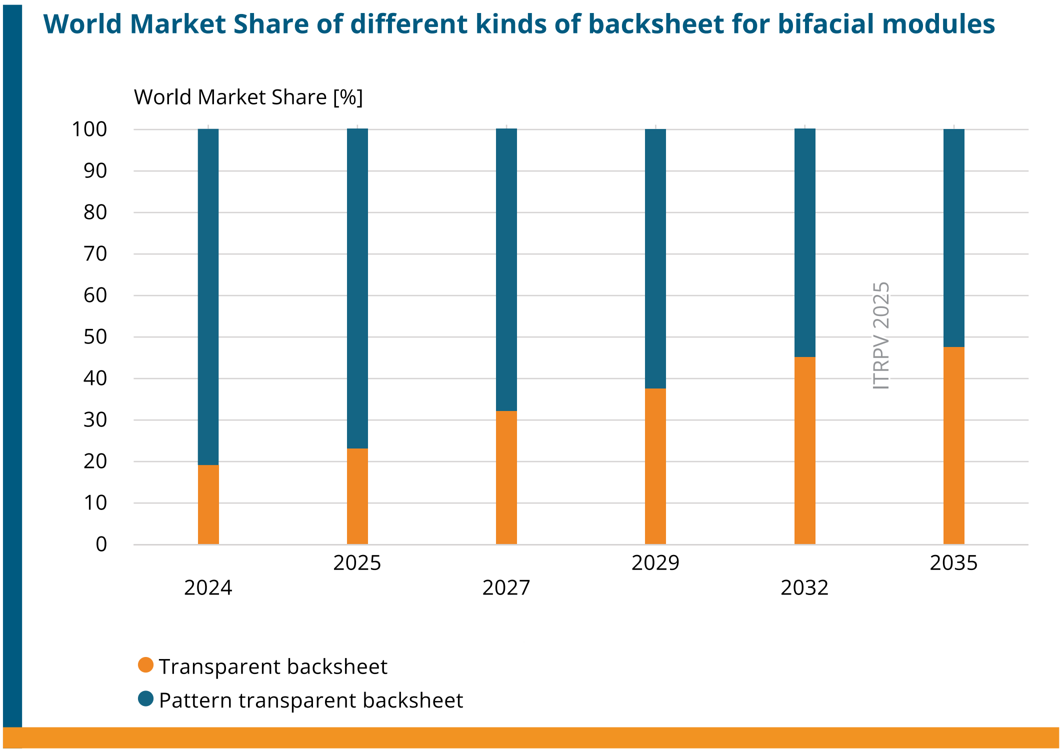

Fig. 63: Market share of different backsheets for bifacial modules.

Fig. 64 looks at the trends for frame materials. Modules with aluminum frames are clearly dominating the market with around 94% in 2024, expected to still have a dominant market share of 80% in 2035. Steel as frame material is expected to witness a gradual increase in its market share to about 8% until 2035. Frameless modules are expected to cover a stable market share ranging between 3% and 5% throughout the decade. Plastics and composite-based frames are considered as niche application with market shares of ≤ 2% together in 2025. Nevertheless, they are expected to have a gradual increase in market share throughout the decade, without losing dominance to aluminum as the standard product.

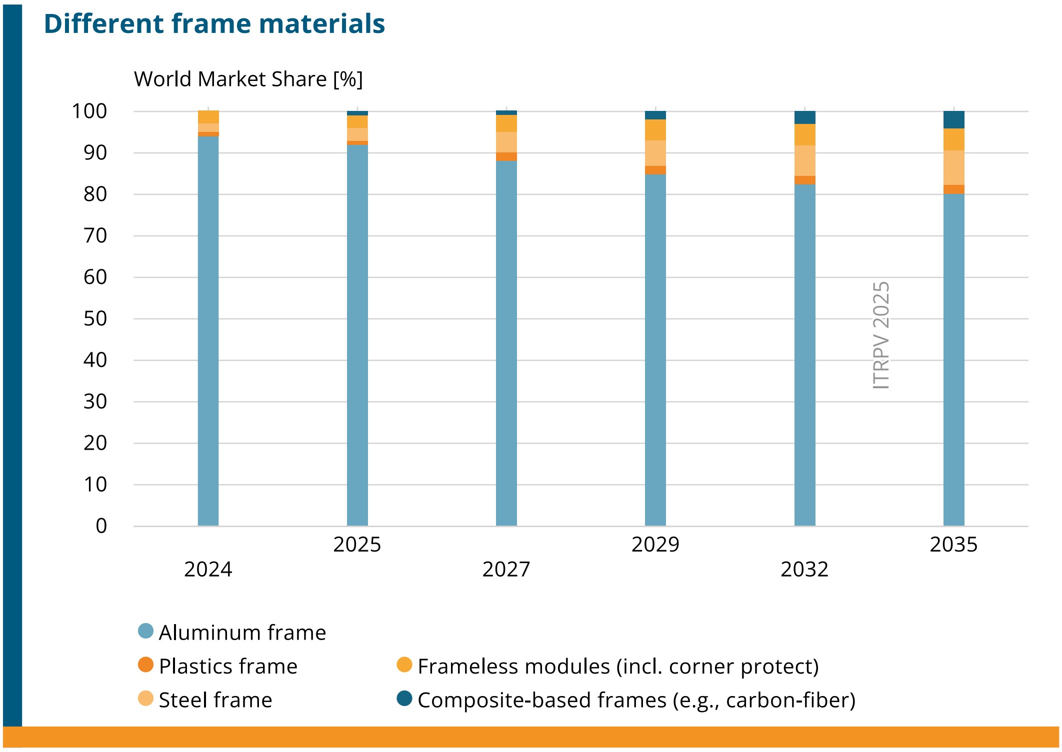

Fig. 64: Market shares for frame materials of c-Si modules.

6.2. Processes

A significant process innovation in module design during the last years was the introduction of half cells, in parallel with the introduction of wires instead of ribbons. The deployment of half-cells is the dominating mainstream today for all wafer sizes, maintaining dominance over the next decade, as shown in Fig. 65 and Fig. 66. Third cells will stay for niche applications for wafer sizes smaller or equal to M10, holding a stable share below 4% throughout the decade.

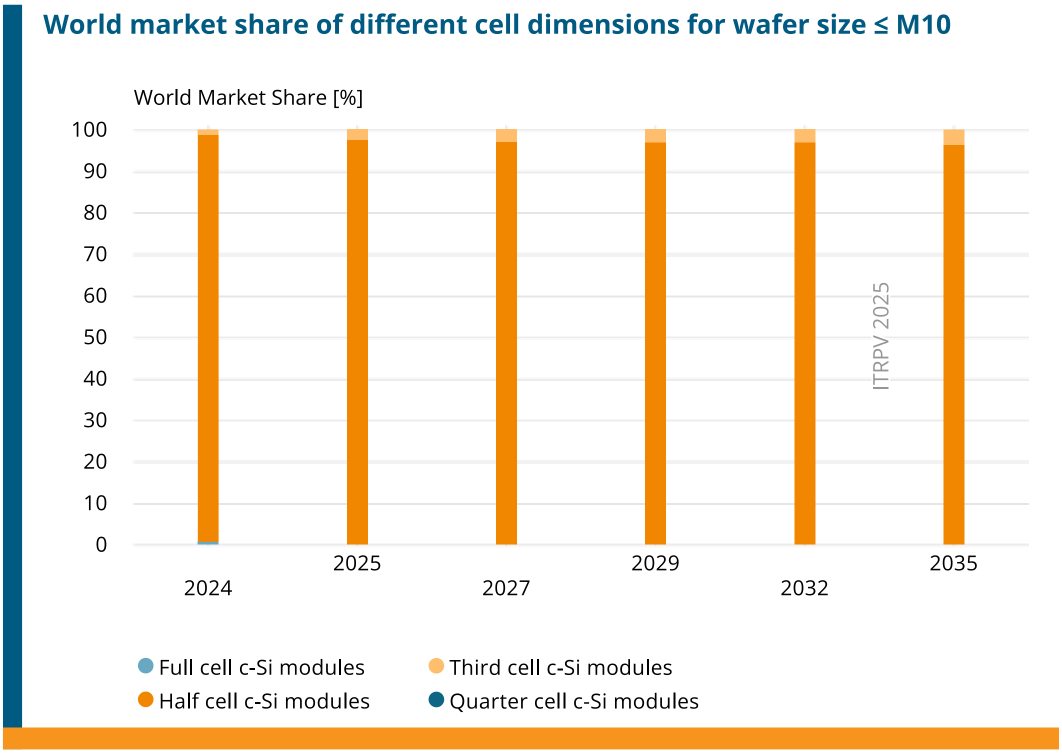

Fig. 65: Market shares of modules deploying half, third, and quarter cells ≤ M10.

In 2024 third cell c-Si modules with wafer sizes greater than M10 and smaller or equal to G12 were represented in the market with 10%. Full cell c-Si modules are not used for these wafer sizes and quarter cell c-Si modules won't take over a significant market representation. Third and quarter cells will be used, especially for G12.

World Market Share of different cell dimensions for wafer size > M10 and ≤ G12

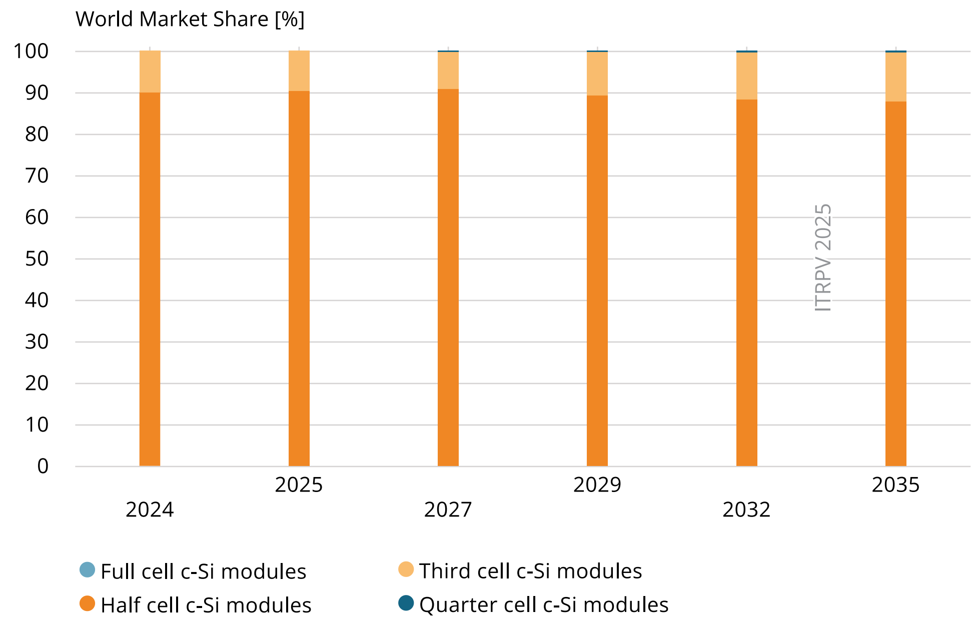

Fig. 66: Market share of different cell dimensions for wafer sizes > M10 and ≤ G12.

Fig. 67 shows that the trend for module production fabs is similar to the trend in cell production. Factories with annual capacities of > 5 GW will dominate the future production landscape. Nevertheless, smaller module fabs with < 5 GW, and < 1 GW are expected to be present for special applications and for regional markets, even after 10 years.

