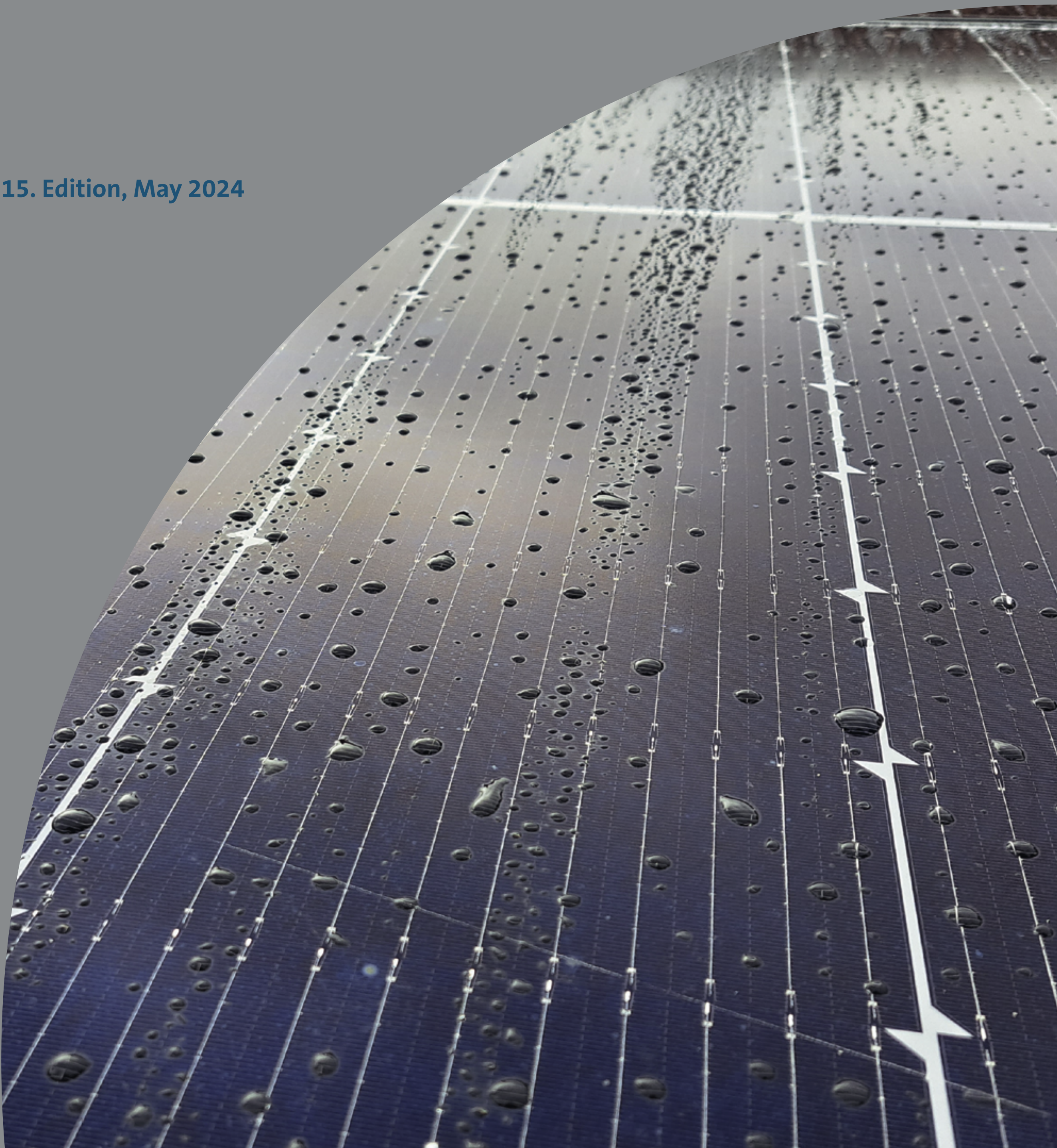
Photovoltaics Equipment

VDMA

# International Technology Roadmap for Photovoltaics (ITRPV)

## 2023 Results

15. Edition, May 2024



# International Technology Roadmap for Photovoltaics (ITRPV)

## Results 2023

### Fifteenth Edition, May 2024

# 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 sources of energy. 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 technology 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, fifteenth edition of the ITRPV was jointly prepared by 50 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 Significant parameters set out in earlier editions are reviewed along with some new ones, outdated parameters are omitted and discussions about emerging trends in the PV industry are reported.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 15th edition of the report, demonstrating 15 years of successful service to the PV community.

The global c-Si cell and PV module production capacity at the end of 2023 is assumed to have further increased to around 1000 GWp due to continued capacity expansions [1]; a market share of about 97% for the c-Si and about 3% for thin-film technologies is considered [2].

The PV module market in 2023 showed an unprecedented growth to around 502 GW [3, 1].

The c-Si module market finally shift to mono-Si . The implementation of innumerable new module products, dominated by M10, and G12 wafer formats together with bifacial module technology, continued. The weighted average spot market price of c-Si modules at year end 2023 dropped by incredible 52% compared to the end of 2022. Considering year on year rate, the price reduction is even 50% [4]. All c-Si based products experienced a price reduction and price premiums for high power, bifacial and n-type modules do not exist anymore. The non-competitiveness of mc-Si based products resulted in an entire disappearance from the market.

Efficiency improvements in passivated emitter rear cell (PERC) technology, the roll out of n-type based products and the deployment of larger wafers in larger modules resulted in higher average module efficiencies. The use of larger wafers enabled new module power classes of 700 W and above [5]. Construction of new cell and module capacities in 2023 continued to shift from PERC to the n-type based tunneling oxide passivated contacts (TOPCon) and silicon heterojunction (SHJ) devices. All new plants will be ready for large cell formats just from the beginning [6]. The price experience curve continued with its historic learning; the calculated learning rate (LR) is 24.9 %. The PV industry can keep the LR up over the next years by continuing the proven combination of cost reduction measures and implementation of cell perfections, with improved wafer material, improved cell front and rear sides, refined layouts, introduction of bifacial cell concepts, improved module technologies as well as with the introduction of new cell technologies. Larger cell formats contributes to PV system cost reduction. Improvements in all fields will result in module area efficiency increase: today’s mainstream p-type mono-Si based PERC modules reach efficiencies of 21.4%, n-type based modules including SHJ provide highest power modules with today’s efficiencies of close to 22.5% that will increase up to 24% within the next 10 years. Si-based tandem cells and modules are expected to enter mass production around 2027, starting with module efficiencies of about 27%. 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 to multi-GW markets as projected by previously discussed scenarios in former editions. All those aspects are again discussed in this revision of the ITRPV.

In its 15th edition VDMA 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 is available at 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 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. For 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.

## 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 in order 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. By providing information on key production technologies and by discussing 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, c-Si 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 2023 US$/Wp) as a function of cumulative module shipments from 1976 to 12/2023 (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 (LR).

Considering all data points from 1976 until 2023 we found an LR of about 24.9%, again an increase compared to the 24.4% in the 14th 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 a strong drop of price is observed.

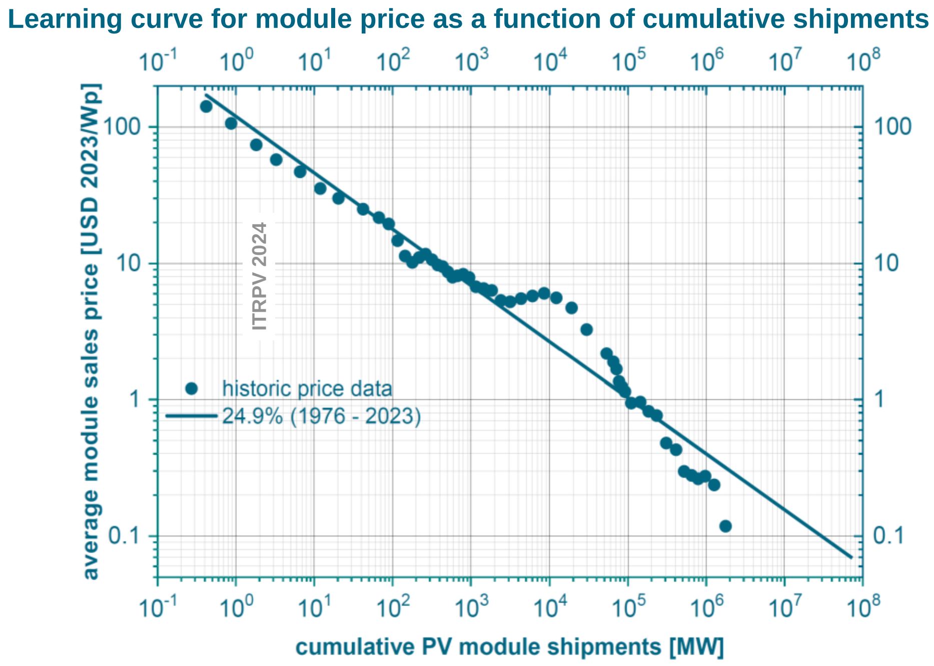


Fig. 1: Learning curve for module spot market price as a function of cumulative PV module shipments.

The last data point indicates the module shipment volume and average spot market price at the end of 2023. The 2023 shipment volume was calculated to be 502 GWp - Installation of 412 GWp plus 90 GWp not yet installed (i.e. in warehouses, at customers, and in transit) until year end. The EU, for instance, imported in 2023 about 100 GW of modules from China while the installation was close to 60 GW, a difference of about 40 GW between shipments and installations [8, 9]. Based on this data the cumulative shipped module power at the end of 2023 was calculated to be 1,769 GWp. The corresponding worldwide installed cumulative module power by the end of 2023 is 1,610 GWp after 1,198 GWp in 2022 [3]. The calculated average module spot market price at the end of 2023 is 0.118 US$/Wp, an incredible drop from 0.228 US$/Wp at year end 2022.

Module production capacity at the end of 2023 is assumed to be about 1000 GWp due to continued capacity expansions [1]. So, the PV module market showed an unprecedented growth to 502 GW. All c-Si based products experienced a price reduction and price premiums for high power, bifacial and n-type modules are non-exisiting.  The reduced competitiveness of multicrystalline silicon (mc-Si) based products resulted in the almost complete disappearance from the market.

Publicly available price data have been reporting since years in addition to mono-Si standard module prices, also prices for poly-Si, cells, and modules with M6, M10, and G12 wafer formats as well as for bifacial modules (both for p-type and n-type devices).  Based on this data for c-Si technology based modules, a price difference between PERC and TOPCon as well as M10 and G12 wafer size base modules respectively is visible.

The average module prices for 12/2023 are calculated based on the following numbers:
0.117 US$/Wp for PERC modules and 0.120 US$/W for n-type modules [10]. We calculated
0.118 US$/Wp as weighted average spot market price for c-Si modules at year end of 2023 based on ITRPV data for 2023. The assumed market shares are therefore: 70% for standard PERC modules, and 30% for n-type based modules.

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 [11]. Those prices also stayed high in 2023 and the situation is not expected to change rapidly. Achieving cost reductions in high price consumables like silver and pre-cursor materials will remain difficult but must be continued. Improving productivity and product performance will stay in the focus resulting in continued pressure on existing and new installed manufacturing lines [1].

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, by implementing upgrades and new production capacities, by using Si and non-Si materials more efficiently, and ensuring higher OEE of new installed capacities.
- Introduce specialized module products for different market applications (i.e., tradeoff between cost-optimized, highest volume products and highest efficiency, higher price roof-top applications or even fully customized niche products).

The first point implies that continuous cell efficiency improvements need to be implemented not only with larger 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 expenditures. It will remain difficult to introduce new, immature technologies that do not show reductions of the cost per Wp from the beginning.

# 4. Results of 2023 | Crystallization and Wafering

## 4.1. Materials

Polysilicon (Poly-Si) is the most expensive material of c-Si solar cell. Siemens process will 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 today. Other technologies with a more direct way of purification approach have no insignificant role in market share.

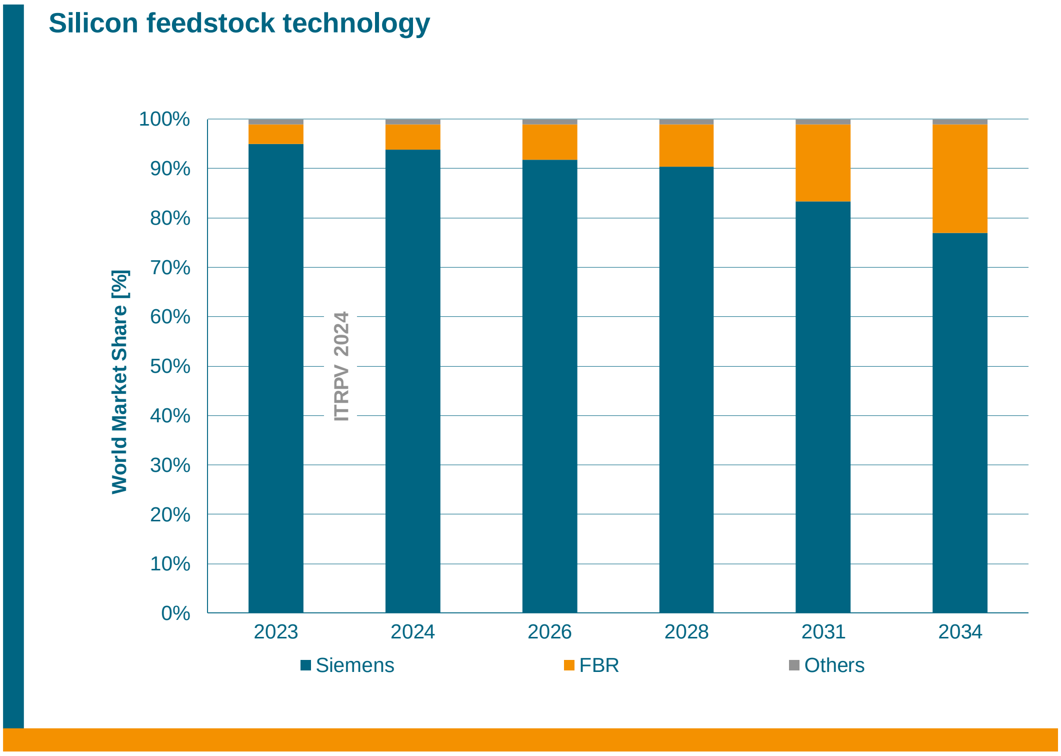


Fig. 2: Expected world market share of poly-Si feedstock technology.

Based on our results, the market share of FBR poly-Si was about 4% in 2023 as shown in Fig. 2, this is close to the analysis in [18]. We expect that this share will increase to around 22% within the next 10 years against the mature and further optimized Siemens process.

Fig. 3 shows the average consumption of poly-Si to produce silicon wafers. All wafer formats will consume significant less silicon within the next 10 years. Expected reductions are in the range of 25% for M10 and about 30% 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.

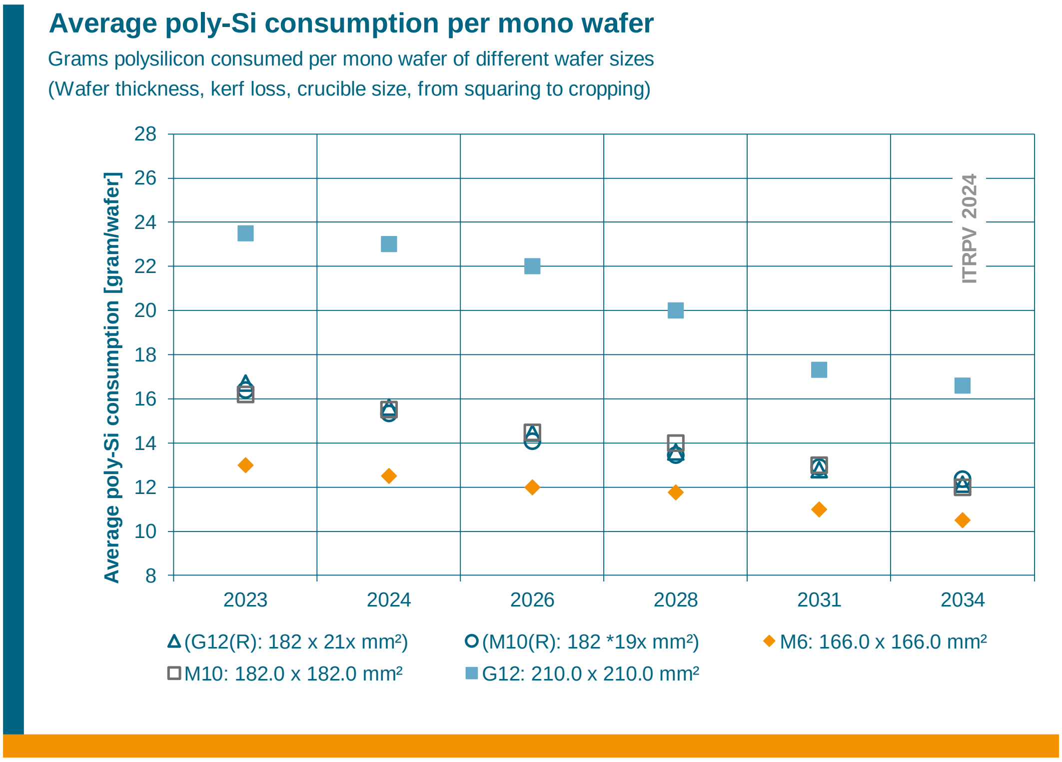


Fig. 3: Average poly-Si consumption for mono-Si wafers with diamond wafer sawing technology.

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

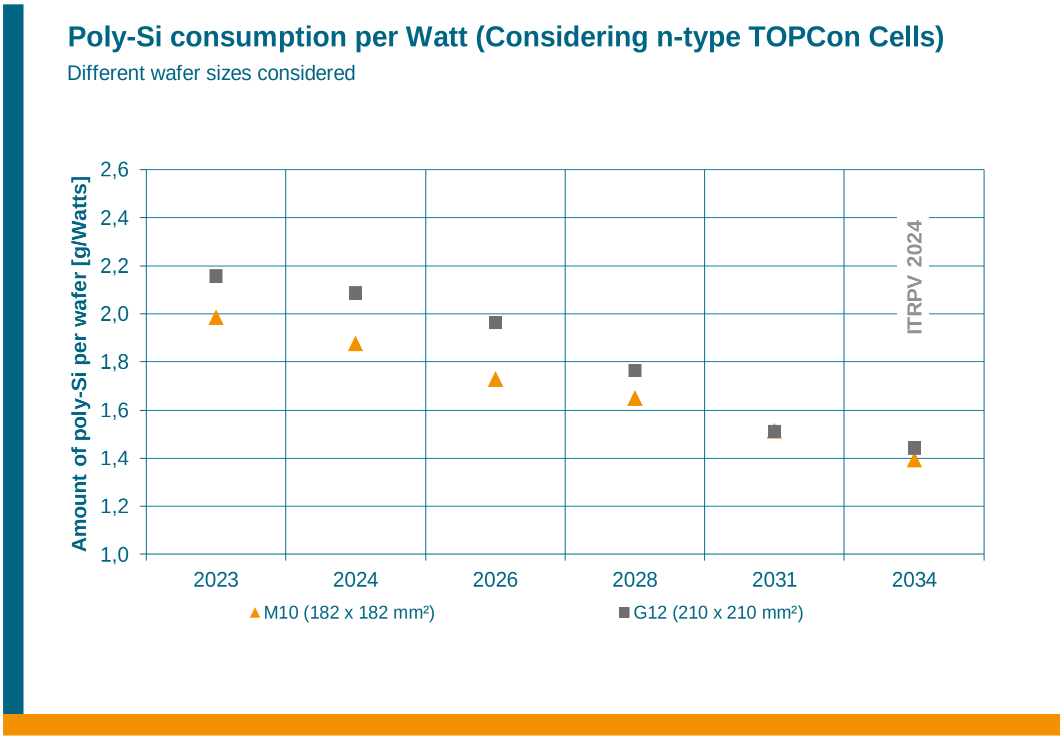


Fig. 4: Average poly-Si consumption for mono-Si wafers calculated for n-type TOPCon cells.

Cell power is calculated according to the cell efficiency trend for TOPCon cells in this report as shown in Fig. 40. Consider the dominant wafer formats M10 and G12, the trend in Fig. 4 shows that, based on current assumptions, M10 wafers consume lower poly-Si per generated power than G12, however the difference is expected to be reduced with time. This emphasizes the need for even faster improvements for the larger formats in order to realize their benefits not only on a module cost per Wp level but on a levelized cost of electricity (LCoE). In 10 years, the poly-Si consumption will be around on average 1.5g/W for the common formats M10 and G12.

## 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 mainstream technology in crystallization.
The mainstream doping element for p-type mono-Si material is Gallium. We found that Boron as dopant for p-type material does not exist in the market share anymore. The main advantage of gallium doping is the significant reduction of Light Induced Degradation (LID) of p-type material [13]. However, the trend towards n-type material dominance is also shown to be inevitable.

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 11% in 2034. Magnetic Cz is expected to be introduced in mass production starting from 2026. With its potential to eliminate further impurities and potential of

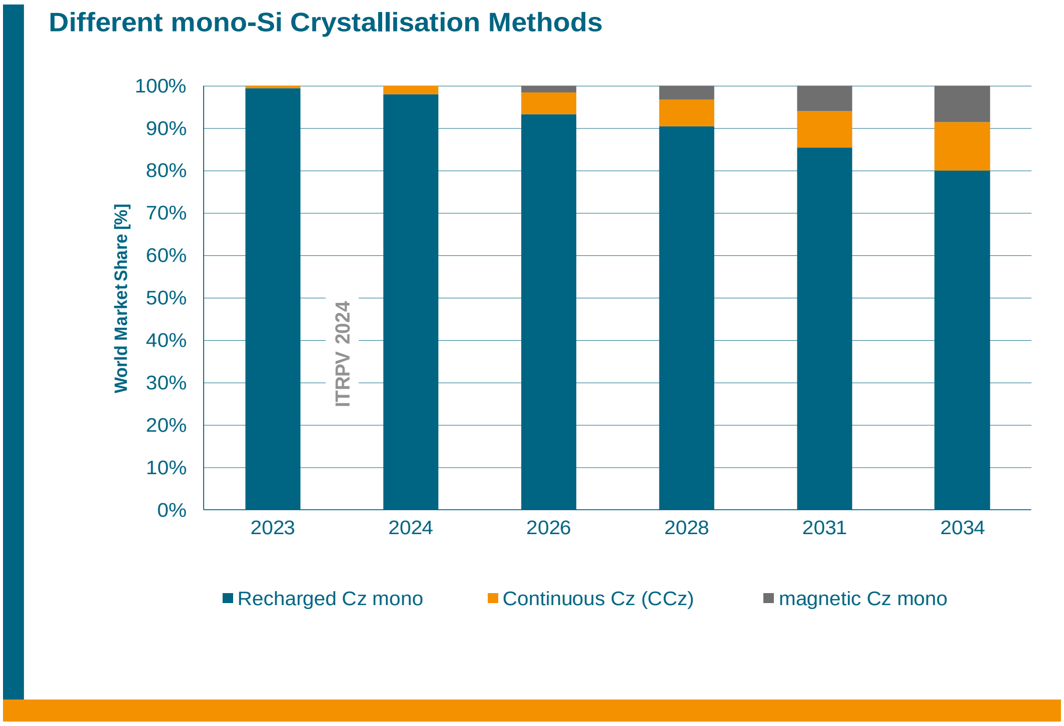


Fig. 5: Different mono-Si crystallization methods.

longer crucible lifetimes, it is expected to gain gradually market share, reaching around 9 percent in 2034. It is however clear that continuous Cz, with the particular RCz will dominate the market share.

### 4.2.2. Wafering

The landscape in wafering technology changed completely during the last years. The advancements of diamond wire sawing (DWS) for mono-Si wafering, guaranteed a significant improvement in terms of wafering process stability and cost reduction. 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.

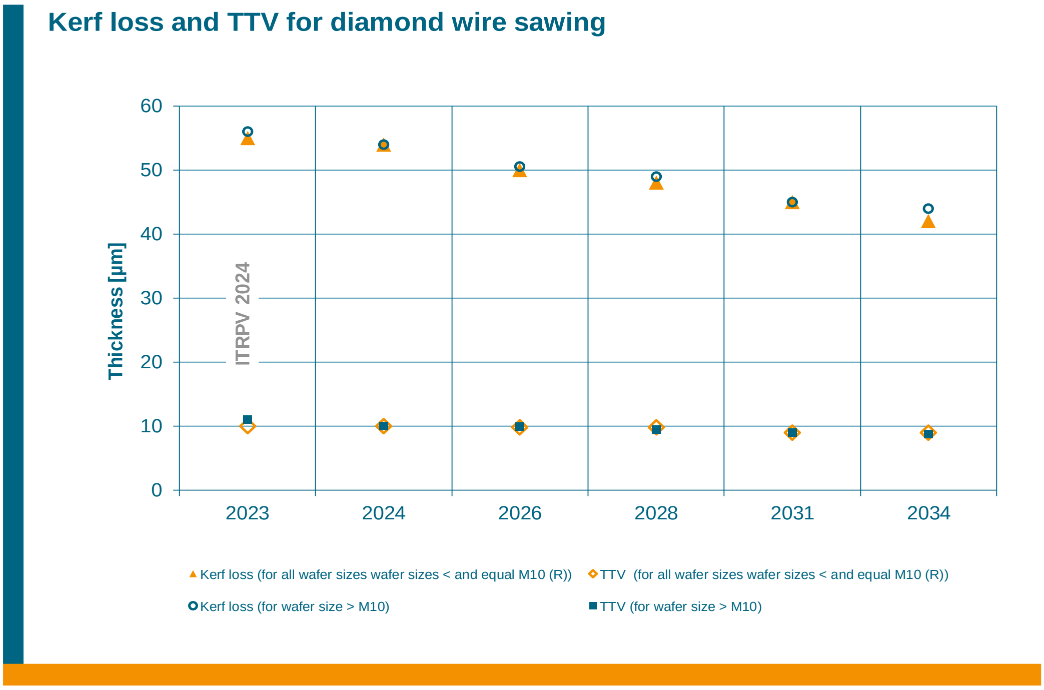


Fig. 6: Kerf loss and Total Thickness Variation (TTV) trend for diamond wire sawing of all wafer formats.

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 describes the trend for kerf loss and for Total Thickness Variation (TTV) for all wafer sizes, whether less than or equal to M10, or larger than M10. A kerf width of 55 µm for M10 and 56 µm for G12 is standard in 2023. Large wafer formats also benefit from this trend. The kerf loss is predicted to decline down to 44 µm within the next 10 years. TTV of 10 µm is attained using today’s technology, and this is in line with the requirements of the ITRPV 13th edition.

### 4.2.3. Process Improvement Trends

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 the 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. New kerfless wafer manufacturing approaches are still being studied.

## 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. 7 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 years of stagnating wafer thickness, we have been seeing since 2020 that mono-Si wafer thickness reduction is making huge progress, even ahead of the trend shown in the 12th edition of the ITRPV. Wafer thickness of 150 µm was the standard in 2023 for p-type mono wafers of all wafer dimension. For wafer sizes less than or equal to M10, the expected thickness reduction will reach 130 µm for the case of p-type and n-type IBC already in 2028. A minimum wafer thickness of 100 µm is expected for SHJ wafers in 2034. For n-type TOPCon cells the thickness expected in 2034 is around 115 µm, as shown in Fig. 7.

Based on the data analyzed there is no clear difference between wafer thicknesses of M10 or G12. The corresponding cell thickness limit trend in module technology is discussed in chapter 5.

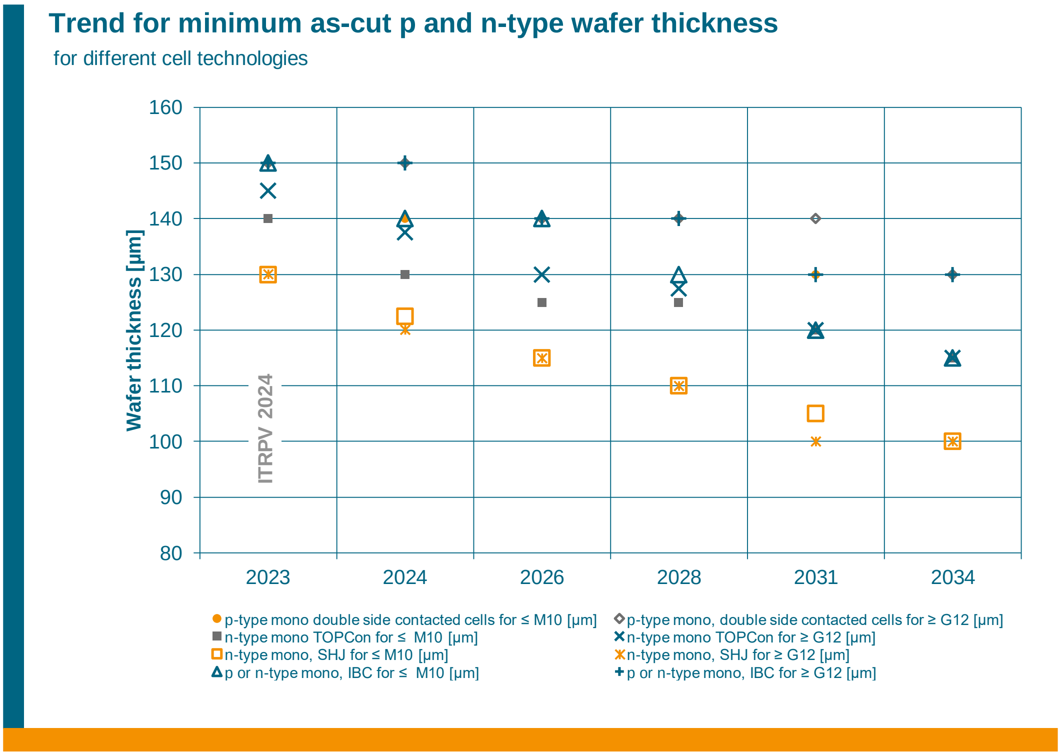


Fig. 7: Predicted trend for minimum as-cut wafer thickness n-type c-Si wafers with different wafer sizes.

For larger than or equal to G12 IBC wafers are expected to reach a wafer thickness of 130 µm. P-type wafers are not expected to progress to values lower than 130 µm, especially with the background that there will be no significant market share expected in 2034 for p-type materials. In 2024 we expect about 4 to 10 µm lower thickness for most wafer formats. Except in the case of wafers larger than or equal to G12 IBC or p-type double side contacted cells, the values are stagnant in 2024. The development in these cases continues in 2026, particularly for the IBC larger than or equal to G12.

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.

