International Technology Roadmap for Photovoltaic (ITRPV)

2016 Results including maturity report

Eighth Edition, September **2017**

In Cooperation with

Photovoltaik Equipment

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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 any necessary improvements. The aim of the International Technology Roadmap for Photovoltaic (ITRPV) is to inform suppliers and customers about anticipated technology trends in the field of crystalline silicon (c-Si) photovoltaics and to stimulate discussion on required improvements and standards. The objective of the roadmap is not to recommend detailed technical solutions for identified areas in need of improvement, but instead to emphasize to the PV community the need for improvement and to encourage the development of comprehensive solutions. The present, eighth edition of the ITRPV was jointly prepared by 40 leading international poly-Si producers, wafer suppliers, c-Si solar cell manufacturers, module manufacturers, PV equipment suppliers, and production material providers, as well as PV research institutes and consultants. The present publication covers the entire c-Si PV value chain from crystallization, wafering, and cell manufacturing to module manufacturing and PV systems. Significant parameters set out in earlier editions are reviewed along with several new ones, and discussions about emerging trends in the PV industry are reported.

Global PV module production capacity at the end of 2016 was estimated to be >90 GWp; the market share of above 90% for the c-Si market and below 10% for thin-film technologies is assumed to stay unchanged [1, 2]. This roadmap describes developments and trends for the c-Si based photovoltaic technology.

In the second half of 2016 the PV module-price significantly decreased in parallel with a large market increase compared to 2015.

The implementation of advanced cell technologies and the use of improved materials resulted in higher average module power. The tremendous price decrease forced the manufacturers accelerate the cost reduction and implementation measures to increase cell efficiency. The price experience curve continued with its historic learning but with a slight increase to about 22.5%. The PV industry can keep this learning rate up over the next few years by linking cost reduction measures with the implementation of enhanced cell concepts with improved Si-wafers, improved cell front and rear sides, refined layouts, and improved module technologies. This aspect is discussed in this revision of the ITRPV. Improvements in these areas will result in 60 cell modules with an average output power of about 325 Wp for mc-Si and about 340 Wp mono-Si respectively by 2027. The combination of significantly lower 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.

Roadmap activity continues in cooperation with VDMA, and updated information will be published annually to ensure comprehensive communication between manufacturers and suppliers throughout the value chain. More information is available at www.itrpv.net.

2. Approach

All topics throughout the value chain are divided into 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. All plotted data points of the parameters reported are median values generated from the input data.Color marking is applicable, as shown in Table 1. It is used for selected parameters to describe the maturity of a technology as of today: grey indicates that the technology is in use, yellow means that an industrial solution is known but is not yet used in mass production, red means that an interim solution exists, but it is too expensive, while purple indicates that there is no known industrial solution available actually. As stated above, the topics are split into three areas: materials, processes, and products. Here, we address issues linked to crystallization, wafers, cells, modules, and PV systems for each of these areas respectively.

Grey	Industrial solution exists, and is being optimized in production
Yellow	Industrial solution is known but not yet in mass production
Red	Interim solution is known, but too expensive or not suitable for production
purple	Industrial solution is not known

Table 1: Color marking to visualize the maturity of technologies.

2.1. Materials

The requirements and trends concerning raw materials and consumables used within the value chain are described in this section. Reducing the consumption or replacing 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 sources of energy.

2.2. Processes

New technologies and materials, and highly productive manufacturing equipment, are required to reduce production costs. By providing information on key production figures, as well as details about processes designed to increase cell efficiency and module power output, this roadmap constitutes a guide to new developments and aims to support their progress. The section on processes identifies 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 part of the value chain has a final product. The product section therefore discusses the anticipated development of key elements such as ingots, wafers, c-Si solar cells, -modules and PV systems over the coming years.

2.4. Accuracy of roadmap projections

ITRPV has been publishing reports since 2010. Since the first edition, the investigated parameters are reported as median values of the past year as well as predictions for the current year and the next 10 years to come. The data of the first reported year are therefore state of the art values of technical parameters and status quo values for others. In [3] we reviewed for the first time the forecast quality of several technical parameters like the amount of remaining silver of a 156/156mm² c-Si cell and the as-cut wafer thickness of c-Si wafers. Fig. 1 and Fig. 2 show the data of all ITRPV reports for remaining silver per cell and for the as-cut wafer thickness of mc-Si wafers. Fig. 1 shows that Silver reduction has been predicted quite well since the first edition. This reveals that the initial cost saving activities have been consistently continued. This is reasonable as Silver is still the costliest non-silicon material in the c-Si PV value chain and a resource used not only by PV but also by other industries. The dependency on the world market requires reduced silver consumption. Reduced usage of Silver will be mandatory to stay competitive.

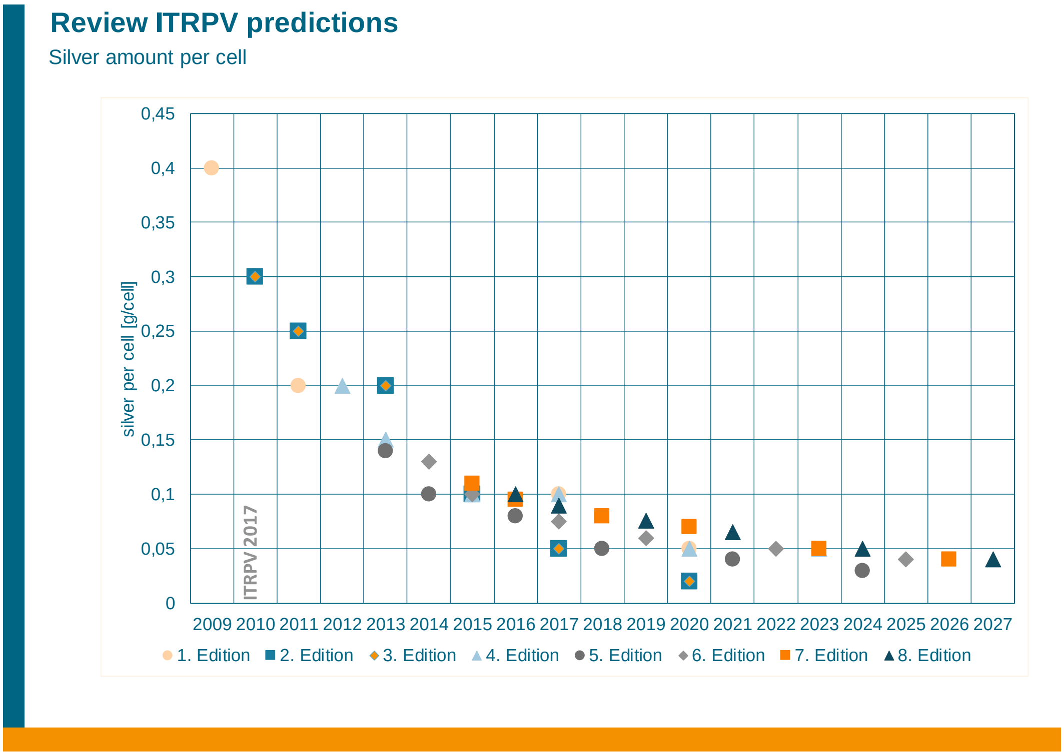

Fig. 1: Predicted trend for remaining silver per cell (156x156mm²) - predictions of ITRPV editions

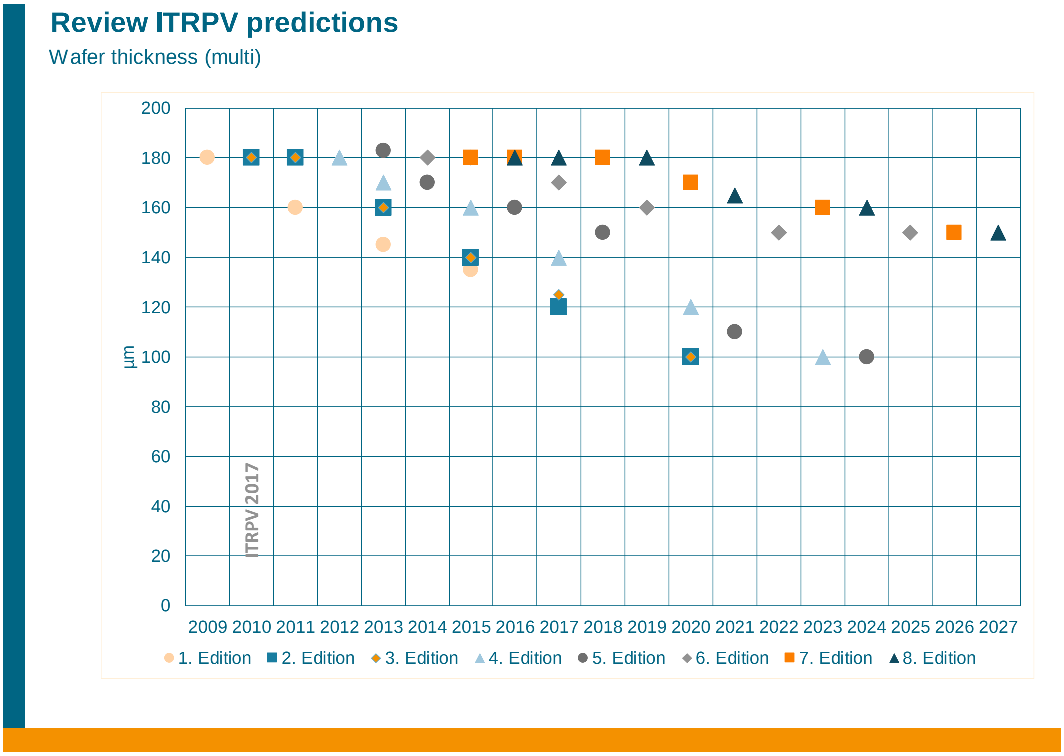

Fig. 2: Predicted trend for minimum as-cut wafer thickness for c-Si solra cells - predictions of ITRPV editions

3. PV learning curve

It is obvious that cost reductions in PV production processes should also result in price reductions [4]. Fig. 3 shows the price experience curve for PV modules, displaying the average module sales price (in 2016 US$/Wp) as a function of cumulative module shipments from 1976 to 12/2016 (in MWp) [1, 2, 5, 6, 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 shipments, the average selling price decreases according to the learning rate (LR). Considering all data points from 1976 until 2016 we found an LR of about 22.5%. The large deviations from this LR plot in Fig.3 are caused by the tremendous market fluctuations between 2003 and 2016.