Market share for size of one module production fab

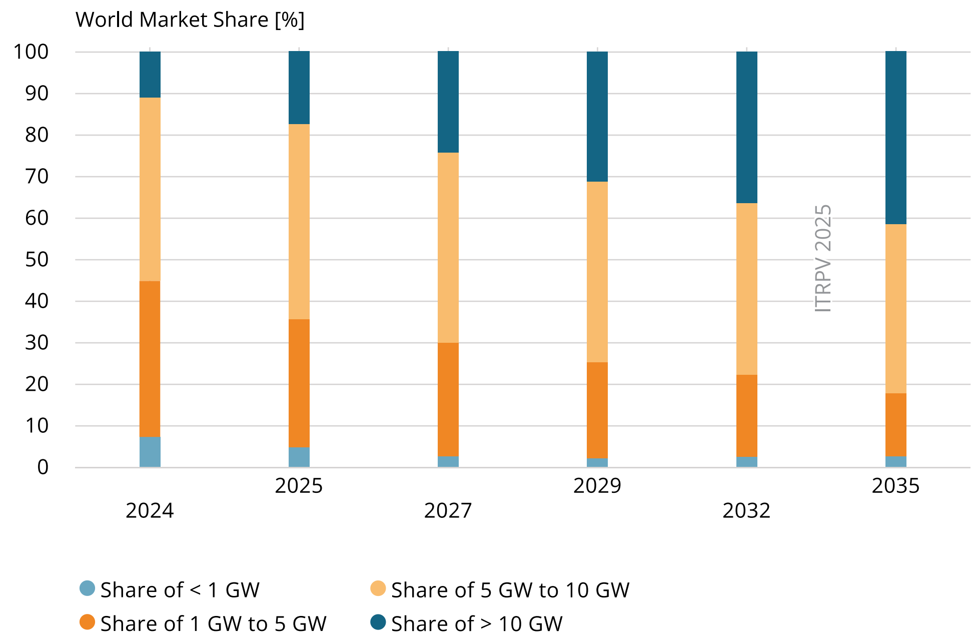

Fig. 67: Market share for nameplate capacity size of one module production fab.

6.3. Products

Due to the current diversification in wafer formats discussed in chapter 4.3., new module dimensions appeared. The introduced standard module width of 1134 mm improved the situation for modules based on cells with 182 mm width, but module power alone does not enable a comparison of comprehensive formats. Therefore, comparing different module types only by the so far common module label power may be misleading as module powers with impressive 720 Wp are present in the market with existing cell technologies [5, 25]. Therefore, module efficiency is a useful parameter to compare different technologies and the final products. Module efficiency is calculated with module label power divided by the module area in m² and the irradiance at standard test conditions (1000 W/m²): (module label power / (module area x 1000 W/m²)). In today's module data sheets, the module efficiency is indicated – for example a value of 22% corresponds to a power density of 220 W/m². Fig. 68 shows the expected trend of average module efficiency for modules in mass production with different cell technologies.

Efficiency trend for c-Si modules in mass production

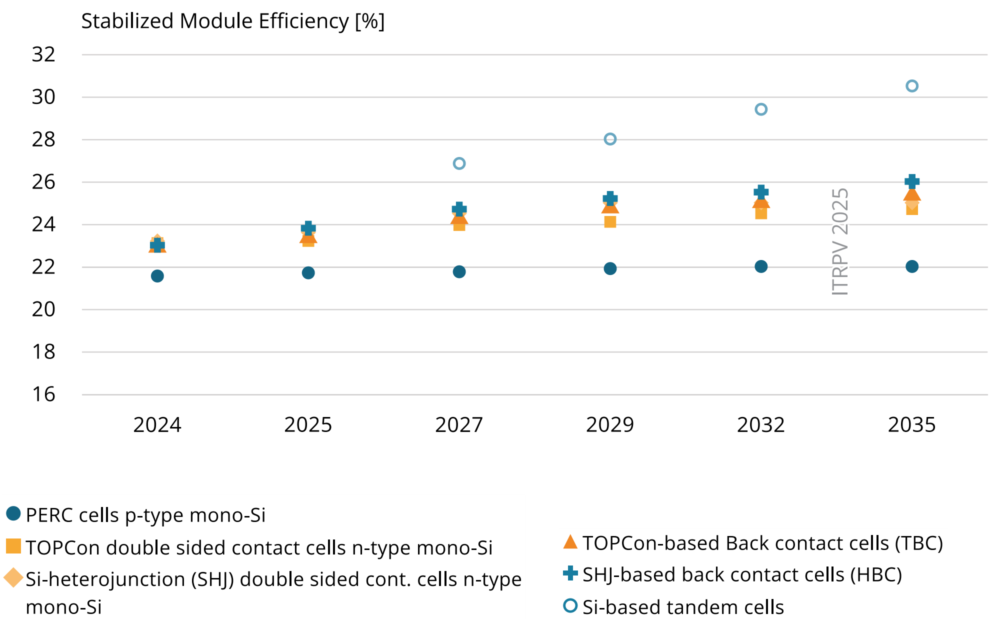

Fig. 68: Average module area efficiency in mass production for different c-Si solar cell technologies.

Current PERC p-type mono-Si modules are expected to show average efficiencies of 21.7% in 2025 and will end up at 22% in 2029. It is not expected that p-type PERC developments will go further than the 22% module level average in mass production. Modules with n-type cells with tunnel oxide passivation technologies, are well ahead of p-type PERC with 23.2% in 2025 and with up to 24.7% in 10 years. SHJ modules reach in 2025 an efficiency of 23.6% and are expected to attain 25% in 2035. Back-contact cells on n-type are expected to show again the highest module efficiencies of around 23.4% for TBC and 23.8% for HBC in 2025 and eventually around 25.4% for TBC and 26% for HBC in 2035. It is important to mention that back contact concepts in combination with passivated contacts are being further developed, allowing to benefit from the advancement of passivated contacts as well as the benefits of the back contact concept. Nevertheless, double-sided contact cells are expected to hold much higher market share. We also report expected efficiencies for modules deploying Si-based tandem concepts. Si-based tandem modules are expected after 2026 with module efficiencies of 26.9% in 2027 and 30.5% in 2035, respectively. This will clearly exceed the practical and the theoretical limit of single junction based silicon technologies. Tandem technologies with perovskite are a high focus point in research and development, nevertheless the developments will have to be monitored.

The big variety of new wafer sizes and wafer form factors in modules lead to various module dimensions. Only the width of modules based on M10 cells was fixed to 1134 mm. This is quite helpful, especially in the rooftop market with its limited space requirements. Fig. 69 shows the trend of module size for residential applications – an average module size above 2.0 m² will have a higher market share in 2025 and the upcoming years. The sizes between 1.8 and 2.0 m² will remain with the highest share. For modules that are smaller than 1.8 m² the current small market share will decline in the next three years to under 6%.

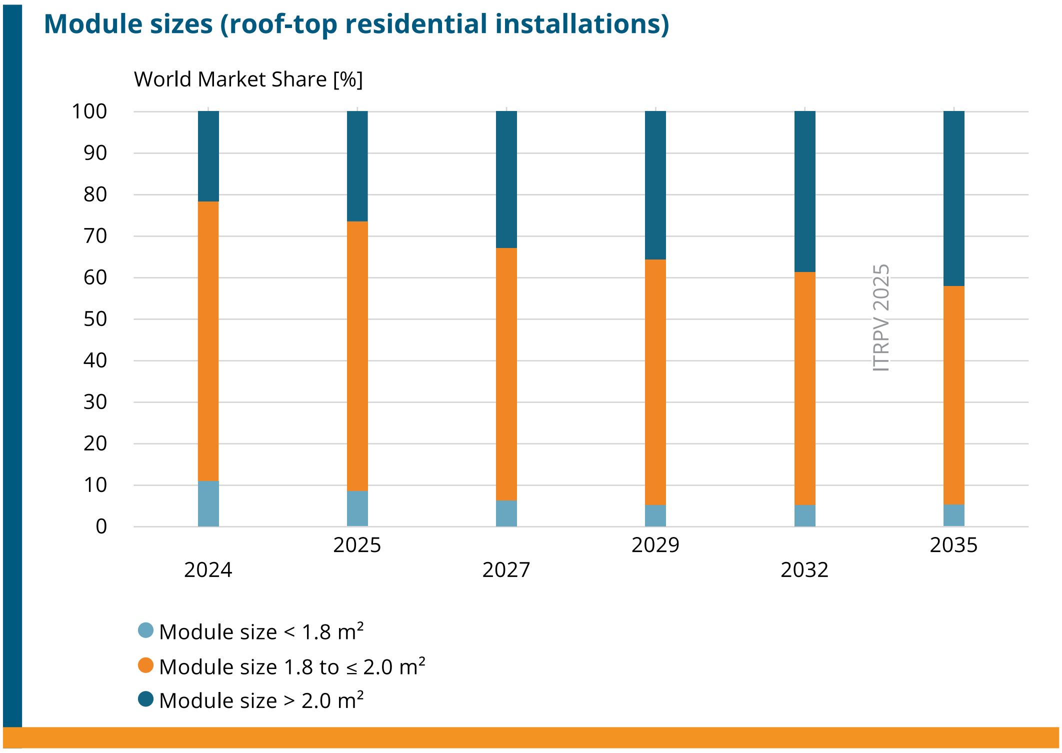

Fig. 69: Trend of module sizes for roof-top residential applications.

The module size development for large-scale ground mounded installations (i.e, power plant) is visualized in Fig. 70. The trend to larger modules is significant in this field in comparison to roof-top residential applications. Module sizes smaller than 2.5 m² are expected to stay niche, while 2.5 – 3.0 m² will be dominating the power plant market and larger modules >3 m² are expected to grow to about 25% in 10 years.

Module sizes (large-scale ground-mounted installations)

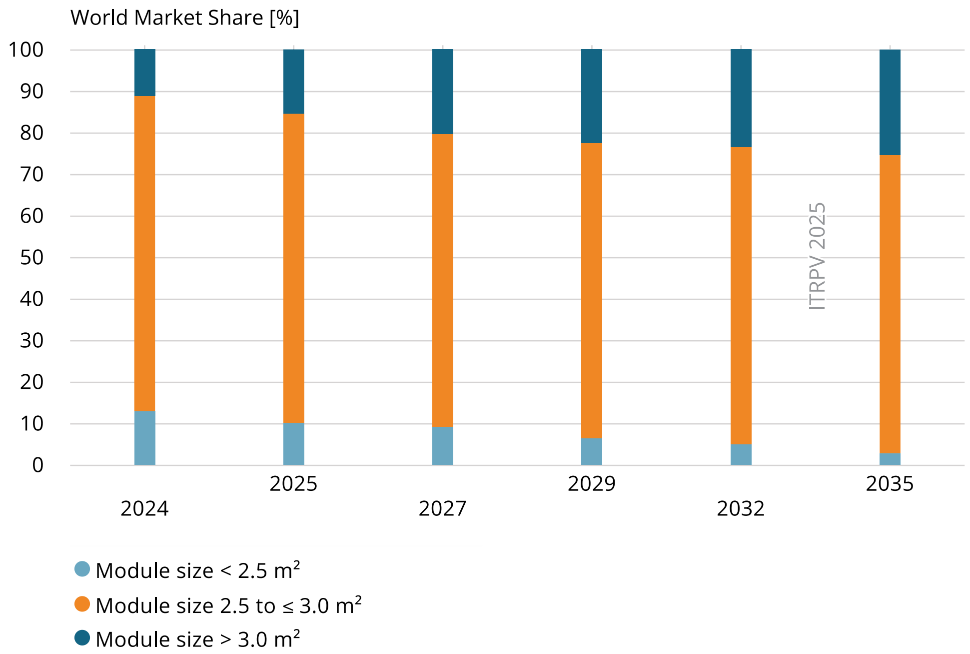

Fig. 70: Trend of module size for large-scale ground mounted applications.

Larger modules will be heavier. Fig. 71 and Fig. 72 show the expected trend of the module weight for residential and for power plant installations, respectively.