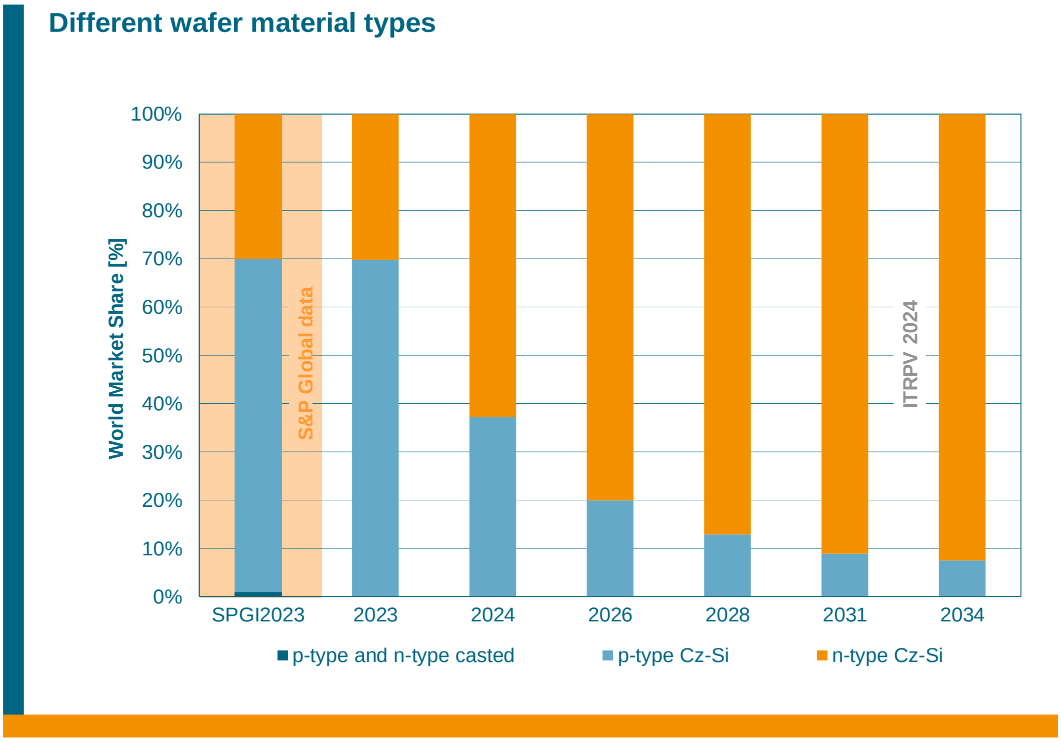


Fig. 8: Market share for different wafer types S&P Global (SPGI) data are indicated for 2024 as reference, [14]. This is a result of the data from all contributors.

Fig. 8 shows the results of the expected market trend for different wafer types from the data collected from all contributors, meanwhile Fig. 9 shows the result from the data of only GW-scale manufacturers.

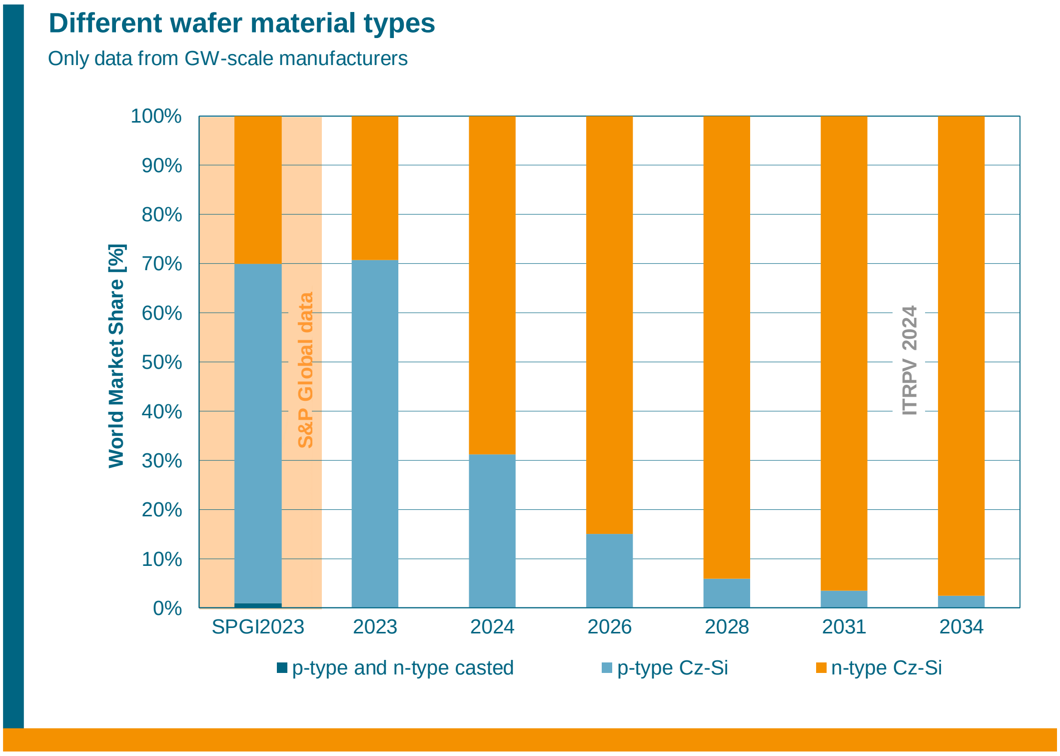


Fig. 9: Market share for different wafer material types from GW-scale manufacturers. This is the analysis of the data only from GW-scale manufacturers.

In 2023, Cz-mono-Si materials had an entire dominance of the market share. The trend of increased Cz-mono-Si market share is in line with the assumptions of previous ITRPV editions for both figures. The plotted analysis of S&P Global for 2023 as a comparison shows, that the ITRPV result is close to it with the exception of a less than 1% for cast mc-Si market share [14].

Casted Si has already disappeared from the market share result. The mono-Si market splits into n- and p-type. The p-type devices are expected to lose dominance already in 2024. That comes hand-in-hand with the increase of market share in the cell types adopting the fast transition towards TOPCon, SHJ and an increase in IBC market share all adopting n-type base materials. The growth of the n-type mono-Si market share is expected to grow to around 89% within the next 10 years, with a more conservative scenario predicted by all data contributors. If only the data of GW-scale manufacturers is included we see a more progressive transition to n-type. A faster transition in terms of market share and also an expected 94% dominance in 2034.

Fig. 10 shows the share of different dimensions for mono wafers. Wafer formats ≤ M6 continue to lose market share and are expected to phase out. M10 and G12 formats have been dominating the market since 2022 with a higher share of M10 wafer format [15].

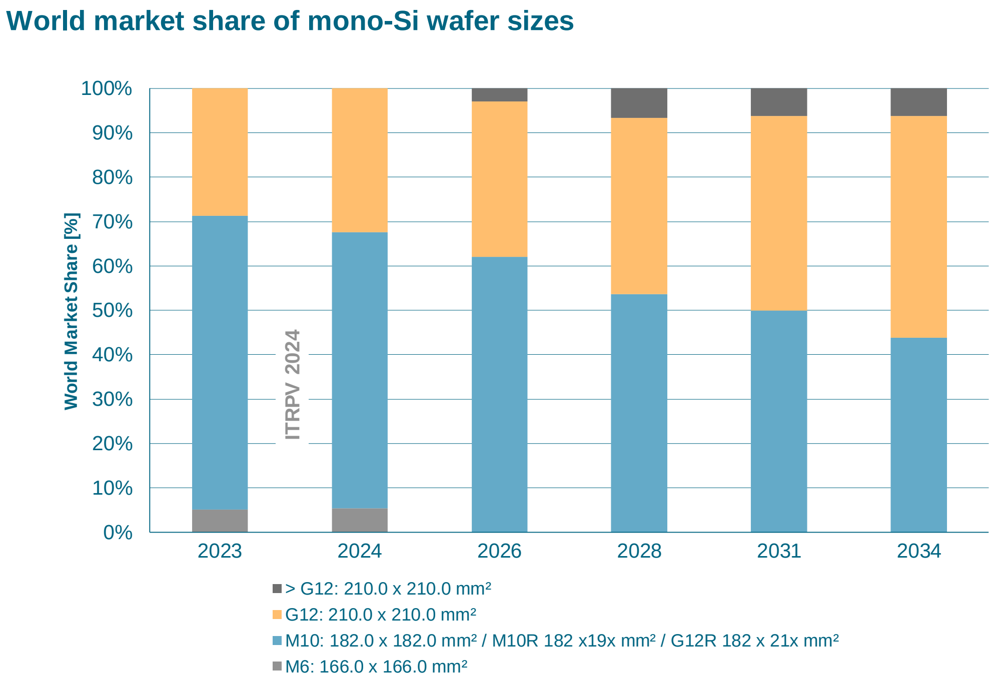

World market share of mono-Si wafer sizes

Fig. 10: Expected trend of Cz-mono-Si wafer size in mass production.

It is still not clear yet, which of the two formats will become mainstream in the future as both have advantages and disadvantages [16]. So new built cell lines will be ready for both formats and have to be prepared for even >G12 formats. It is interesting to mention that M10(R) 182 x 19X mm$^2$ and G12(R): 182 x 21x mm$^2$ formats also have a certain market share.

A 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 [17]. In addition, there are activities at IEC for a new wafer standard [18]. M10 based modules have now a standard width of 1134 mm, which makes the product comparison easier.

# 5. Result of 2023 | 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. 11 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 shows the reduction of silver expected for 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.

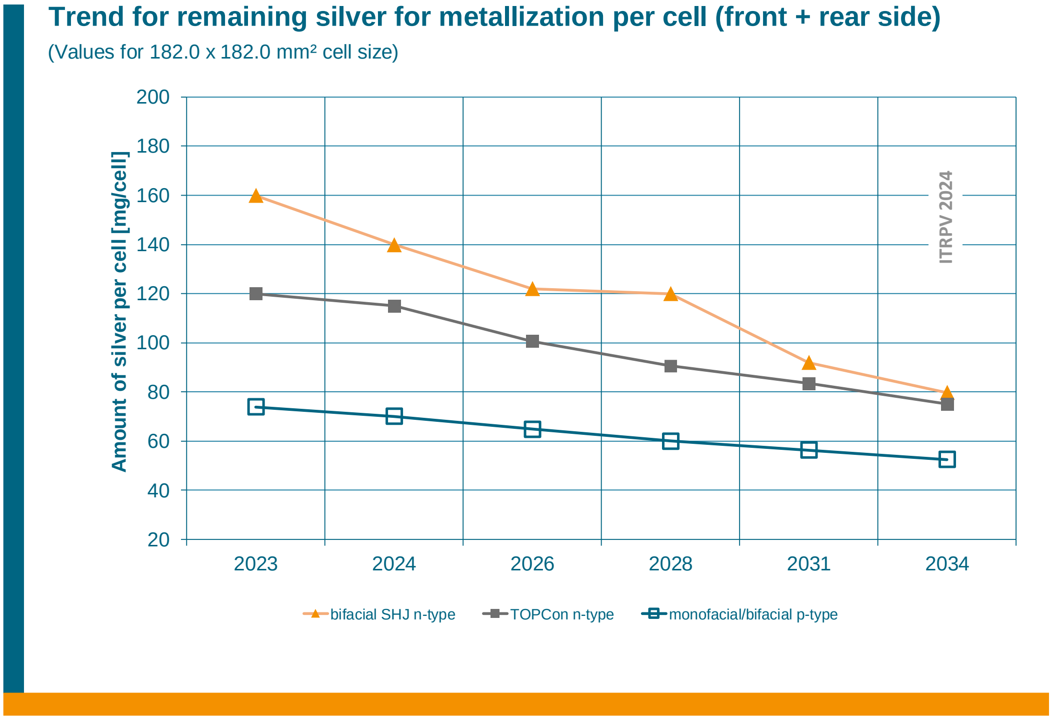


Fig. 11: Trend for remaining silver per cell for different cell concepts in M10 wafer format (182.0 x 182.0 mm²).

Our report results show that n-type cell concepts have an expected higher silver consumption than p-type PERC that consumes 74 mg/cell in M10 format. TOPCon consumes 120 mg/cell and SHJ 160 mg/cell. This is mainly due to the use of silver for front and entire rear side metallization in these n-type concepts. The difference between the TOPCon and SHJ silver consumption is expected to fade away in the upcoming 10 years.

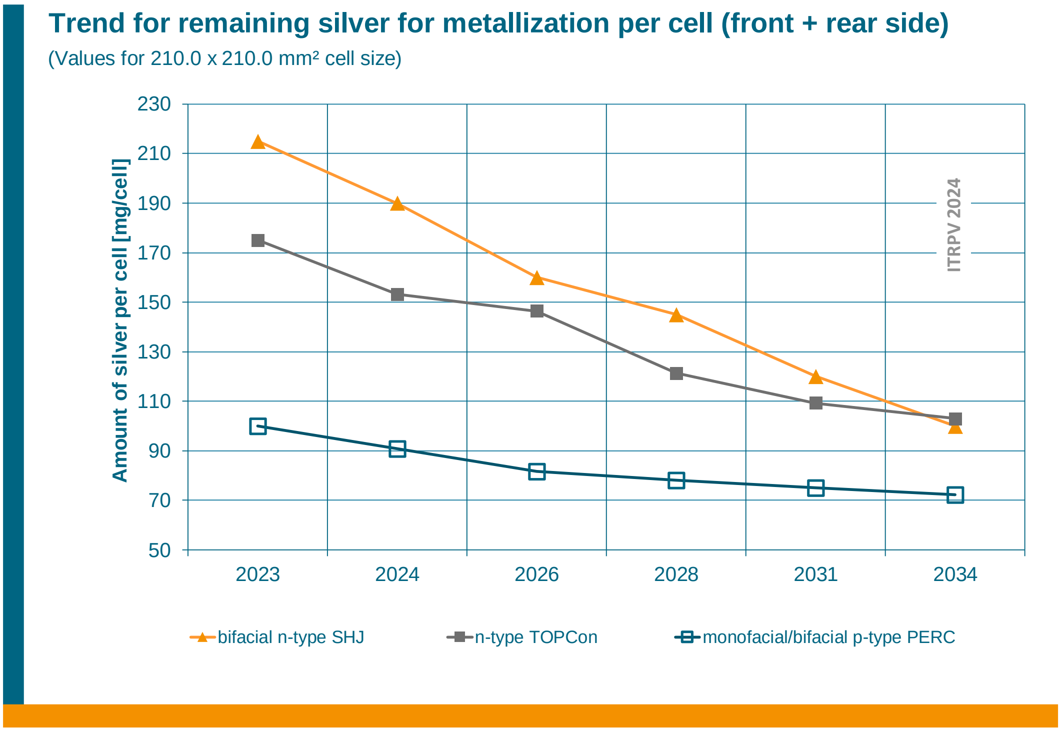


Fig. 12: Trend for remaining silver per cell for different cell concepts in G12 wafer format (210.0 x 210.0 mm²).

To get a better understanding of the Ag consumption, Fig. 13 shows the corresponding average cell level silver consumption per Wp calculated with the expected cell efficiencies according to Fig. 40. Values in units of mg/Wp are equal to units of t/GWp.

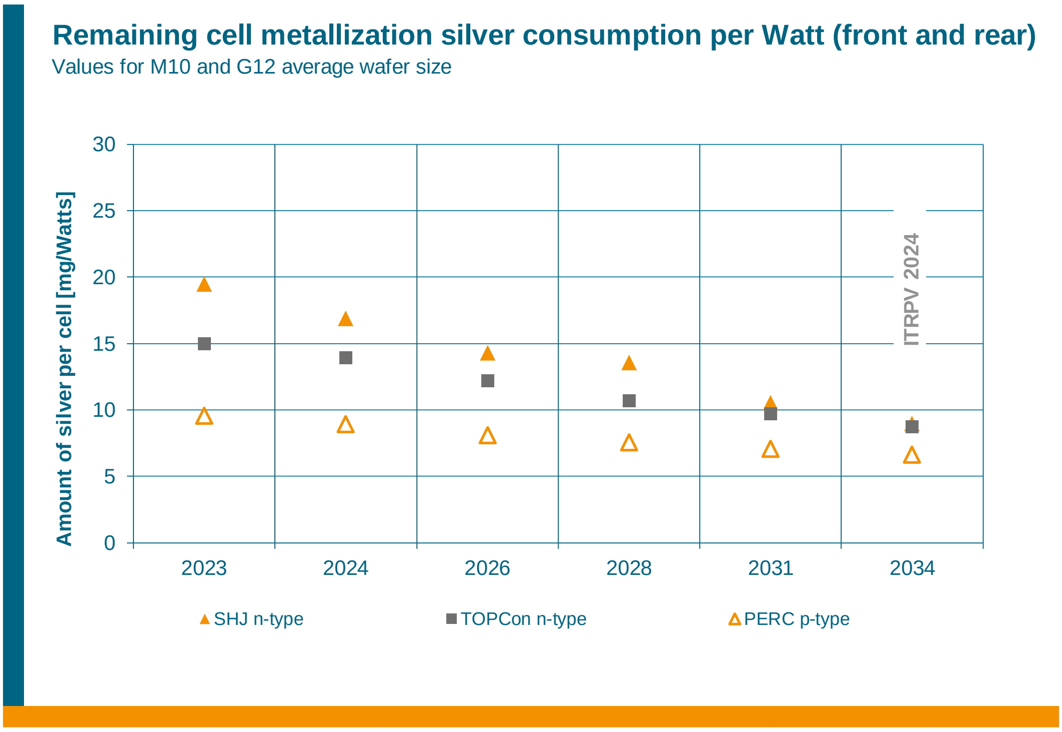


Fig. 13: Remaining silver per Watt cell (values in units of mg/Wp are equal to units of t/GWp).

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 9.6 mg/W on cell level as the median value in 2023 standard PERC monofacial and bifacial cells as average of M10, and G12 format. For TOPCon 15 mg/W and SHJ around 19 mg/W are the current values. Moreover, a reduction down to values around 9 mg/W for TOPCon and SHJ is expected to be reached within the next 10 years. New developments in pastes and screens must enable 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 be fluctuating frequently which has a direct impact on the cost of pastes and cells. For instance the price of May 5 2024: 853.92 US$/kg [19] was corresponding to around 0.98 $cent/W of a cell. A year prior, the price was around 650 US$/kg. Our results are in very good agreement with the values reported independently by Tier 1 manufacturers [20].

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. 500 GW PERC cells in 2023 consumed about 5,750 tons of silver, assuming 9.6 mg/W for PERC and 15mg/W for TOPCon respectively (assuming a share PERC:TOPCon of 65:35). This corresponds to about 18% of world silver supply in 2023 and is within the assumptions of the World Silver Survey 2024. So TOPCon consumes about 50% more than PERC a considerable reduction compared to the findings in the ITRPV 14th edition [15]. However, the continued reduction in silver consumption is essential to meet future production and cost targets for c-Si PV and also decouple 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 considered. Copper (Cu), as less expensive material, applied with plating technologies or even with silver coated copper as another approach. 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 seen in Fig. 14.

Silver is expected to remain the most widely used front metallization material for c-Si cells in the years to come. The trend of remaining aluminum for bifacial PERC solar cells is also expected to decrease from 230 mg/cell to 212 mg/cell in 2026, in the case of M10 formats.

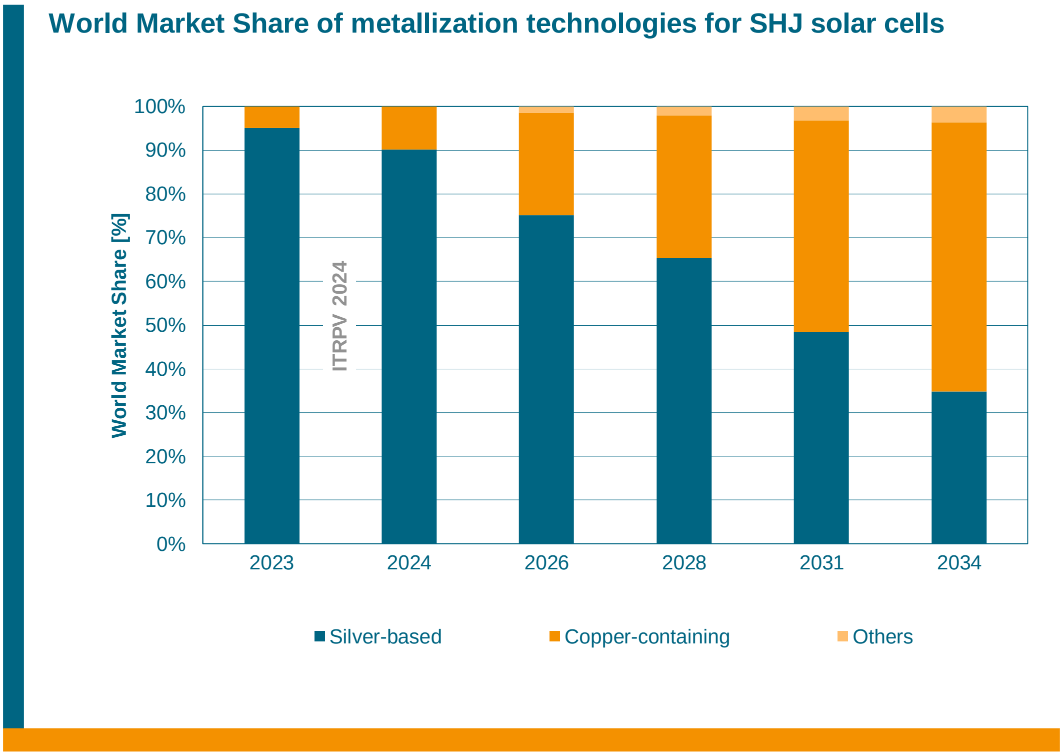


Fig. 14: Market share of metallization for SHJ solar cells.

SHJ cells already use lead free pastes. As shown in Fig. 15 we see lead free pastes to become more used in the mass production of non SHJ c-Si cells as well.

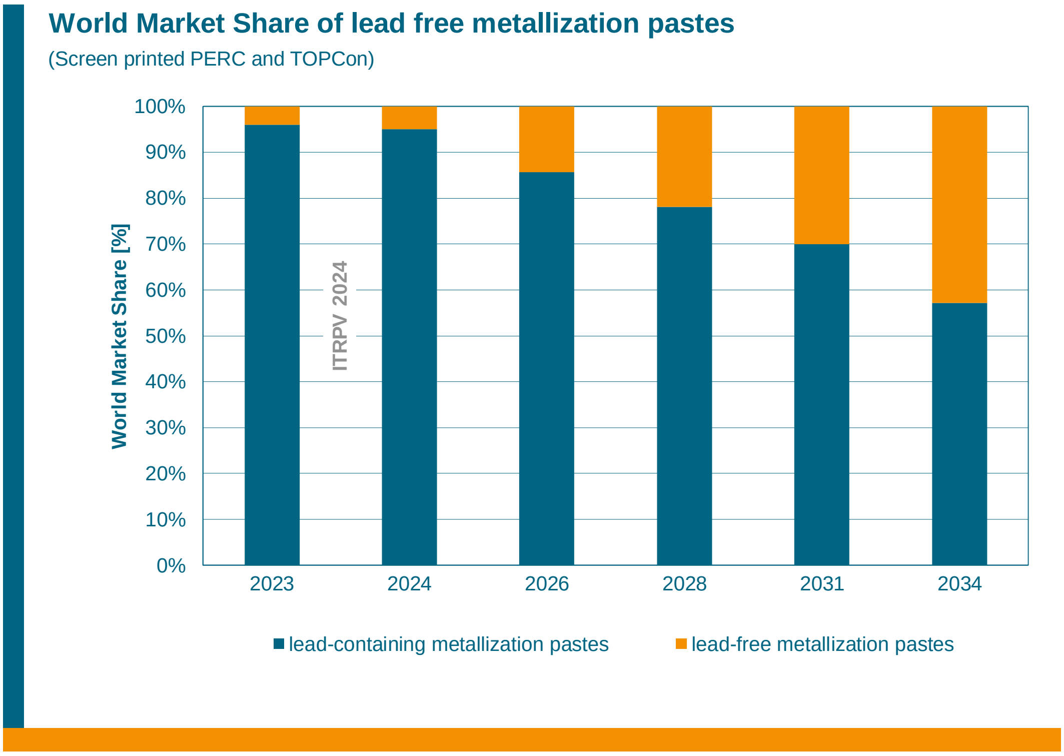


Fig. 15: World Market Share of lead free metallization pastes for PERC and TOPCon cells.

## 5.2. Processes

The first production process in cell manufacturing is texturing. Reducing the 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. 16 and Fig. 17 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 [22], or they can be extracted from the I-V-curve if the other J0 components are known.

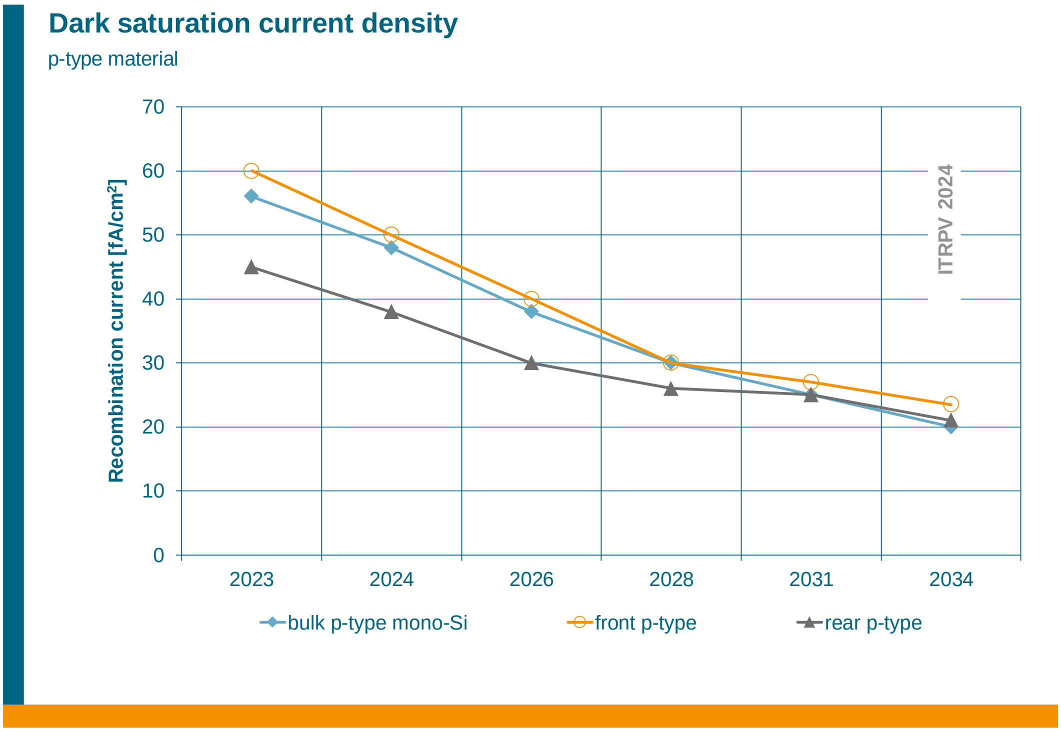


Fig. 16: Predicted trend for recombination currents J0bulk, J0front, J0rear for p-type cell concepts.

As shown in Fig. 16, the improvement of the p-type mono silicon material quality will continue. J0bulk for mono-Si is expected to reach about 20 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 2034. 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.

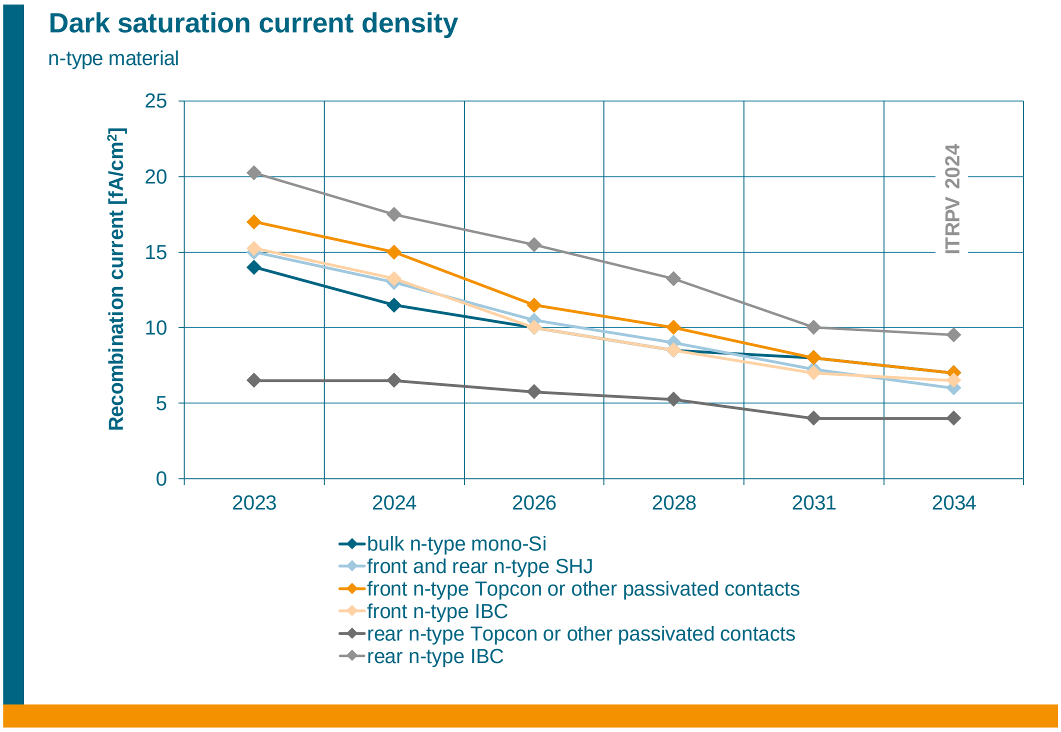


Fig. 17: Predicted trend for recombination currents J0bulk, J0front, J0rear for n-type cell concepts.

Fig. 17 shows that today's n-type mono-Si wafers have J0bulk values below 14 fA/cm² much lower than the 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 140 Ohm/square can be realized with and without 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. 18 shows the current situation for homogenous and selective phosphorous doping: today's sheet resistance of homogenous doped p-type emitters is around 126 Ohm/square and it is expected to increase to around 150 Ohm/square. Selective doping allows higher sheet resistances: 160 Ohm/square were standard in 2023. 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.

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 2023 and will dominate the remaining future of p-type cells. Laser doped selective emitters are the technology of choice.