The last data point indicates the shipment volumes (average of available 2016 PV installation data values [8-10]) and the corresponding price at the end of 2016: 75 GWp/0.37 US$/Wp [7]. Based on this data the 300 GWp landmark was exceeded in 2016 and the current cumulated shipped module power is calculated to be approximately 308 GWp.

Assuming that installations as well as shipments were 2016 about 75GWp the calculated worldwide installed module power reached 303GWp end of 2016 after 228GWp in 2015 [11]

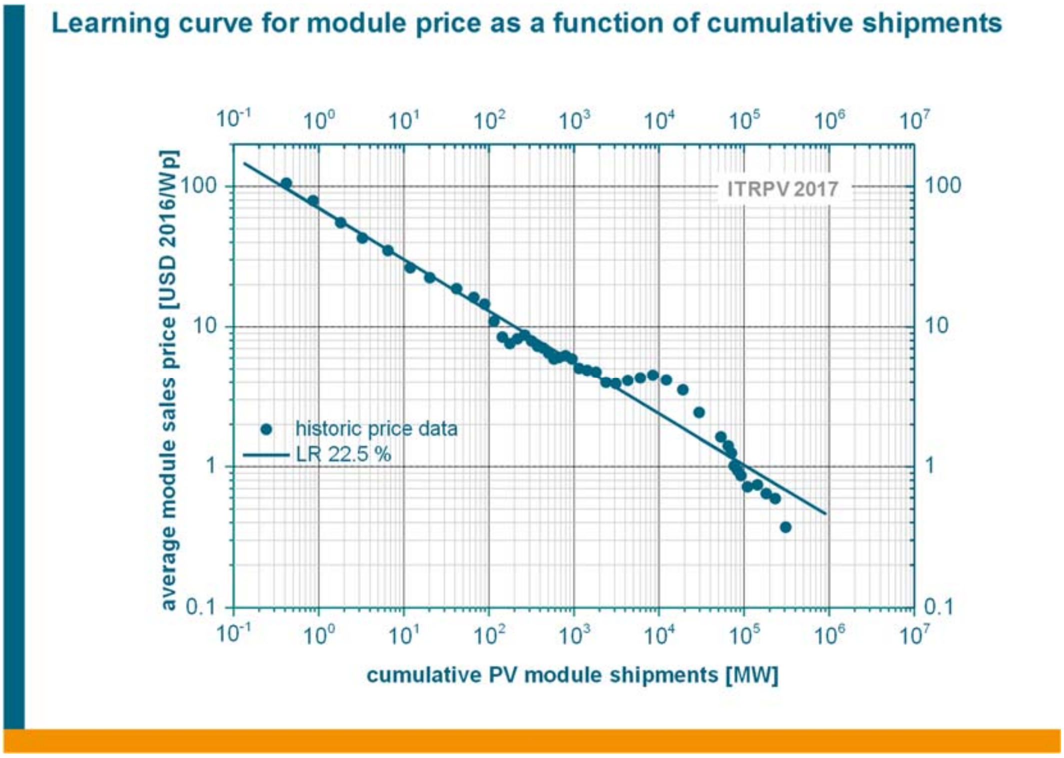

Fig. 3: Learning curve for module price as a function of cumulative PV module shipments.

4. Cost consideration

Fig. 4 shows the price development of mc-Si modules from January 2010 to January 2017 with separate price trends for poly-Si, multi crystalline (mc) wafers, and cells [7]. The price erosion during the second half of 2016 is comparable to the price drop 2011/2012. It was also caused by huge overcapacities especially at PV module production. Due to additional capacity expansions since 2015 the 2016 module production capacity is assumed to be >100 GWp, exceeding cell production capacity of >75 GWp [11]. We see currently a similar, critical situation of eroding margins for PV manufacturers like the industry experienced in 2012 when module prices also fell short of the cost of c-Si modules [9, 12, 13]. The inset of Fig. 4 shows the comparison of the proportion of prices attributable to silicon, wafer, cell, and module price. The overall price level between 01/2016 to 01/2017 decreased by over 35% and the share of the different cost elements shifted as well. The cost reduction in use of all other value chain elements and materials in parallel with increased poly-Si prices resulted in a significant increased price fraction of poly-Si. Wafer and cell conversion prices decreased but the main price decrease was imposed to module conversion.

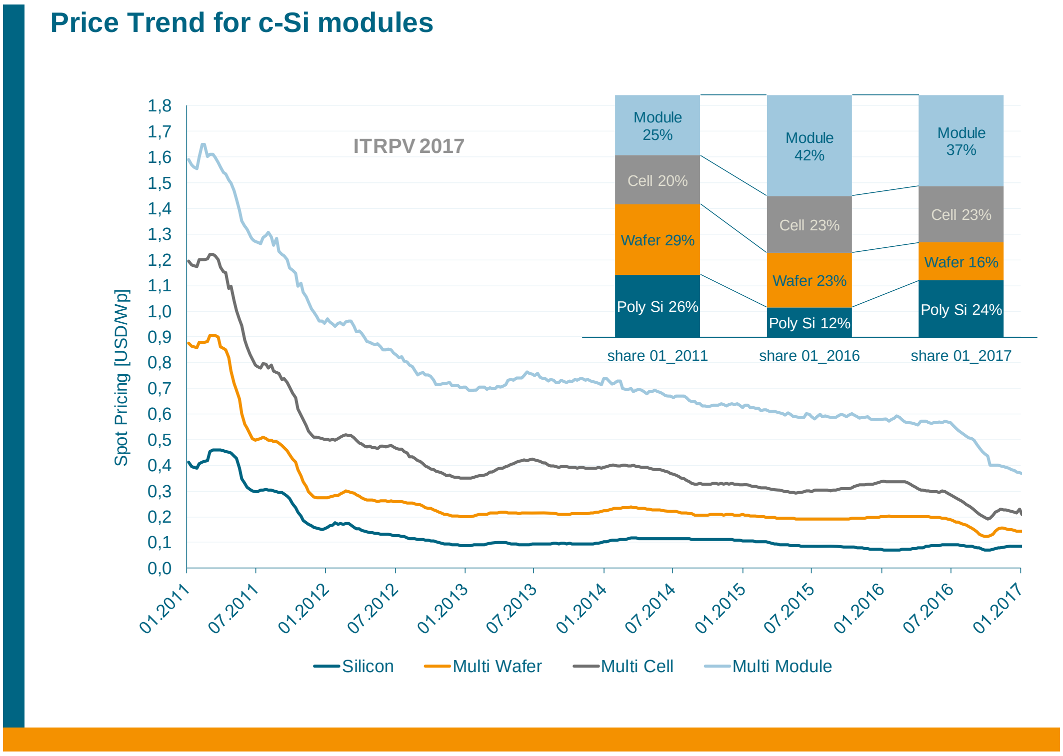

Fig. 4: Price trends for poly-Si, mc-Si wafers, cells, and c-Si modules (assumption 01/2017: 5.26g poly-Si per Wp, average mc-Si cell efficiency of 18.35% {4,47Wp}); inset: comparison of the proportion of the price attributable to different module cost elements between 01/2011, 01/2016, and 01/2017 (1.60, 0.57, and 0.37 US$/Wp) [7].

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. Taken into account the fact that the anticipated global PV module production capacity of about 100 GWp in 2016 [1] will increase in 2017 due to capacity expansions or – at least - stay constant, production capacity will again exceed the predicted global market demand of above 75 GWp in 2017 [8, 9, 10]. Therefore, prices will not compensate for any cost increases as there is no shortage expected — in other words, the pressure on wafer, cell and – more - painful on module manufacturing will persist. Achieving cost reductions in consumables, and materials as well as improving production and product performance will therefore remain the main tasks.

Three strategies help to address this challenge:

- Continue the cost reduction per piece along the entire value chain by increasing the Overall Equipment Efficiency (OEE) of the installed production capacity and by using Si and non-Si materials more efficiently.

- Introduce specialized module products for different market applications (i.e. tradeoff between cost-optimized, highest volume products and higher price fully customized niche products).

- Improve module power/cell efficiency without significantly increasing processing costs.

The latter implies that efficiency improvements need to be implemented with lean processes that require minimum investment in new tool sets, including the extension of the service life of depreciated tool sets in order to avoid a significant increase in depreciation costs.

5. Results of 2016

5.1. Materials

5.1.1. Materials – crystallization and wafering

The introduction of diamond wire sawing is expected to lead to a significant improvement in terms of wafering process cost reductions. Slurry-based wafer sawing is currently still the dominant technology. Fig. 6 and 7 show the expected share of different wafering technologies for mono-Si and mc-Si respectively in volume production. Diamond wire sawing has been the mainstream technology in mono-Si wafering since 2016 and is maturing further. It is expected to replace slurry-based wafering technology with a market share of >90% from 2019 onwards. Electroplated diamond wire is considered as the dominating wire material. Diamond wire sawing of mc-Si is expected to gain market shares at the expense of slurry-based wafering over the next 10 years despite current challenges in wet chemical texturing. We do not believe that other new wafer manufacturing techniques, especially kerfless technologies, will gain market shares above 5%, mainly due to the maturity of the established sawing technologies.

Producing thinner wafers, reducing kerf loss, increasing recycling rates, and reducing the cost of consumables, can yield savings. Wire diameters will be reduced continuously over the next few years. Fig. 8 shows the expected recycling rates of SiC, Diamond wire and Si. There will be more recycling of Si and diamond wire over the next years while SiC recycling rate is expected to increase only slightly from 80% to about 90% within the next 10 years.