Module weight (roof-top installations)

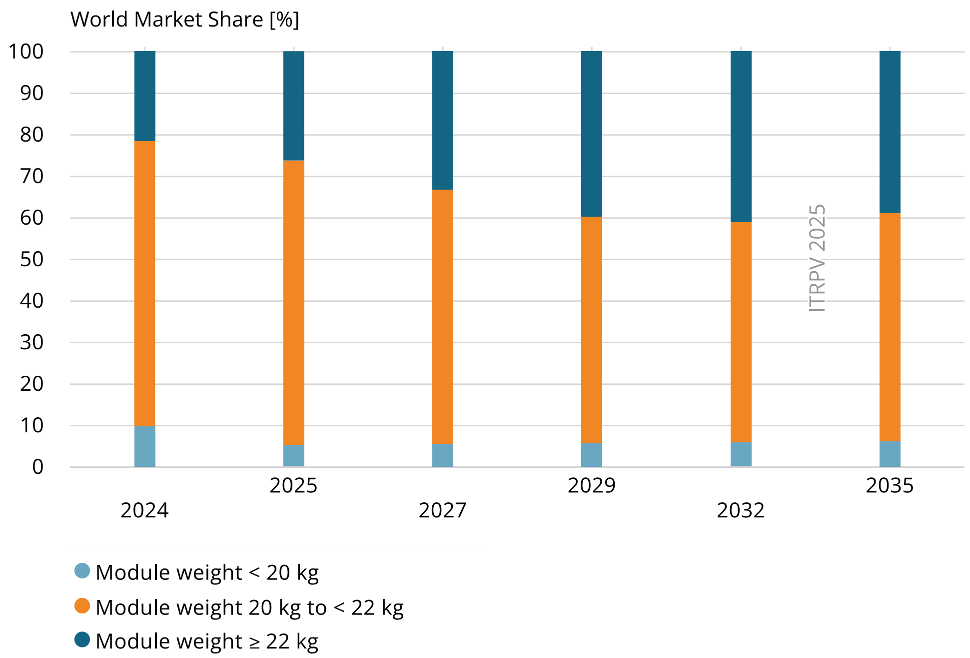

Fig. 71: Market share for the weight of modules for rooftop applications.

Roof top modules weight is expected to stay below the US limit of 50lbs / 24kg. Modules weighing 30 kg to 40 kg are expected to dominate the power plant market. Modules weighing between 25 kg to 30 kg still play a dominant role even after losing market share with development of the decade.

Module weight (large-scale ground-mounted installations)

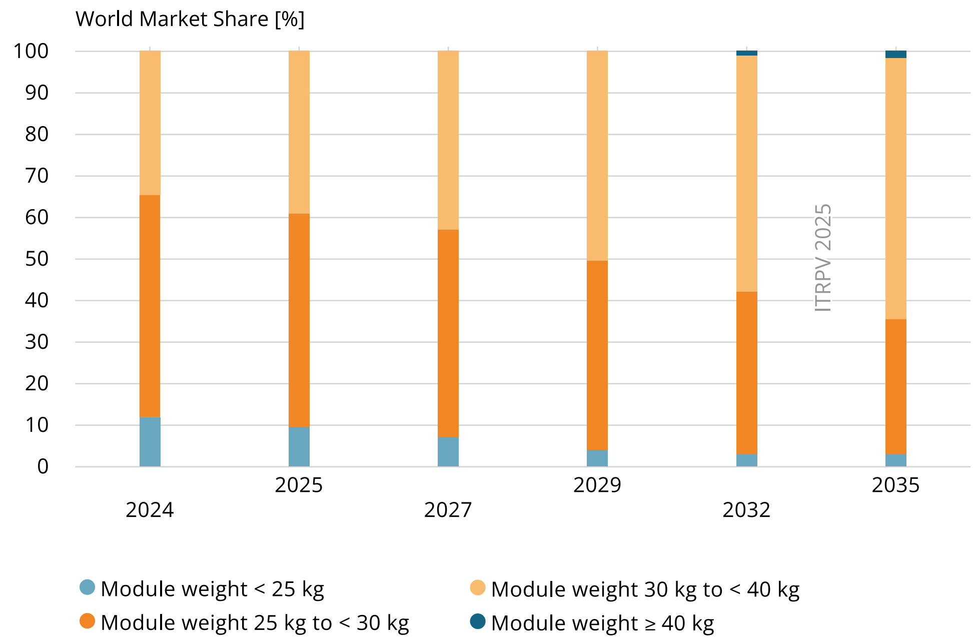

Fig. 72: Market share for the weight of modules for large-scale ground-mounted applications

Today, bifacial modules are dominating with about 64% as shown in Fig. 73. The share of bifacial modules will further grow to about 81% in 2035 also due to the increased use of glass-glass modules as shown in Fig. 61.

Bifacial cells are dominating the market as discussed in chapter 5.3, Fig. 42. The results show that around 26% of bifacial cells will be used in monofacial modules. Bifacial modules will mainly be deployed in power plant installations.

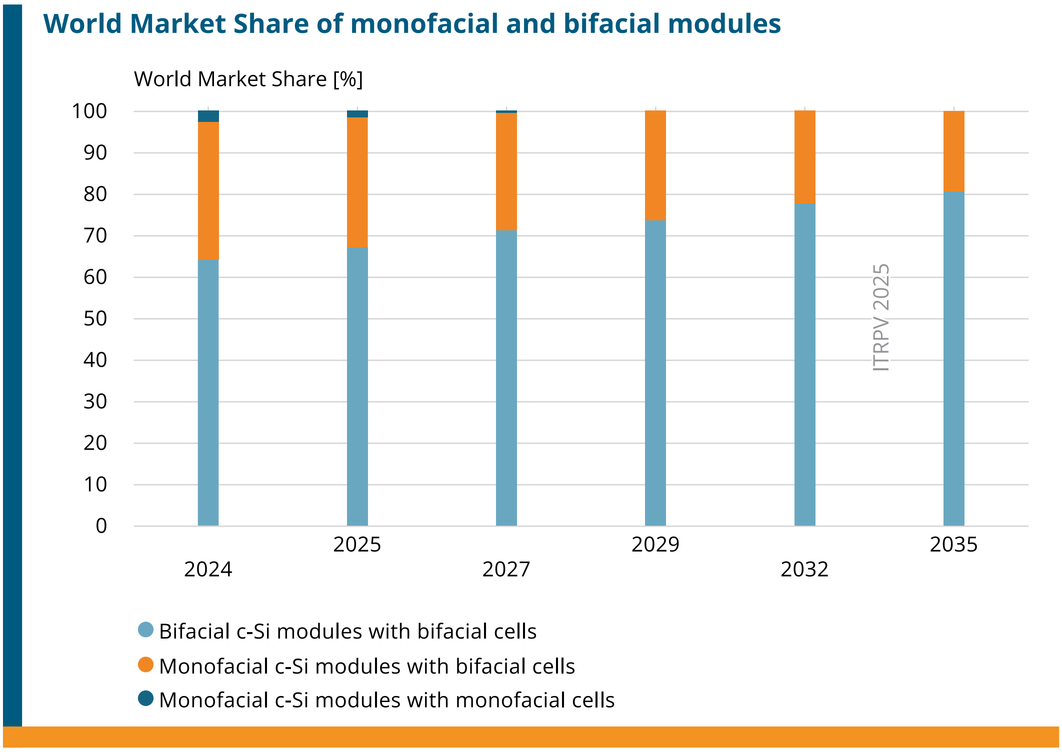

Fig. 73: Market share of bifacial modules.

Framed glass-glass modules will keep up their market dominance over the next decade as Fig. 74 shows. Frameless glass-glass modules on the other hand play a small role in the market for special applications.

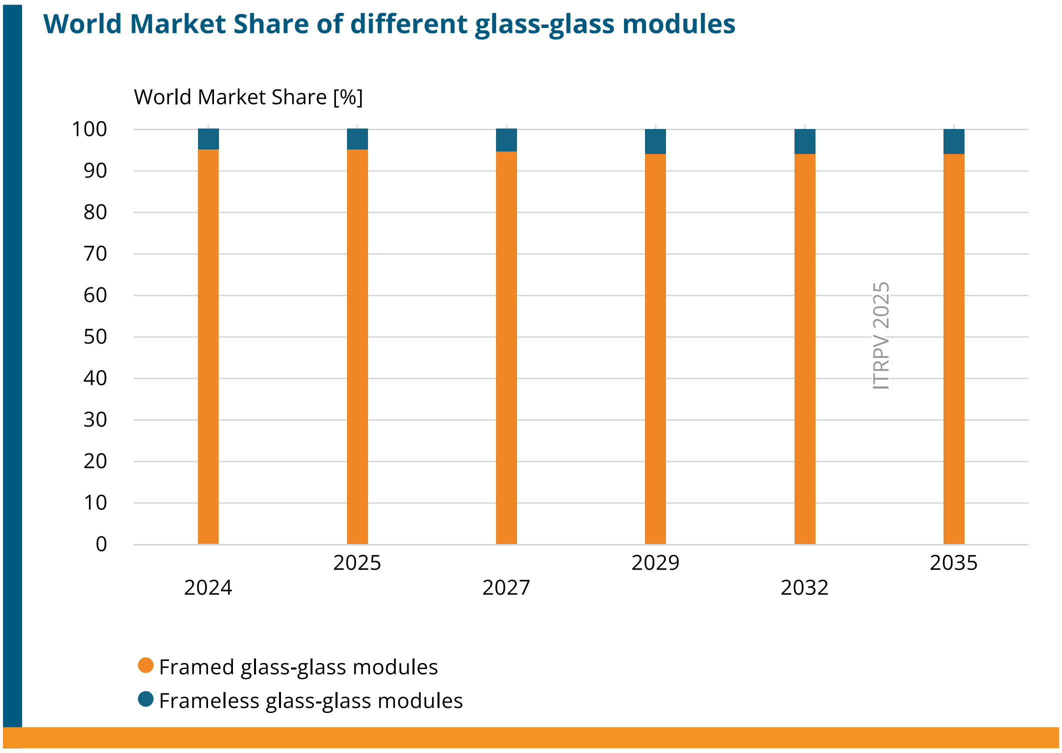

Fig. 74: Market Shares of framed and frameless glass-glass modules.

An important parameter to characterize the performance of bifacial modules is the bifaciality factor. It describes the ratio between rear-side and front-side efficiency, measured under STC (standard test conditions). Fig. 75 shows the bifaciality factors of modules with different cell technologies.

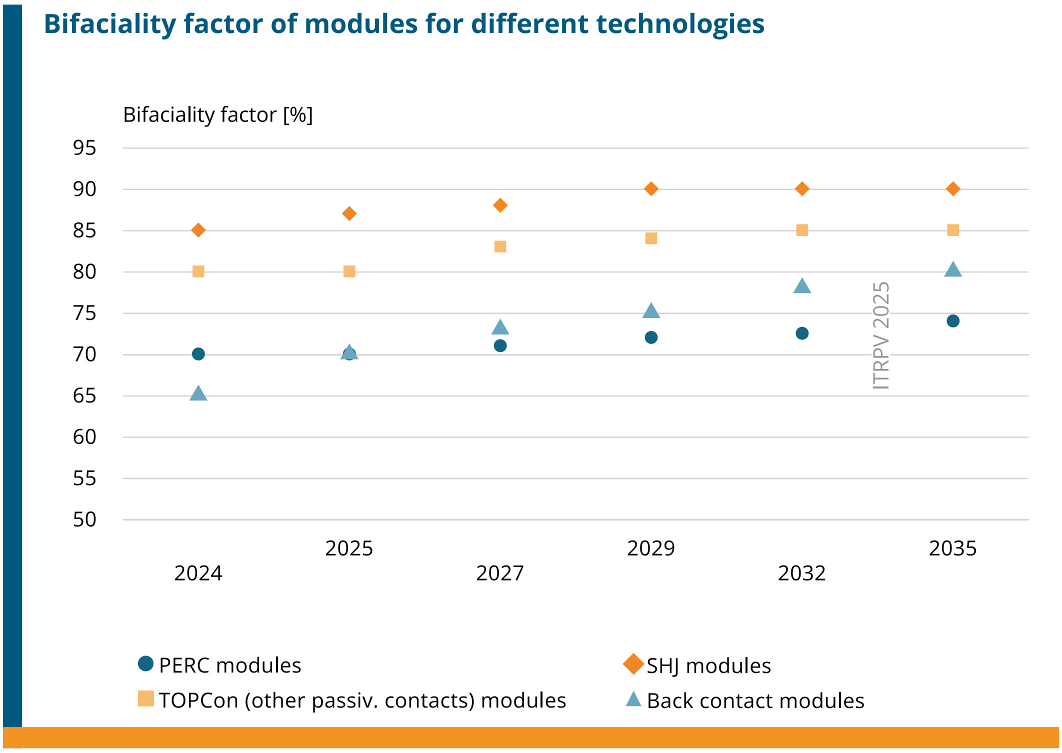

Fig. 75: Trend of bifaciality factor for modules with different cell technologies.