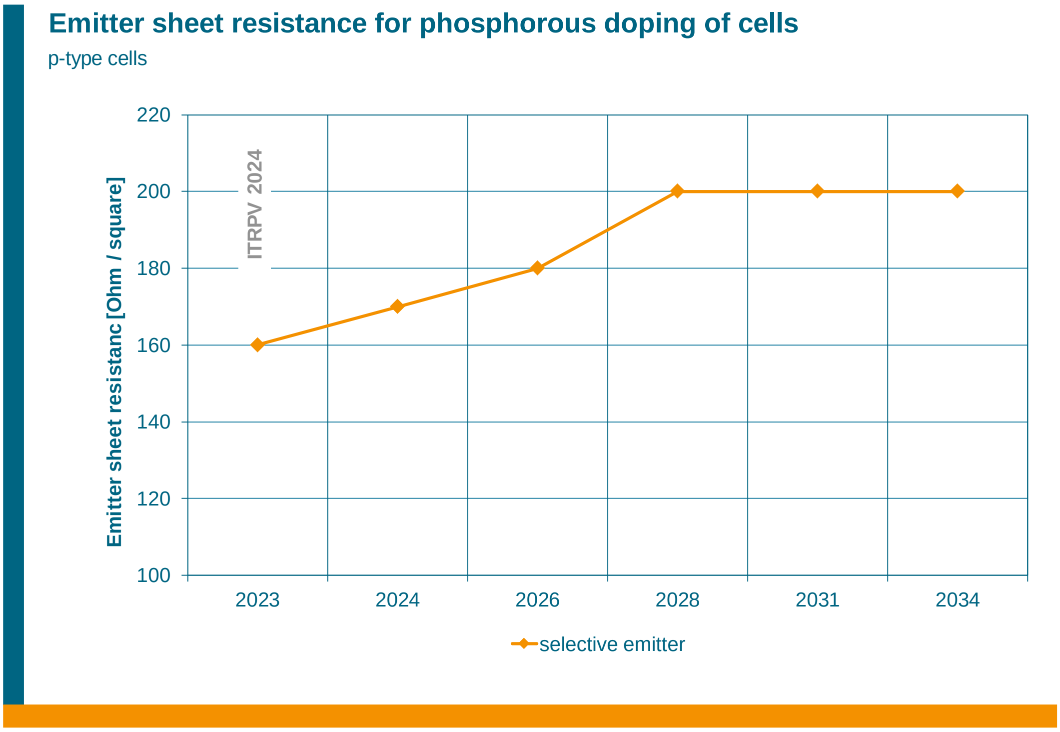


Fig. 18: Expected trend for emitter sheet resistance of phosporous doped emitters for p-type cell concepts. In case of selective emitter the sheet resistance value refers only to the lower doped region.

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. 19. For Boron diffusion we also distinguish between homogenous and selective doping. An emitter sheet resistance of over 130 Ohm/square is mostly used in 2023 lower-doped region. An increase to above 170 Ohm/square is expected.

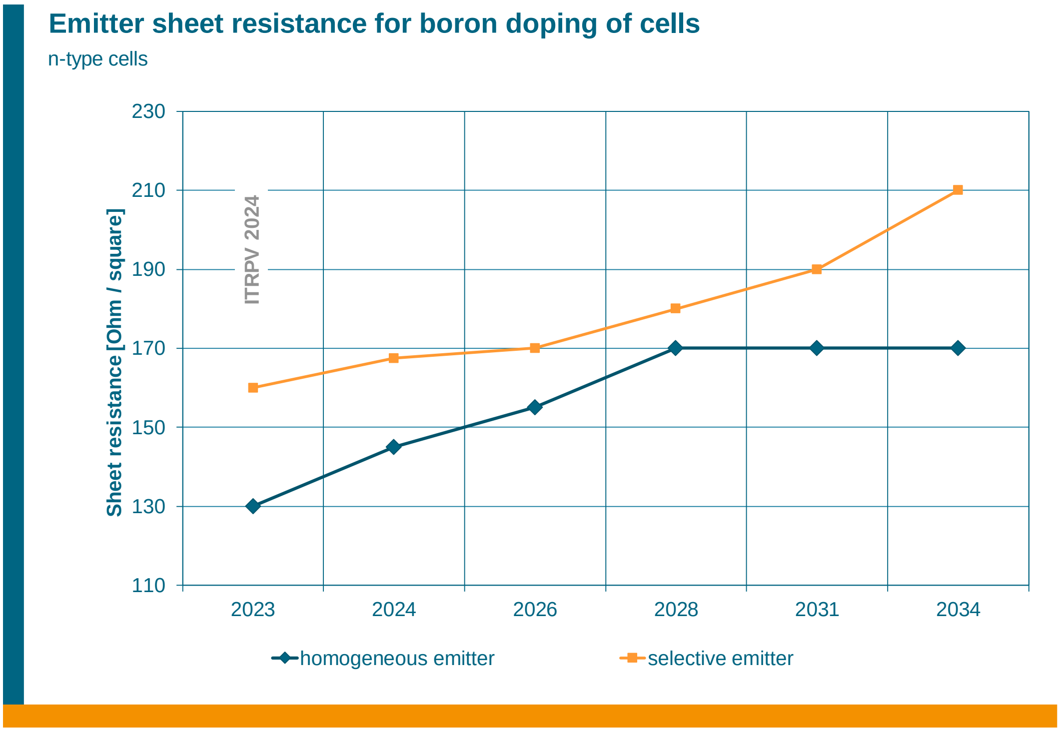


Fig. 19: Expected trend for emitter sheet resistance for boron doping for n-type cell concepts.

Selective emitters categorized by a highly-doped region show in 2023 165 Ohm/square. This value will reach 210 Ohm/square until 2034.

Fig. 20 shows the market share of homogenous and selective emitter for n-type TOPCon cells. Although the market share of selective emitter based technology is always dominant, homogeneous emitter remains with fluctuating shares of around 20% to 32% throughput the projected years.

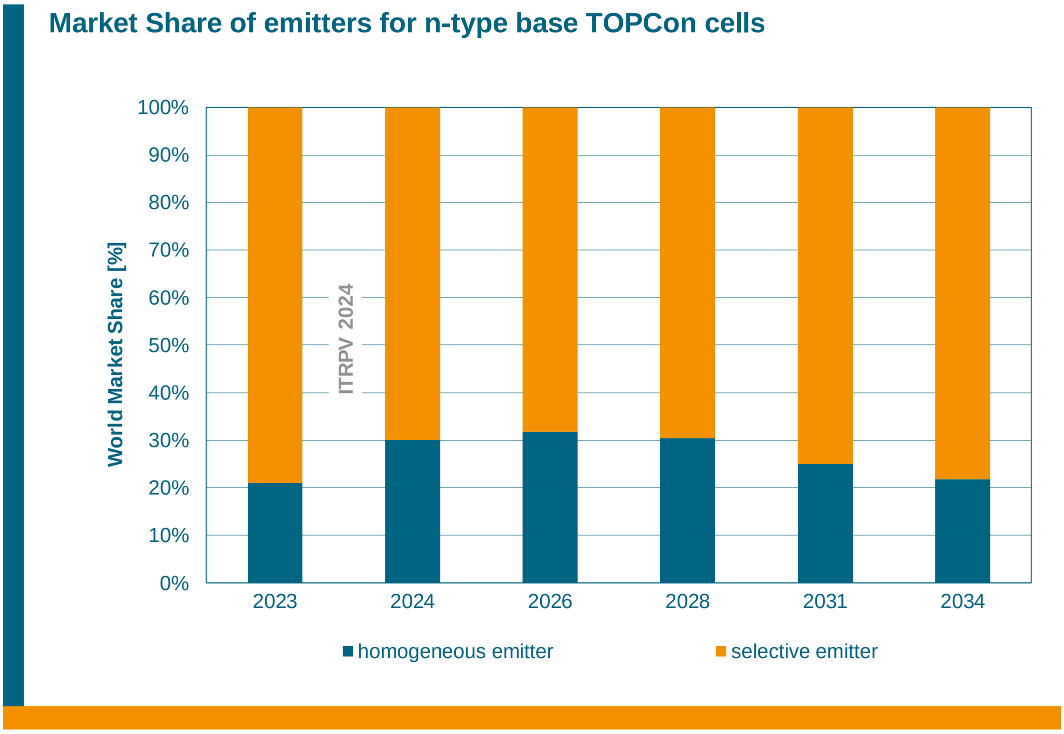


Fig. 20: Market Share of emitters for n-type base TOPCon cells.

Boron doping for n-type cells in 2023 is to about 90% done with the $BCl_3$ thermal diffusion technique. 10% of the current market share goes to $BBr_3$ diffusion technique. However, $BBr_3$ based diffusion is expected to phase out after 2024. Alternative processes are not seen with significant market shares so far.

To separate the pn junction from bulk, an edge isolation is required. Wet chemical edge isolation is performed in manufacturing lines. Fig. 21 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 83% of the market share. It is expected that the dominance continues until 2034. 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 2034, 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 fume.

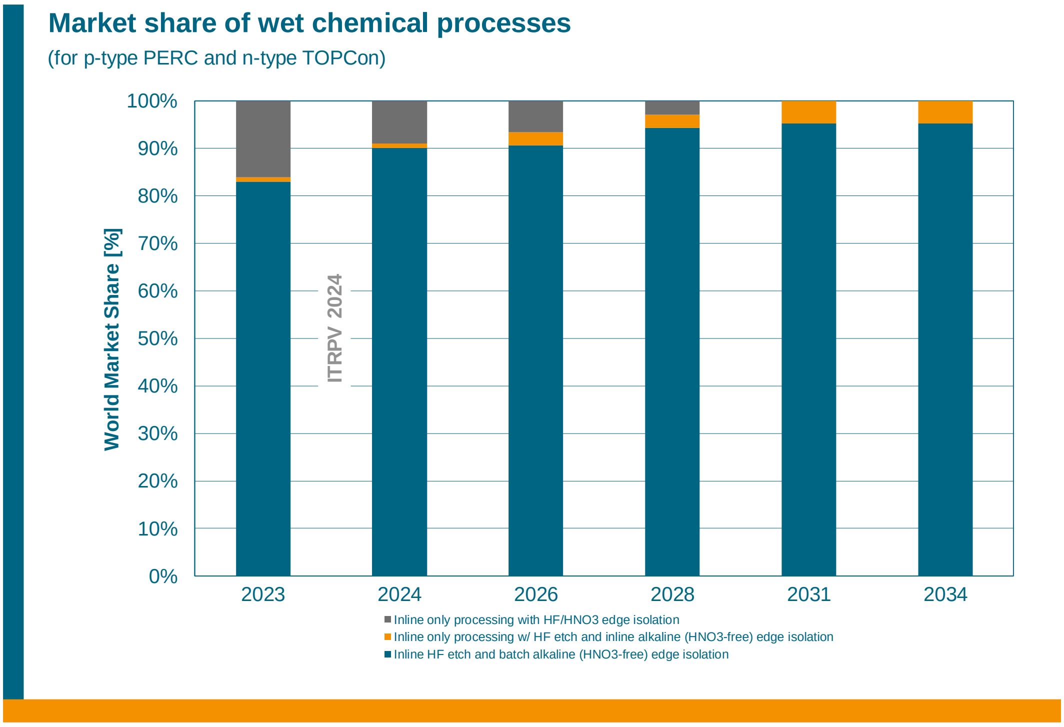


Fig. 21: Market share of wet chemical processes.

Cleaning processes are mandatory for high efficiency cell production lines. $H_2O_2$ based cleaning was mostly used in the past. Fig. 22 and Fig. 23 show that ozone based cleaning processes are already mainstream for SHJ and PERC/TOPCon cells, respectively. The ozone-based cleaning will continue gaining market share in the upcoming years. In the case of SHJ solar cells, RCA processes have a stable market share ranging between 5% and 7% throughout the decade.

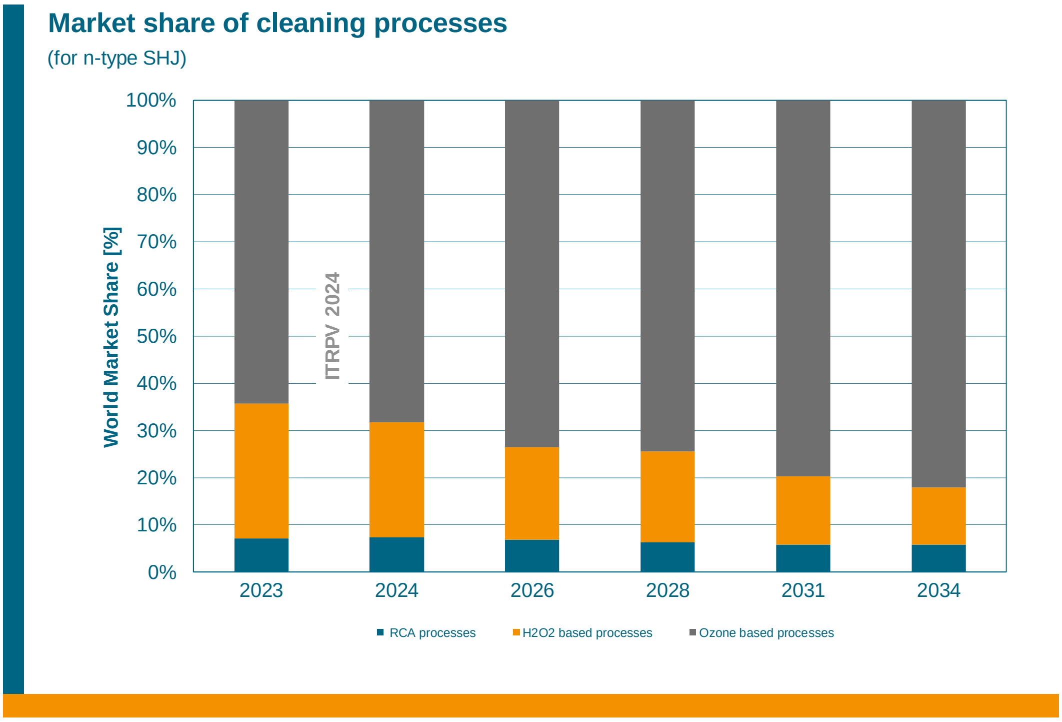


Fig. 22: Market trend of cleaning processes for n-type SHJ.

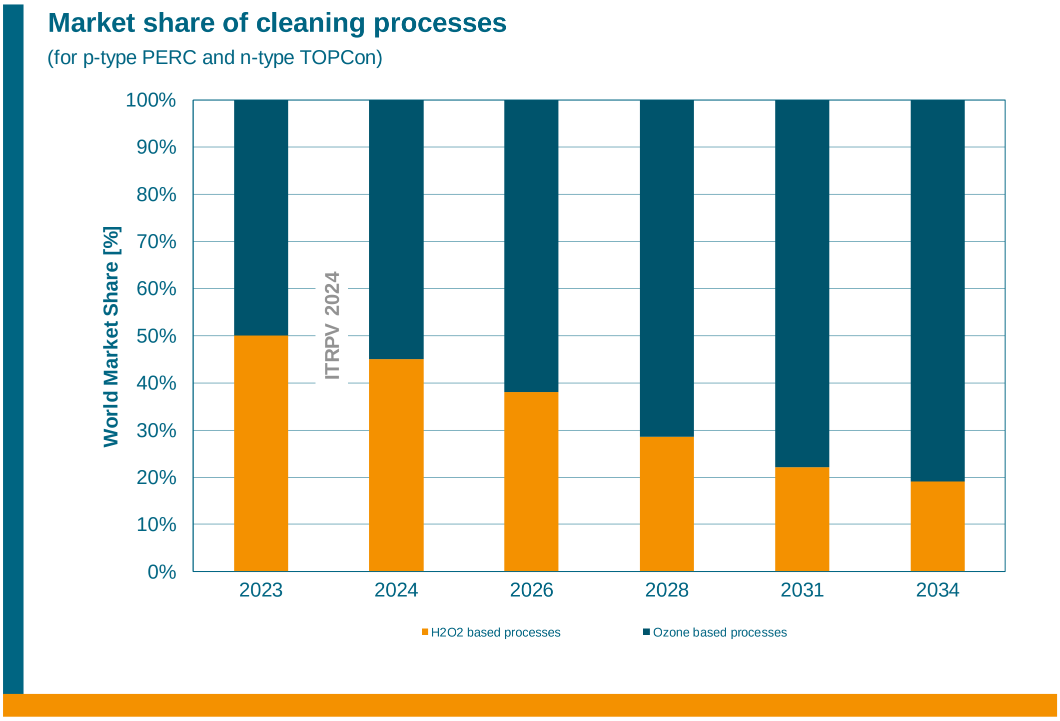
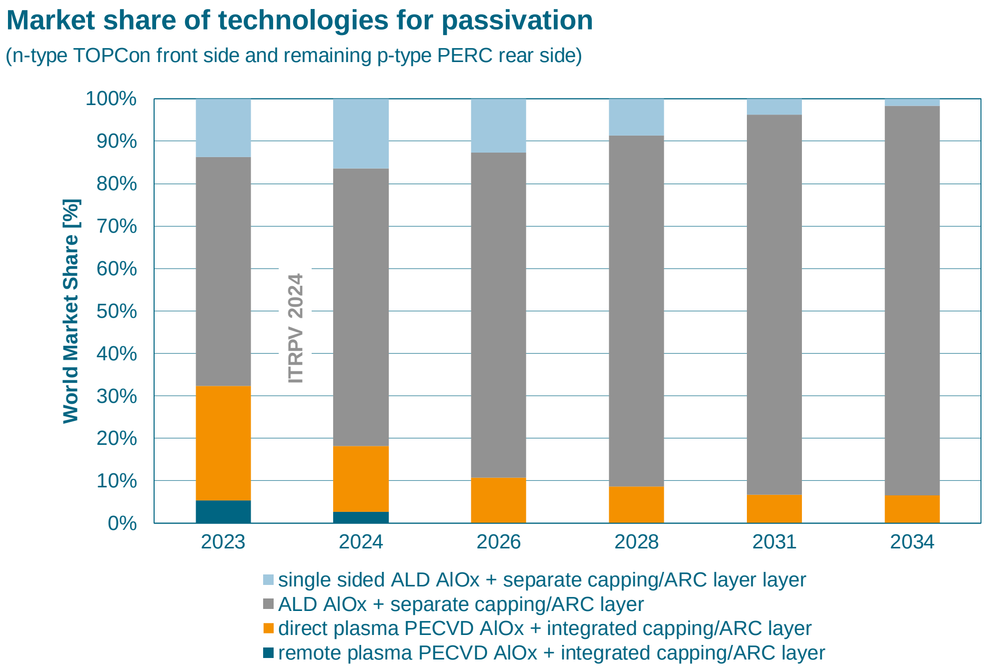


Fig. 23: Market trend of cleaning processes for p-type PERC and n-type TOPCon.

Since 2013, cell concepts using rear side passivation with dielectric layer stacks have been in mass production particularly 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. 24 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 2024. Currently in 2023, the main $Al_2O_3$ passivation process is batch ALD followed by the deposition of the capping layer, reaching a market share of 63%. The use of direct plasma PECVD $Al_2O_3$ with integrated capping layer deposition holds around 27% and 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.

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.


Market share of technologies for passivation

(n-type TOPCon front side and remaining p-type PERC rear side)

Fig. 24: Market share of technologies for passivation.

Tunnel oxide formation can be done in an individual process step or in in situ with another process. In situ formation of tunneling oxide in combination with another process is mainstream in TOPCon manufacturing. The forming of the poly-Si layer is done either by LPCVD, or by PECVD. Fig. 25 indicates that LPCVD, dominating in 2023 with about 74% market share will lose market share to PECVD in the upcoming years. PECVD market share in 2034 is expected to be 70% for the formation of tunneling oxide with an insitu oxidation.

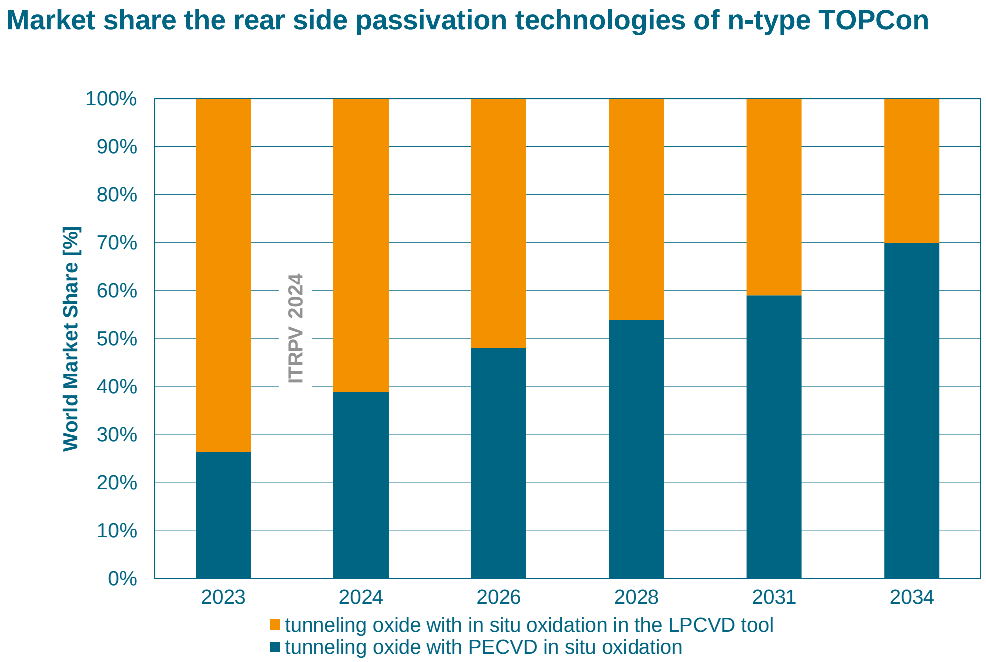

Market share the rear side passivation technologies of n-type TOPCon

Fig. 25: Expected trend of forming the rear side tunneling oxide in tools for n-type TOPCon solar cells.

Considering the deposition processes of poly-Si for TOPCon cells, PECVD and LPCVD seem to hold significant market share. Fig. 26 shows the market share of different deposition techniques for the poly-Si layer. Considering the data of all contributors, it seems like the main technologies of choice are PECVD and LPCVD, with a slight market share of 3% for PVD technology. It is expected that PECVD, and LPCVD remain main technologies.

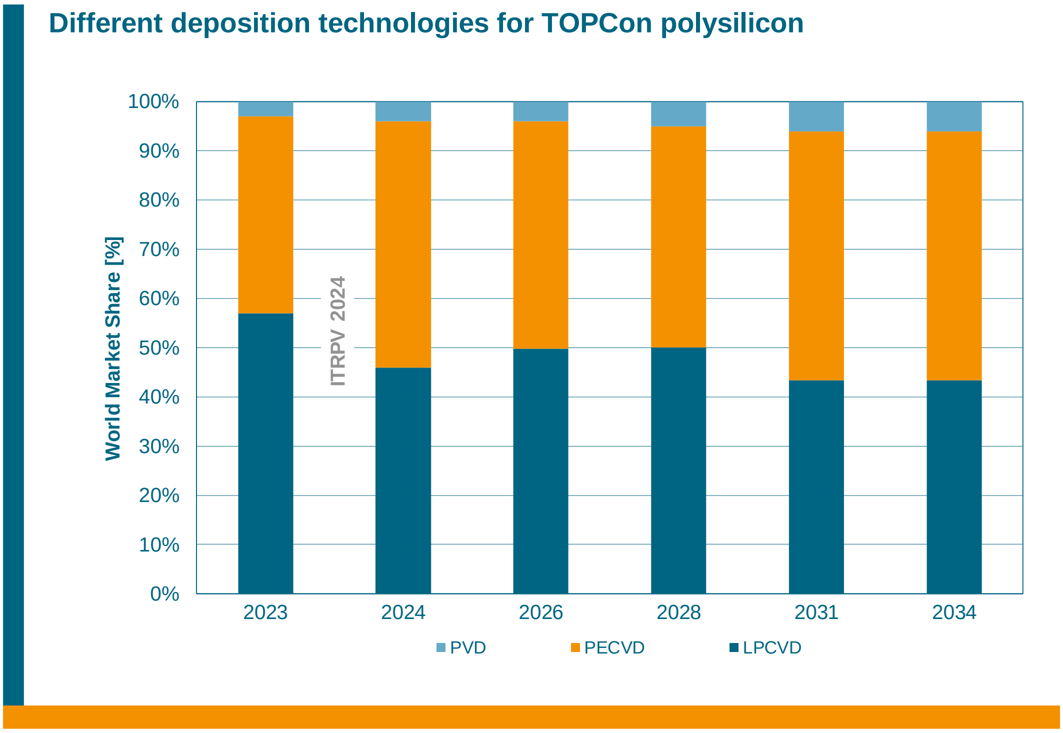


Fig. 26: Expected trend of forming the polysilicon layer of TOPCon contacts.

GW-scale manufacturers do not expect a significant market share of PVD after 2026, as seen in Fig.27.

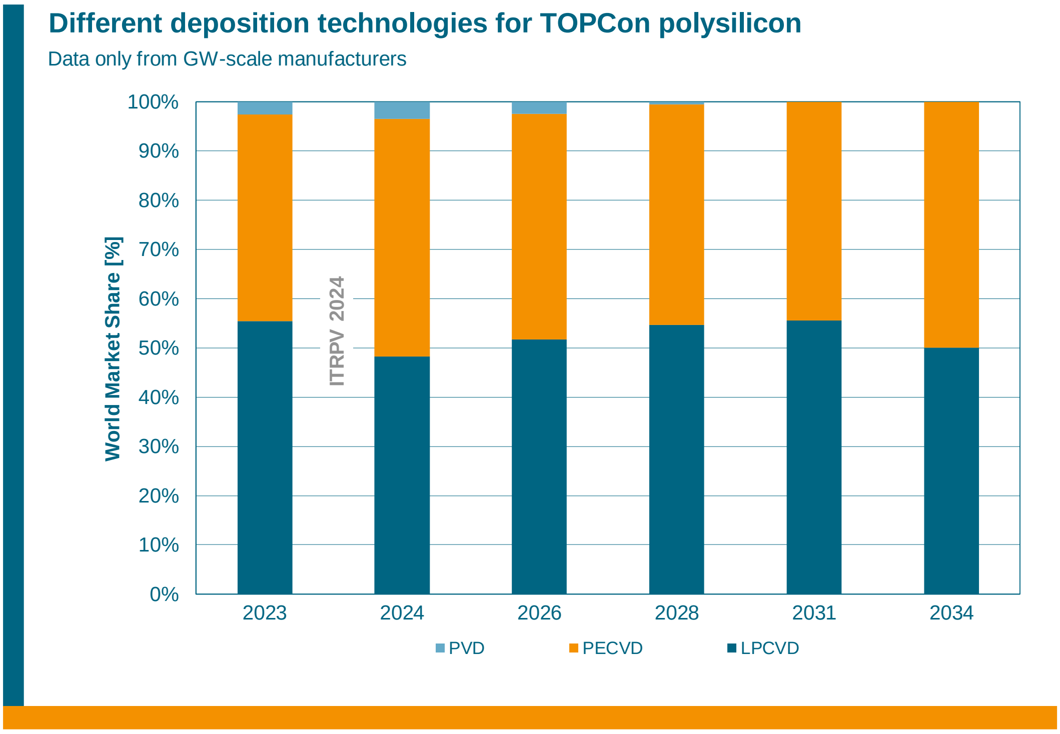


Fig. 27: Expected trend of forming the polysilicon layer of TOPCon contacts (Only data from GW-scale manufacturers).

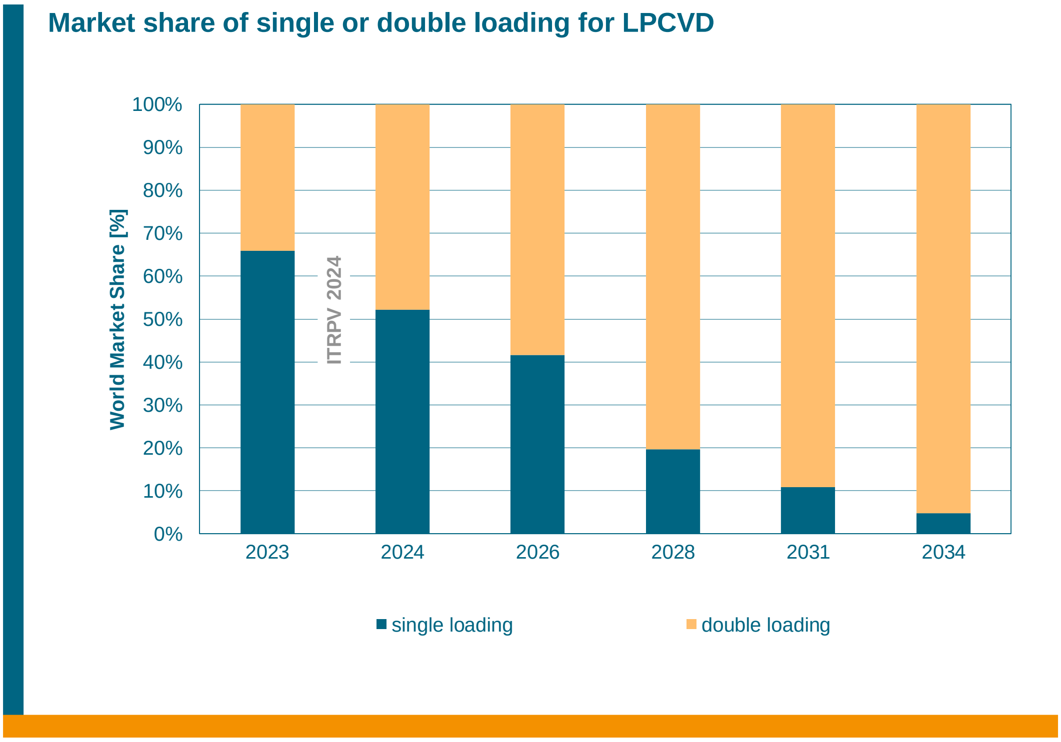


Fig. 28: Market share of single or double loading for LPCVD.

For LPCVD processes, the loading process is also of interest. Around 66% in 2023 is done in a single loading process, expected to lose market share towards a double loading process. In 10 years double loading process is expected to have a 95% market share, as shown in Fig. 28.