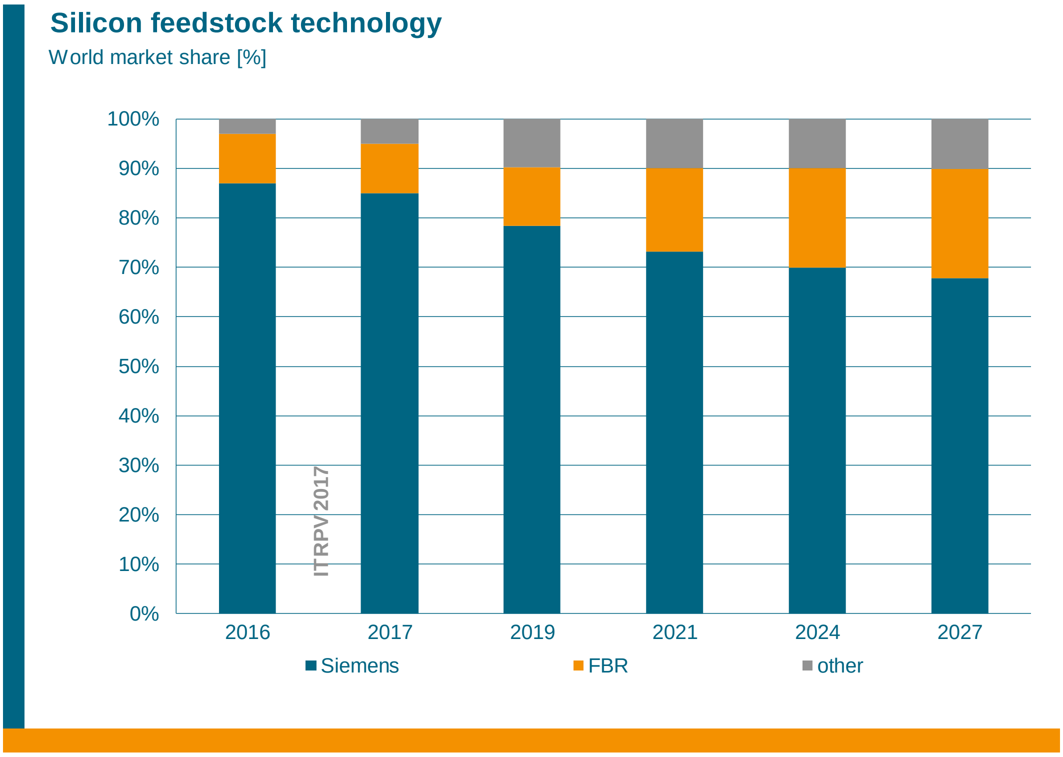

Fig.5: Expected change in the distribution of poly-Si production technologies.

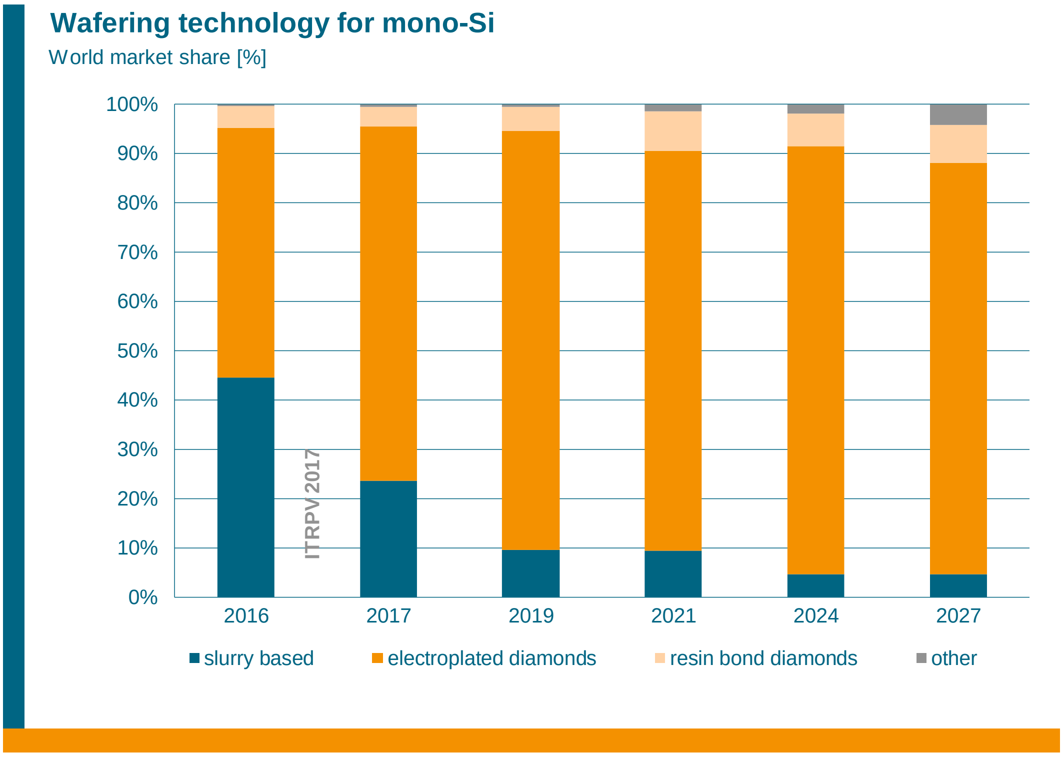

Fig.6: Market share of wafering technologies for mono-Si.

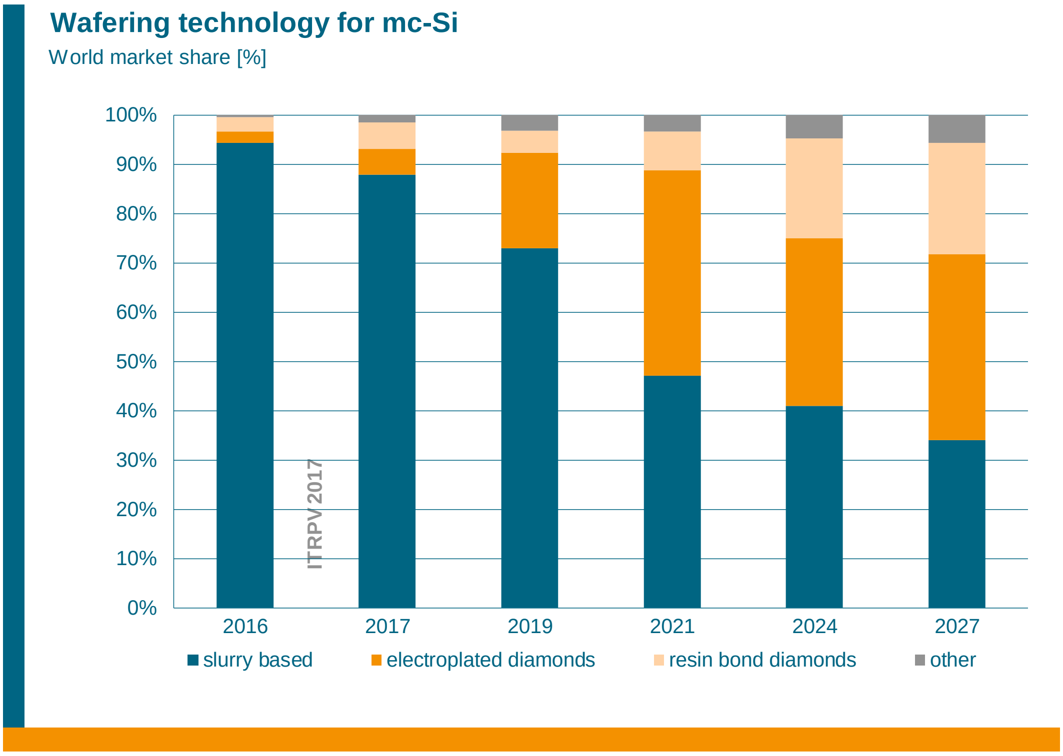

Fig. 7: Market share of wafering technologies for mc-Si.

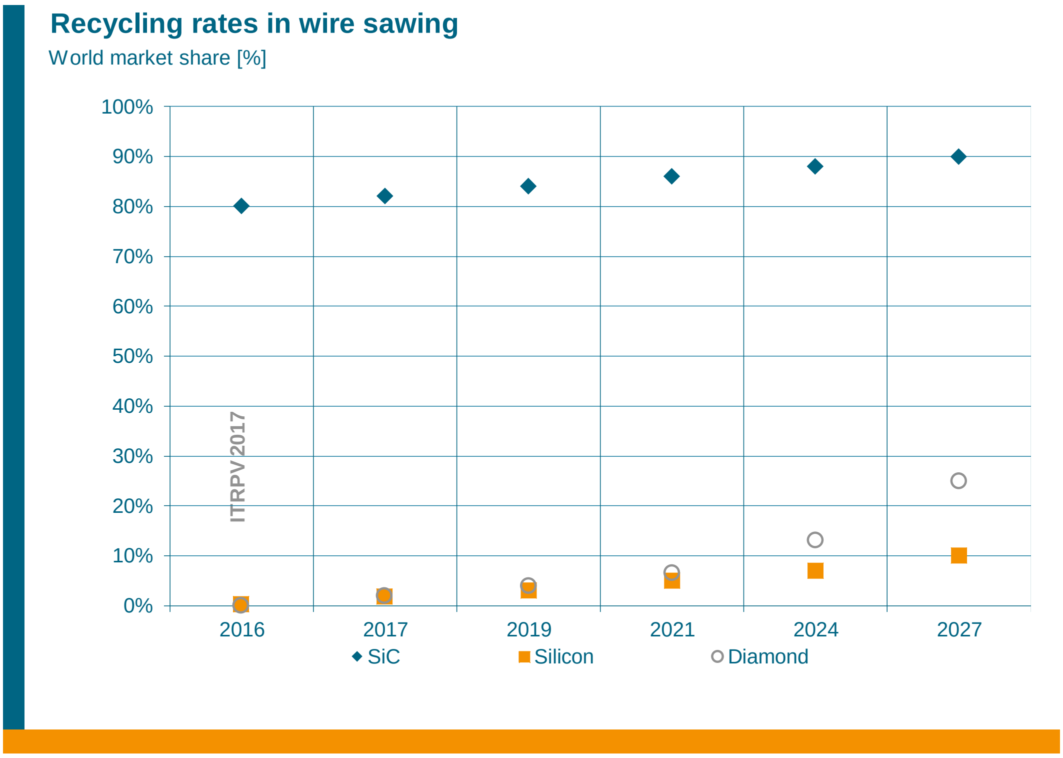

Fig. 8: Recycling rates of some consumables in wafering.