We see, that SHJ modules have the highest bifaciality factor that is expected to improve to up to 90%. The bifaciality factor of standard PERC cells is expected to improve to a maximum of 74% within the next 10 years. TOPCon cells show a bifaciality in between that of SHJ and PERC, expected to improve to up to 85%. Back contacted modules have today the lowest bifaciality factor of 65% in 2024 but show the relative highest increase to up to 80% in 2035.

Another trend in module technology is the development of modules for special markets and environmental conditions. Fig. 76 shows the assumed market share of modules for special environmental conditions. It is still expected that the main market will be for standard modules. Modules for special environmental conditions like tropical climate, desert environment, floating, or heavy snow load will together account for about 20% over the next 10 years.

Fig. 76: Market share for special regional applications.

The junction box (J-box) is the electrical interface between the module and the system. So-called smart J-box technologies are deployed to improve the power output of PV systems. Smart J-boxes will increase their market share to about 20% within the next 10 years. So, the participants in our survey believe that standard J-box without any additional function except the bypass diodes will clearly dominate the market.

The trend for J-box with special internal functions is shown in Fig. 77. Special features will be used in special markets. Standard junction boxes without additional functions will stay mainstream. Module level shut down (MLS) and module level monitoring (MLM) will experience increase in market share.

Market share of J-box monitoring technology

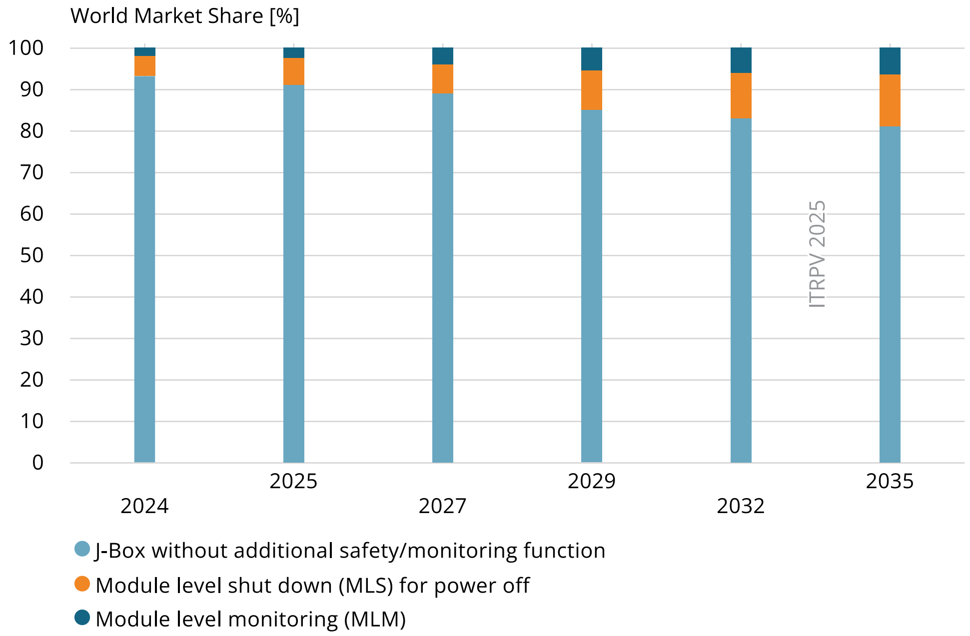

Fig. 77: Junction box monitoring technology.

Fig. 78 shows the market share of microinverter based technologies, showing the clear dominance of frame and rack mounted microinverters rather than module integrated ones.

Market share of microinverter based technologies

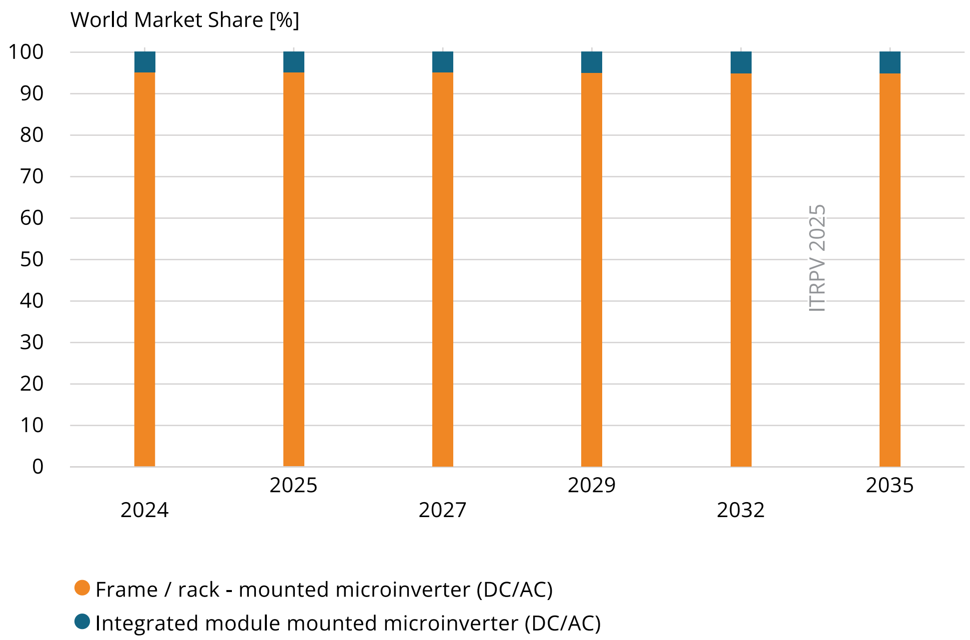

Fig. 78: Market share of microinverter based technologies.

Fig. 79 shows that modules without DC optimizers dominate the market. Module-based DC optimizers are expected to gain market share in the upcoming decade reaching around 17% in 10 years.

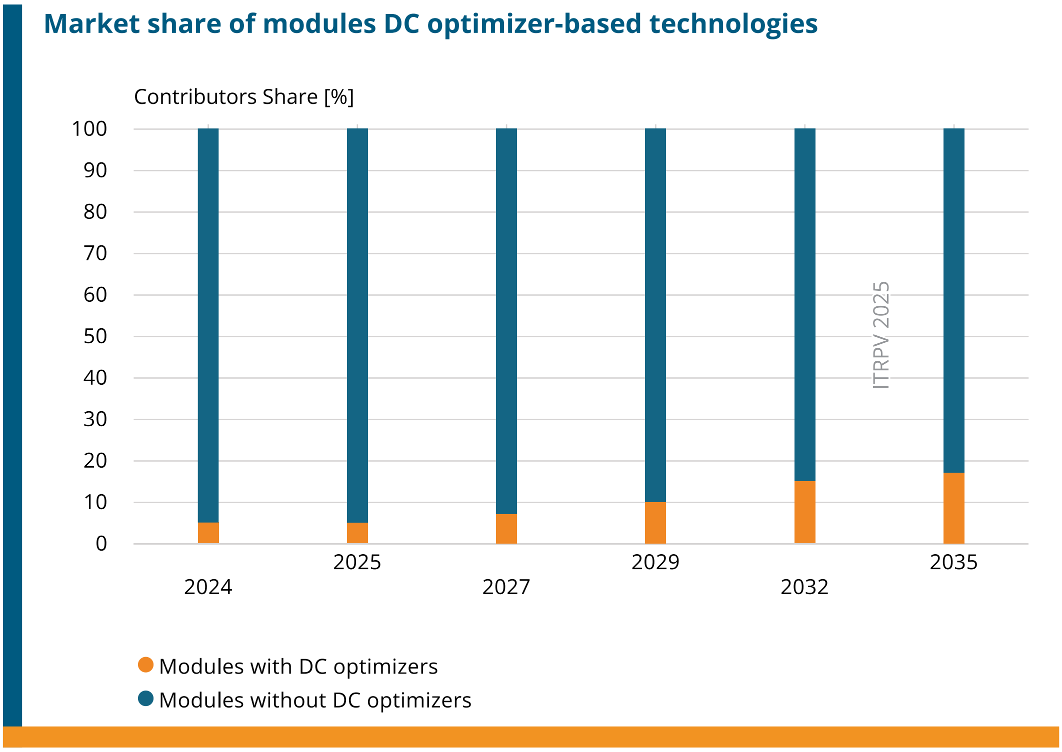

Fig. 79: Market share of modules DC optimizer-based technologies.

Fig. 80 shows the trend of module product and module performance warranty for the next years. The product warranty is expected to increase from today's 15 to 20 years after 2029. The performance warranty is expected to increase to 35 years from today's 25 years.

Warranty requirements for c-Si PV modules

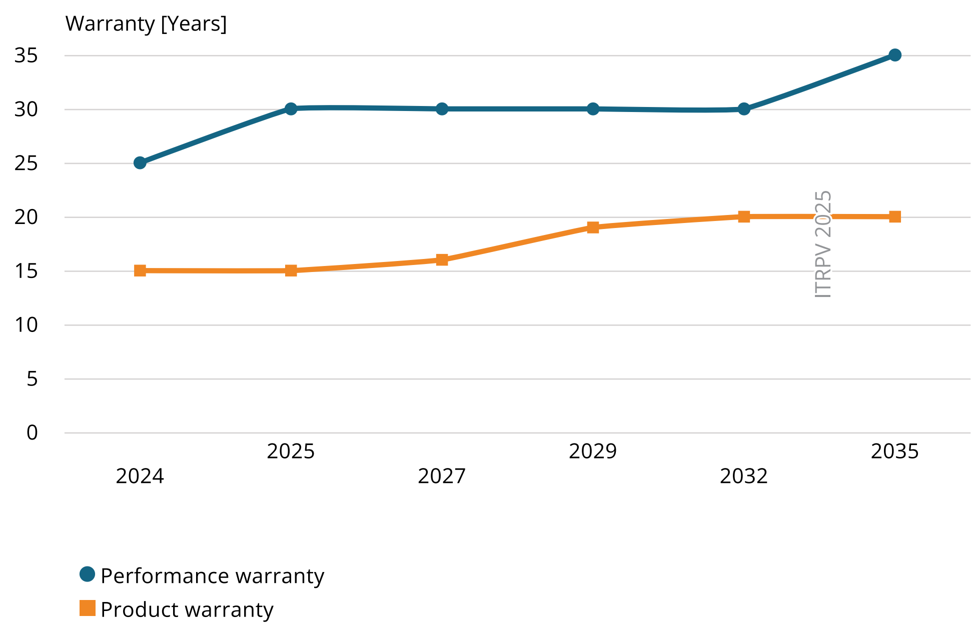

Fig. 80: Expected trend for product warranty and degradation of c-Si modules.

Fig. 81 shows the degradation behavior after the 1st year of operation that will be reduced from 1.8% to 1% in 2025. Annual degradation is expected to be reduced slightly from 0.5% continuously to 0.3% within the next 10 years.

Degradation of c-Si PV modules

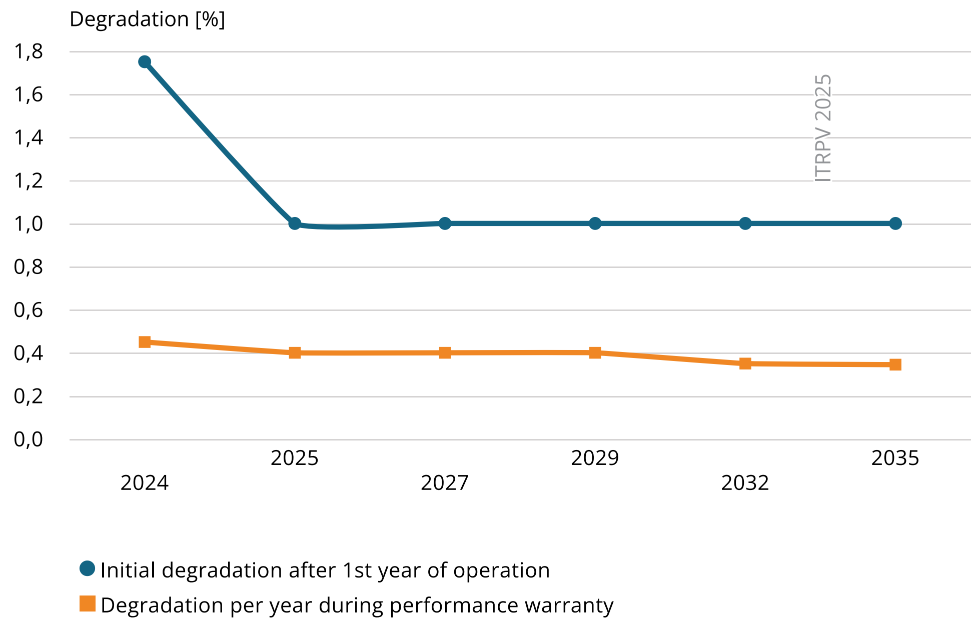

Fig. 81: Degradation of c-Si PV modules.