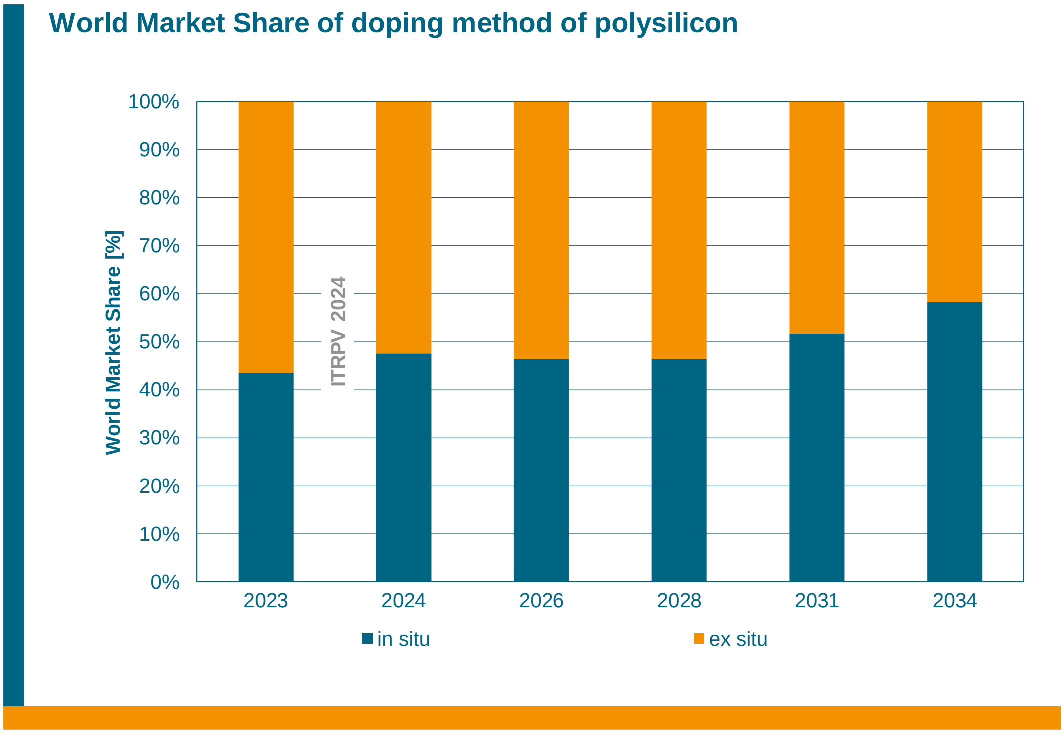


Fig. 29: World Market Share of doping method of polysilicon.

Fig. 29 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 42% is still expected in 10 years. Developments in this topic have to be carefully observed.

Fig. 30 shows the anticipated thickness trend of the poly-Si layer deposited for TOPCon concepts. The 120 nm in 2023 will be reduced to around 70 nm in 10 years.

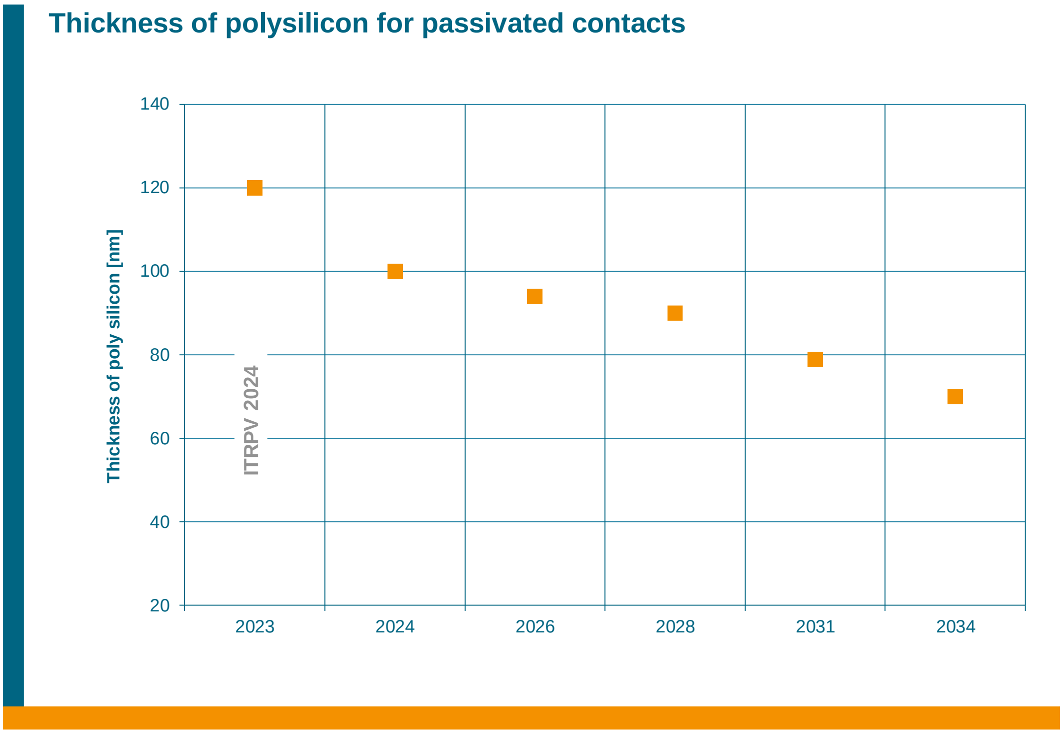


Fig. 30: Expected trend of polysilicon thickness for TOPCon layer stack formation.

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. 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 interesting as rear side metallization technology with market shares around 6% after 2034. 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. 31 summarizes the available technologies and their estimated market share during the next 10 years. New front side metallization pastes 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 84% in 2023 and will extend its domination. Single print is expected to continue losing market share, with a disappearance in the upcoming decade. Double printing with a minor market share of about 2% in 2023 is expected to disappear already in 2024. Dual und double print require an additional printing step with fine-alignment capabilities. Dual print is the attractive choice and is expected to remain so in the coming decade.

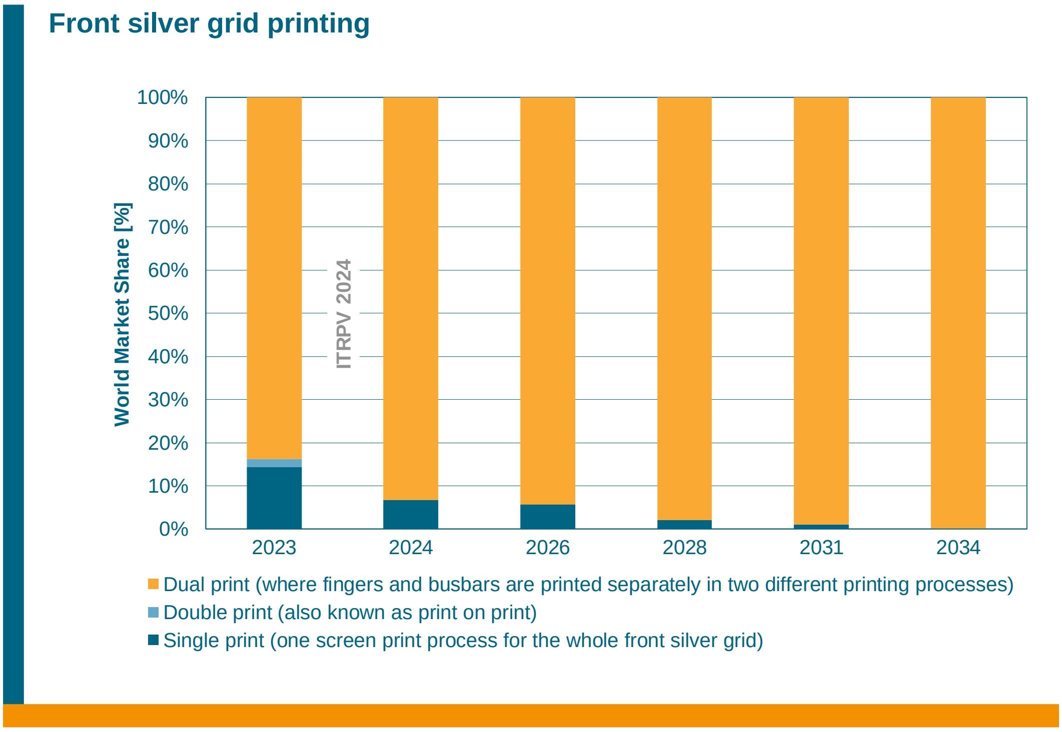


Fig. 31: Expected market share of different front side printing techniques.

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.

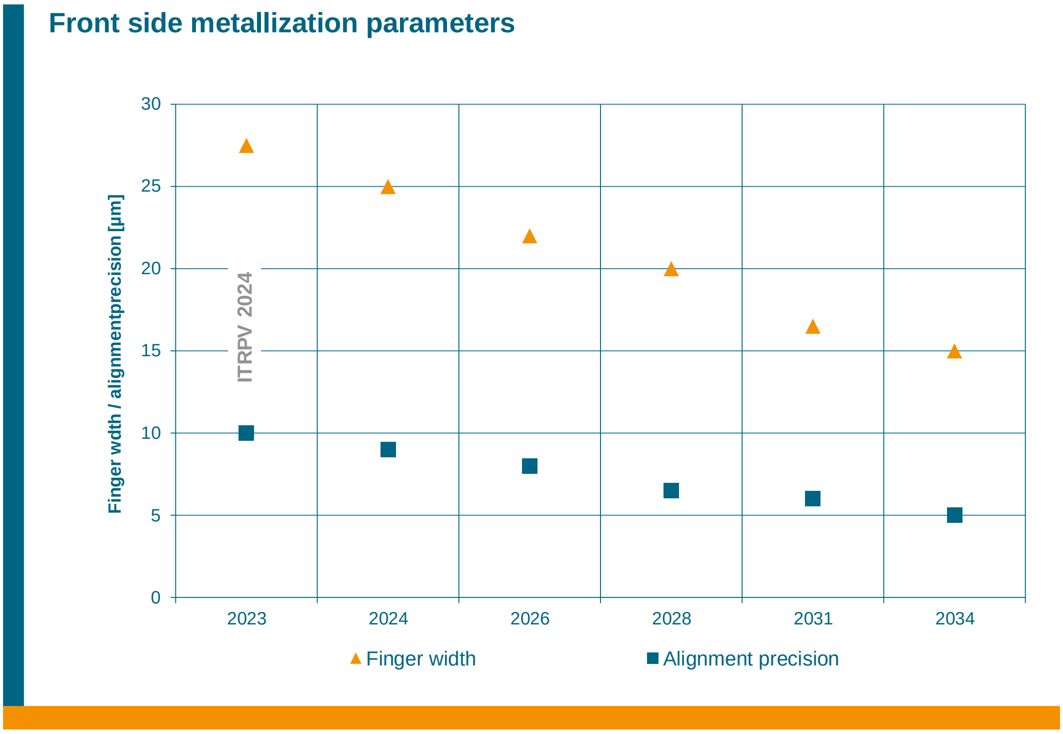


Fig. 32: Predicted trend for finger width and alignment precision in screen-printing. Finger width needs to be reduced without any significant reduction in conductivity.

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 27 µm were standard in 2023 as shown in Fig. 32. A further reduction down to 15 µm over the next 10 years is expected.

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. 32 shows. This will be necessary especially regarding an improved alignment to subjacent structures as in the case of selective emitter structures.

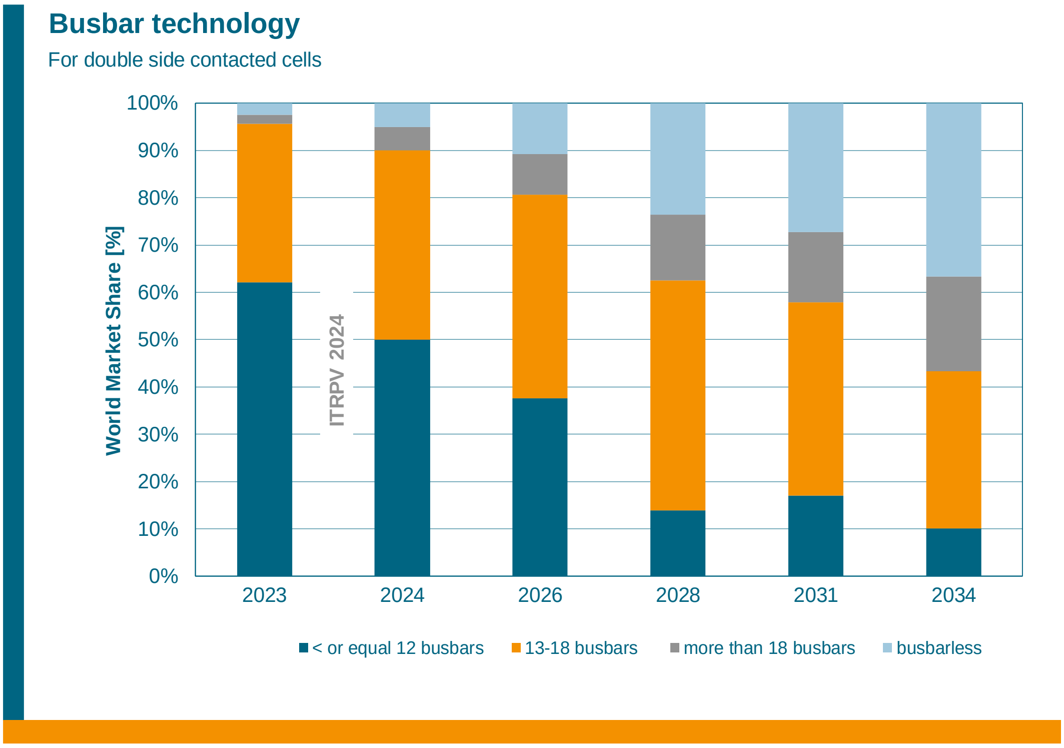


Fig. 33: Market share for different busbar technologies.

Reducing the finger width is going in parallel with increasing the number of busbars. Fig. 33 shows details on this metallization trend for cells. Busbar layouts less than or equal to 12 dominated the market with 62% in 2023. The transition however to busbar layouts between 13 – 18 busbars as well as layouts with more than 18 busbars and busbarless formats are increasing. In 2034, only 10% of the market share is expected to be covered by 12 busbar or less metallization layouts. It is important to mention that layouts with 5 and 6 BBs do not exist, also in line with the development towards larger wafer formats M10 and G12. It is very interesting to see the trend towards busbarless layouts, which are expected to cover around 37% of the market in 2034. 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 to process all those formats.

In Fig. 34, Fig. 35, and Fig. 36 we summarize the expected throughput trends of new tools capable for processing cell formats M10.

Fig. 34 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 2023 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 5,000 wafers/h in 2023. Throughput for B-diffusion is expected to increase to above 8,000 wafers/h within the next 10 years.

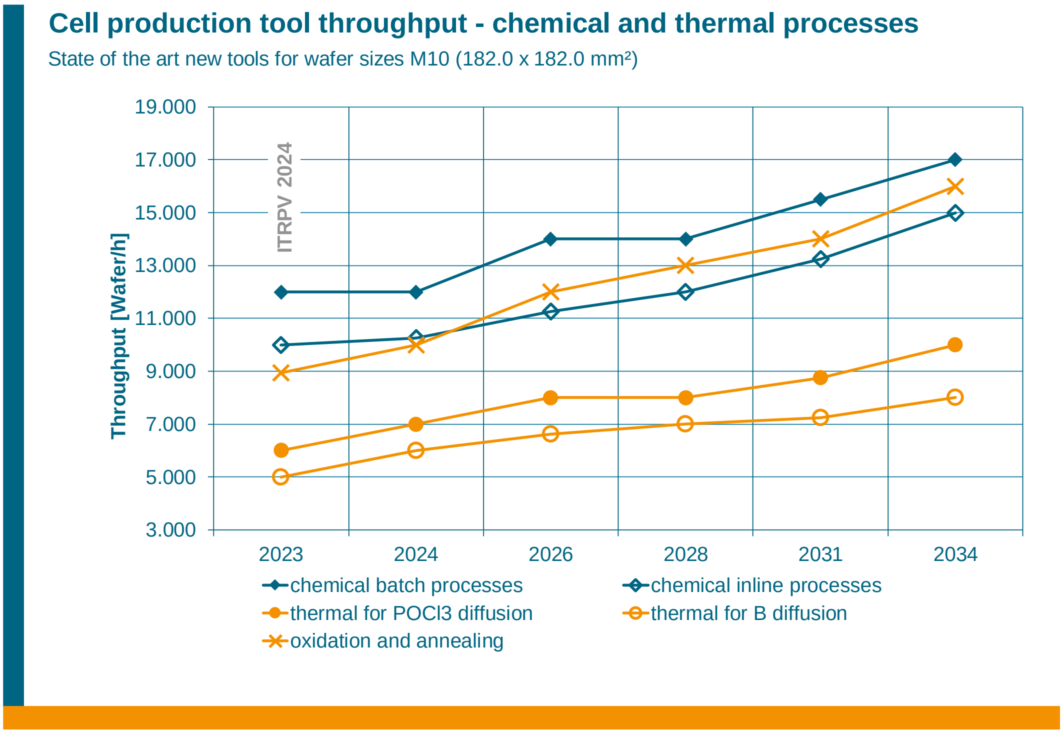


Fig. 34: Predicted trend for throughput per tool of cell production equipment in the frontend.

Fig. 35 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 16,000 wafers/h in 2034.

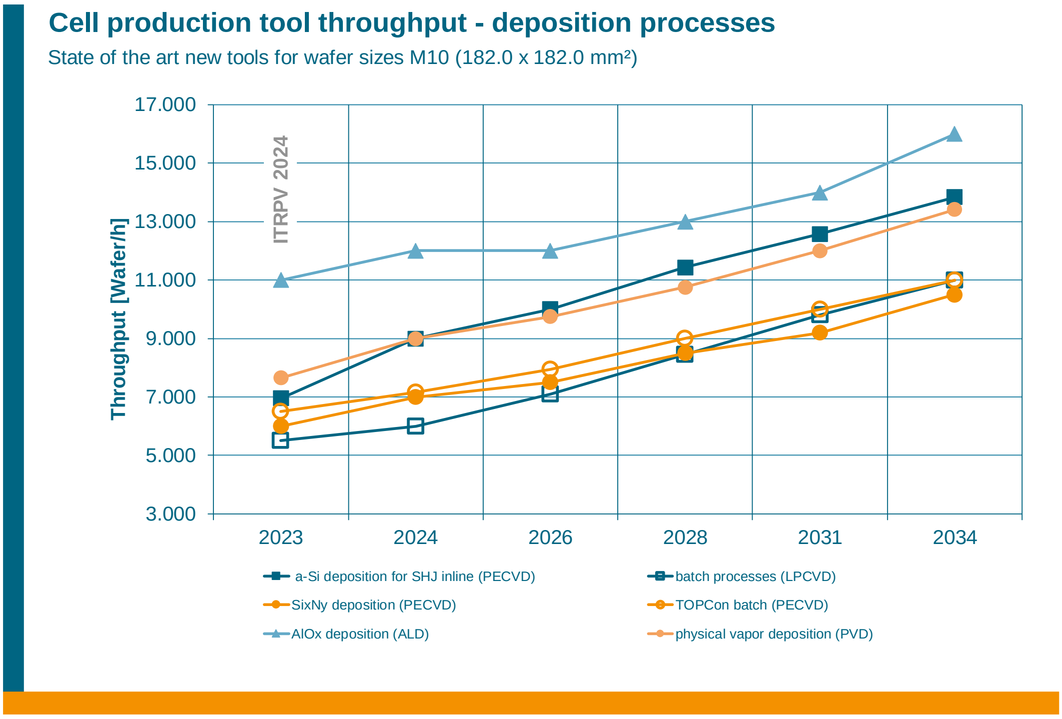


Fig. 35: Predicted trend for throughput per tool of cell production equipment for layer deposition.

The throughput trend in cell processing backend is shown in Fig. 36. Screen printing tools with throughputs of around 7,900 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.

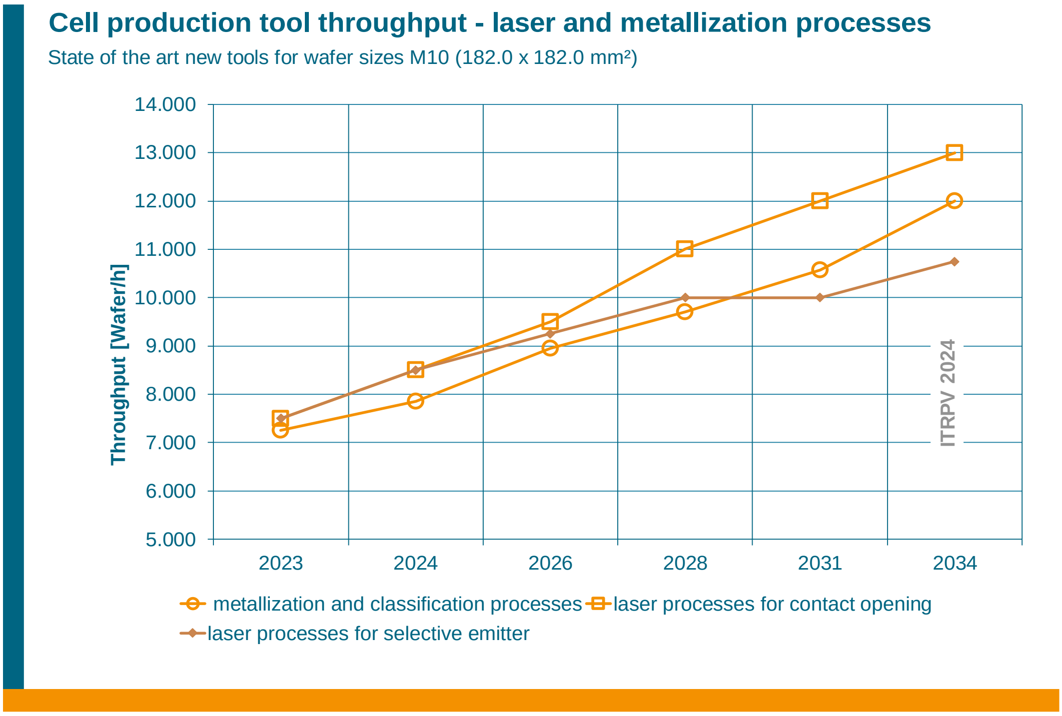


Fig. 36: Predicted trend for throughput per tool of cell production equipment in backend processing.

## 5.3. Products

According to our results, the aluminum BSF cell concept was phased out in 2023. 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 2023 was the PERC technology, using p-type material with a passivating layer of $Al_2O_3$ and a $SiN_x$ capping layer. In 2023 the market share of PERC p-type mono-Si was 64% as shown in Fig. 37, considering the data of all contributors.

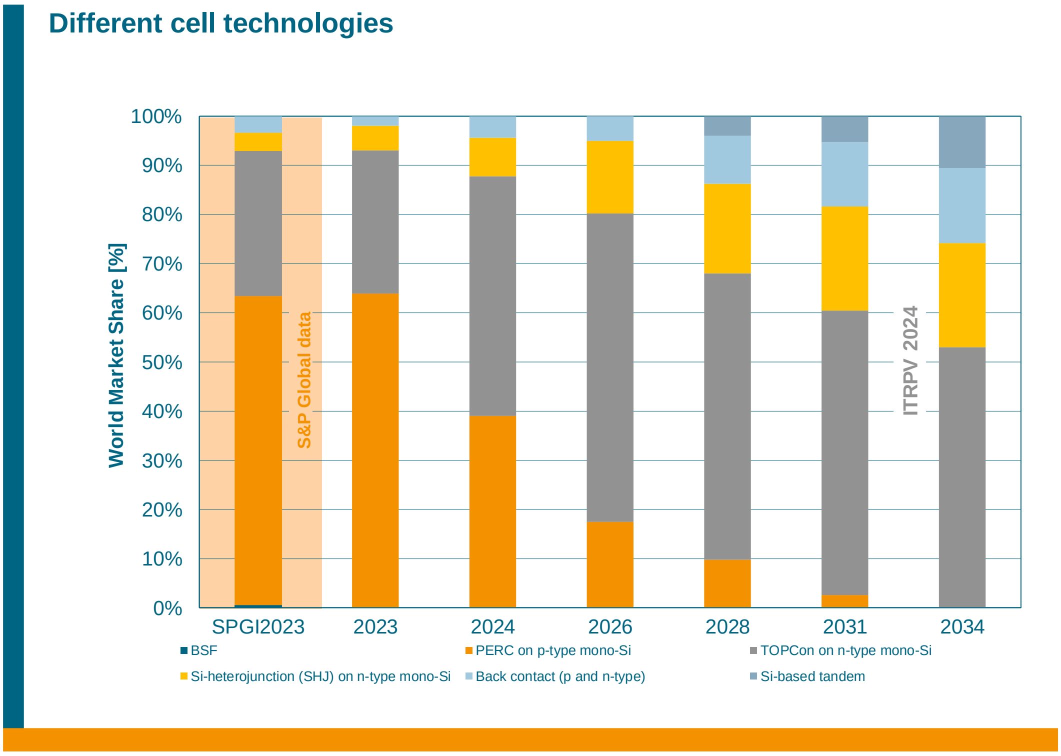


Fig. 37: Market shares for different cell technologies. S&P Global (SPGI) data for 2023 are indicated as reference [14].

The p-type mono-Si PERC will phase out in the upcoming decade. TOPCon on n-material using tunnel oxide passivation stacks at the rear side, will gain market share from about 29% in 2023 up to 53% within the next 10 years. Based on our results, TOPCon on n-type is expected to become the dominating cell concept already in 2024 in terms of market share. If we consider the data of only GW-scale manufacturers, as shown in Fig. 38, the transition towards n-type concepts is more progressive, and PERC is not expected to remain at all after 2028. The data from all contributors show a more conservative approach.

According to GW-scale manufacturers, SHJ cell technology, the second most available n-type concept nowadays is expected to increase the 2023 market share of about 5% to over around 19% within the next ten years. The first pillar in Fig. 37 and Fig. 38 shows, that our findings for 2023 are in line with the SPGI analysis [20]. There is still a clear market dominance of double-sided contact cell concepts. Rear-side contact cells are not expected to have significant market share: we assume a change from ≈ 2% in 2023 to about 19% in 10 years. Si-based tandem cells are expected to appear in mass production after 2026, a delay compared to the assumptions in the 12th edition.

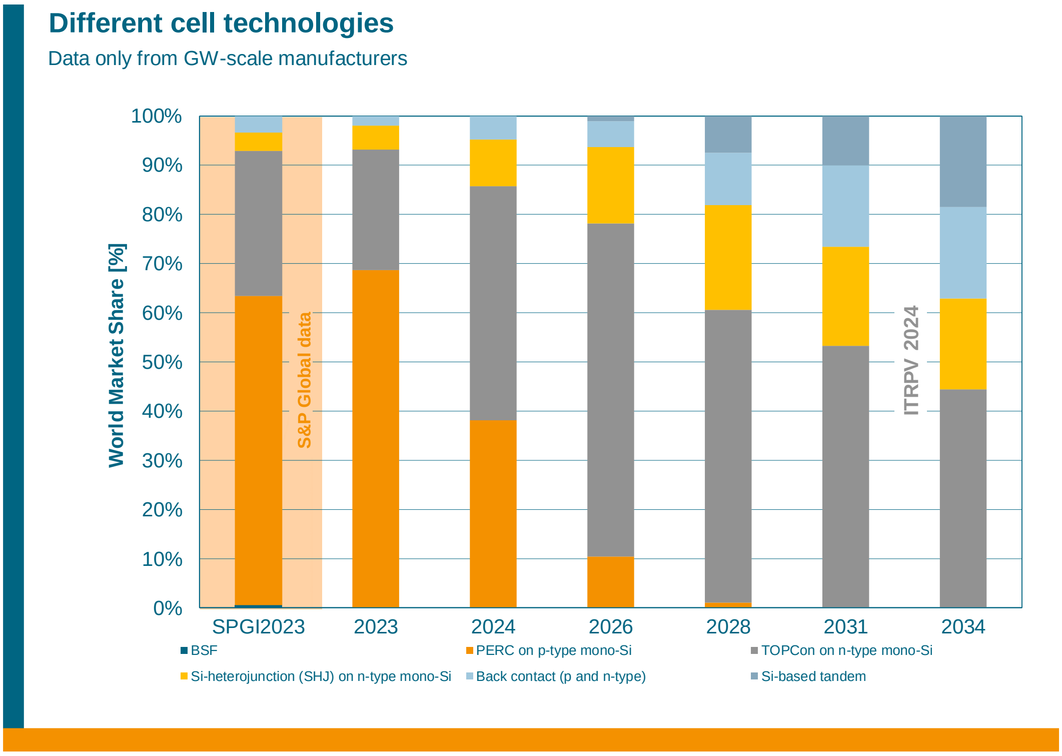


Fig. 38: Market shares for different cell technologies from GW-scale manufacturers. S&P Global (SPGI) data for 2023 are indicated as reference [14].

PERC, TOPCon, and SHJ cells 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. 39 shows the expected market trend for bifacial cells. The market share of 90% in 2024 is expected to remain stable within the next 10 years.

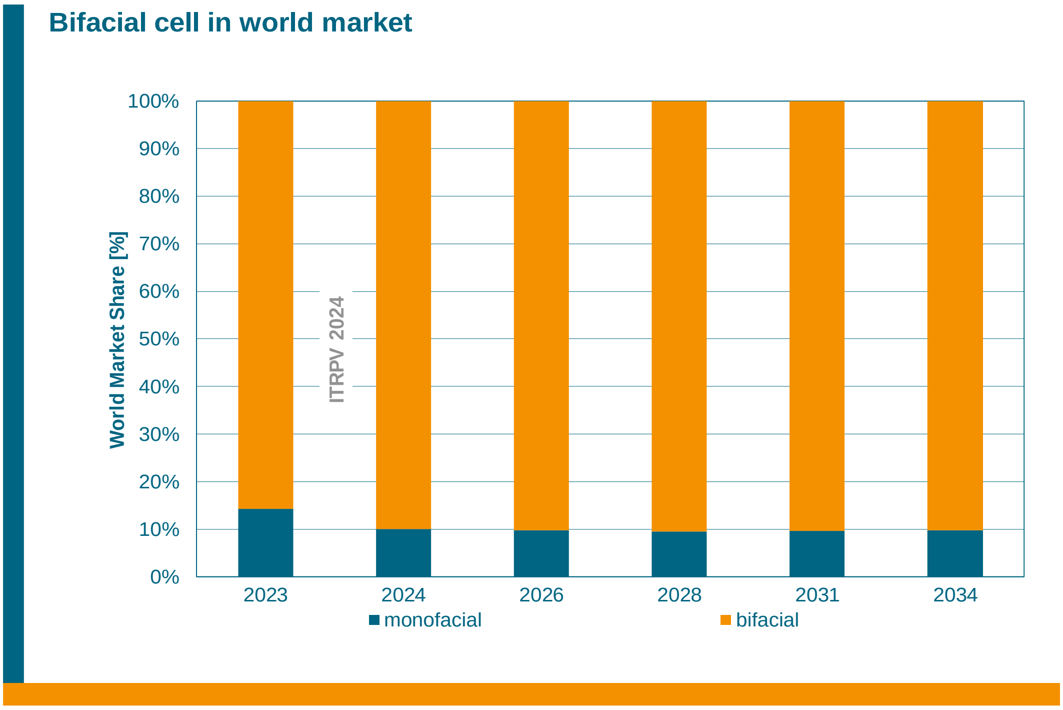


Fig. 39: Market share for bifacial cell technology.

Bifacial cells can be used in conventional, monofacial modules or in bifacial modules with transparent rear sides. Based on these results, there will however always be remaining cell manufacturing (around 10%) focusing on monofacial cells.