5.1.2. Materials – cell processing

Si wafers account for approximately 40% of today's cell price, as shown in Fig. 4. Reducing as-cut wafer thickness will lead to more efficient use of silicon. The developments anticipated in previous editions of the roadmap did not materialize due to declining Poly-Si market prices as discussed in 2.4, 180 µm is the preferred thickness of mc-Si wafers used today on cell and module production lines as shown in Fig. 9, mainly due to the higher stability. Mono wafers are expected to reduce faster to 140 µm. Nevertheless, an even faster reduction may take place especially for mono wafers ascolor coding shows in Fig. 9. 160µm mono wafers are already in mass production by today. It is assumed that the thickness of mc-Si wafers will slowly approach a minimum value of 150 µm until 2027. Mono-Si wafer thickness will follow a faster thickness reduction down to 140 µm in 2027. This trend may proceed faster as the industrial solutions are known today but not yet in mass production, indicated by the yellow color for the multi/mono wafer thicknesses trend until 2027. Module technology will be ready soon for thicknesses down to 125µm as shown by the gray/yellow color coding while handling technologies for thicknesses below 120µm need further development.

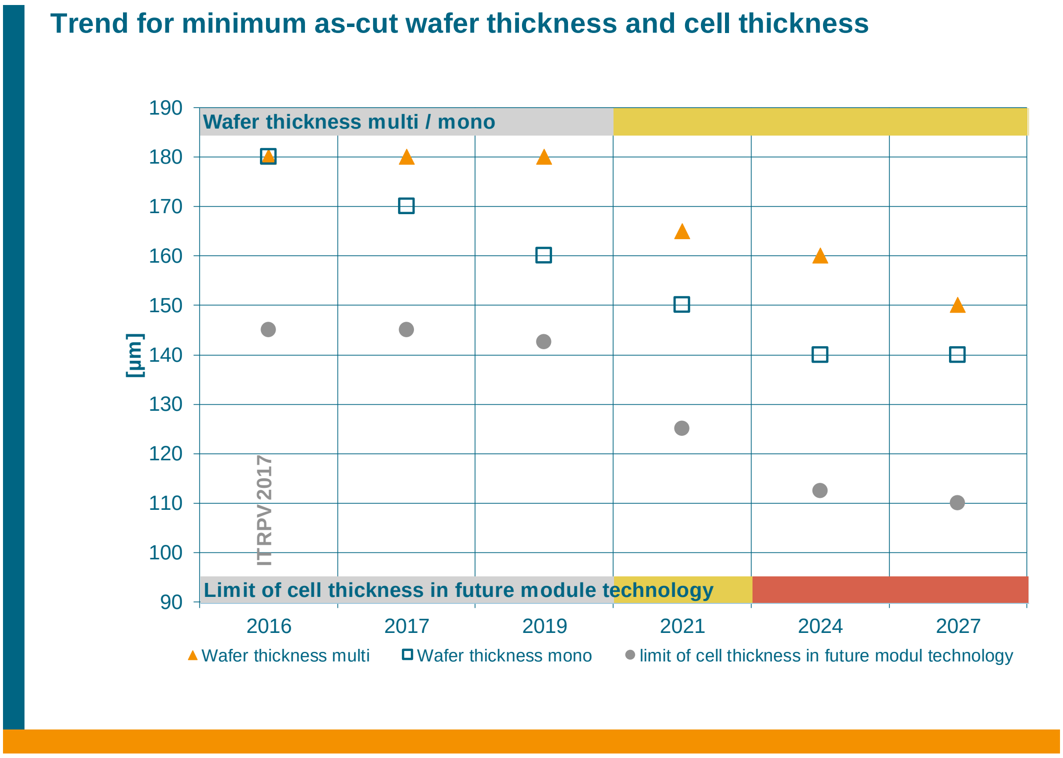

Fig. 9: Predicted trend for minimum as-cut wafer thickness and cell thickness for mass production of c-Si solar cells and modules.

Metallization pastes/inks 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. 10 shows our estimations regarding the future reduction of the silver that remains on a 156x156mm² cell after processing. The reduction of remaining Silver per cell is expected to continue during the next years. The current study found 100 mg as the median value for 2016 and 90mg for 2017. A reduction down to 40 mg per cell is expected to be possible by 2027. New developments in pastes and screens will enable this reduction, and this clearly shows the reaction of suppliers to the needs of cell manufacturers. Yellow coding down to 45mg indicates that the reduction might occur much faster as assumed today. Solutions for 40mg need further development to be implemented as the red coding shows. The average silver price of 548 US$/kg end of January 2017 will result in costs of 5.2 US$ cents/cell (1.1 US$ cents/Wp, for a 19.6% mc-Si PERC cell), or about 13% of the non-Si cell price, shown in Fig. 4.

Because silver will remain expensive due to the world market dependency as discussed in 2.4., it is extremely important to continue all efforts to lower silver consumption as a means of achieving further cost reductions.

Despite a continuous reduction of silver consumption at the cell manufacturing level, silver might still be replaced on a large scale by a more cost-effective material. Copper (Cu), applied with plating technologies, is the envisioned substitute. It is still assumed that it will be introduced in mass production. The market share is expected to climb in 2019 to 5%, and it is then expected to account for around 20% of the market in 2027 - again a delay versus former ITRPV expectations. Technical issues related to reliability and adhesion have to be resolved before alternative metallization techniques can be introduced. Appropriate equipment and processes also need to be made ready for mass production. Silver is expected to remain the most widely used front side metallization material for c-Si cells in the years to come.

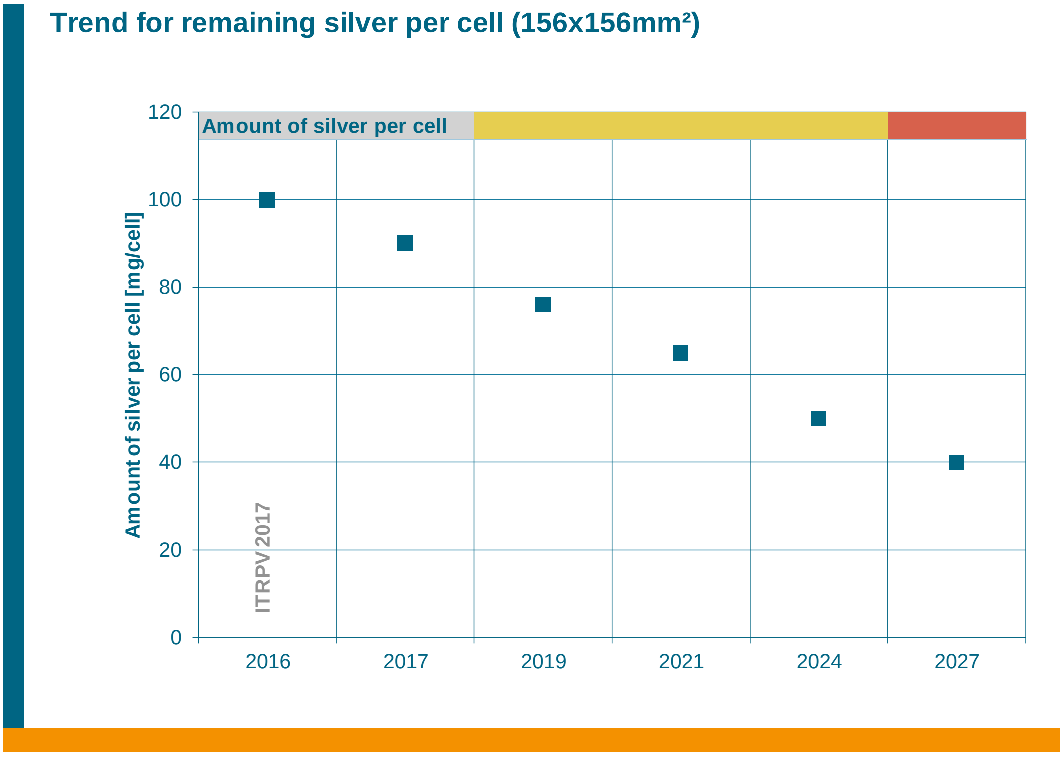

Fig. 10: Trend for remaining silver per cell (156x156mm²).

Pastes 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). 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 panels are excluded from RoHS 2, meaning that they may contain lead and do not have to comply with the maximum weight concentration thresholds set out in the Directive[1]. PV's exclusion from the Directive will remain in effect for the next few years — a review of RoHS 2 will likely take place by

[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."

mid-2021 at the latest.[2] Cell manufacturers should act carefully, especially, as the exclusion 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 also be useable in other equipment that is not excluded from RoHS 2 (e.g. to charge calculators), then the component must comply with the Directive’s provisions.

We anticipate lead free pastes to become widely used in the mass production of c-Si cells in 2019.

5.1.3. Materials – modules

Module add-on costs are clearly dominated today by material costs. Both improvements in module performance as shown in Section 5.3 and reductions in material costs are required if module add-on costs are to be reduced. Approaches for increasing performance include the reduction of optical losses (e.g. reflection of front cover glass) and the reduction of interconnector losses. Approaches for reducing material costs include:

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

The use of antireflective (AR) coatings has become common in recent years as a means of improving the transmission of the front cover glass. As can be seen in Fig. 11, AR-coated glass is expected to remain the dominant front cover material for c-Si PV modules for the next ten years, with market shares well above 90%.