7. Smart Fabrication

The concept of "smart fabs" has been widely discussed over the past decade, yet large-scale implementation in photovoltaic manufacturing — particularly in solar cell and module production — has remained limited. This is now beginning to change, driven by the structured framework of Industry 4.0, which outlines a progressive digital transformation of manufacturing environments through data integration, intelligent systems, and automation.

Smart fabs can be categorized into four levels of digital maturity, based on the Industry 4.0 hierarchy:

Level 1 – Connected Fabs
All relevant machinery and infrastructure components are networked with centralized servers, enabling basic data flow and communication.

Level 2 – Transparent Fabs
Real-time data is not only collected but also visualized in meaningful ways, enabling operators to monitor processes effectively and make informed decisions.

Level 3 – Assisted Fabs
Advanced assistance systems analyze data and proactively suggest optimization strategies or troubleshooting measures. These systems function as digital co-pilots for operators and engineers.

Level 4 – Autonomous Fabs
The highest level of automation: the system itself makes real-time decisions and adjusts machine parameters autonomously to optimize yield, quality, and throughput.

Importantly, each higher level encapsulates the functionality of the preceding levels. For example, a Level 3 fab inherently includes full connectivity (Level 1) and transparency (Level 2).

Fig. 82 illustrates the projected development of smart fabrication in solar cell production through to 2035.

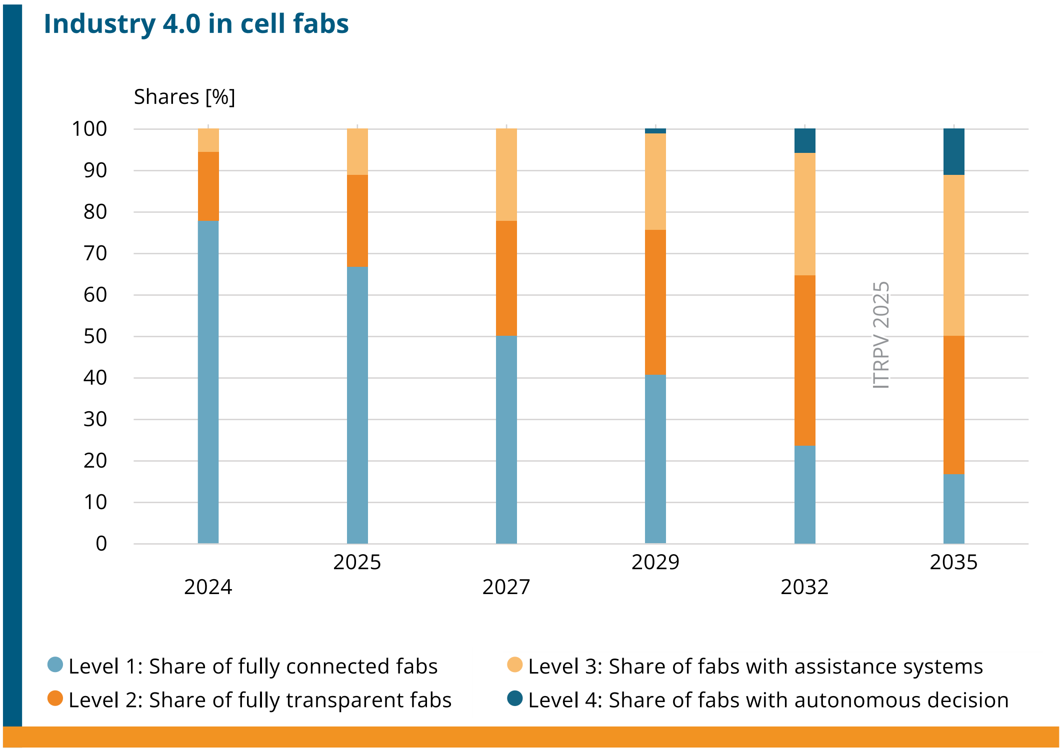

Fig. 82: Trend of end of line (EOL) testing in c-Si module manufacturing.

Only around 20% of PV fabs currently qualify as Level 2 or higher. Manual data analysis remains the norm, with substantial reliance on skilled operators and engineers for root cause analysis and optimization. By 2035, approximately 80% of all PV manufacturing facilities are expected to operate at Level 2 or higher, offering full data transparency. Additionally, intelligent assistance systems (Levels 3 and 4) will support production workflows in roughly 50% of fabs, enabling faster decision-making and reduced downtime.

The adoption curve shows that the majority of facilities will achieve data transparency within the next decade, with only 15% of fabs still operating without real-time data visibility by 2035 (down from 75% in 2024).

High-quality, granular data is essential for enabling effective assistance and autonomous systems. One key enabler is advanced tracking technology.

Fig. 83 shows that as of 2024, batch-level tracking is standard across most production lines, with only 20% of fabs lacking any form of traceability. Single-wafer tracking is poised for significant growth, expected to reach 50% market penetration by 2035. Single-wafer traceability is crucial for advanced defect correlation, predictive maintenance, and in-line yield optimization. By 2032, nearly all manufacturing lines are expected to have some form of wafer tracking implemented, to enhance process control and yield analysis.

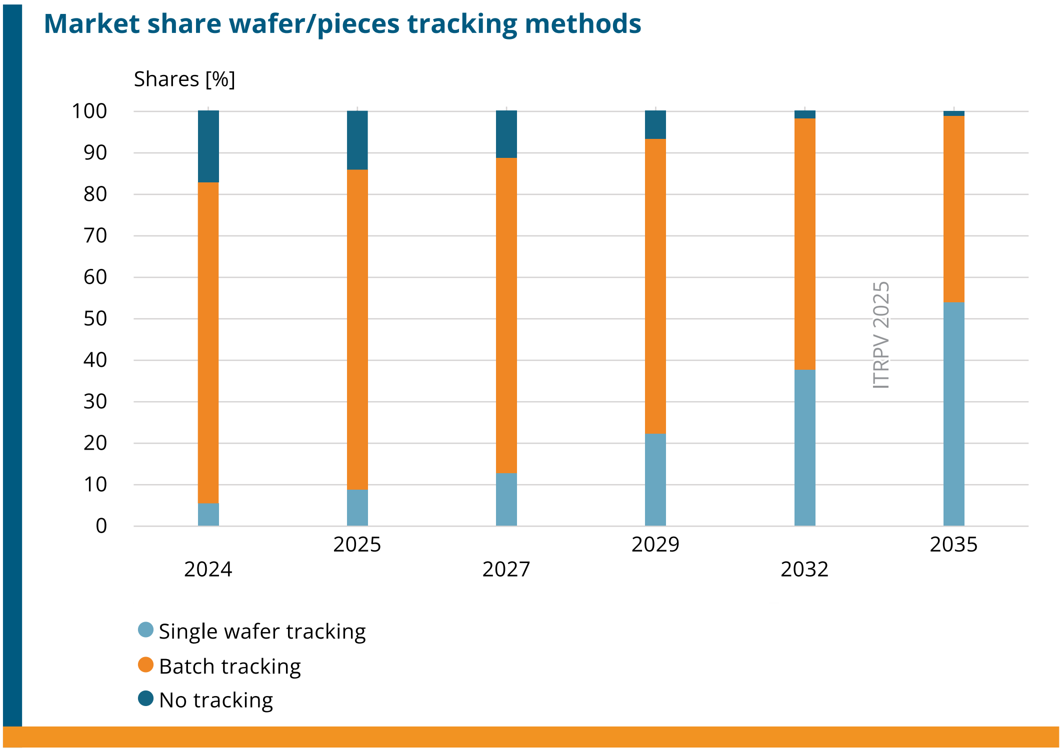

Fig. 83: Market share of tracking methods in c-Si cell manufacturing.

Historically, cell-level EOL testing focused on core parameters such as power conversion efficiency, current-voltage (IV) curve characteristics, and electroluminescence (EL) imaging.

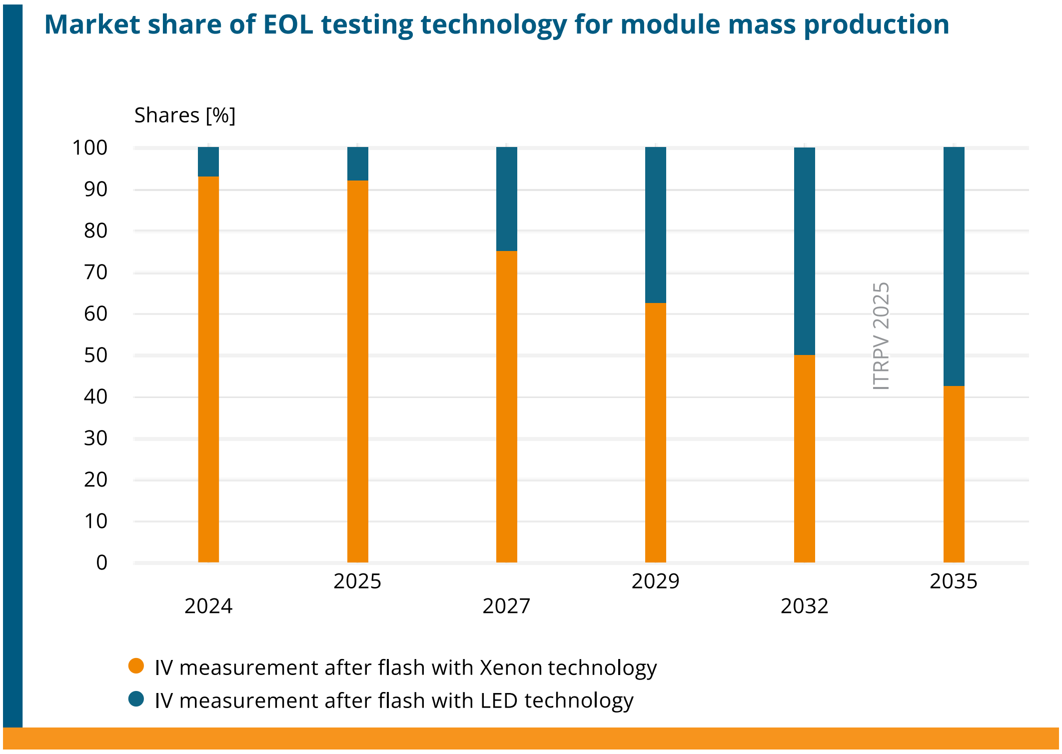

Fig. 84: Trend of end-of-line (EOL) testing in c-Si module manufacturing.

Techniques such as SunsVoc, External Quantum Efficiency (EQE), and reflectance measurement are becoming increasingly relevant. These methods enable deeper insights into loss mechanisms and process stability. While industry demand for these advanced diagnostics is growing, current data availability remains inconsistent, limiting quantitative forecasts.

Module-level EOL testing is currently dominated by Xenon light sources, with over 90% of modules tested this way in 2024, as seen in Fig. 84. However, by 2032 LED sources are expected to achieve parity with Xenon, each holding approximately 50% of the market. LED-based systems offer advantages in spectral accuracy, precision, tuning, and operational stability, making them increasingly attractive for modern mass production environments.

The PV manufacturing industry is entering a transformative phase. As smart fab technologies become more accessible and cost-effective, we anticipate a rapid acceleration in adoption rates—particularly in data-driven assistance systems and advanced measurements. This evolution will not only reduce dependence on human expertise for daily operations but also significantly enhance production stability, yield, and product quality.

8. Results of 2024 | System

8.1. Components

An important parameter is the degradation rate of the whole PV system. Fig. 85 shows the expected average annual degradation rates of PV systems in comparison with the module degradation trend. Annual system degradation is expected to improve over the next 10 years.