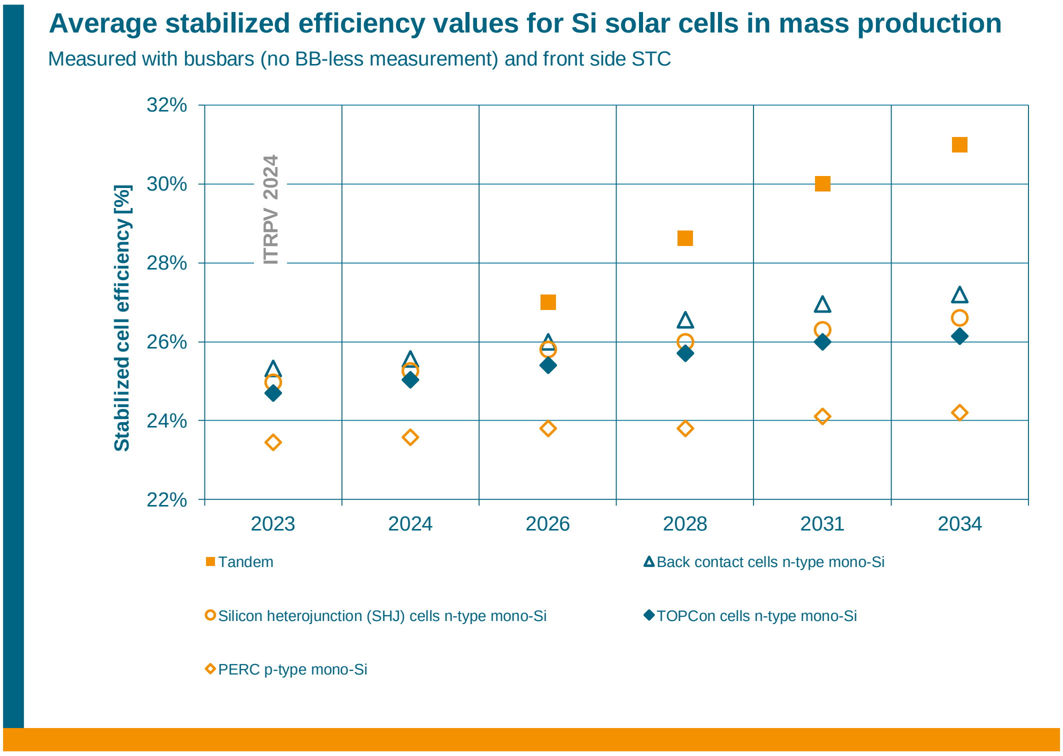


Fig. 40: Average stabilized efficiency values of c-Si solar cells in mass production.

Fig. 40 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 n-type material show the highest efficiency potential of today's cell technology concepts. We found that p- and n-type mono-Si cells with diffused pn junction at the front side will attain efficiency values reaching up to 24.2% and 26.1% 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% and 27.2% in mass production until 2034. 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% [23]. Tandem cells will overcome this limit. Mass production cell efficiencies of Si based tandem cells concepts are expected to start at about 27%. It was extremely difficult to predict the start of tandem mass production in the past. The introduction in the market is expected after 2026 according to the data analyzed in this edition of the report.

Fig. 41 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 2024. It is expected that the trend continues to such that in 2034 around 55% 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 and on the long run. Nevertheless, there will always be room for new factories that are rated to be less than 5 GW capacity, event lower than 1 GW. It is expected that these factories would mainly serve local markets and in some cases niche products.

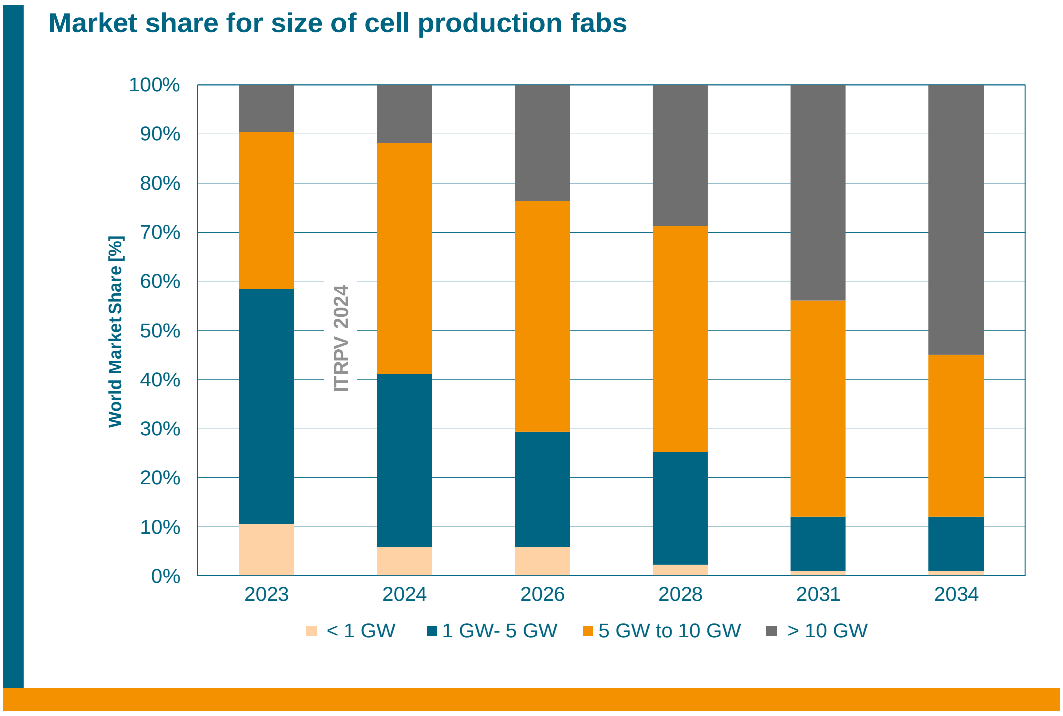


Fig. 41: Trend for name plate capacity of cell manufacturing fabs.

# 6. Results of 2023 | Module

## 6.1. Materials

The module related price share contributes with ≈ 50% to the module sales price. 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 7.2. 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 most heavy material of a module. It determines weight and light transmission properties. The thickness is also important for the mechanical stability 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.

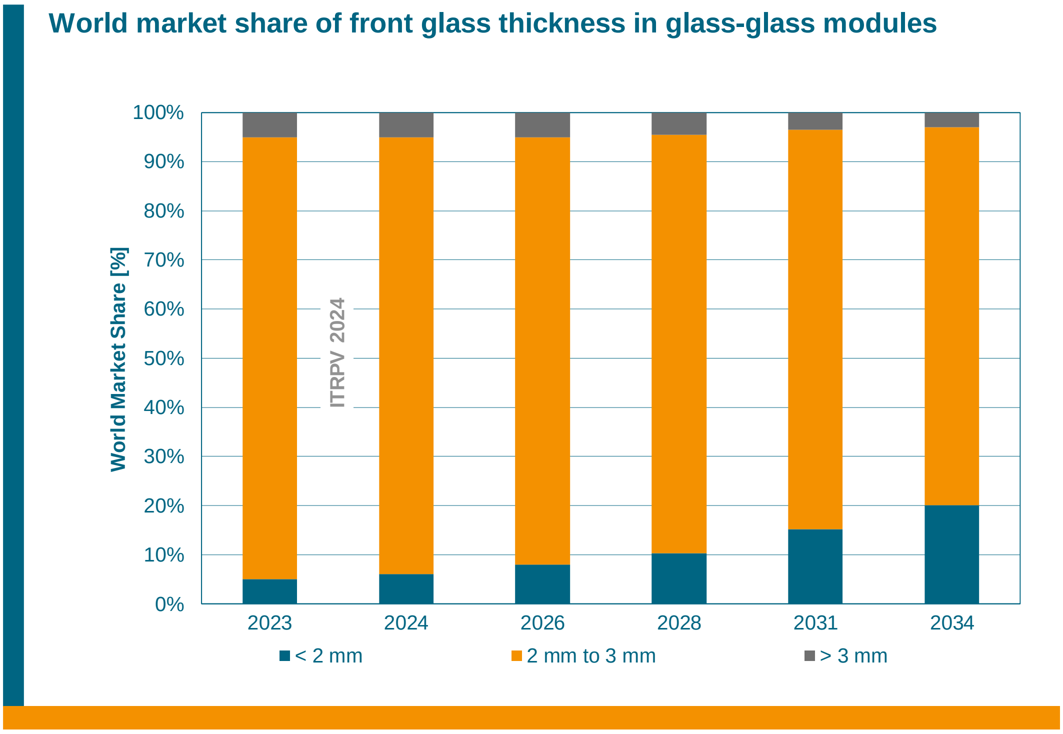


Fig. 42: Expected trend of front glass thickness in c-Si modules.

Fig. 42 and Fig. 43 summarize the trend of front side glass thickness for glass-glass and glass-foil modules respectively.

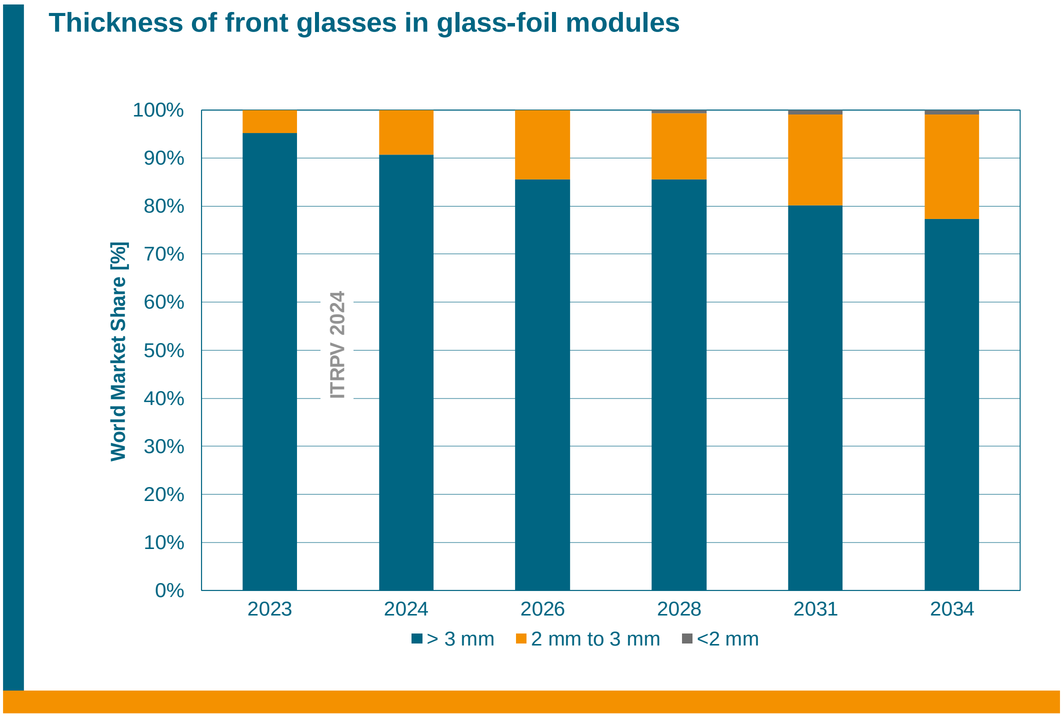


Fig. 43: Thickness of front glasses in glass-foil modules.

A thickness between 2 and 3 mm is mainstream 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 5% in 2024, and is expected increasing share over the next years reaching around 20% in 2034. 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.

Rolled/structured glass is mainly used in today's module manufacturing. The float glass market share of about 4% in 2023 will grow to about 10% within the next 10 years as shown in Fig. 44.

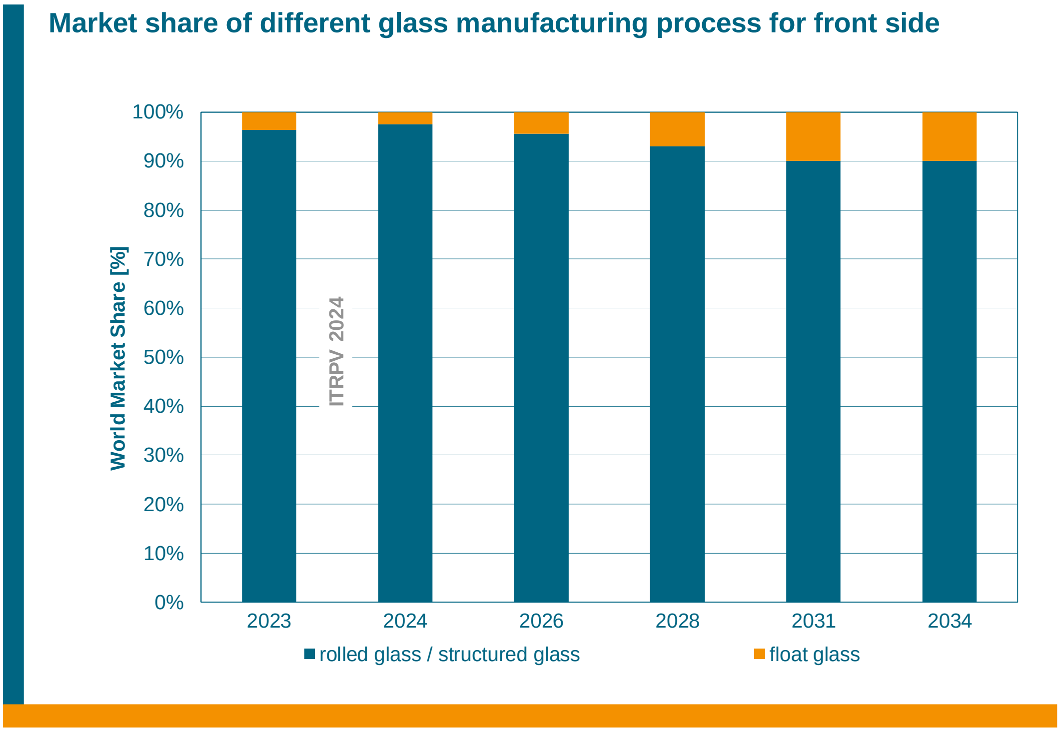


Fig. 44: Trend of front glass material market share.

Back side glass thickness is similar to front side glass, in some cases it is thinner. 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 around 25% in 2034; shown in Fig. 45.

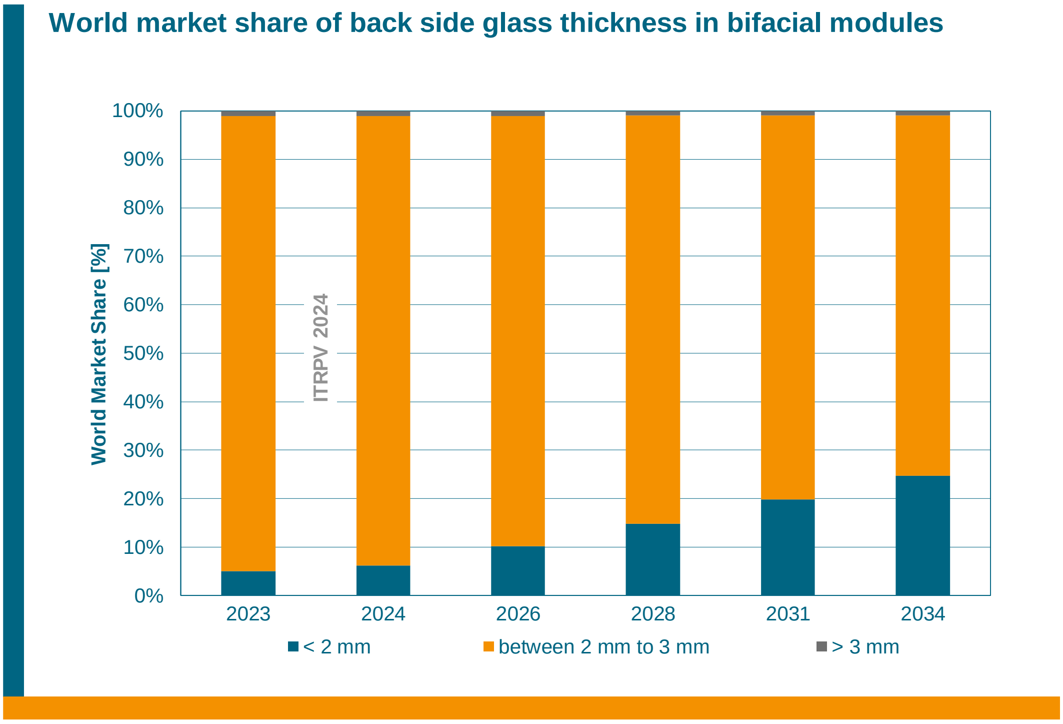


Fig. 45: Expected trend of back side glass thickness in bifacial modules.

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 30% in 2034, as shown in Fig. 46. Also some market share will be covered by relatively cost-effective architectural grade glass reaching around 4% in 2034, according to the analysis in this report's edition.

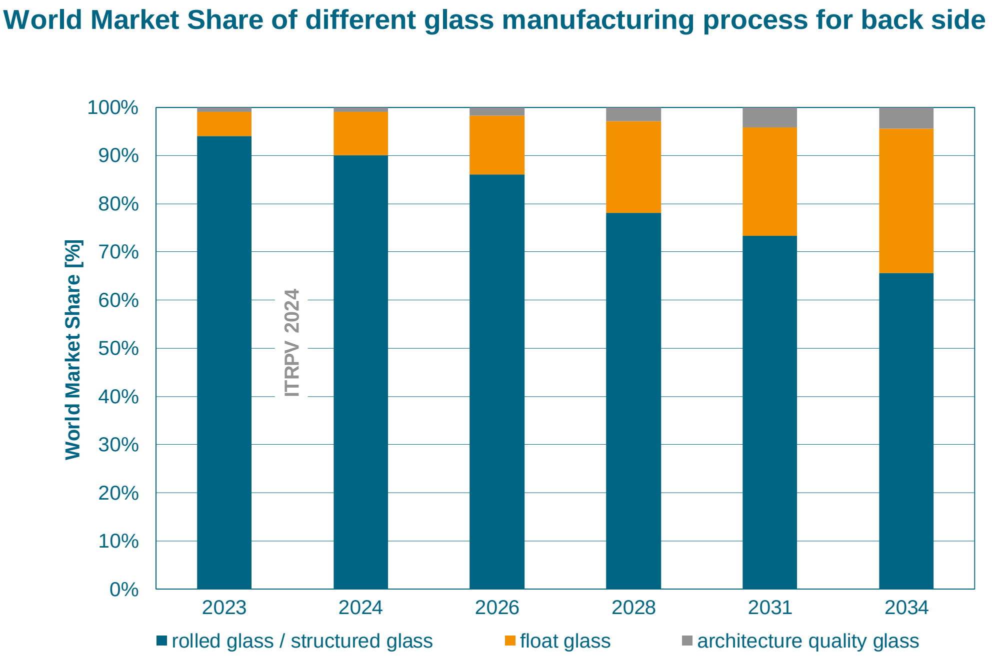


Fig. 46: Trend of back side glass market share.

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.

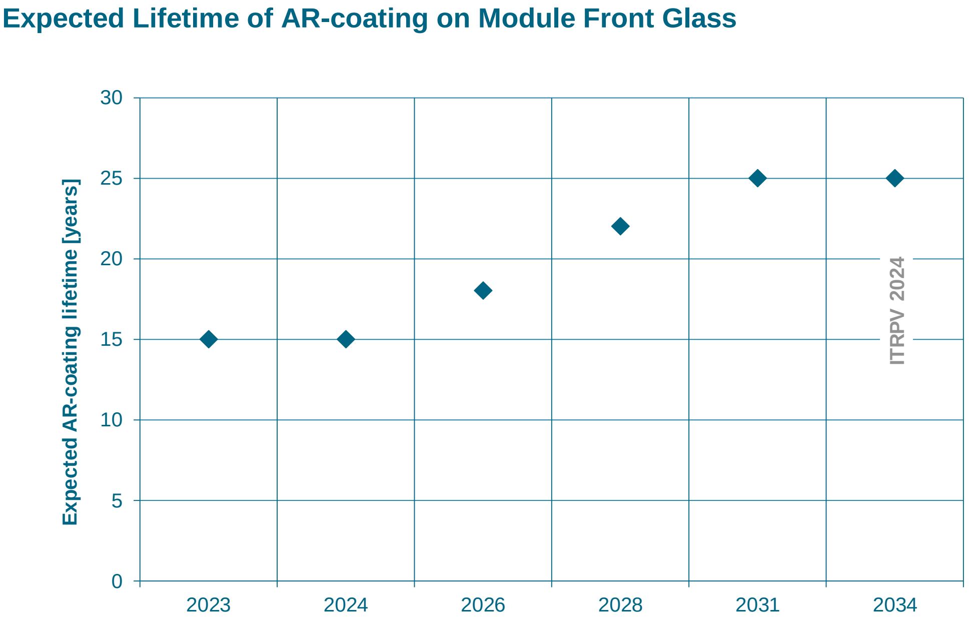


Fig. 47: Expected Lieftime of AR-coating on Module Front Glass.

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. 47 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 a stable 25 years already by 2031.

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 application and for SHJ cells and IBC cell concepts.

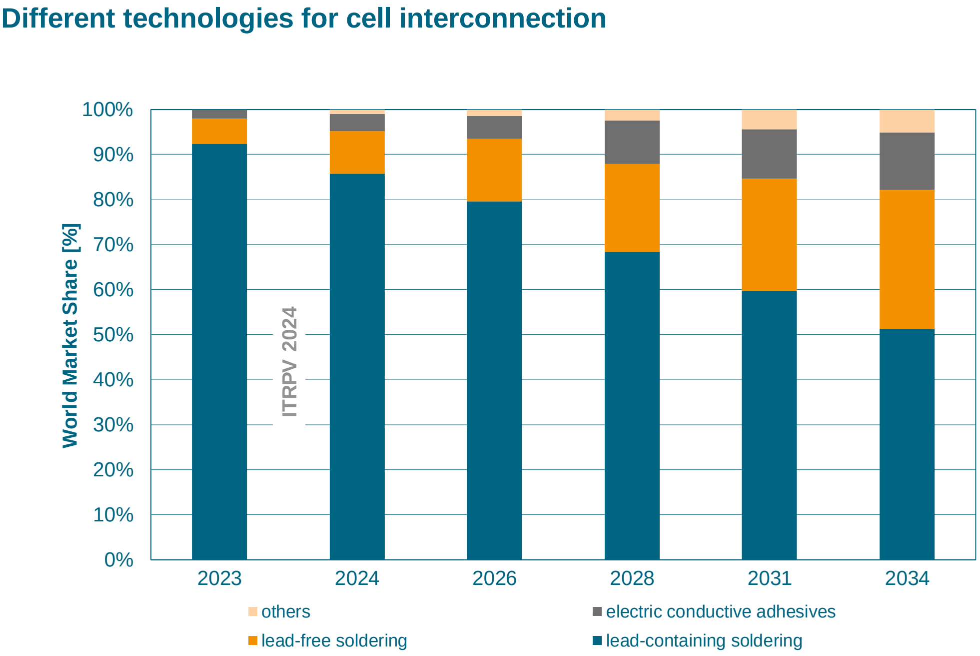


Fig. 48: Expected market share for different cell interconnection technologies.

Fig. 48 and Fig. 49 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 for cell interconnection are expected to gain market share from about 2% in 2023 to about 13% within the next 10 years, in 2034. Lead free soldering for cell interconnection, mainly driven by SHJ, is expected to gain market share from 6% in 2023 to 31% in 2034. 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 collected data. The trends for string interconnection technologies in Fig. 49 show similar tendencies with different market share values.

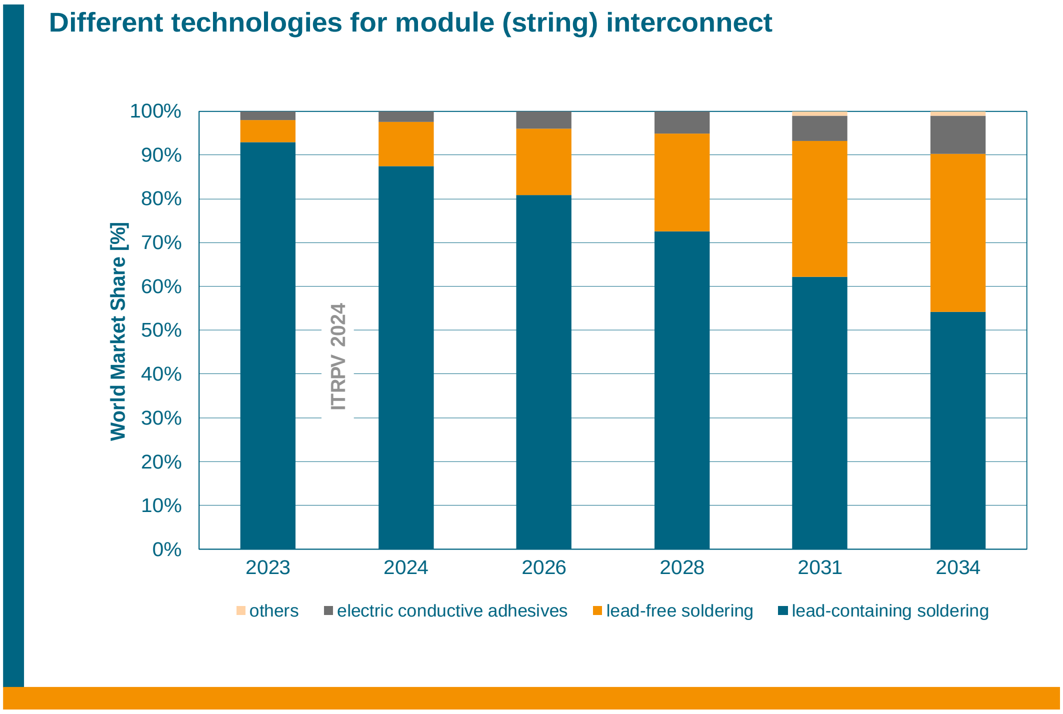


Fig. 49: Expected market share for different module interconnection technologies (i. e., for string interconnection).

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) [24]. 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 falls 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 at least until the ongoing review process of this directive is finished.[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.

Fig. 50 shows that copper wires, introduced some years ago for half-cell technology will stay the dominating cell interconnection material within the next 10 years, with around 90% market share. Copper ribbons will further lose market share from 10% in 2023 to less than 5% after 2026. Within the next 10 years, overlapping interconnection technologies and structured foils will gain market share to about 4% and 6% respectively.

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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 consultation and process has not been finished so far and all exclusions are still valid.

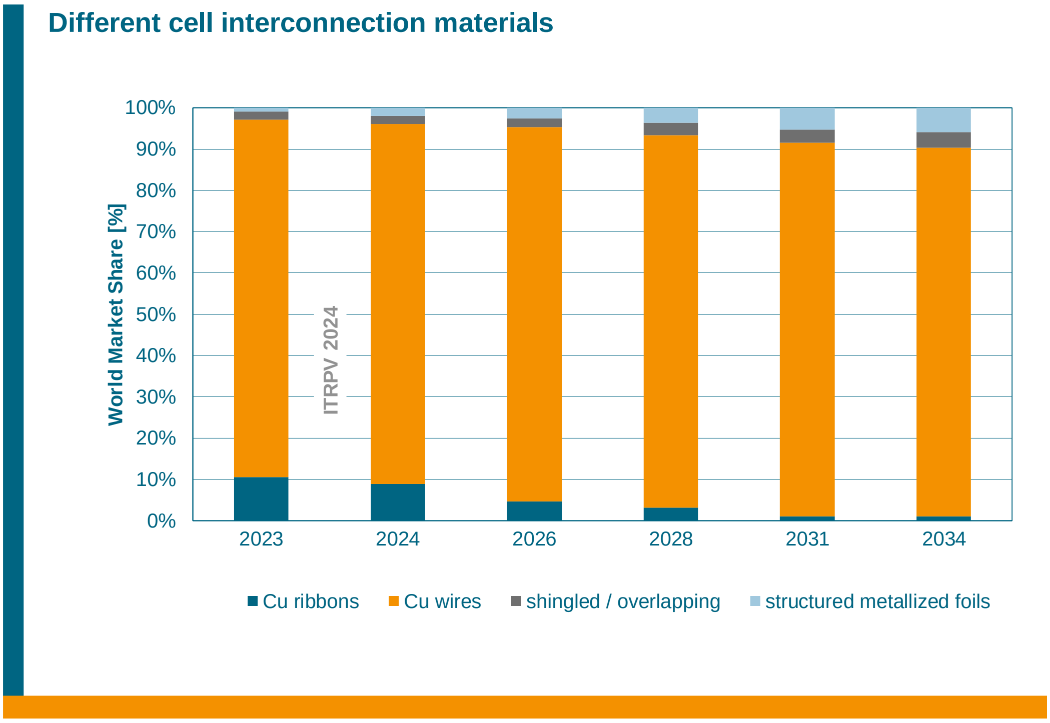

Fig. 50: Expected market shares for different cell interconnection materials.

The expected trend of the diameter of copper wires for cell interconnection is shown in Fig. 51. The standard in 2023 is 280 µm. The diameter will reduce to 200 µm until 2034.

It is important to note that the existing and upcoming interconnection technologies will need to be compatible with all cell formats and thickness as well as upcoming cell technologies. In this respect,

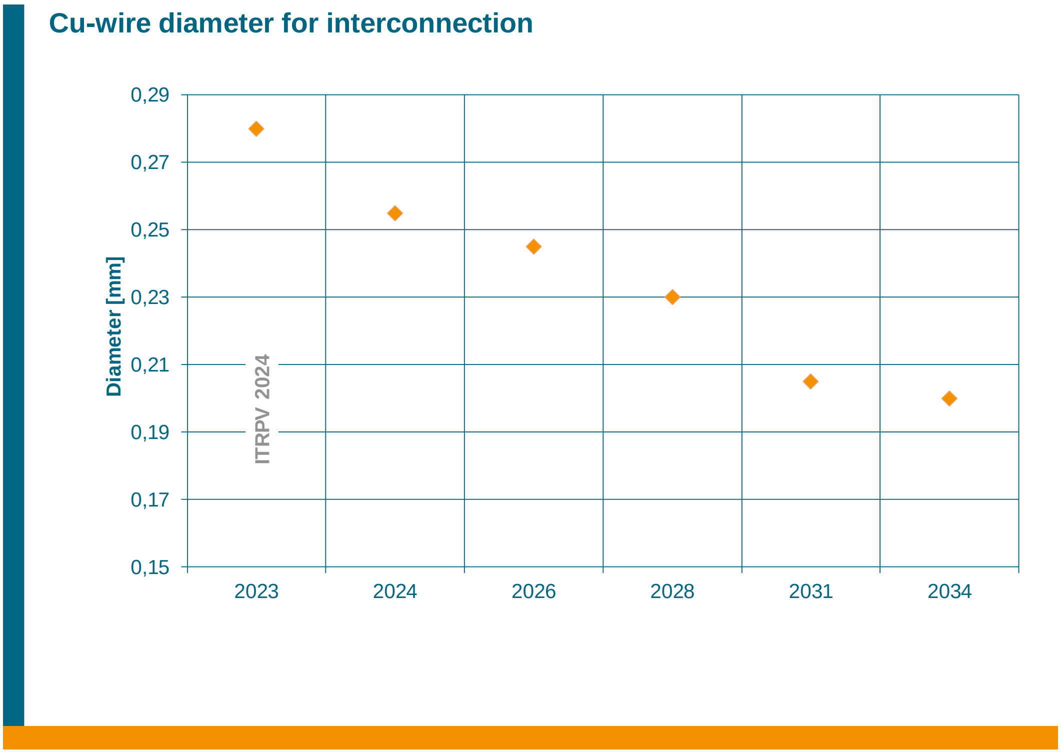

Fig. 51: Expected copper wire diameter for cell interconnection.

low-temperature approaches using conductive adhesives or wire-based connections have an inherent advantage due to the lower thermal stresses associated with them.