Since AR-coated glass will be the most commonly used front cover, it is important that the AR coating remains effective and stable under various outdoor conditions during the entire lifecycle of the module. It appears that not all AR coatings on the market meet this requirement even for a 10-year period. However, there is a clear trend indicating that the average service life of these coatings will improve over the next seven years to a level in the range of the anticipated module service life (as can be seen in Fig. 12). Arc coatings for a service life of 20 years and above are currently not available for mass production as the red color coding indicates.

[2] Article 24 of the RoHS Directive [2011/65/EU] requires an evaluation and possible revision of the Directive, including its scope, by July 22, 2021.

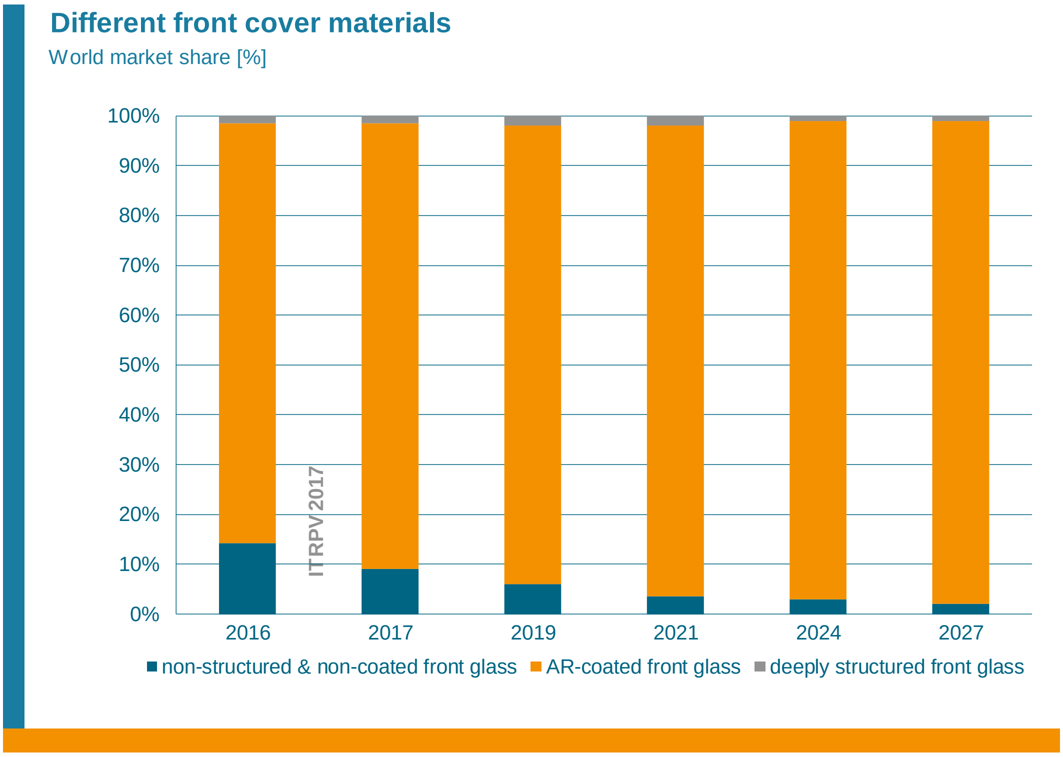

Fig. 11: Expected relative market share of different front cover materials.

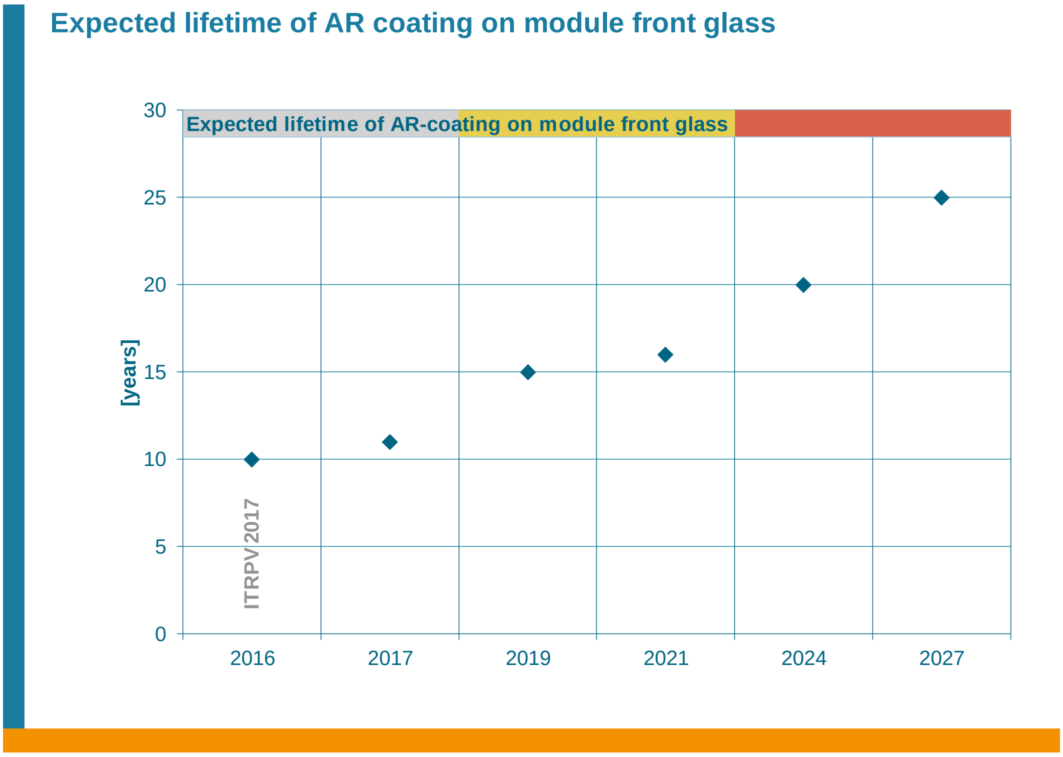

Fig. 12: Predicted trend for the average service life of AR coatings on front glass.

For a long period of time, solders that contain lead have served as the standard interconnection technology for solar cells in module manufacturing. Due to environmental and other considerations, more and more PV manufacturers are striving towards lead-free alternatives, as can be seen in Fig. 13.

Lead-free solder and conductive adhesive technologies are expected to gain market shares over the next five to seven years. In the long-term perspective, these lead-free interconnection technologies are expected to advance to become the leading technologies.

With regard to the interconnector material, copper ribbons will remain the dominating material as shown in Fig. 14. Copper-wires are expected to gain over 30% market share during the next decade. Structured foils mainly used for the interconnection of back contact cells and shingled or overlapping cell interconnection remain niche technologies with market shares around 5%.

It is important to note that the up-and-coming interconnection technologies will need to be compatible with the ever-thinner wafers that will be used in the future. In this respect, low-temperature approaches using conductive adhesives or wire-based connections have an inherent advantage due to the lower thermal stresses associated with them.

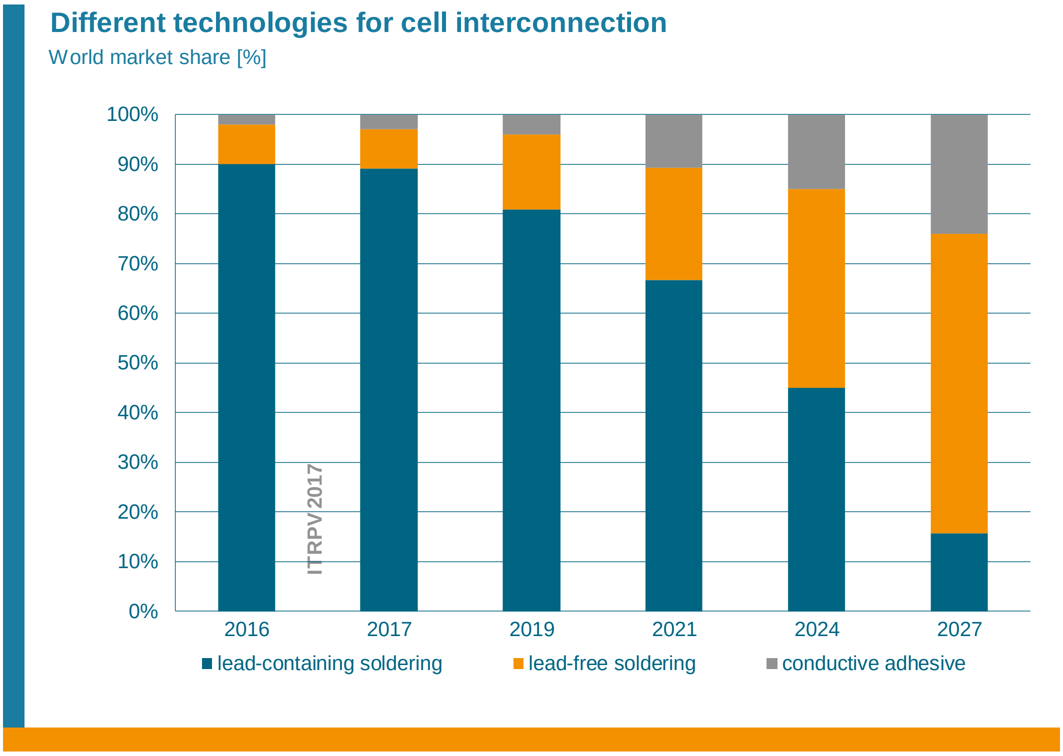

Fig. 13: Expected market shares for different cell interconnection technologies.