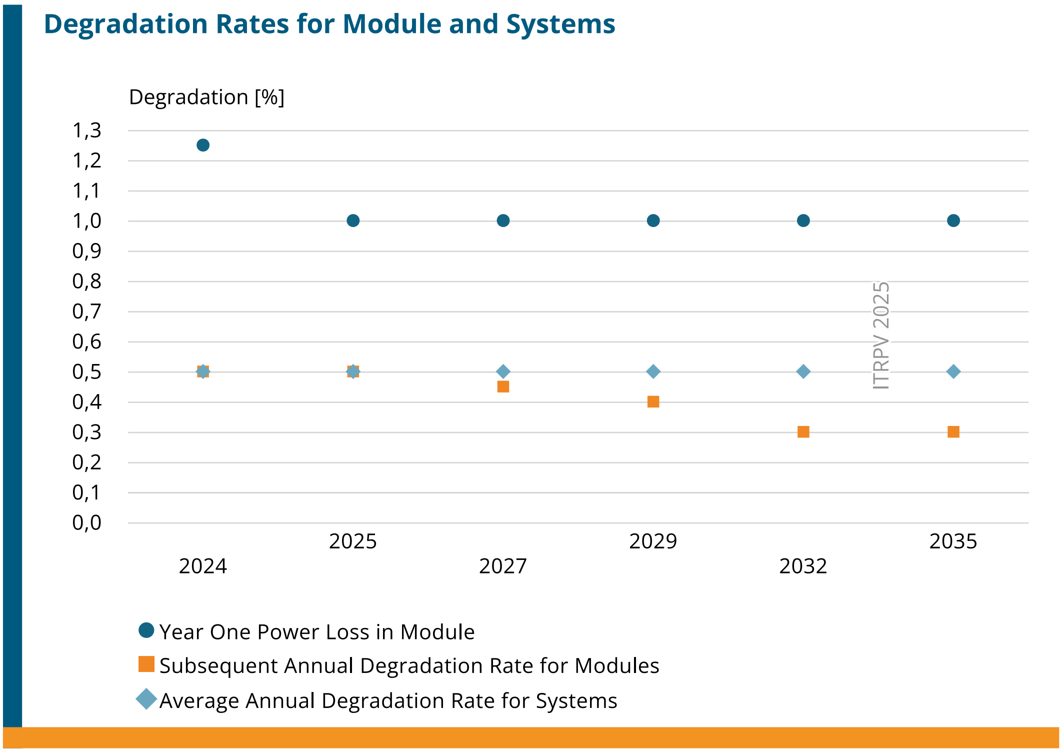

Fig. 85: Trend of modules and PV system degradation.

Fig. 86 shows the expected trend for the technical lifetimes of modules and inverters. The technical lifetime of modules is expected to be on average above the performance warranty shown in Fig. 80. Up to 40 years technical lifetime is expected for modules. Based on this year's results, inverters technical lifetime is expected to remain 15 years.

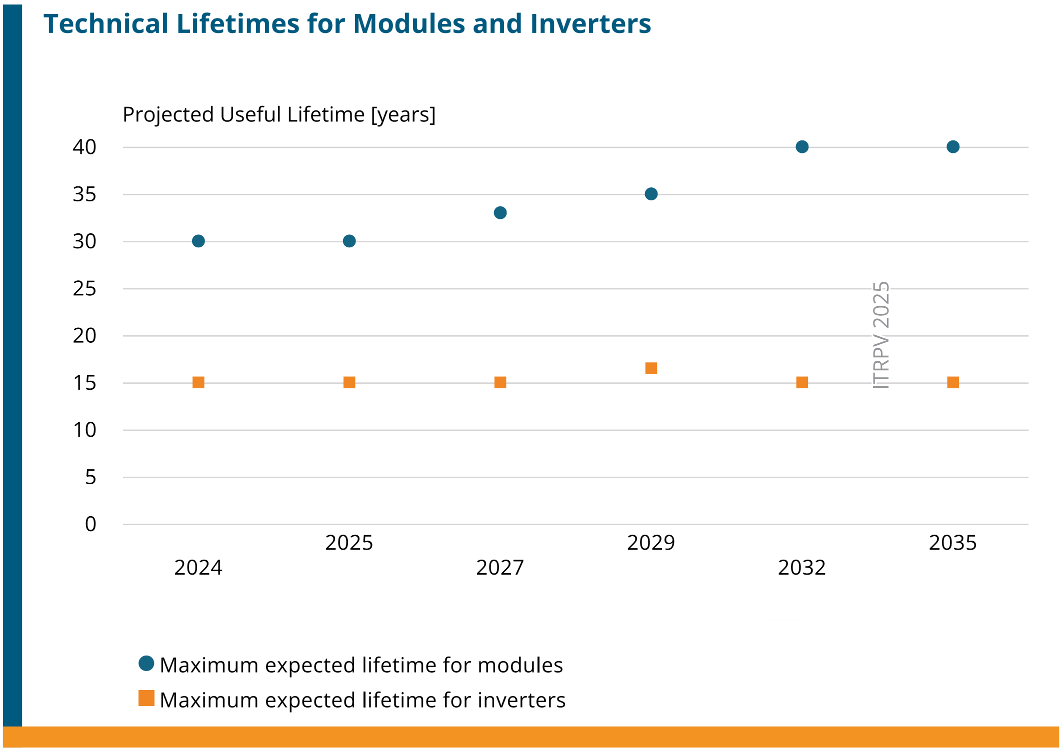

Fig. 86: Trend of technical lifetime of PV System electrical components.

Fig. 87 shows the share of tracking systems for PV power plants. The 1-axis tracking systems dominate the market, whereas no tracking systems also hold a significant 42% market share in 2025. The 2-axis system will remain a niche throughout the decade, based on the results we have obtained.

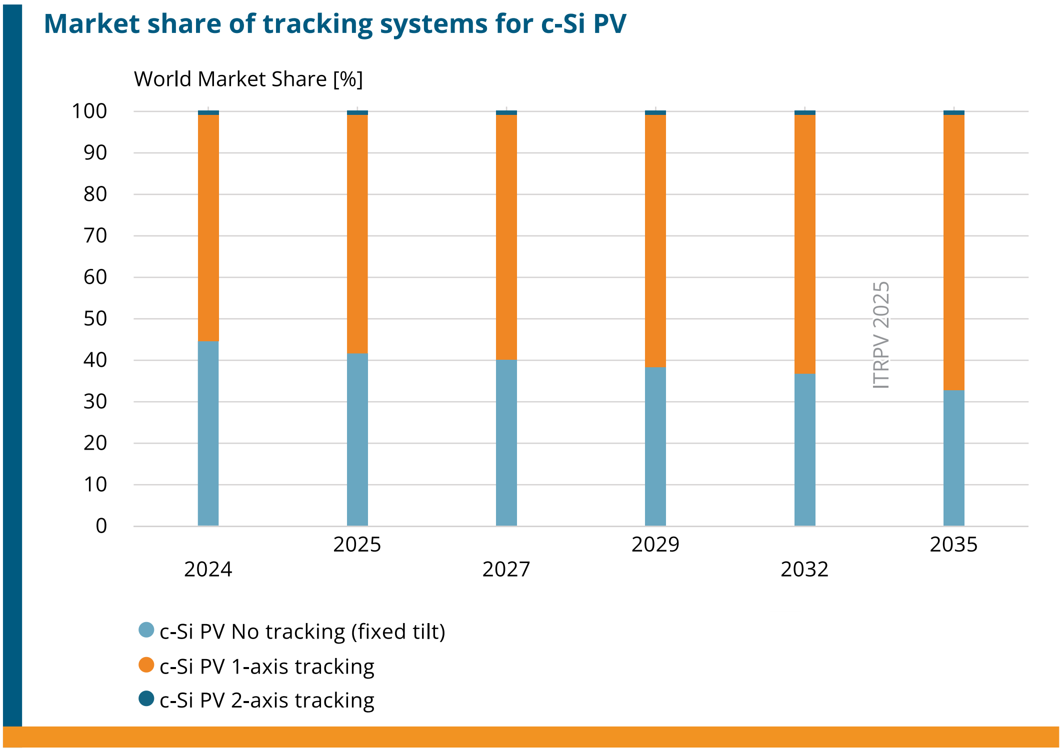

Fig. 87: Market share of tracking systems for PV power plant installations.

The market share of different end-use systems is visualized in Fig. 88. “Classic” power plant systems account for 57% in 2025. Roof top systems are expected to stay stable at around 30% within the next 10 years.

Market share of different end-use systems

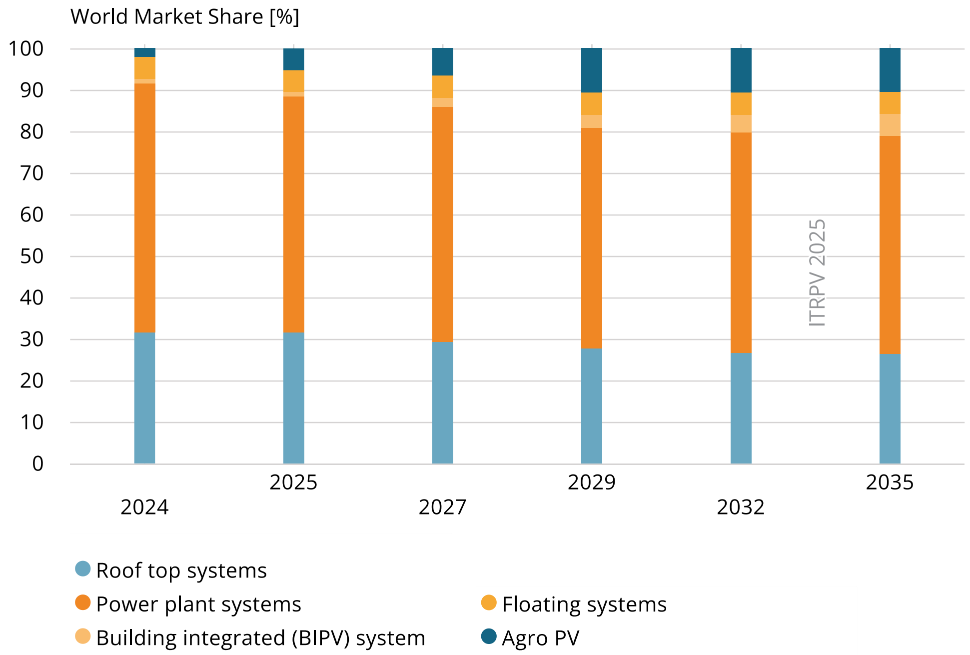

Fig. 88: Market share of different PV end-use systems.

Building integrated PV systems as well as agro PV, and floating PV power plants are expected to gain market share from “classical” PV power plants within the next 10 years. The share of PV installations expected to be combined with storage systems will increase.

For systems larger than or equal to 10 MW, string inverters reach 60% market share, in comparison to central inverters covering the rest of the market. This share will remain consistent throughout the decade, as seen in Fig. 89.

Market share of Inverter technology for systems larger than or equal to 10 MW

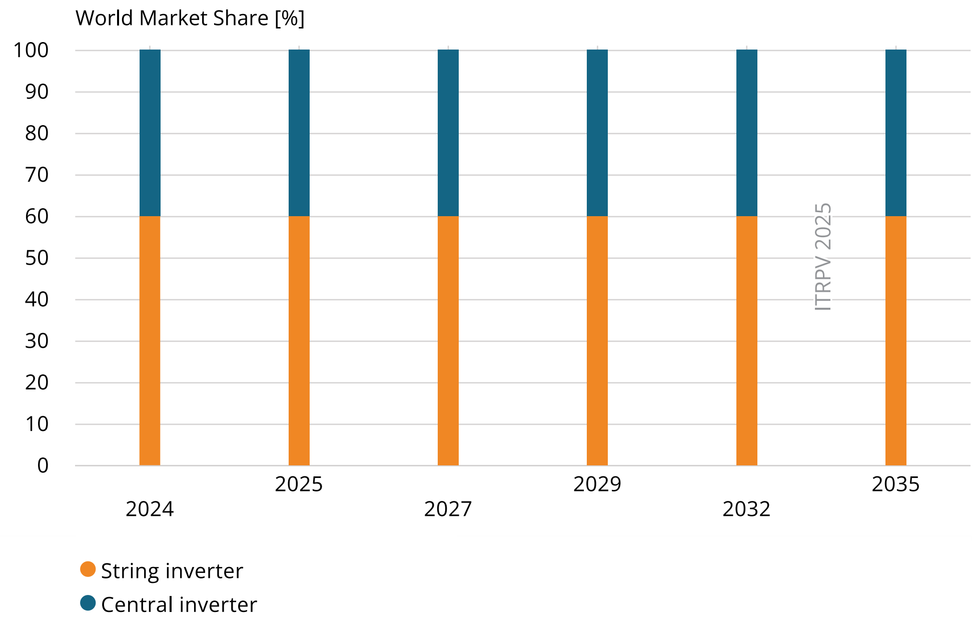

Fig. 89: Market share of Inverter technology for systems larger than or equal to 10 MW.