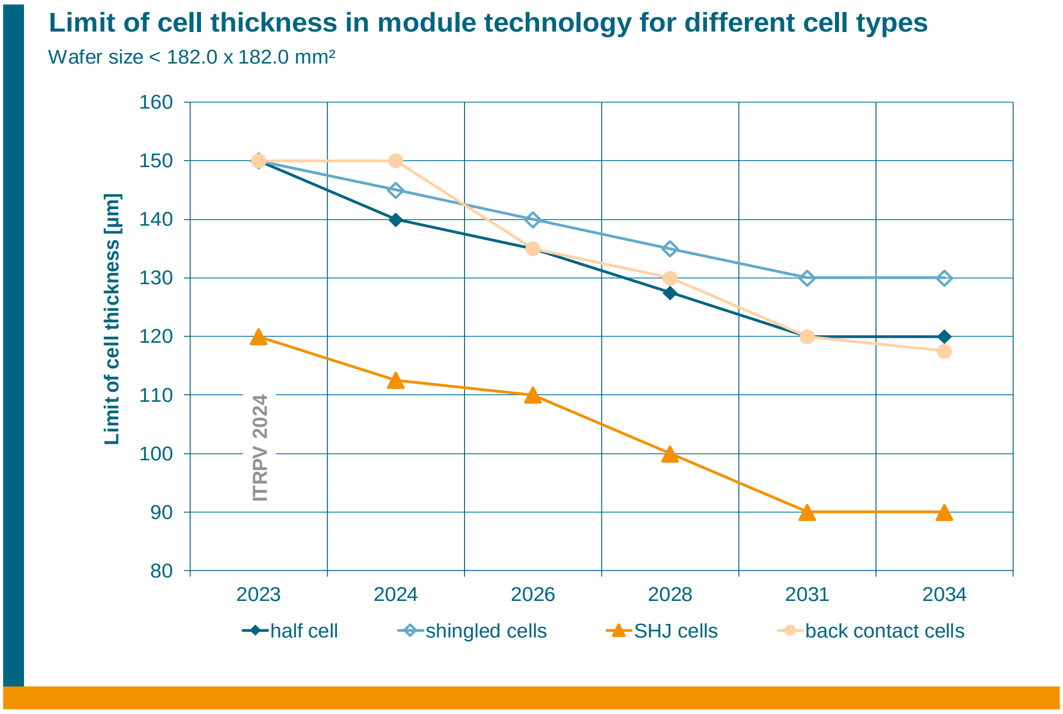

Fig. 52: Predicted trend of average cell thickness limit in different module technologies for wafer sizes < 182.0 x 182.0 mm^2.

In Fig. 52 and Fig. 53 we see how module technology will be capable of processing thinner cells for smaller than M10 and larger than or equal to M10 formats, discussed in chapter 5.3. Cell thickness reductions will not be limited by module technology. So, silicon material savings have to and will contribute to future Wp cost reductions.

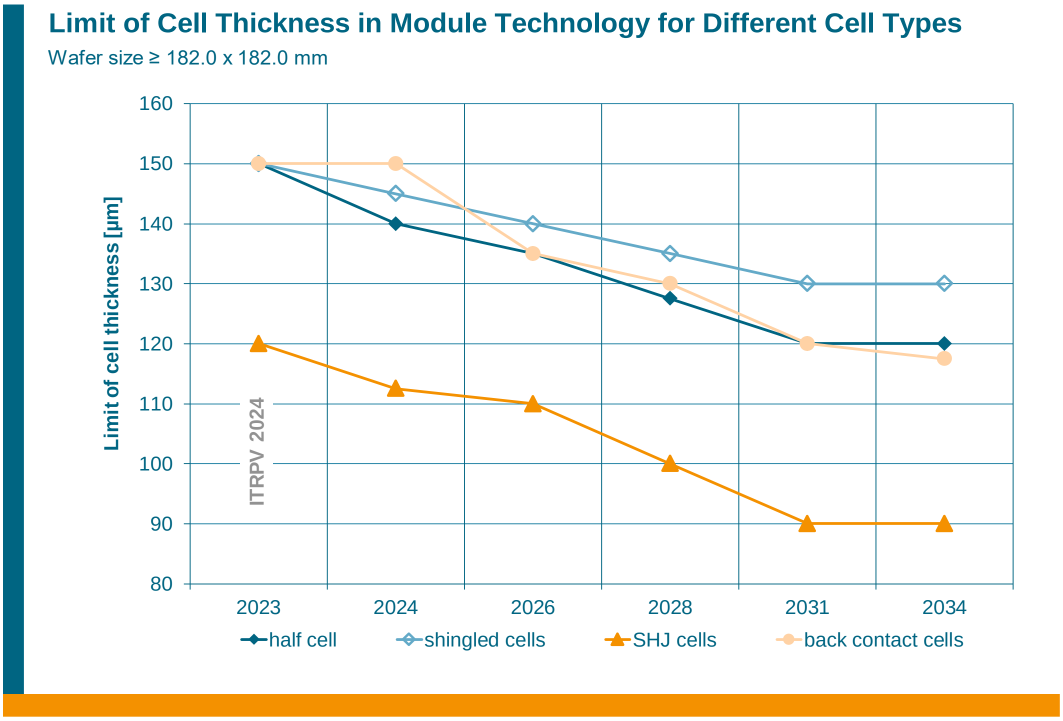

Fig. 53: Predicted trend of average cell thickness limit in different module technologies for wafer sizes > 182.0 x 182.0 mm^2.

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 this key components is mandatory to ensure the module service lifetime.

Fig. 54 shows that EVA, being mainstream in 2023 with about 69% market share, has 50% share in 2024 and is expected to follow a trend of market share loss.

Polyolefins (POE) are an upcoming alternative especially for bifacial products in glass-glass combination and for SHJ [25]. The results show a slightly increasing market share for POE or for EVA/POE mixture based encapsulants. Other materials are expected to keep low market share for niche applications.

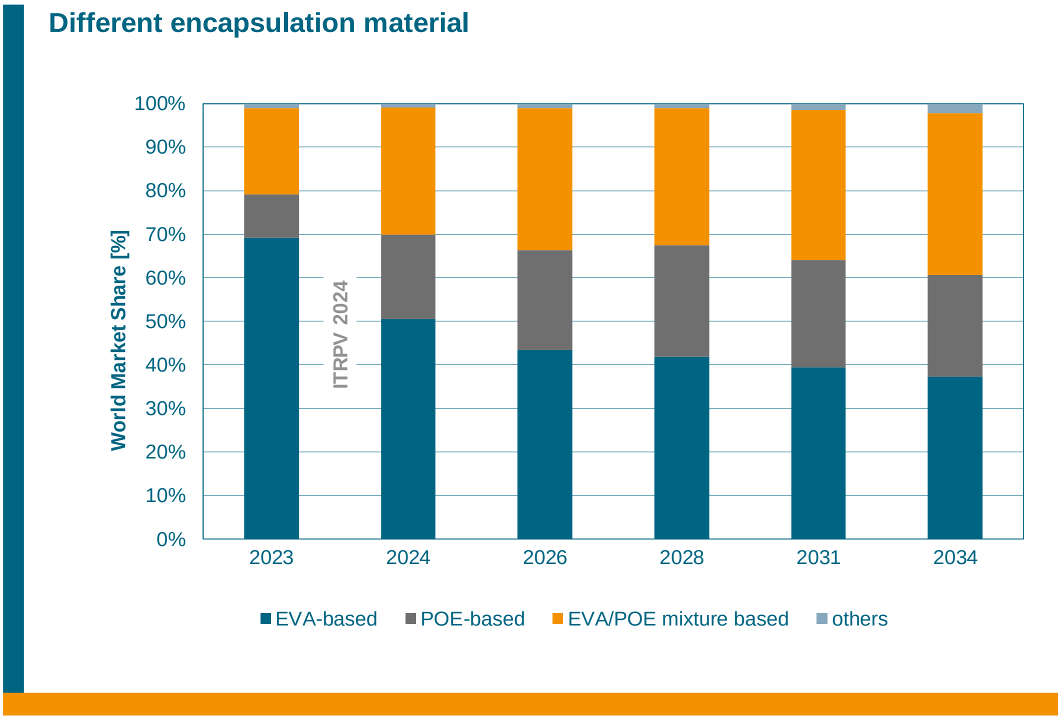

Fig. 54: Market share for different encapsulation materials.

Fig. 55 shows, that glass will become the dominant back cover material within the next years. Foils as back cover material will reduce their market share to about 23% within the next 10 years. Foil based front side covers will stay a niche. The thickness of the back glass will be reduced in the future to below 2 mm as shown in the previous results in Fig. 45.

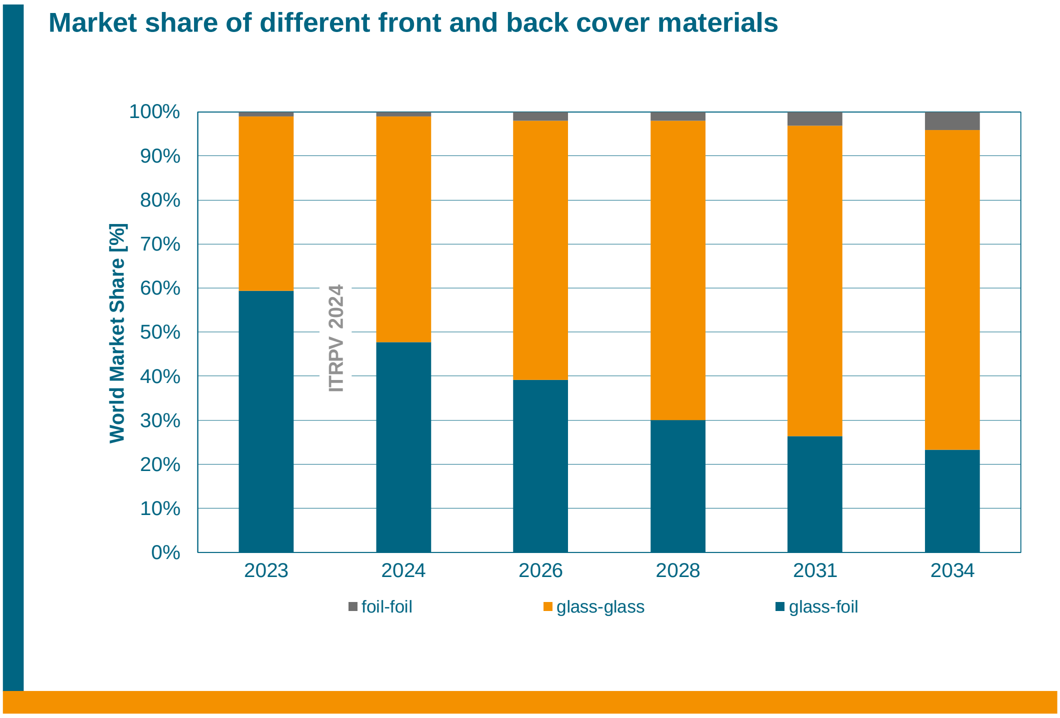

Fig. 55: Market share of glass and foil as front and back cover.

Fig. 56 looks at the trends for frame materials. Modules with aluminum frames are clearly dominating the market with around 91% in 2024, expected to still have a dominant market share of 80% in 2034. Frameless modules are expected to cover a stable market share ranging between 4% and 7% throughout the decade. Steel as frame material is expected to witness a gradual increase in its market share

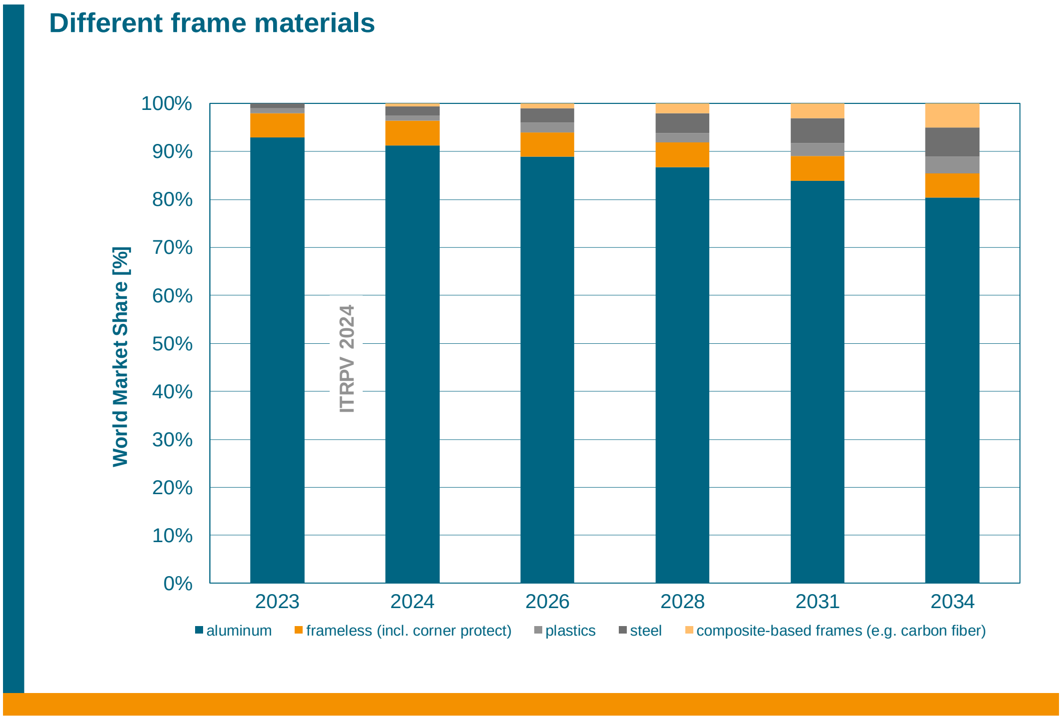

Fig. 56: Market shares for frame materials of c-Si modules.

to about 6% until 2034. Plastics and composite-based frames are considered as niche application with market shares of ≤ 2% together in 2024. Nevertheless, they are expected to have a gradual increase in market share throughout the decade, without losing dominance to aluminum as a standard product.

## 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 cells larger than or equal to M10 as shown in Fig. 57. Third and quarter cells will stay for niche applications in this cell format also with stable shares below 5% throughout the decade.

In general cells ≥ M10 use half cells whereas, full cells are not in use for large wafers. Third and quarter cells will be deployed, especially for G12.

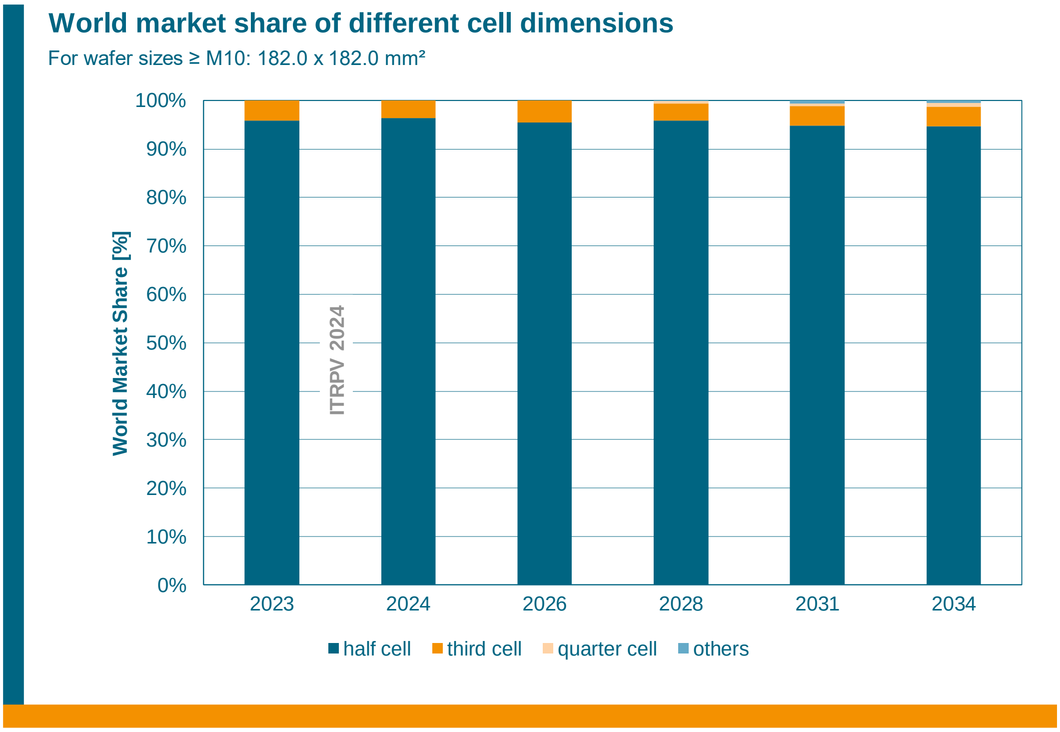

Fig. 57: Market shares of modules deploying half, third, and quarter cells ≥ M10.

Fig. 58 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.

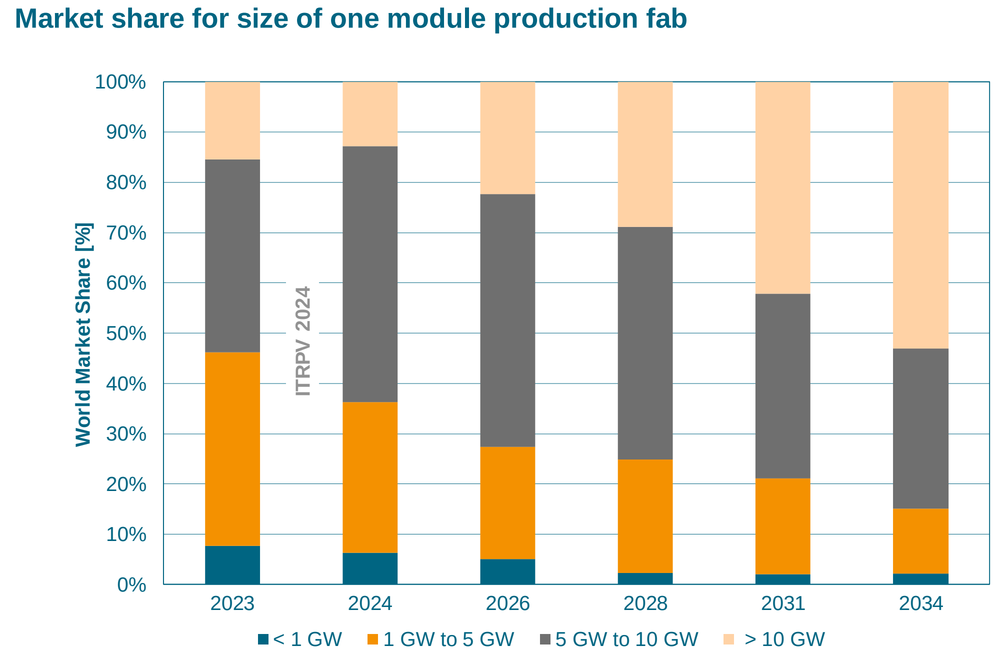

Fig. 58: Market share for nameplate capacity size of one module production fab.

## 6.3. Products

Due to the current diversification in wafer formats discussed in chapter 4.3., also module dimensions are changing leading to various dimensions. This has changed in the last years, where standard module sizes dominated, and a comparison of module powers was appropriate. Therefore, comparing different module types only by the so far common module label power may be misleading as module powers with impressive ≥ 700 Wp are possible with existing cell technologies [5, 26]. Therefore, the 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. 59 shows the expected trend of average module efficiency for modules in mass production with different cell technologies.

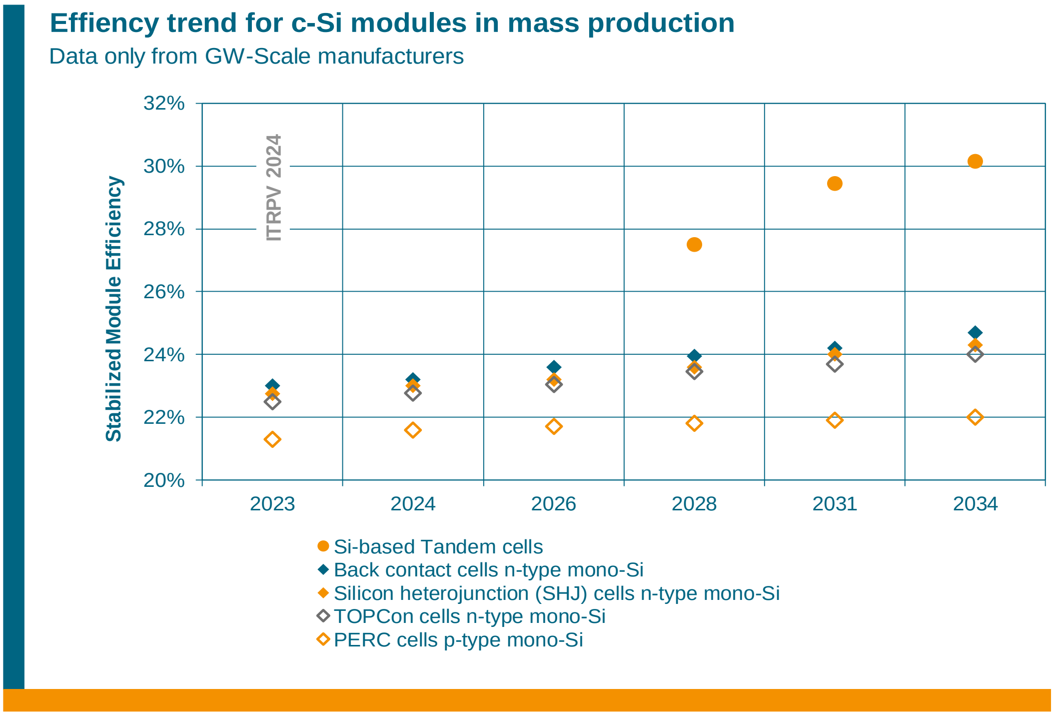

Fig. 59: Average module area efficiency in mass production for different c-Si solar cell technologies (Only data from GW-scale manufacturers).

Current PERC p-type mono-Si modules are expected to show average efficiencies of 21.6% in 2024 and up to 22% within the next 10 years. It is not expected that p-type PERC developments go further than the 22% module level average in mass production. Modules with n-type cells with tunnel oxide passivation technologies, are expected to be ahead of p-type PERC with 22.8% in 2024 and with up to 24% in 10 years. SHJ modules reach in 2024 an efficiency of 23% and are expected to attain 24.3% in 2034. Back-contact cells on n-type are expected to show again the highest module efficiencies of around 23.2% in 2024 and eventually around 24.7% in 2034. 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 27% in 2028 and with close to 30% in 2034, respectively. That would clearly exceed the practical limit of silicon. Tandem technologies with perovskite are a high focus point in research and development, nevertheless the developments will have to be monitored. Perovskite-perovskite tandems seem to be a more challenging product that will only be possible after the establishment of silicon-perovskite tandem. This is based on the surveying performed throughout the preparation of the report.

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. 60 shows the trend of module size for residential applications – an average module size above 2.0 m² will have a higher market share in 2024 and the upcoming years. The sizes between 1.8 and 2.0 $m^2$ will remain with the highest share. For modules that are smaller than 1.8 m² a stable share throughout the decade without exceeding 6% market share is projected.

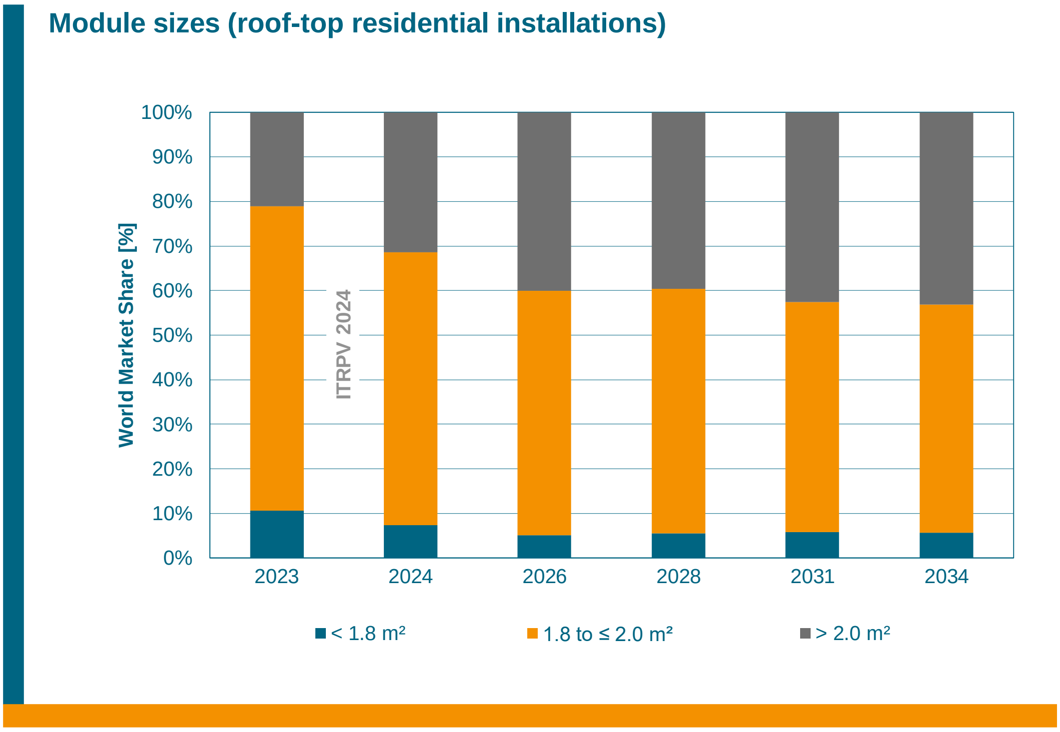

Fig. 60: Trend of module sizes for roof-top residential applications.

The module size development for large-scale ground mounded installations (i.e, power plant) is visualized in Fig. 61. The trend to larger modules is significant in this field in comparison to roof-top residential applications. Module sizes smaller than 2.5 $m^2$ are expected to lose market share, while 2.5 – 3.0 m² will be dominating the power plant market and larger modules >3 m² are expected to grow to about 31% in 10 years.

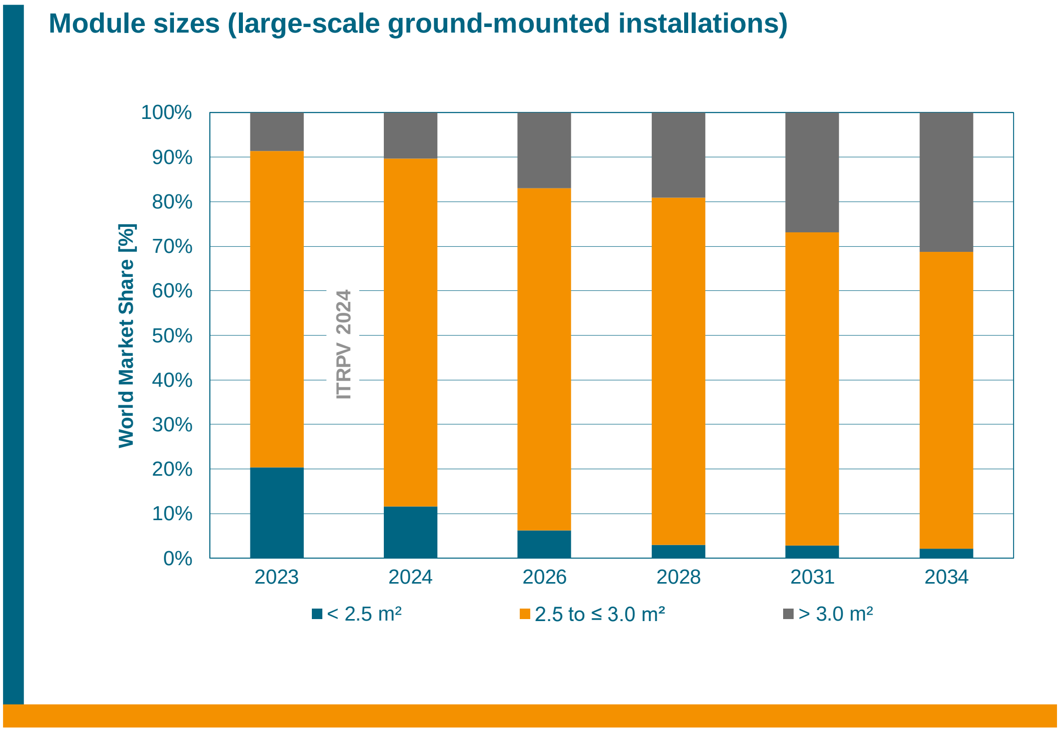

Fig. 61: Trend of module size for large-scale ground-mounted applications.

Larger modules will be heavier. Fig. 62 and Fig. 63 show the expected trend of the module weight for residential and for power plant installations, respectively. 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.