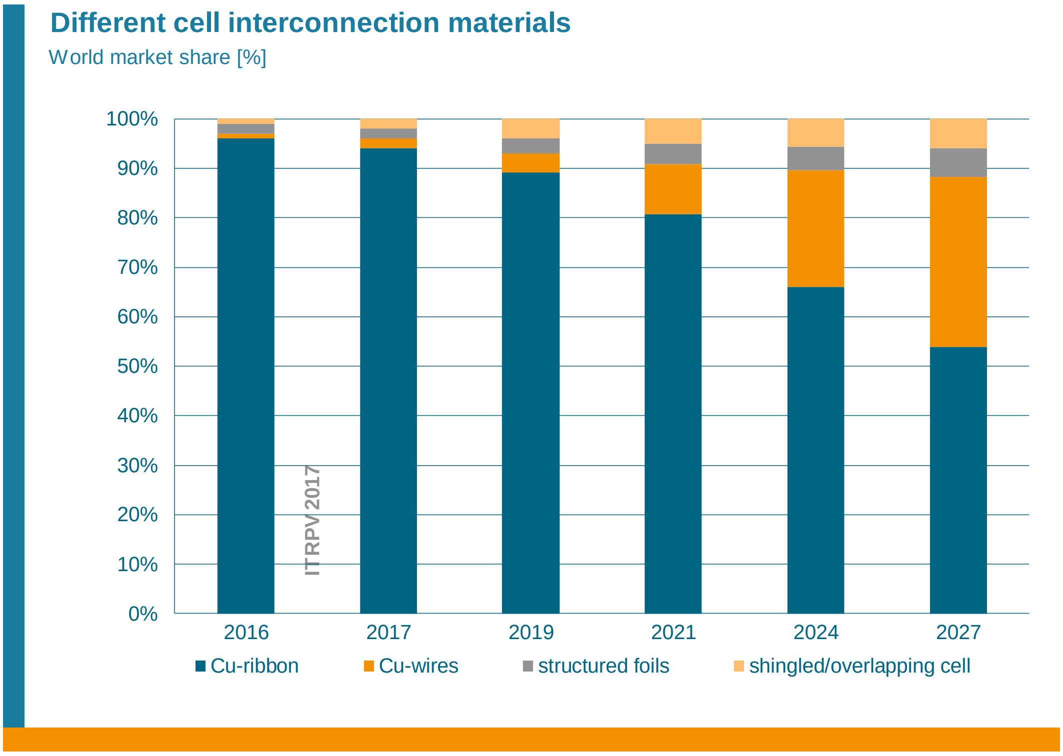

Fig. 14: Expected market shares for different cell interconnection materials.

Similar to the cell interconnection we find a clear trend towards lead-free module interconnection covering all interconnections between the cell strings and the junction box, as shown in Fig. 15. However, in contrast to cell interconnection it appears that conductive adhesives will play a less important role in module interconnection.

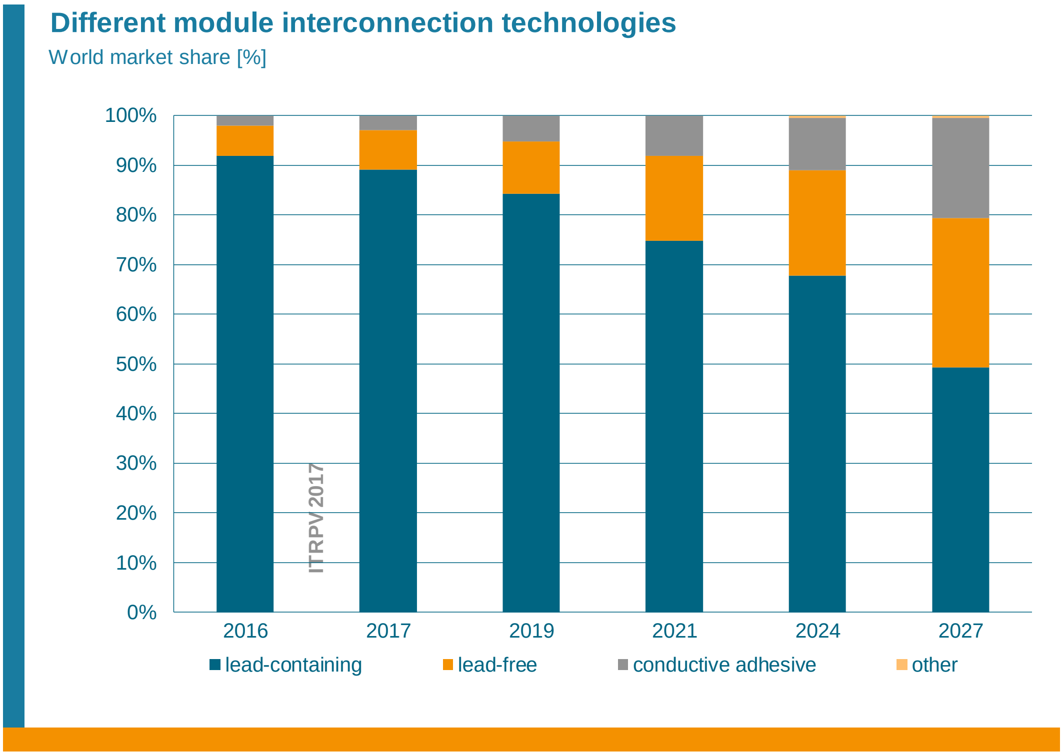

Fig. 15: Expected market share of different module interconnection material.

Because the encapsulant material and the back sheet represent major cost components in module manufacturing, intensive development efforts have been made to reduce the cost of these materials, while at the same time maintaining or even improving those properties relevant to the module service life. This has led to a trend toward new materials, as is shown in Fig. 16 for encapsulants. However, it is also predicted that EVA will remain the dominant encapsulant with a market share still above 60% over the ten-year period of this survey.

Glass is expected to gain a significant higher market share as backside cover material for c-Si modules over the next decade.

As can be seen in Fig. 17, it is expected that the market share of Glass will increase from 3% in 2016 to around 35% in 2027. In addition to this analysis, we found that the market share of modules with black back sheets is expected to remain constant at a level of about 10%.

Currently modules with aluminum frames are clearly dominating the market. As can be seen in Fig. 18 plastics frames will slowly come into the markets together with other materials (like steel) to reach a market share of more than 25% until 2027.

In order to maintain quality (for thinner cells as well), the solar cells used for module assembly should be free of micro cracks. The majority of the contributing companies are now testing all of their products during the manufacturing process. Among other things, the contributors have agreed to offer Potential Induced Degradation (PID)-resistant cell and module concepts only.

The IEC TS 62804 standard for PID test should eliminate “over testing”. At the same time, there is no industry-wide accepted and applied definition of micro-cracks.

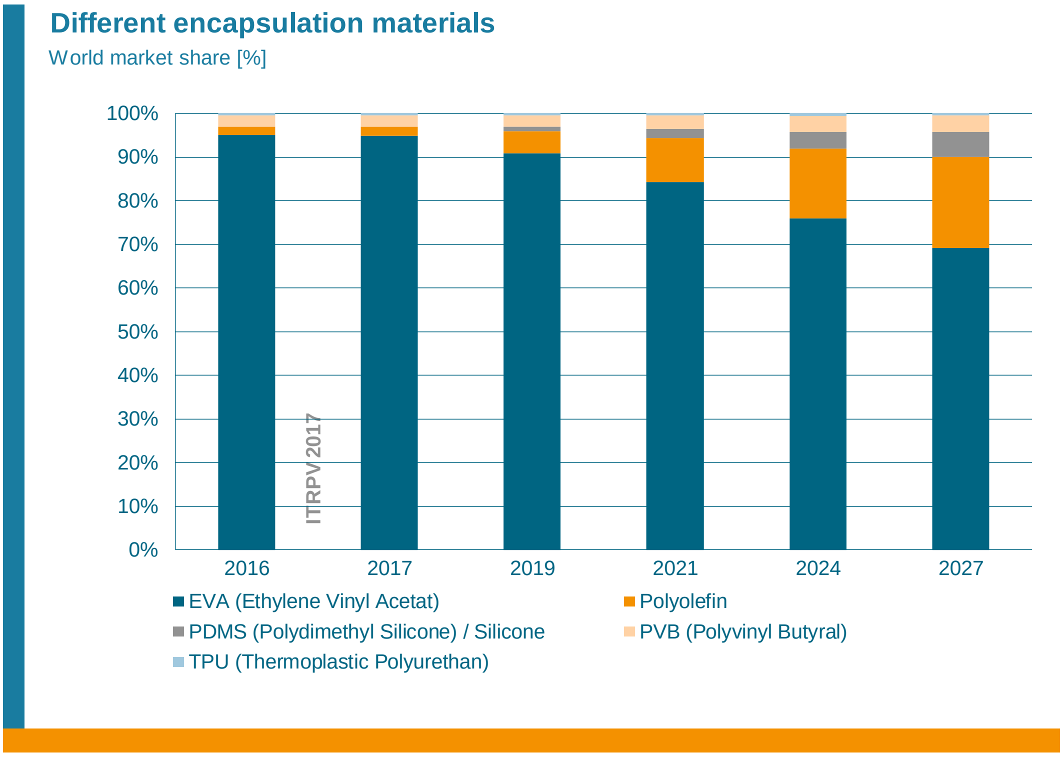

Fig. 16: Expected market shares for different encapsulation materials.