8.2. LCoE Calculation Section

Levelized cost of electricity (LCOE) is a commonly utilized metric to assess the lifecycle economics of power generation systems. Module, balance of system (BOS) components, and project development costs are the largest contributors to the initial expense for solar PV systems. After installation, to sustain electricity production, operations and maintenance expenses are also typically incurred throughout the life of a PV project. The denominator of LCOE is determined by the solar resource and the system energy yield—meaning, all else being equal, LCOE is lower in higher solar resource areas or for systems with improved energy yield (e.g., bifacial, tracking, more efficient inverters, etc.). Taken together, LCOE is a discounted cash flow analysis of costs ($) divided by yielded benefits (kWh).

Fig. 90 shows the ITRPV costs survey trends for systems > 10 MW-dc (right axis). The trends represent the BOS and development costs data that were contributed by PV project developers and installers of systems from across three regions—Europe, Asia, and the US. Figure 90 layers in 2024 global module prices into BOS and development costs data from the previous year ITRPV. Due to industry-wide overcapacity and oversupply across the supply chain, global module prices have changed the most significantly among all components in PV systems. PV module prices were substantially lower in 2024 than any of the previous years—dropping from more than 20 U.S. cents per Watt in last year's ITRPV to around 8 U.S. cents per Watt in this 2025 ITRPV.

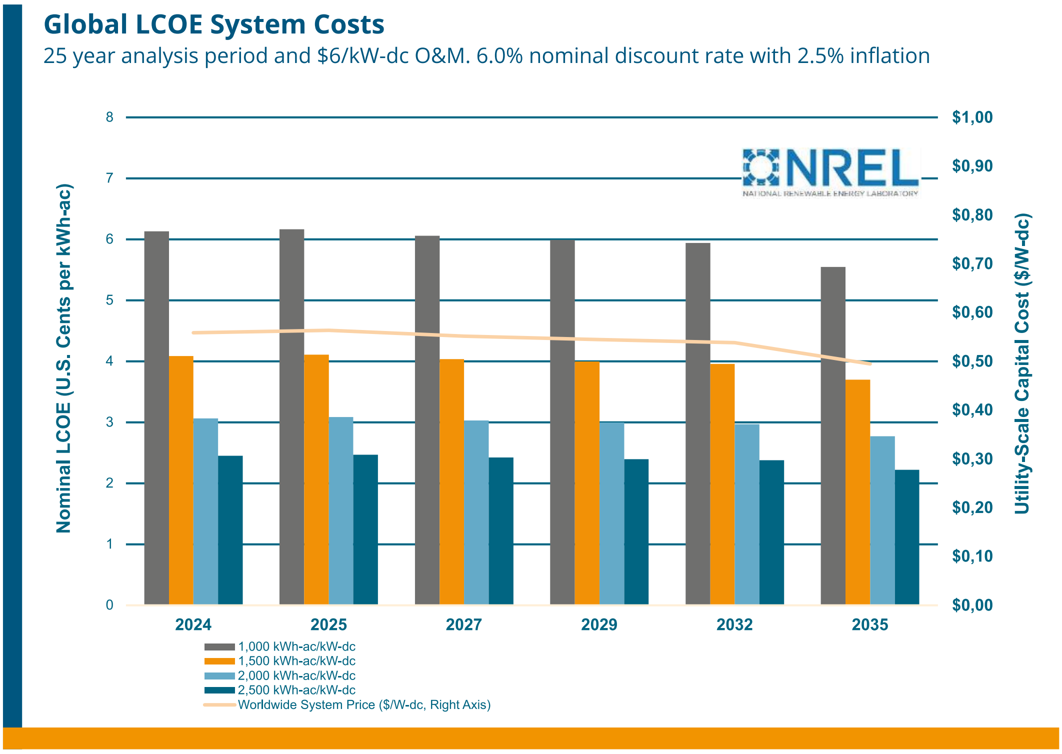

Fig. 90: Calculated LCoE values for different insolation conditions and median capital costs from the 2025 ITRPV survey. The calculations were performed using NREL's System Advisor Model (SAM) cash flow structure.

Module prices and total PV system capital costs do vary significantly by region. Using 2024 module prices within each market, the average results were 500—550 US $/kW-dc median capital cost for utility-scale systems in the EU and Asia (approximately 120 US US $/kW-dc lower than last year), and 850—1,000 US $/kW-dc median capital cost for utility-scale systems in the United States (no significant change). Module prices in 2024 were 170—220 US $/kW-dc higher in the U.S. versus the EU and Asia. The so-called 'soft costs', including project developer costs, sales tax, permitting fees, and overhead and profit, also vary across the globe. Utility-scale PV system soft costs in the United States were $100 to $110 US $/kW-dc higher than the EU and Asia, respectively. The U.S. utility-scale PV market also has a higher market share for tracking PV systems, which do have higher upfront capital costs than fixed-tilt but offer improved system lifetime energy yield. U.S. electrical plus structural BOS totals were $80 to $110 US $/kW-dc higher than BOS totals for the EU and Asia, respectively.

Affecting the denominator of the LCOE calculation, there is a strong dependence between solar resource, system energy yield, and LCOE. Ranging from 1,000 kWh-ac/kW-dc to 2,500 kWh-ac/kW-dc, the ITRPV results reflect most possibilities for utility-scale PV system energy yield across the globe. The LCOE calculations across the range of energy yield values are shown as bars at each year (left axis). From analysis of the projections from the ITRPV contributors, each year has a different system capital cost (right axis), which affects the numerator of the LCOE results. All else being equal, as system capital costs decline, and for higher solar resource and energy yield, LCOE will decrease.

To compare these ITRPV results to global utility-scale solar PV auction prices, the average bid in Germany in 2024 was 4.9 cents per kWh-ac [26], while U.S. utility-scale power purchase agreements were lower, at 2.9 to 4.8 cents per kWh-ac [27]. While module and BOS costs are relatively higher in the U.S., the U.S. does have relatively strong solar resource for utility-scale projects, and system energy yield is also enhanced with one-axis tracking. More broadly, world average auction prices measured by the IEA in 2023 were 3.7 cents per kWh-ac, and the Bloomberg 2024 benchmark global solar PV LCOE was 3.6 cents per kWh-ac [28]. As hosts to some of the most abundant solar resource areas in the world, PV auction prices approaching 2 cents per kWh-ac have been reported in the Middle East. Finally, it is also remarkable to note that the highest LCOE scenario that is calculated in the 2025 ITRPV, around 6 cents per kWh-ac, is 25—30% lower than the 2030 global average LCOE projected by the IEA in 2015 [29]. At this same time in history that solar PV really does seem to have overdelivered on LCOE, the trajectory of future growth depends upon the capabilities and costs for storage partners, as well as the ability of Solar PV to integrate with other sources of electrical power.

9. Outlook

9.1. PV learning curve

Chapter 3 reviews the learning curve status. Fig. 1 shows the price learning curve and the calculated price learning rate. The current learning rate is calculated to be 25.8% using all historic price data points from 1976 to 2024. However, considering only the data points from 2006 - 2024, the learning rate is 40.7% as shown in Fig. 91.

Learning curve for module price as a function of cumulative shipments

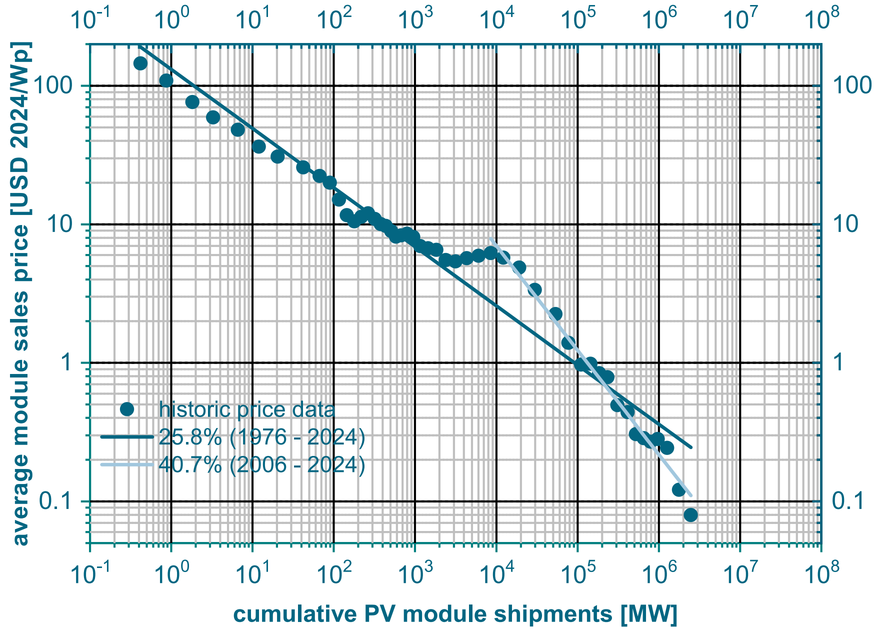

Fig. 91: Learning curve of module spot market prices as a function of cumulative PV module shipments and calculated learning rates for the period 1976 to 2024 and 2006 to 2024, respectively.

The year 2006 was the last year of a longer period of silicon shortage. It marks the beginning of c-Si PV mass production in China and thereby the entry into a period of continuous capacity extensions after the scarcity situation of polysilicon and PV modules during the period between 2004 and 2006.

Based on the findings in the ITRPV we started in the 8th edition the analysis about the breakdown to the two basic learning contributors - module power learning and reduction of price (cost) per piece learning.

Tab. 1 summarizes average module efficiencies at different years. The price values were taken from the learning curve while module efficiencies between 2010 and 2019 were calculated, based on average module powers of p-type mc-Si and mono-Si modules reported by the ITRPV (3rd to 11th edition) in combination with a standardized module size of about 1.64 m² for 60 cell modules. The module efficiency of 1980 was found in [30]. Average module efficiencies for PERC modules in 2020 are assumed to 20% based on the ITRPV 12th edition and in 2021 to 20.9% in the 13th edition, 21.2 in the 14th edition, and 21.8 in the 15th edition respectively. 2024 module efficiency is calculated according to Fig. 68 in this edition.

Tab. 1: Yearly learning for module efficiency and price per piece based on module price data (2010 = 100%) [6,7,8], module efficiencies are calculated from ITRPV module power values (3rd to 11th edition) and taken from 12th ff ITRPV editions; 1980 module power is calculated from the efficiency indicated in [30].

Year over year learning

Year	1980	2010	2011	...	2021	2022	2023	2024
avg. Module power p- type 60 cell: ITRPV-data, calculated for 2021ff: ITRPV data incl. product market share (Module area 108 HC M10 2021- 2022 1.93m², 2023 1.96m², 2024 2.0m²)	148	242	248		403	409	426	451
Module efficency 60 cell [%], avg. Mod. area: 1.64m², 2021ff: ITRPV efficiency	9	14.7	15.1		20.9	21.2	21.8	22.6
Module price [$2024]	48.15	2.24	1.40		0.28	0.24	0.12	0.08
Relative module price reduction [%]		95.34%	37.77%		-4.57%	13.87%	50.11%	34.44%
Module price (Wp-increase only) [$2024/Wp]		2.24	2.18		1.58	1.56	1.52	1.46
Module price (cost reduction per piece only) [$2024/Wp]		2.24	1.46		0.95	0.93	0.85	0.86

The trend to larger wafer formats as shown in Fig. 11 results in a variety module formats. Until 2019 the mainstream module format was 60 full-cells / 120 half-cells. The corresponding averaged module area increased from 1.64 m² to about 1.7 m² in 2019 [31] and 1.8 m² in 2020 [32]. The module size for rooftop applications increased further according to Fig. 69. For 2021/2022 we took 1.93 m², 1.96m² for 2023, and 2.0m² for 2024, respectively, as average size of M10 108 HC modules (see also Tab. 1). The average module power is calculated to 403 Wp,409 Wp, 426 Wp, and 451 respectively.