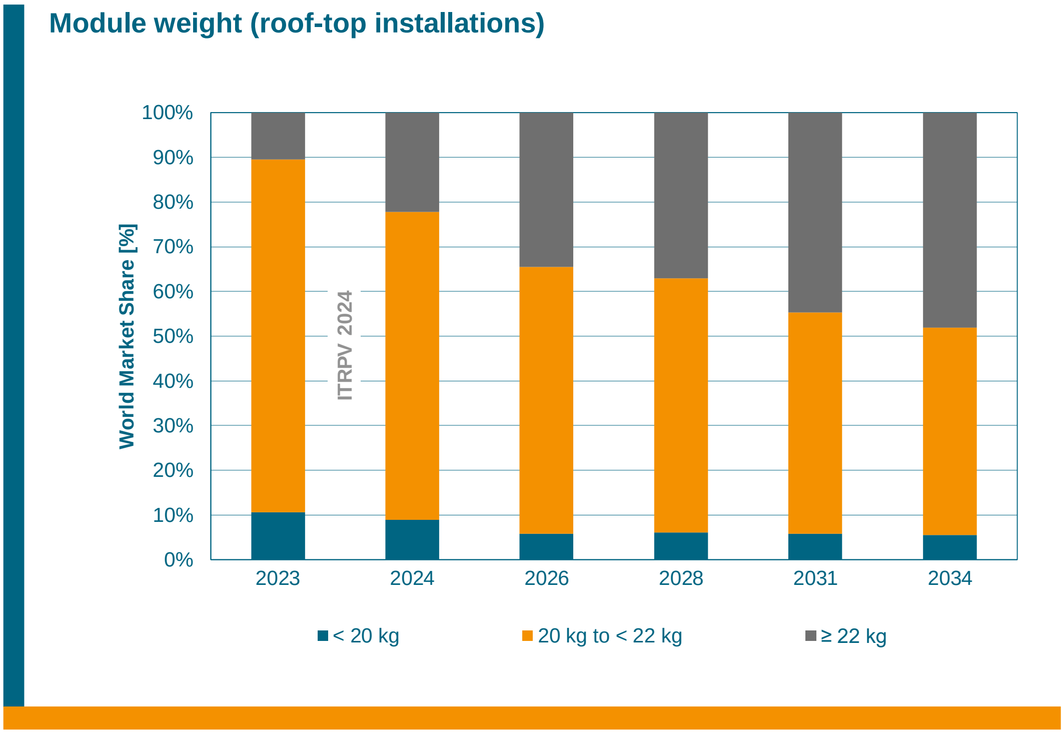

Fig. 62: Market share for the weight of modules for rooftop applications.

## Module weight (large-scale ground-mounted installations)

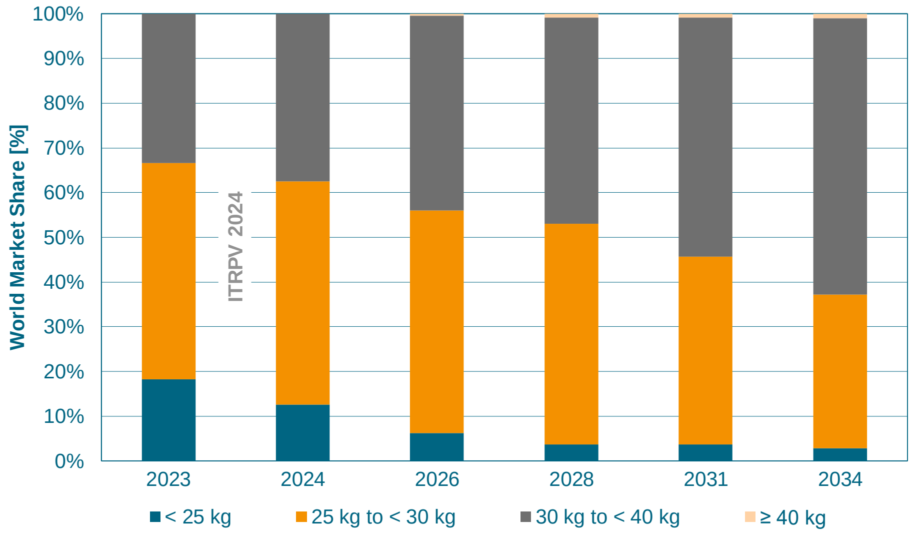

Fig. 63: Market share for the weight of modules for large-scale ground-mounted applications.

Today, almost 50% of modules were monofacial modules in 2023. In 2024, the bifacial modules are dominant with about 63% as shown in Fig. 64. The share of bifacial modules will further grow to about 73% in 2034. Bifacial cells can be used in bifacial modules as well as in conventional, monofacial modules.

## World Market Share of monofacial and bifacial modules

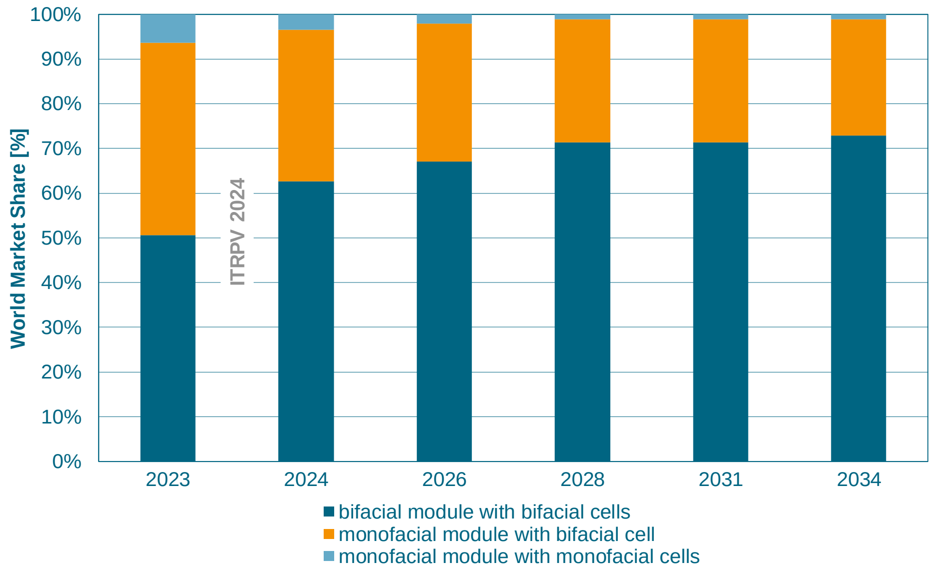

Fig. 64: Market share of bifacial modules.

Bifacial cells are dominating the market as discussed in chapter 5.3, Fig. 40. 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.

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. 65 shows the bifaciality factors of modules with different cell technologies. We see, that SHJ modules have the highest bifaciality factor that is expected to improve to up to 92%. The bifaciality factor of standard PERC cells is expected to improve to a maximum of 73% within the next 10 years. TOPCon cells show a bifaciality in between that of SHJ and PERC, expected to improve to up to 85%.

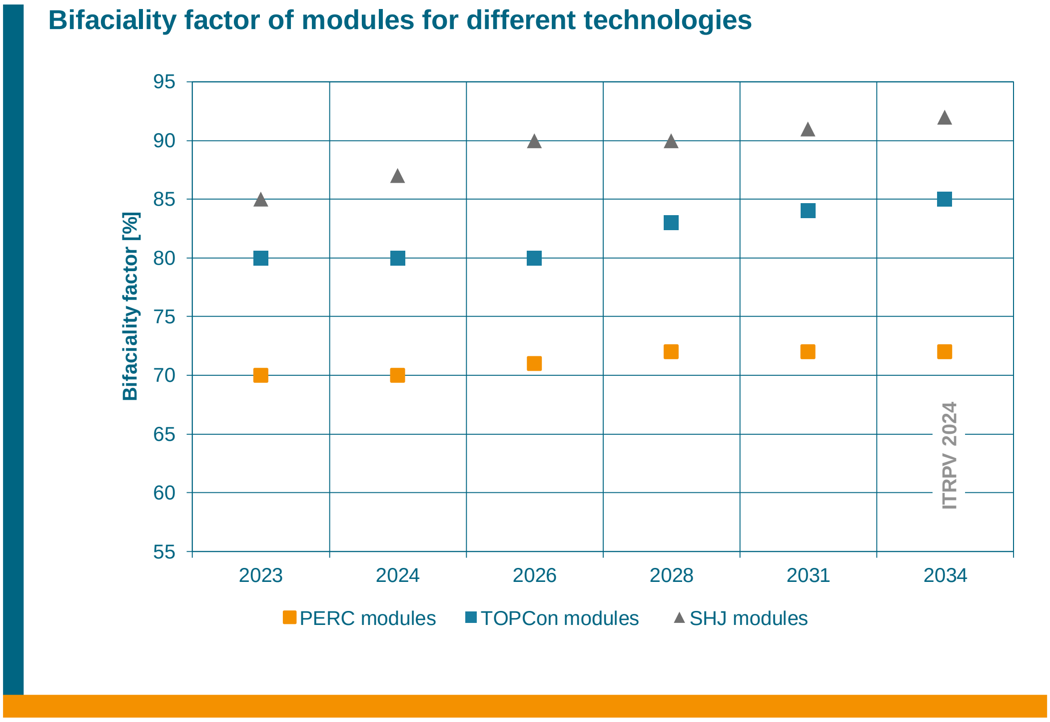

Fig. 65: Trend of bifaciality factor for modules with different cell technologies.

Another trend in module technology is the development of modules for special markets and environmental conditions. Fig. 66 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, or floating will together account for up to 19% over the next 10 years.

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.

Fig. 66: Market share for special regional applications.

The trend for J-box with special internal functions is shown in Fig. 67. 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.

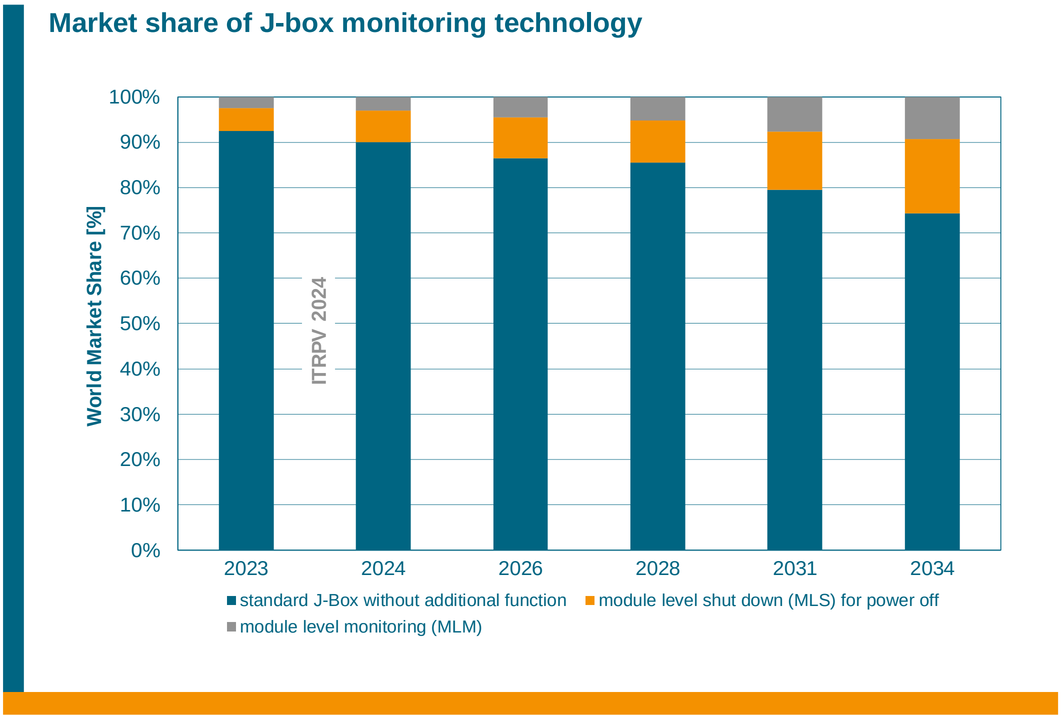

Fig. 67: Junction box monitoring technology.

Fig. 68 shows the market share of microinverter based technologies, showing the clear dominance of frame and rack mounted microinverters rather than module integrated ones.

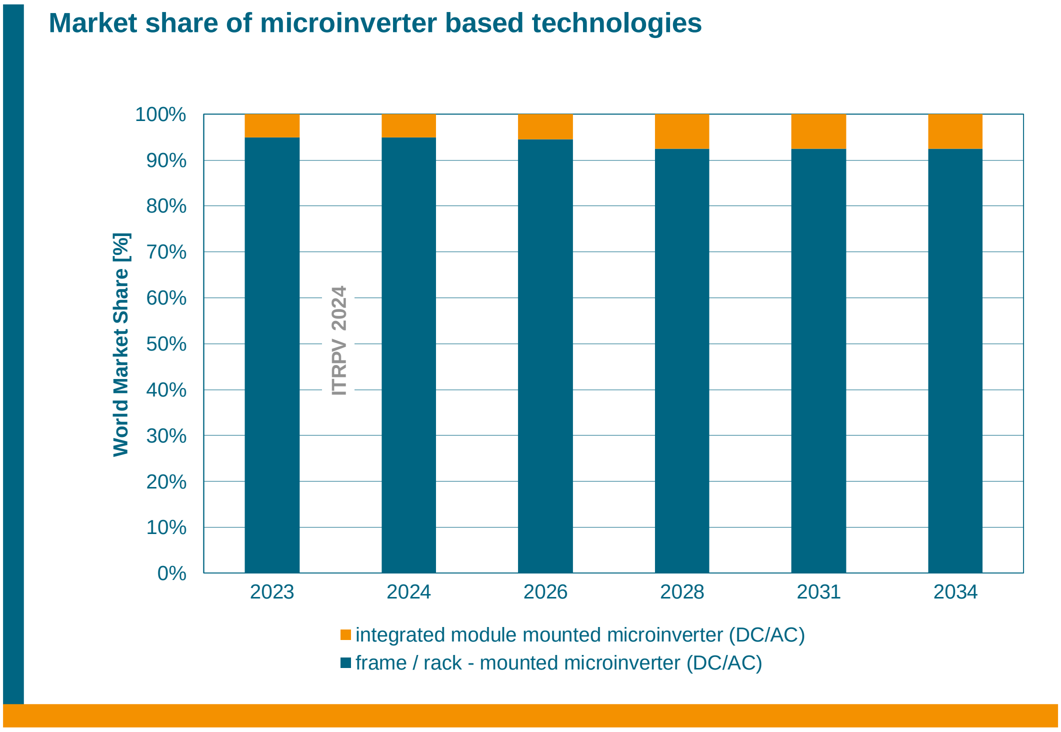

Fig. 68: Market share of microinverter based technologies.

Fig. 69 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 15% in 10 years.

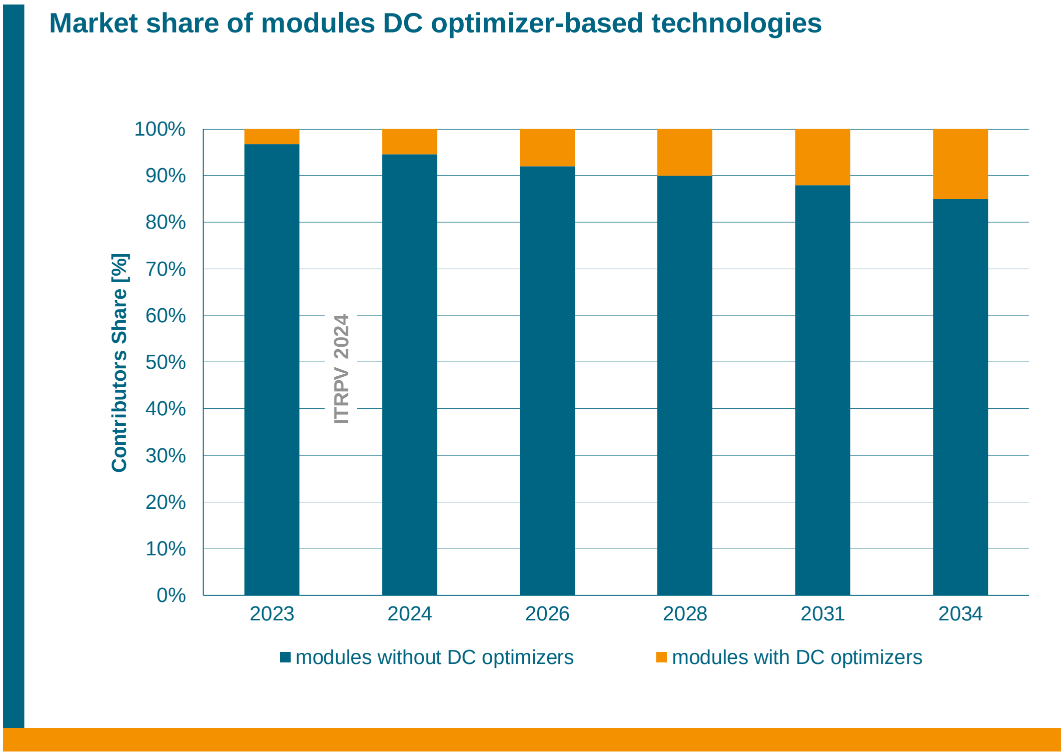

Fig. 69: Market share of modules DC optimizer-based technologies.

Fig. 70 shows the trend of module product and module performance warranty for the next years. The product warranty is expected to increase from 15 to 17 years. Performance warranty is expected to increase to 30 years from today's 25 years.

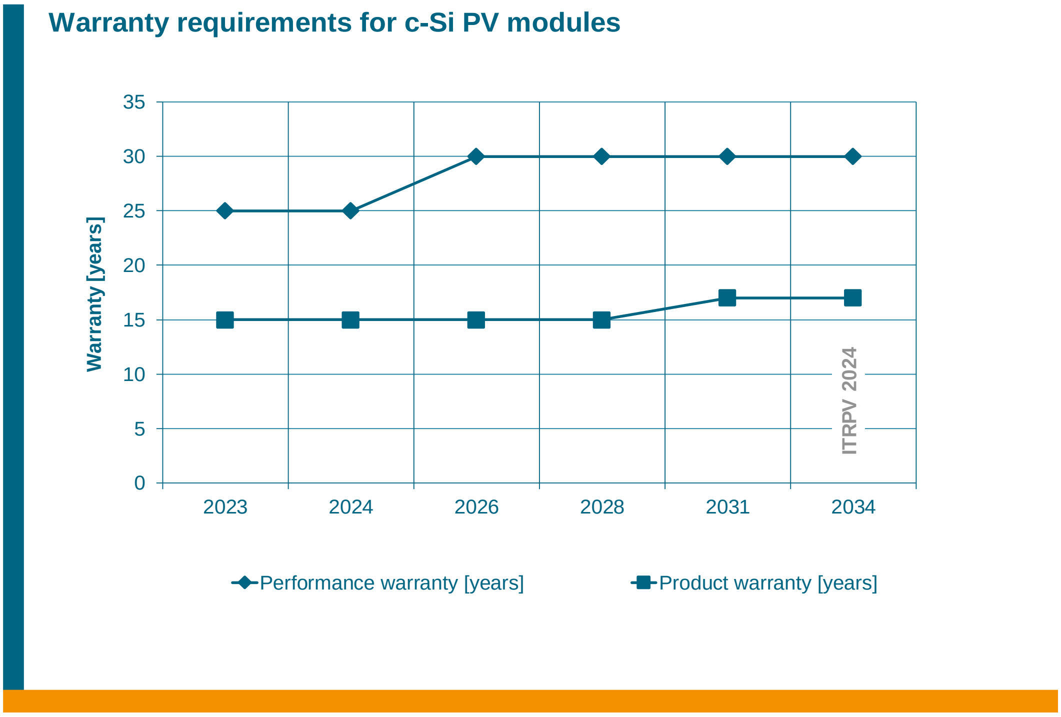

Fig. 70: Expected trend for product warranty and degradation of c-Si modules.

Fig. 71 shows the degradation behavior after the 1st year of operation that will be reduced from 2% to 1% in 2026. Annual degradation is expected to be reduced slightly from 0.45% continuously to below 0.4% within the next 10 years.

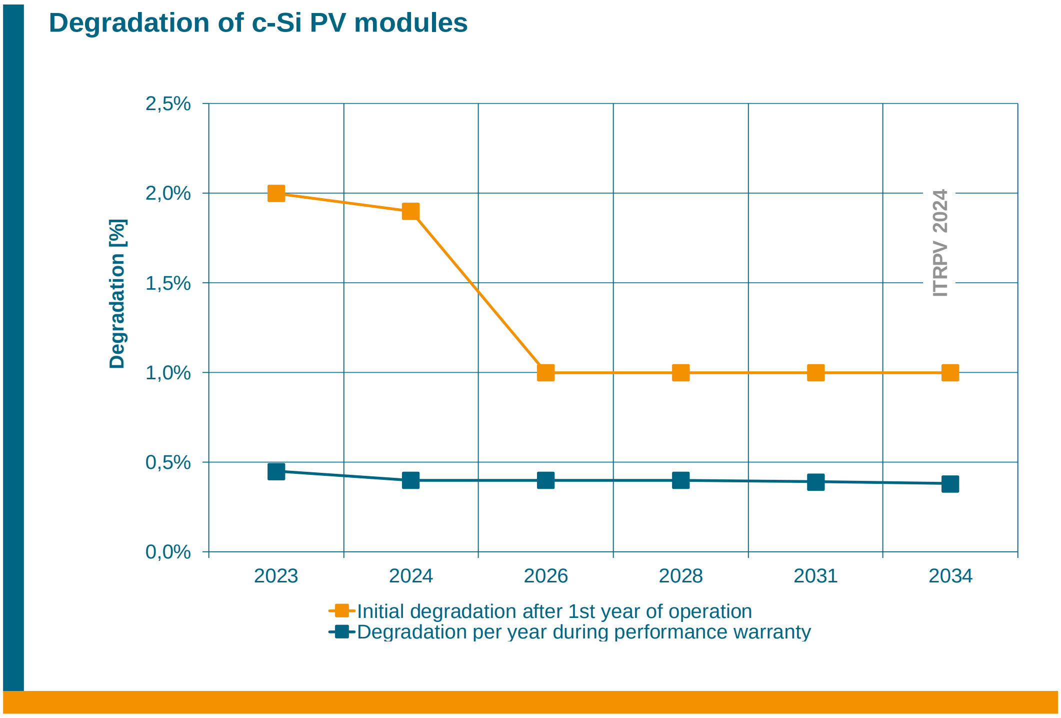

Fig. 71: Degradation of c-Si PV modules.

The control of light induced degradation (LID) and of the light and elevated temperature induced degradation (LeTID) enabled these warranties. Understanding the degradation mechanisms and a tight control of the degradation were the basis [13, 27]. The implementation of gallium doped wafers for p-type PERC and n-type material solves the LID concern. The availability of a standard for LeTID testing [28] is supporting this trend too.

To maintain quality (for thinner cells as well), the solar cells used for module assembly should be free of micro-cracks. The contributors consider Potential Induced Degradation (PID)-resistant cell and module concepts also as market standard.

# 7. Results of 2023 | System

## 7.1. Components

An important parameter is the degradation rate of the whole PV system. Fig. 72 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. 73 shows the expected trend for the technical lifetimes for the main electrical components of PV system.

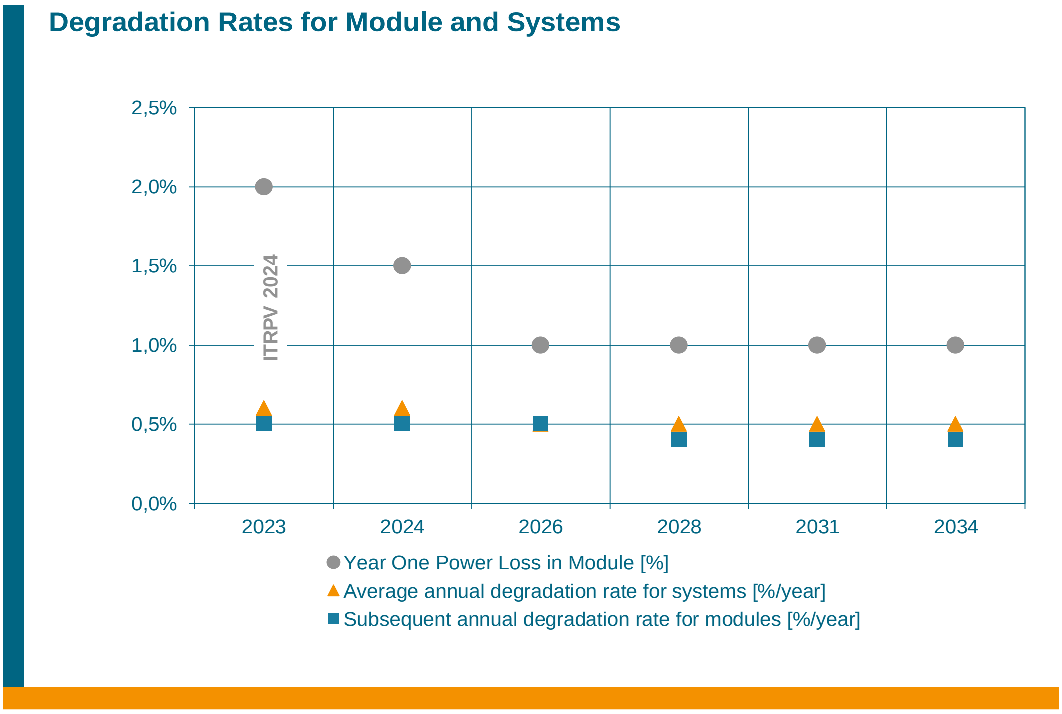

Fig. 72: Trend of modules and PV system degradation.

Technical lifetime of modules is expected to be on average above the performance warranty shown in Fig. 70. Up to 40 years technical lifetime is expected for modules. Batteries are expected to witness an improvement of the technical lifetime from 10 years to 15 years already by 2031. Based on this year's results, inverters technical lifetime is expected to remain 15 years.

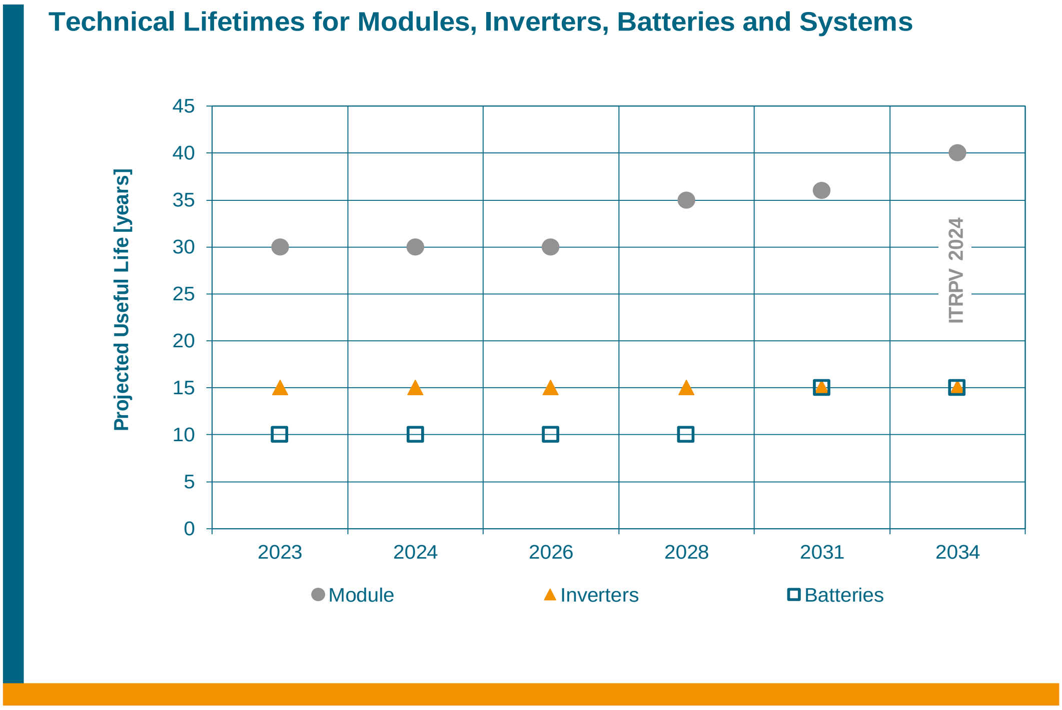

Fig. 73: Trend of technical lifetime of PV System electrical components.

Fig. 74 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 41% market share in 2024. The 2-axis system will remain a niche throughout the decade, based on the results we have obtained.

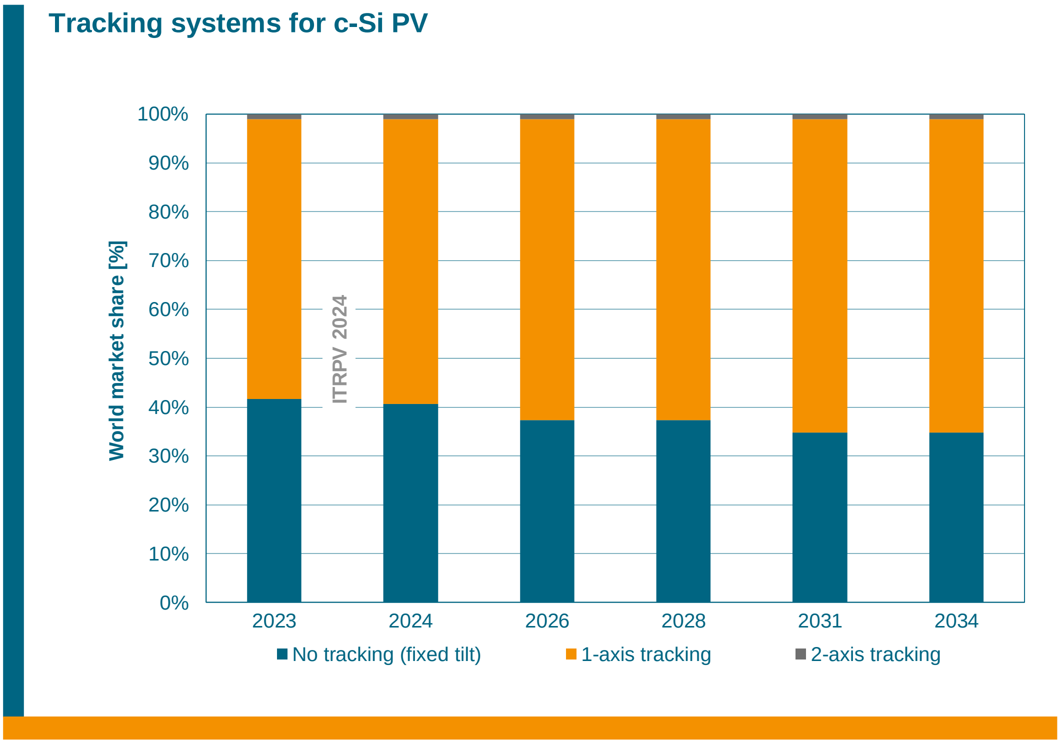

Fig. 74: Market share of tracking systems for PV power plant installations.

The market share of different end-use systems is visualized in Fig. 75. Roof top systems are expected to stay stable at about 25 - 30% within the next 10 years.