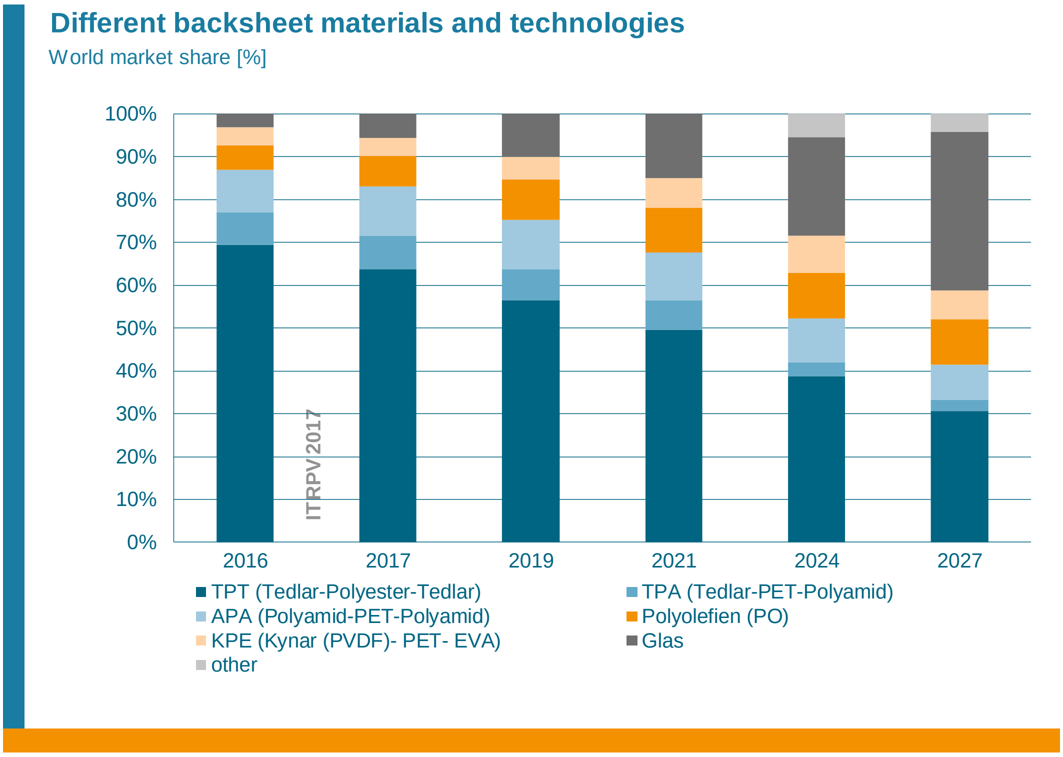

Fig. 17: Back cover technologies

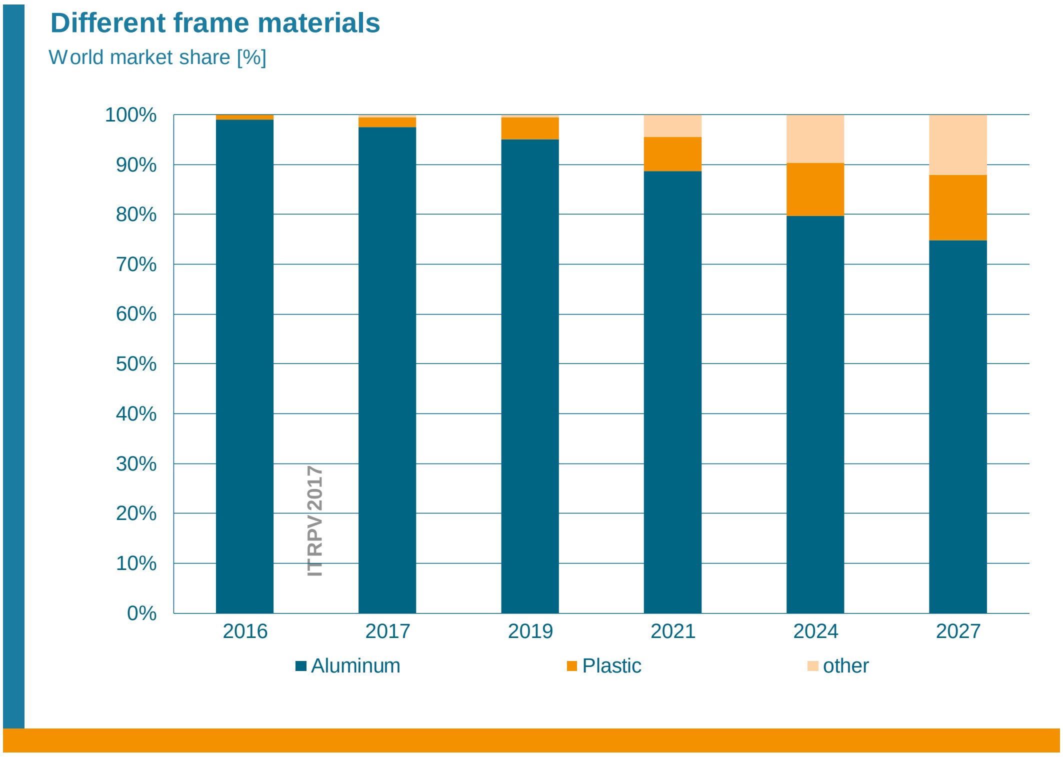

Fig. 18: Expected market shares for frame materials.

5.2. Processes

5.2.1. Processes – manufacturing

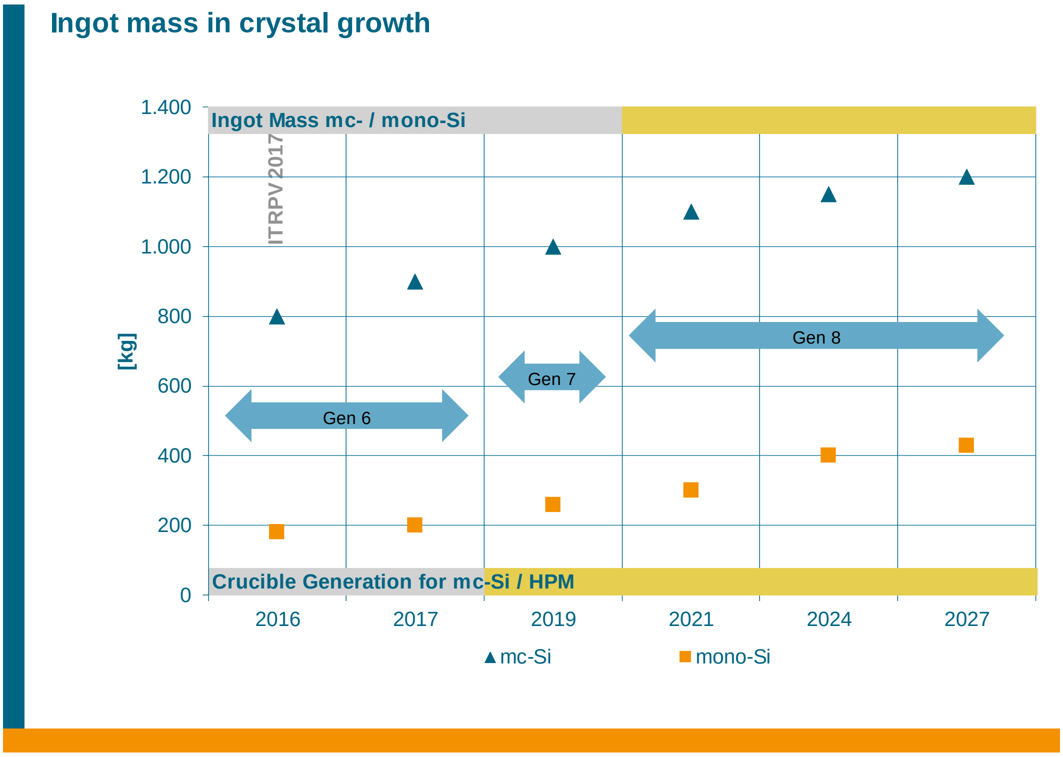

Fig. 19: Predicted trend for ingot mass for mc-Si, mono-like, and HPmc-Si, as well as for mono-Si.

It is possible to increase the throughput of the crystallization process by changing the common sizes of the ingots. Fig. 19 shows the increase in ingot mass for casted silicon materials and for Czochralski / Continuous Czochralski (Cz/CCz) growth of mono-Si, as predicted by the roadmap. Gen6 ingoting is mainstream today with ingot masses of 800 kg as indicated by the grey bar. Starting in 2019, the transition to Gen7 will take place, enabling ingoting with masses of up to 1,000 kg in mainstream. Casted ingot mass will increase further towards 1,200 kg and will mark the move to Gen8 around 2020. Transition to Gen8 in mass production may go even faster as the grey and yellow color coding indicates. The ingot mass of mono is expected to double within the next 10 years (driven by CCz technology) and also this may occur faster as anticipated by the grey and yellow color coding too.

Fig. 20 shows the share of different technologies used for mono-Si crystallization. CCz will only make small increase in market share over classical Cz Float zone (FZ) material is disappearing in PV mass production.

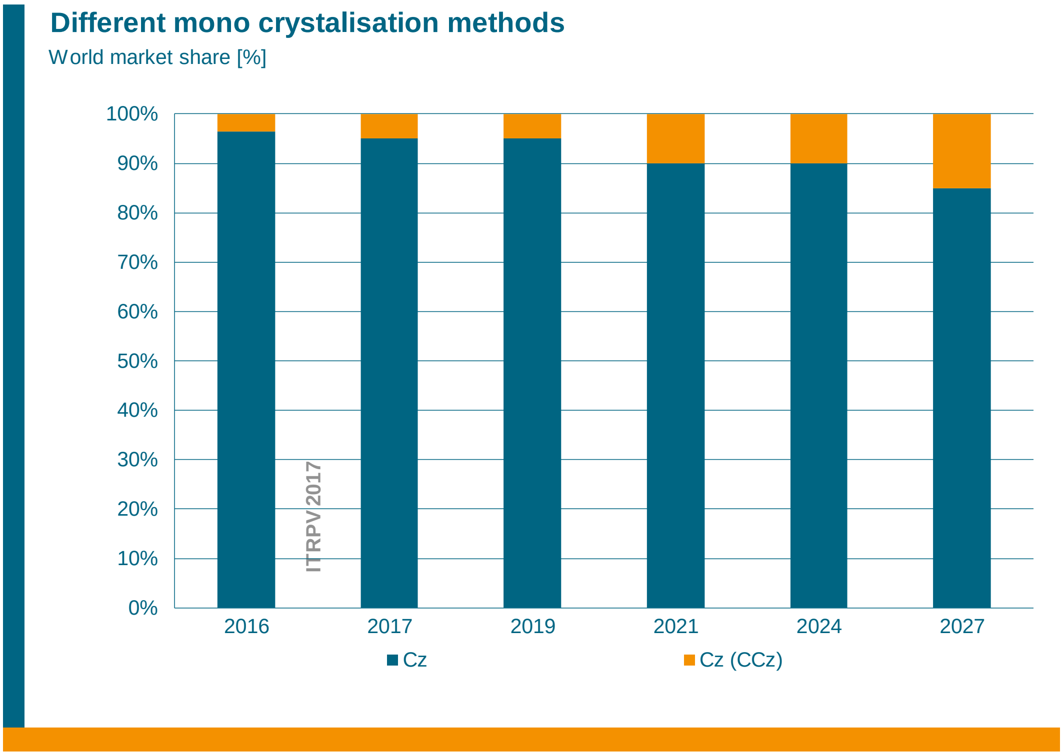

Fig. 20: World market share for different mono crystalisation methods

The throughput of crystal growth for both types, casted and mono, will be continuously increased by 30%-40% over the next 10 years, as predicted in Fig. 21 or even faster as the grey and yellow coding anticipates.