Fig. 92 shows the plot of Tab. 1 data points for efficiency learning and per piece learning, respectively. The corresponding calculated learning rates of 8% for efficiency learning and 12% for per piece learning indicate that the main contribution of the price learning arose from per piece reductions. The 2024 year end spot market price is ≈ 0.10 US$/Wp as discussed in chapter 3.

Learning curve for module price as a function of cumulative shipments

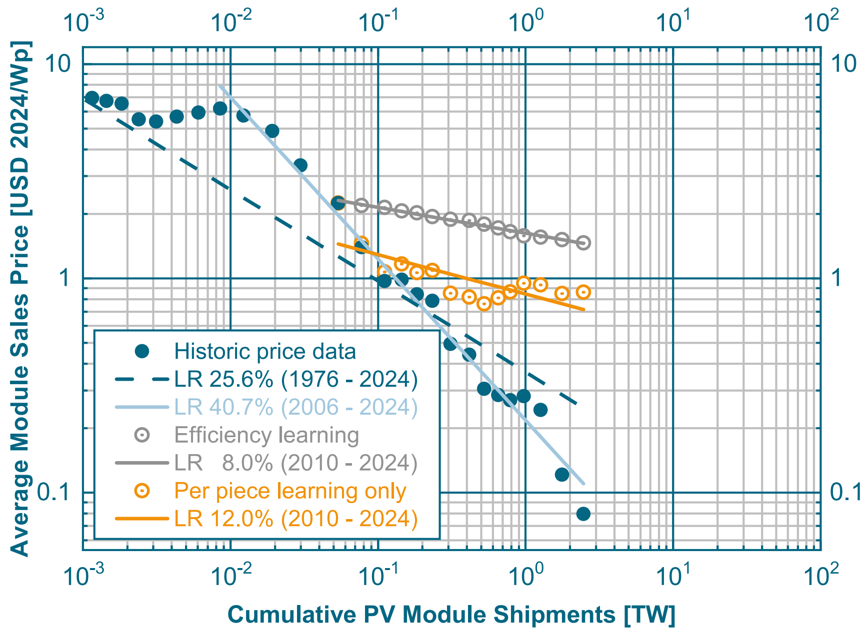

Fig. 92: Log-log plot of the learning curve for module spot market prices as a function of cumulative PV modules shipments; for the period 1976 to 2024 and 2006 to 2024, respectively. Calculated rates for Wp learning and per piece learning are based on Tab. 1.

Per piece learning has slowed down since 2019 and is currently stabilizing. It is remarkable that the efficiency learning rate has been quite stable since the first calculation in the 8th edition of the ITRPV, highlighting the continued technology progress of the PV industry.

This analysis emphasizes again that only the combination of efficiency learning, and cost reduction grants the resulting learning even though per piece learnings in 2019 until 2021 were not in line with the learnings until 2018, mainly due to the introduction of the larger module formats and due to overall cost increases.

Learning curve for module price as a function of cumulative shipments

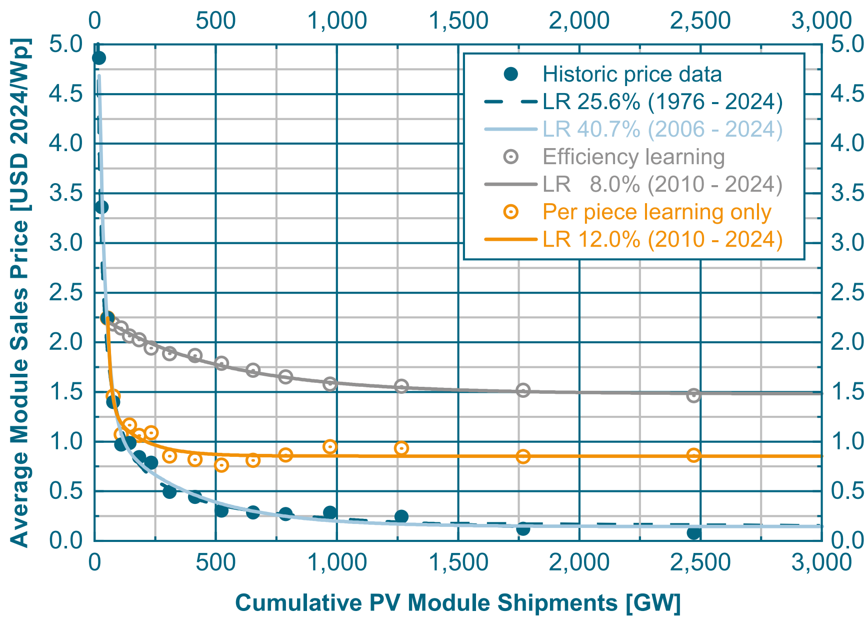

Fig. 93: Linear plot of the learning curve for module spot market prices as function of cumulative PV modules shipments; for the period 1976 to 2024 and 2006 to 2024, respectively. Calculated rates for Wp learning and per piece learning are based on Tab. 1.

Progress in per piece learning has been visible again since 2022. Fig. 93 shows the data of Fig. 92 in a linear plot.

9.2. PV market development considerations

PV will play a key role in a future net zero greenhouse gas emission energy system that has to be installed until 2050 [33]. The most widely publicly discussed PV-related topics and trends are about installed PV module power (DC), module shipments, and PV generated electricity scenarios.

A look at the supplier side, to see the trend of the market for PV modules, cells, wafers, and polysilicon, is less spectacular, but it is essential for investment planning.

The analysis of the annual PV market development until 2050 started in the ITRPV 6th edition. In this 15th edition we review the current PV market shipments in relation to the broad electrification scenario of Bogdanov & Breyer et. al. [34]. A comparison to the annually updated World Energy Outlook of the IEA as we did in the ITRPV 12th, 13th, and 14th editions does not make sense anymore as WEO energy scenarios permanently underestimate the PV growth potential [40].

Broad electrification:	63.4 TWp installed PV and ≈4.5 TWp avg. annual PV market in 2050
(all sector)	generating 104 PWh ≈69% of global primary energy demand (including power & heat, transport, and desalination) [34].

This scenario considers the need of a net zero greenhouse gas emission energy system no later than 2050. PV will be the key technology to reach a 100% renewable energy and greenhouse gas emission free energy economy by 2050, considering the three main energy consumption fields of power, heat, transportation, and desalination for 9 major global regions as summarized in Tab. 2, a model presented in [34] and [35] is used. An updated calculation result for 2050 is 75 TW [41]. Research for ambitious energy transition scenarios for the long-term PV demand until 2100 lead to a range of 150-200 TWp installed solar PV capacity [42,43].

Fig. 94 shows the required PV installation trend together with the corresponding average annual PV market to reach the Broad Electrification Scenario. This will be the path towards a zero-greenhouse gas emission economy in 2050. An average system energy yield of approximately 1650 kWh/kWp is assumed, realized by power plant installations in higher insolation regions, also taking single axis tracking with higher yields into account.

Tab. 2: Summary of regional results of the scenario net zero greenhouse gas emissions energy system by 2050.

Summary of regional results for the different scenarios

Scenario	Region	Installed power 2050 [TWp]	PV Power generation 2050 [PWh]
100% Renewables	Sub-Saharan Africa	2.9	
	MENA	4.6	
	North America	7.0	
	Northeast Asia	17.8	
	SAARC	11.9	
	South America	2.3	
	Southeast Asia	5.3	
	Eurasia	2.6	
	Europe	8.9	
	Total	63.4	104

Global PV Installation and corresponding PV market
PV based energy mix scenario

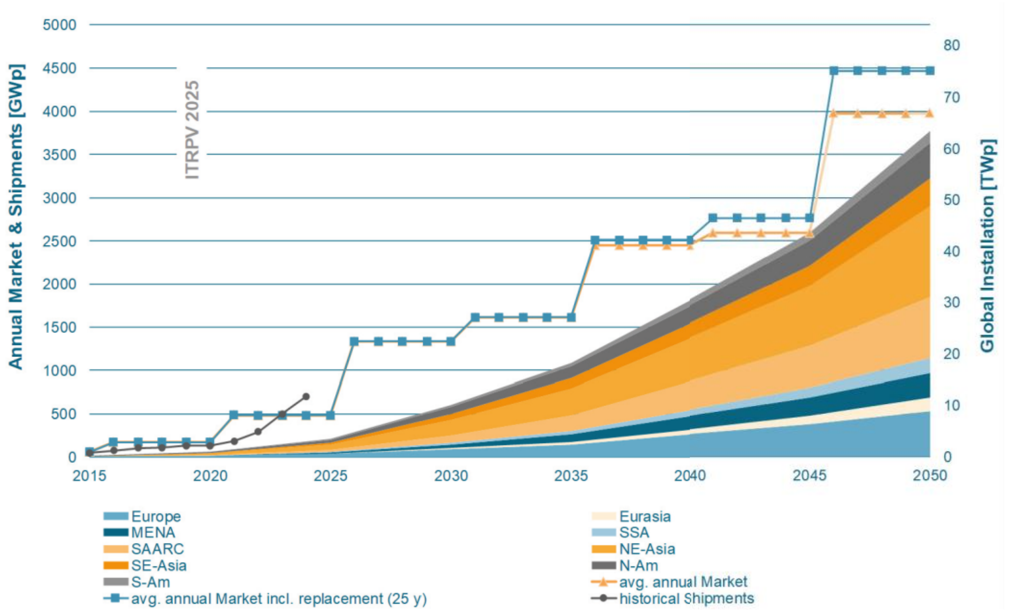

Fig. 94: Cumulative installed PV module power and 5-year average annual market for global PV module installation of 63.4 TWp in 2050 in a zero greenhouse gas emission economy - Broad Electrification [34].

The 5-year average annual market values - calculated as in former editions - are shown in Fig. 94 in corresponding 5-year steps to better visualize the requirements for meeting the 2050 target installations *. We can see that the historical shipments are close to the required market in this scenario. It is remarkable that 2024 shipments are well in line with the requirements.

* the 5-year average values are assumed as step function in the diagram, as the model is operated in 5-years steps, while in reality the market values will be a smooth development between the 5-year steps.

In parallel with the expected increase of PV production and installation, recycling will become more important in the future - as business opportunity and as challenge [36, 37, 38, 39]. Improved tool concepts in cell manufacturing for production lines with matched throughput between front and backend, as discussed in chapter 6.2, will support future production capacity increase.

Anyhow, a capacity increase beyond the 1 TWp level will require further improved production technologies. PV equipment suppliers have to support the installation of new production capacities.

New c-Si capacities for cell and module will deploy n-type concepts TOPCon, and SHJ, as well as IBC. PERC p-type capacity will still take place mostly outside China. The n-type cell technologies should also be considered as possible upgrades for existing PERC lines especially in the case of TOPCon and for future c-Si based Tandem concepts. The continued support of depreciated production lines, the replacement of worn-out equipment and the building of capacity expansions with smart factory approaches will constitute considerable business segments to support the projected growth. All these facts emphasize the positive outlook for the whole c-Si PV industry.

The current ITRPV edition discussed possible trends and improvements in c-Si PV technology like increasing cell and module efficiency, increasing module power, more efficient usage of poly-Si and all non-Si materials as well as a higher utilization of all production capacities. All these measures will help manufacturers in their efforts to supply the market with highly competitive and reliable c-Si PV power generation products in the years to come. The market conditions are playing a strong role too in determining the price of modules that dropped extremely in 2023 and continue to experience such prices, particularly with continued over-capacities in manufacturing. The price learning of PV modules is expected to continue, and this will further push the LCoE reduction of PV systems.

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