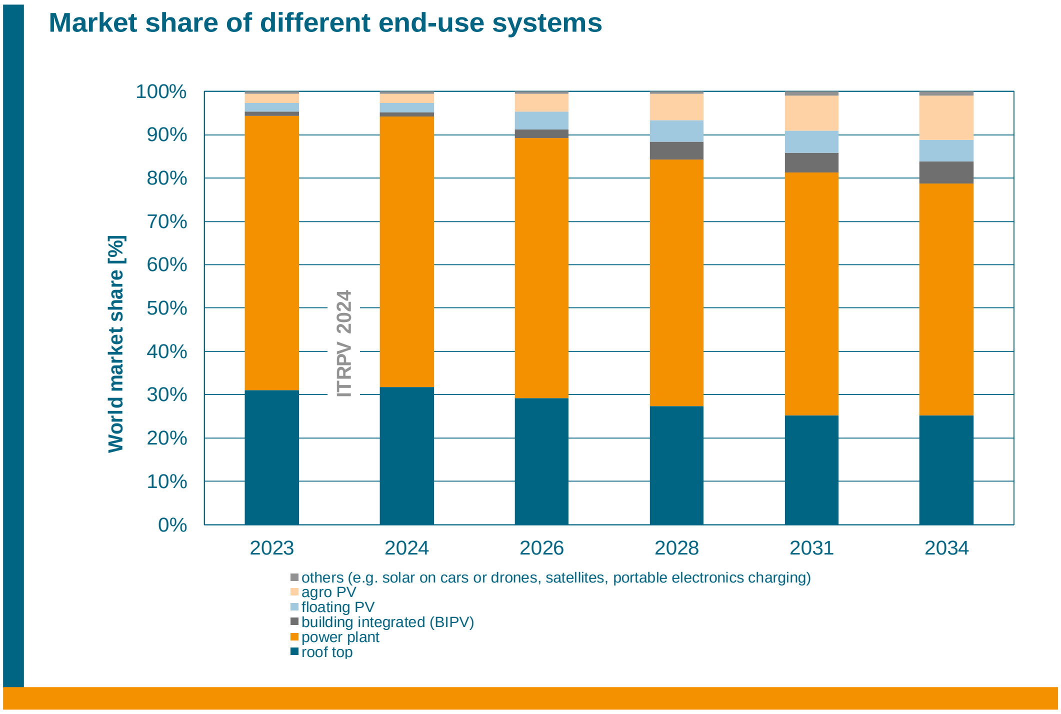

Fig. 75: Market share of different PV enduse systems.

Building integrated PV systems as well as agro PV, and floating PV are expected to gain market share while “classical” PV power plants will stay dominant at around 53% market share. The share of PV installations expected to be combined with storage systems will increase.

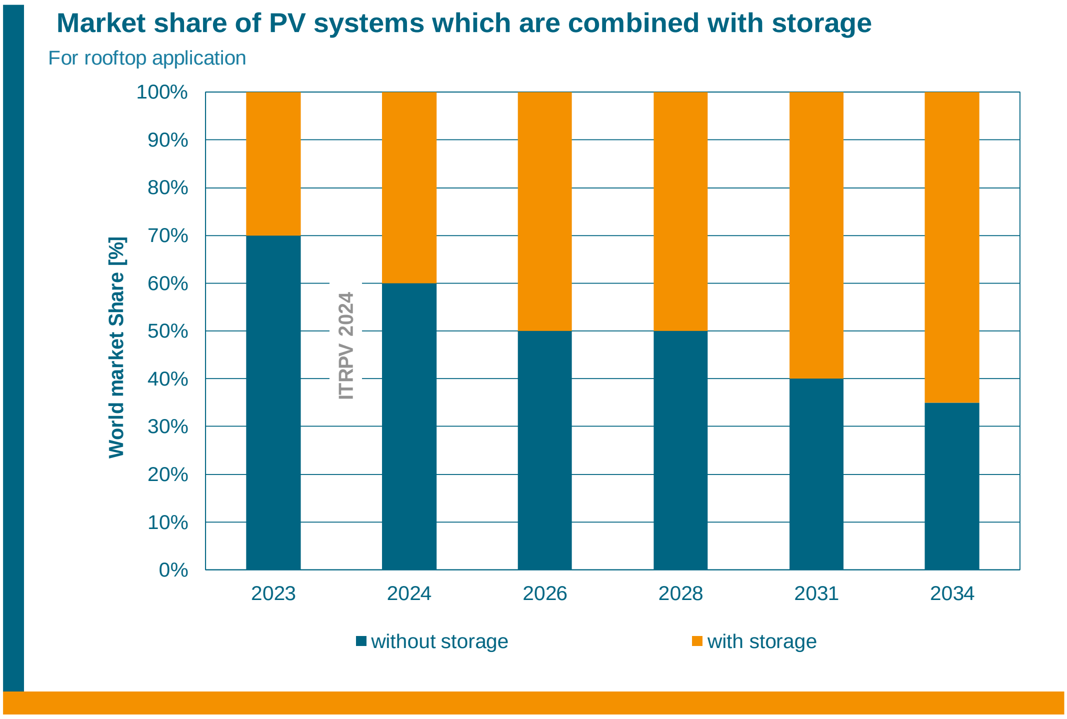

Fig. 76: Market trend of rooftop PV systems with storage.

Fig. 76 and Fig. 77 show the market share for the different market fields of rooftop applications, commercial & small industrial (C&I) applications. Such a trend is also expected for power plant installations too.

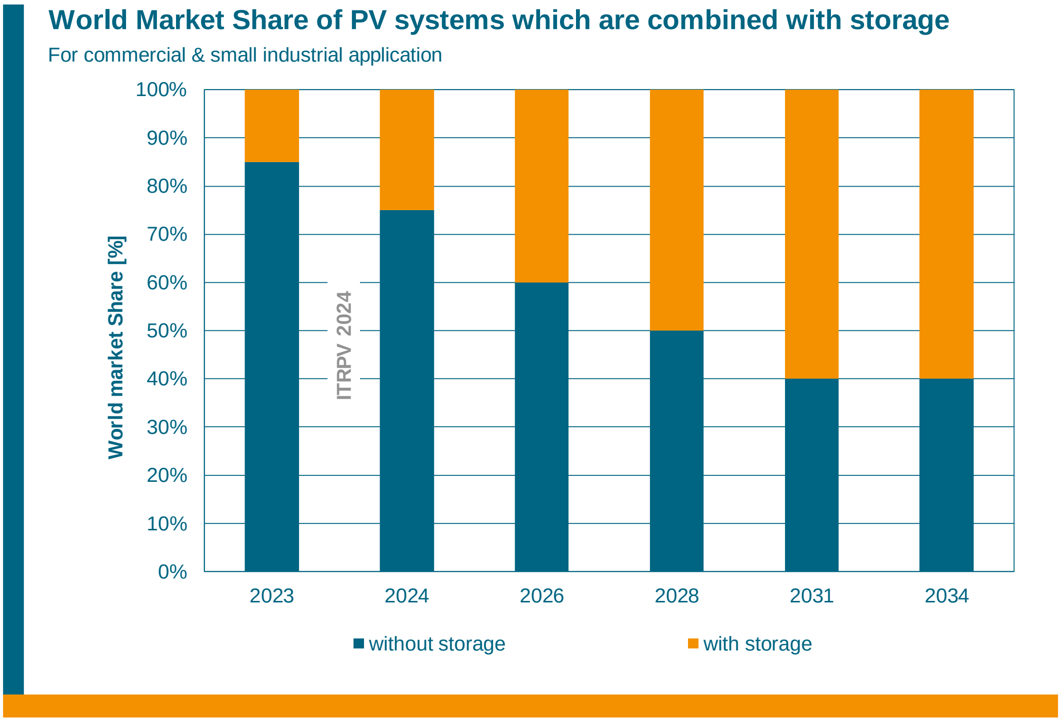

Fig. 77: Market trend for C&I PV installations with storage.

For systems larger than or equal to 10 MW, string inverters reach around 62% market share, in comparison to central inverters covering the rest of the market. This will remain in a similar range throughout the decade, as seen in Fig. 78.

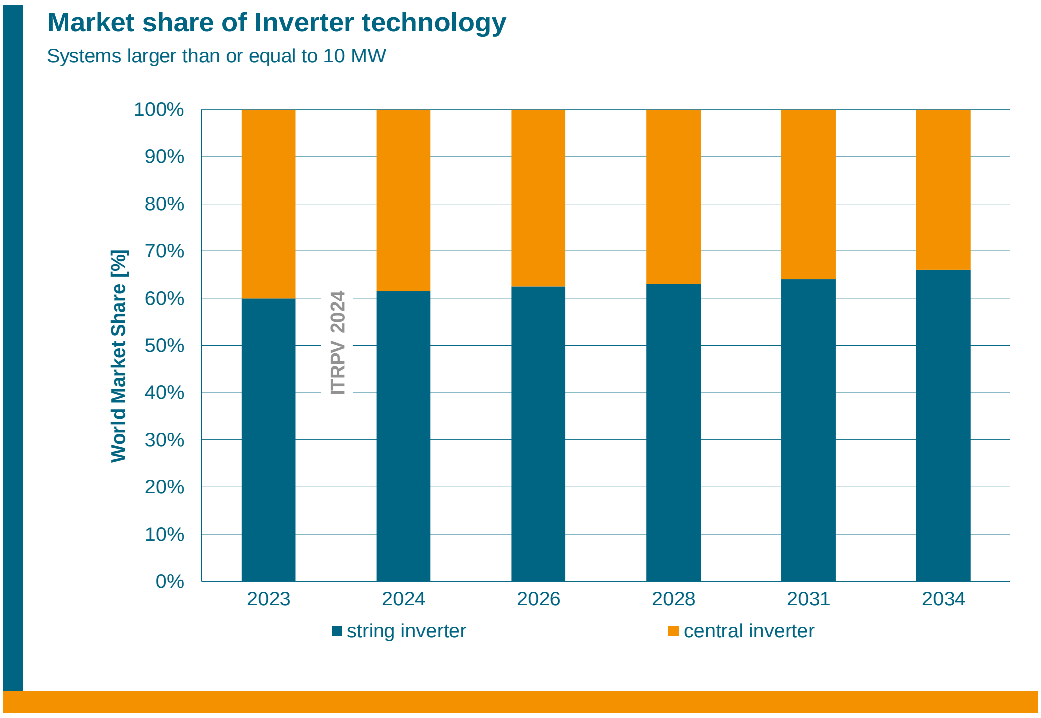

Fig. 78: Market share of Inverter technology for Systems larger than or equal to 10 MW.

## 7.2. LCoE Calculation Section

The Levelized Cost of Electricity (LCoE) is a commonly recognized economic metric for comparing the relative costs of different renewable and non-renewable electricity generation technologies. Along with the system capital cost and the solar insolation level, LCoE is also dependent upon operations and maintenance (O&M) expenses, the project financing structure, the expected rates of return for debt and equity stakeholders, national and local incentives, and the degradation and usable service life of the system. We have used the system capital costs results collected in the 2024 ITRPV and NREL's free and publicly available System Advisor Model (SAM) discounted cash flow structure[3] to calculate 2024 benchmark and future scenarios of PV LCOE for large PV systems under different insolation conditions, see Fig. 79 [29, 30, 31].

Using the worldwide median capital costs collected in the 2024 ITRPV survey, nominal LCoE values between 2.9 and 7.3 cents per kWh-ac are calculated across the range of solar insolation levels. Using the system capital trends from this year's ITRPV survey, nominal and unsubsidized LCoE is projected to be between 2.3 to 5.7 U.S. cents per kWh-ac in the year 2033 from the high (2,500 kWh-ac/kW-dc) to low (1,000 kWh-ac/kW-dc) insolation conditions. Improvements in product reliability and lifetime energy yield could be achieved lower degradation rates and longer service lifetimes than the 25 years we have assumed to be typical for today. These improvements would lower LCoE by lowering operations and maintenance (O&M) expenses and lower risk and financing rates for system owners. Further advances in module and BOS technologies, increased system voltages, better power electronics, and more robust national and local incentives, are also all potential opportunities to further reduce system LCoE and to help PV become even more costs-competitive on a complete lifecycle basis.

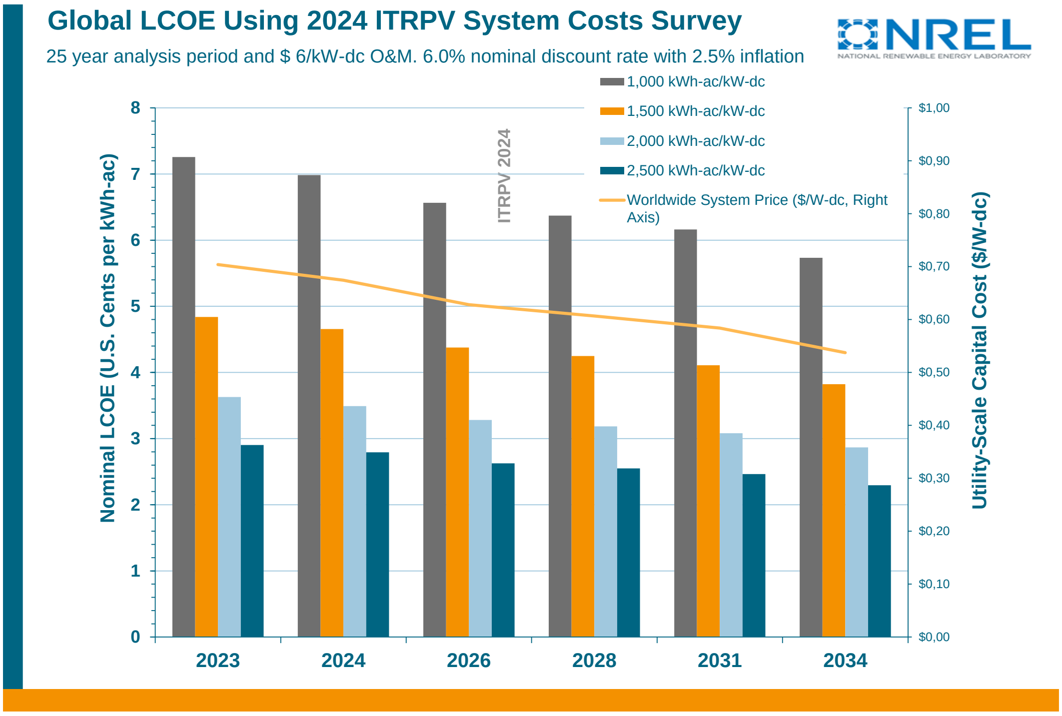

Fig. 79: Calculated LCoE values for different insolation conditions and median capital costs from the 2024 ITRPV survey. The calculations were performed using NREL's System Advisor Model (SAM) cash flow structure.

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[3] https://sam.nrel.gov/financial-models.html

# 8. Outlook

## 8.1. 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 24.9% using all historic price data points from 1976 to 2023. However, considering only the data points from 2006 - 2023, the learning rate is 39.9% as shown in Fig. 80.

Learning curve for module price as a function of cumulative shipments

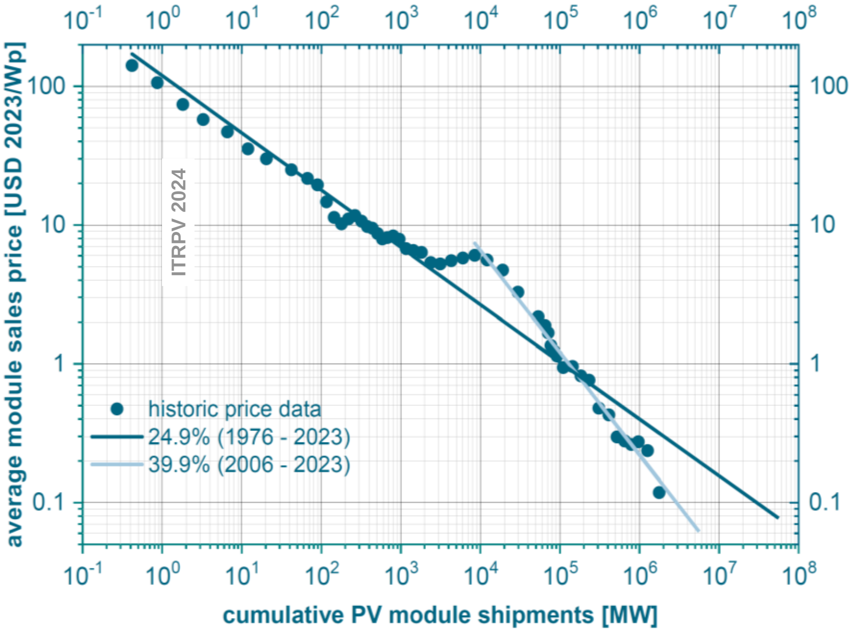


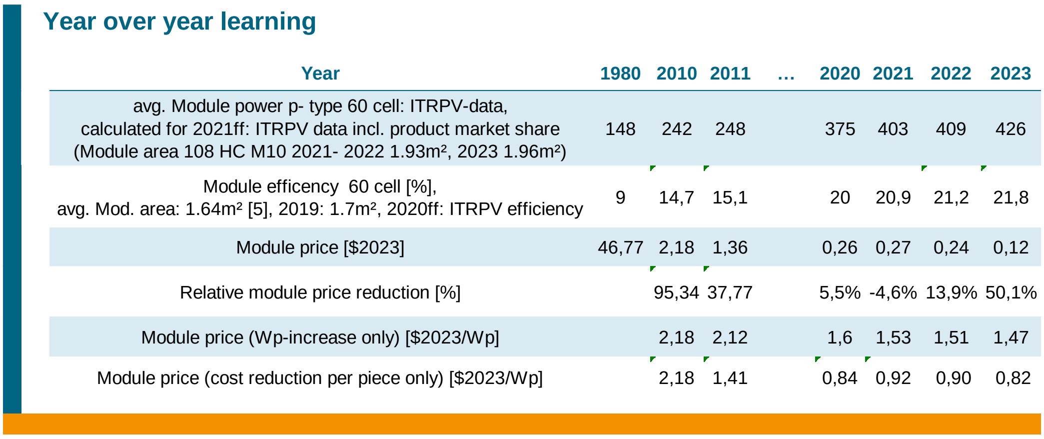
Fig. 80: Learning curve of module spot market price as a function of cumulative PV module shipments and calculated learning rates for the period 1976 to 2023 and 2006 to 2023, respectively.

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 [32]. 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 and 21.11 in the 14th edition respectively. 2023 module efficiency is according to Fig 60.

Tab. 1: Yearly learning for module efficiency and price per piece based on module price data (2010 = 100%) [6, 7, 10], 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 [32].



**Year over year learning**

| Year | 1980 | 2010 | 2011 | … | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|
| 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) | 148 | 242 | 248 | | 375 | 403 | 409 | 426 |
| Module efficency 60 cell [%], avg. Mod. area: 1.64m² [5], 2019: 1.7m², 2020ff: ITRPV efficiency | 9 | 14,7 | 15,1 | | 20 | 20,9 | 21,2 | 21,8 |
| Module price [$2023] | 46,77 | 2,18 | 1,36 | | 0,26 | 0,27 | 0,24 | 0,12 |
| Relative module price reduction [%] | | 95,34 | 37,77 | | 5,5% | -4,6% | 13,9% | 50,1% |
| Module price (Wp-increase only) [$2023/Wp] | | 2,18 | 2,12 | | 1,6 | 1,53 | 1,51 | 1,47 |
| Module price (cost reduction per piece only) [$2023/Wp] | | 2,18 | 1,41 | | 0,84 | 0,92 | 0,90 | 0,82 |

The trend to larger wafer formats as shown in Fig. 10 results in a variety module formats. Until 2019 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 [33] and 1.8 m² in 2020 [12]. The module size for rooftop applications increased further according to Fig. 60. For 2021/2022 we took 1.93 m² and 1.96m² 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, and 426 Wp respectively.

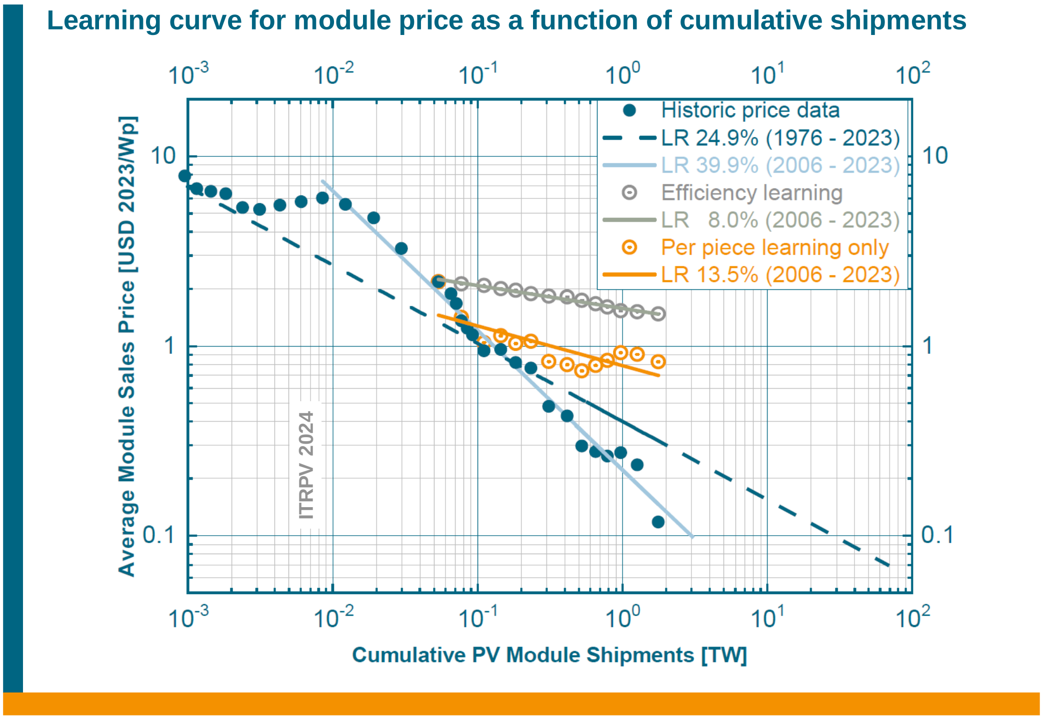


Fig. 81: Log-log plot of the learning curve for module spot market prices as a function of cumulative PV modules shipments; for the period 1976 to 2023 and 2006 to 2023, respectively. Calculated rates for Wp learning and per piece learning are based on Tab. 1.

Fig. 81 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 15% for per piece learning indicate that the main contribution of the price learning arose from per piece reductions. The 2023 year end spot market price is ≈ 0.12 US$/Wp as discussed in chapter 3.

The high price increase in 2021 is the reason for the considerable reduction of the per piece learning compared to the calculation in the former editions. This analysis emphasizes again that only the combination of efficiency learning, and cost reduction grants the resulting learning despite the fact that 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.

Progress in per piece learning has been visible again since 2022. Fig. 82 shows the data of Fig. 81 in a linear plot.

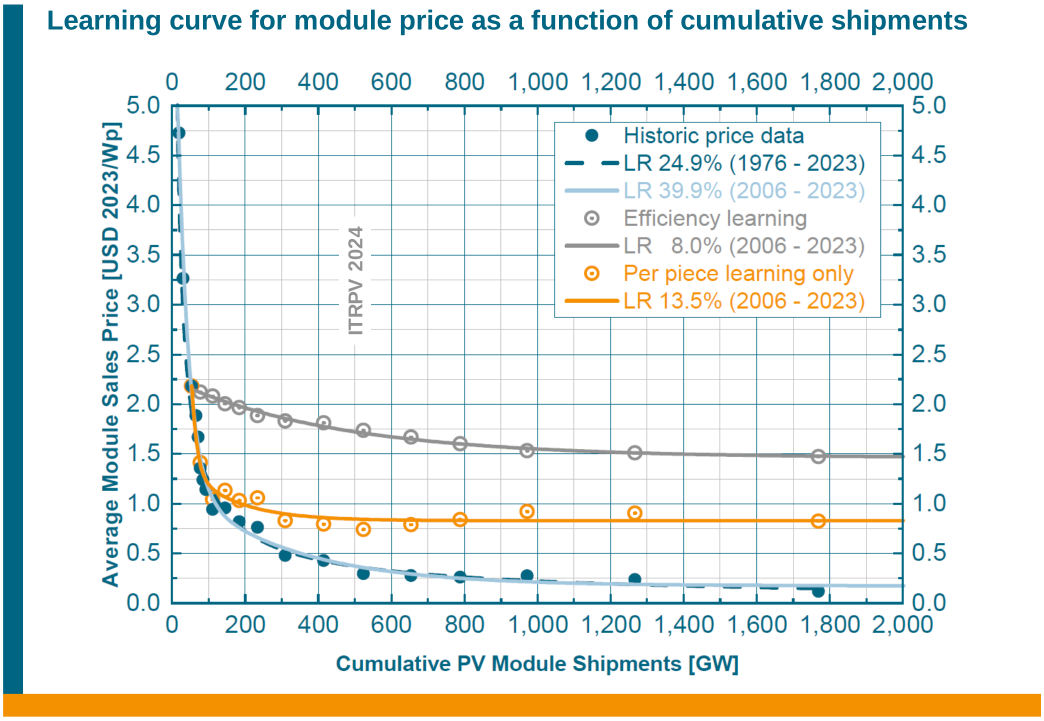


Fig. 82: Linear plot of the learning curve for module spot market prices as a function of cumulative PV modules shipments; for the period 1976 to 2023 and 2006 to 2023, respectively. Calculated rates for Wp learning and per piece learning are based on Tab. 1.

## 8.2. 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 [34]. The most widely publicly discussed PV-related topics and trends are about installed PV module power (DC), module shipments, and PV generated electricity scenarios.

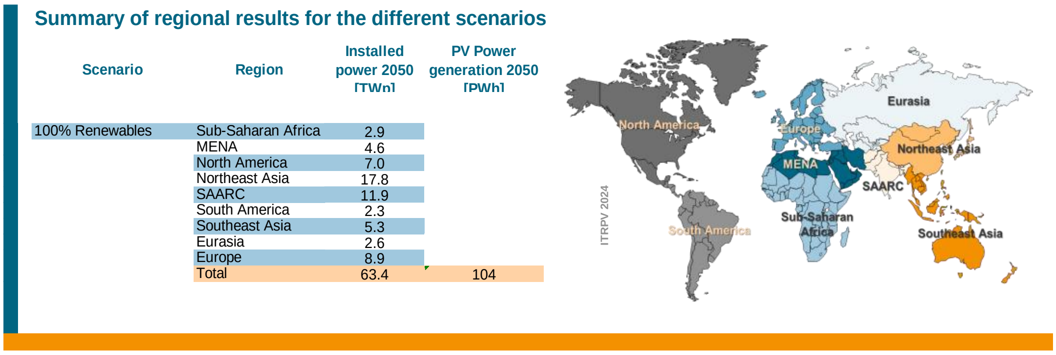
A look at the supplier side, to see the trend of the market for PV modules, cells, wafers, and polysilicon, is less spectacular, but it is essential for investment planning.

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]

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 [35] and [36] is used.

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 |

Fig. 83 shows the required PV installation trend 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.

It is remarkable that the historic shipments are close to the required shipments in this scenario. 2023 shipments are even above the requirements.

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 [38, 39, 40]. 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.

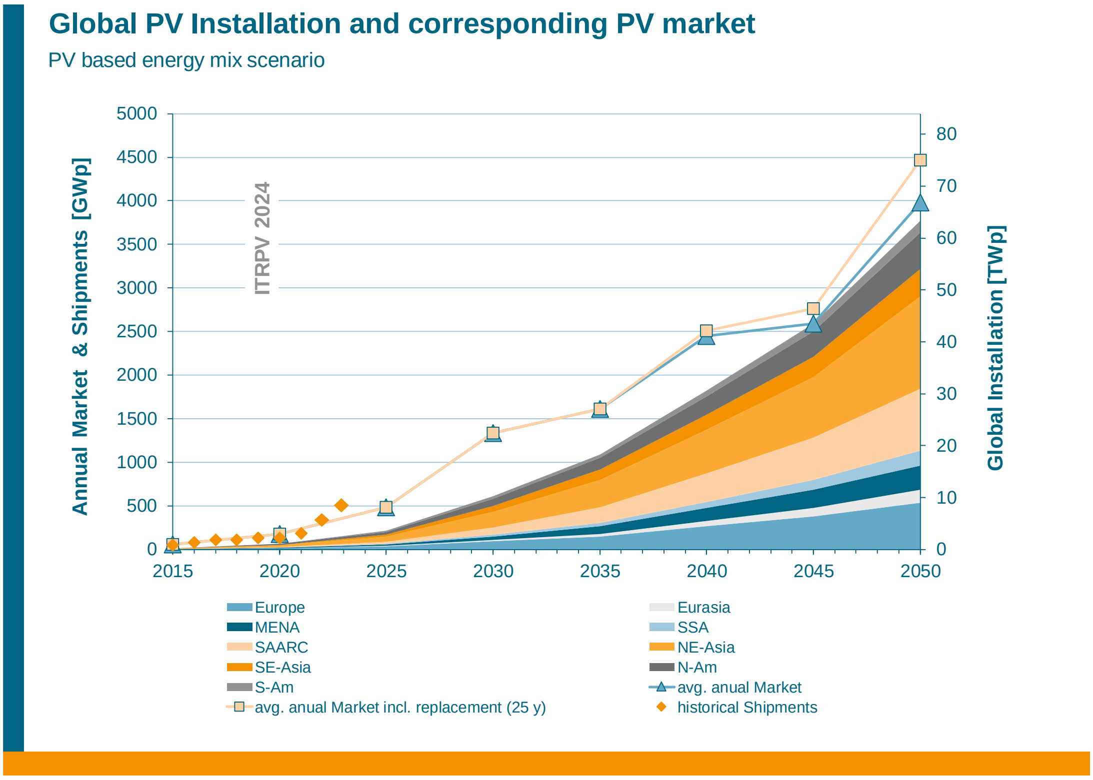


Fig. 83: Cumulative installed PV module power and 5-year average annual market for global PV module installation of 63.4 TWp in 2050 in a zero greenhouse gas emission economy - broad electrification [34]).

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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Intersolar is the world's leading exhibition series for the solar industry and its partners. The exhibition and conference series focus on the areas of photovoltaics, PV production technologies, energy storage systems and solar thermal technologies. Since being founded, Intersolar has become the most important industry platform for manufacturers, suppliers, distributors, service providers and partners in the global solar industry. With more than 28 years of experience, Intersolar has the unique ability to bring together members of the solar industry from across the world's most influential markets.

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VDMA

Photovoltaics Equipment

The VDMA represents more than 3,600 German and European mechanical and plant engineering companies. The industry stands for innovation, export orientation and SMEs. The companies employ around 3 million people in the EU-27, more than 1.2 million of them in Germany alone. This makes mechanical and plant engineering the largest employer among the capital goods industries, both in the EU-27 and in Germany. The sector group Photovoltaics Equipment delivers key services to the photovoltaic equipment industry in Germany. VDMA is running and regularly updating the International Technology Roadmap for Photovoltaics (ITRPV).

pv.vdma.org
itrpv.vdma.org

SIEMENS

Siemens is partner for machine builders and offers Automation solutions for the complete production chain in the solar industry. The solutions are based on our innovative and comprehensive controller and drives product portfolio, combined with industry know-how and an understanding of the solar industry requirements.

siemens.com/solar-industry

**VDMA**
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