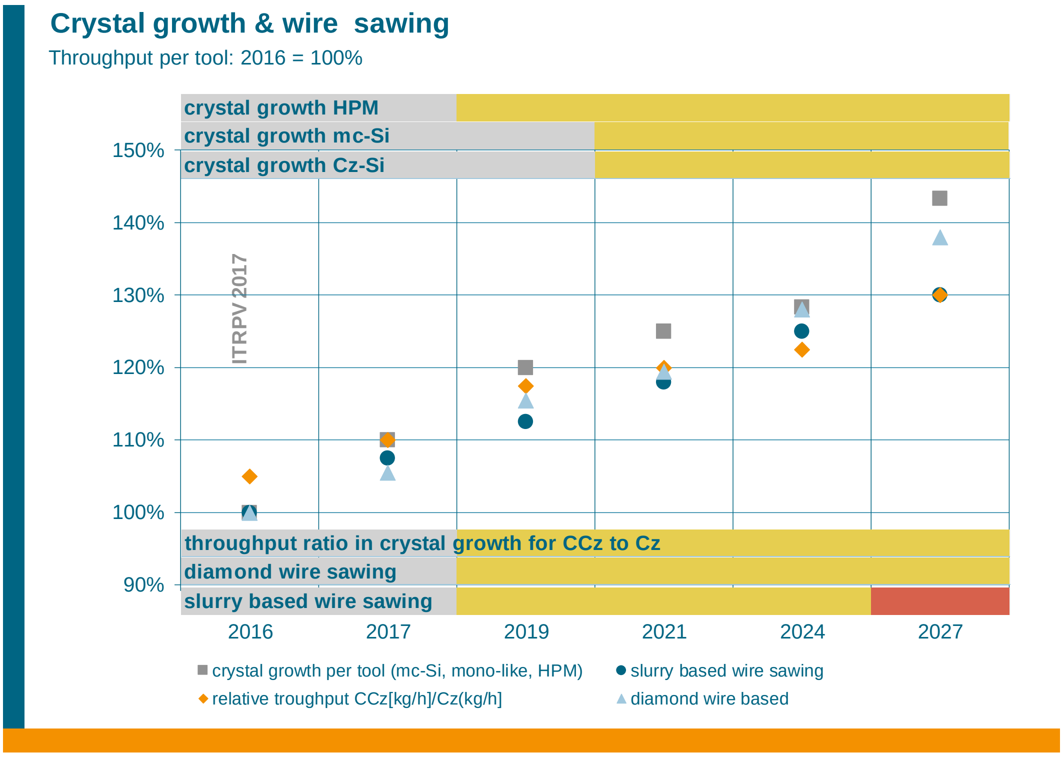

Fig. 21: Predicted trend for throughput per tool for ingot growth of casted Si materials and mono-Si, and for wafer sawing technology.

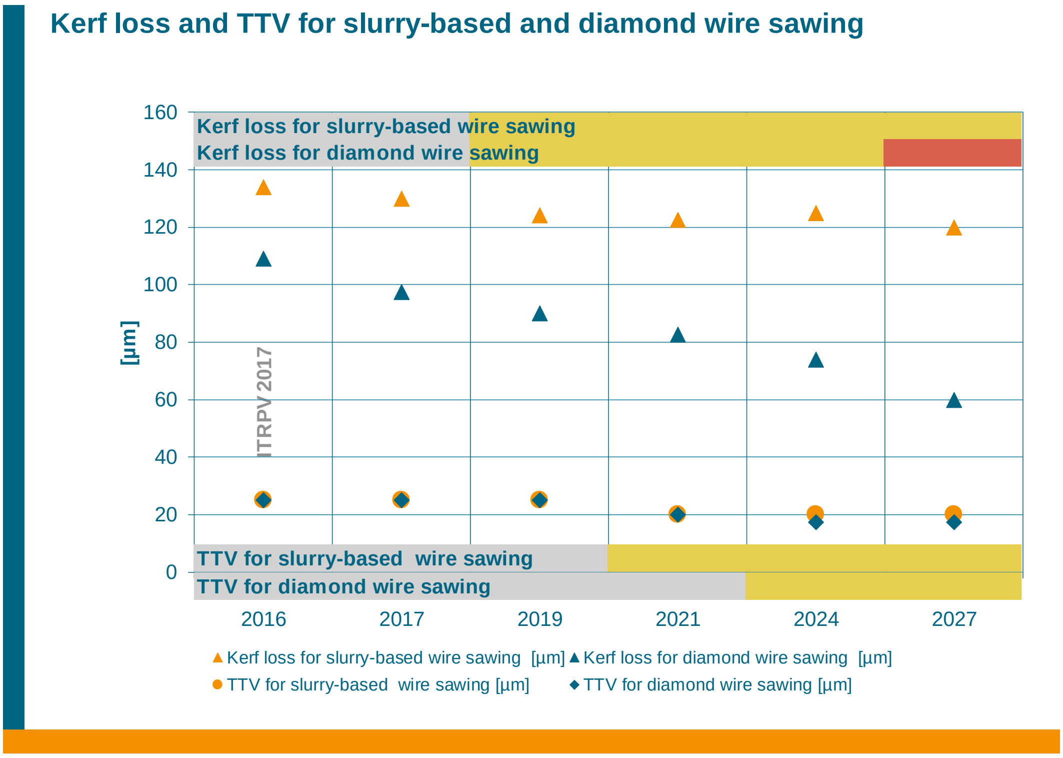

Fig. 22: Kerf loss and TTV

The throughput trend for sawing technologies is also summarized in Fig. 21. Similar trends are predicted for the throughput of both sawing technologies — however, throughput is expected to increase by 30%-35% between now and 2027. Slurry based sawing will make less fast progress as indicated by the red coding for 2027. This will be mainly due to the expected shrinking market share.

Yield enhancement by reducing the kerf loss will further improve productivity in wafering on top of the effect of the increased throughput. This is important to improve the usage of silicon as discussed in 5.1.1. Fig. 22 describes the trend for kerf loss and for Total Thickness Variation (TTV). The kerf loss of slurry-based sawing is generally higher than for diamond wire based sawing. Today's kerf loss of about 135 µm for slurry-based and 110 µm for diamond wire-based sawing is predicted to decline to 60 µm by 2027. This underscores the long-term advantages of diamond wiring technology, leading to a higher market share for diamond wiring, as shown in Fig. 6 and Fig. 7. Nevertheless, the reduction below 70µm kerf loss is not yet suitable for mass production as the red color coding indicates, but seems possible according some of our contributors. Today's TTV is 25 µm for it is expected to decrease only slowly – to around 20/17.5µm for slurry and diamond wire sawing respectively.

Optimizing productivity is essential to stay 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. In order 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. Fig. 23 summarizes the expected throughput of cell production equipment, with synchronized front-end and back-end throughput processes anticipated by 2027.

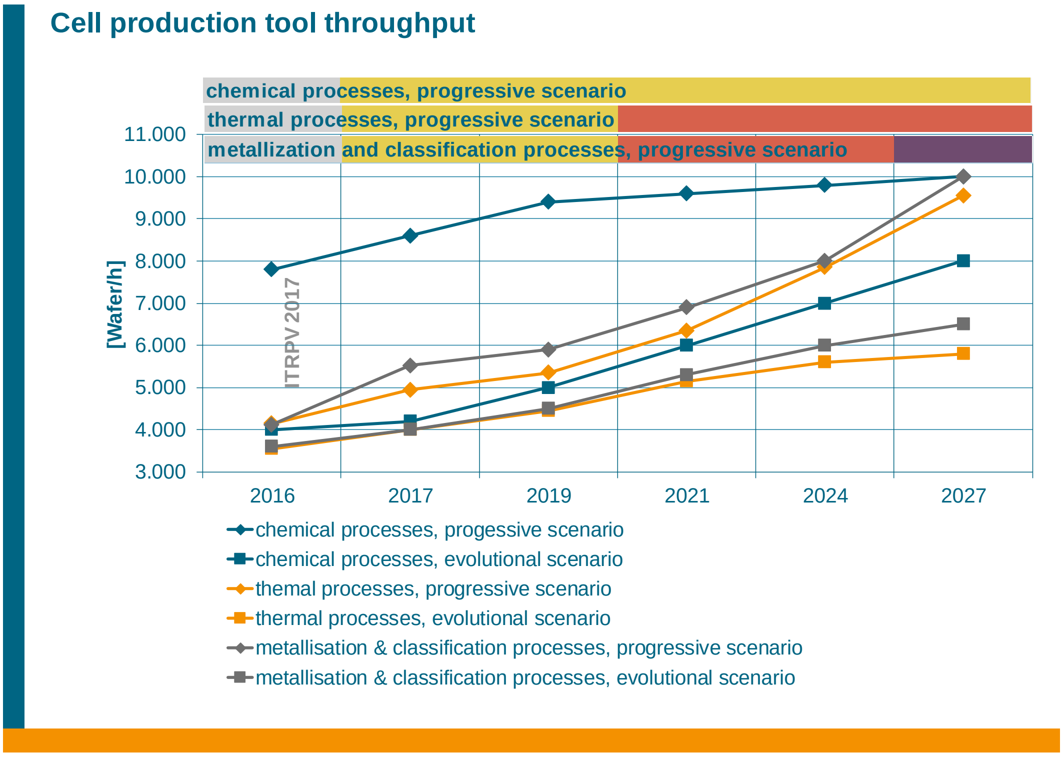

Fig. 23: Predicted trend for throughput per tool cell production tools

Metallization tools with throughputs of > 4000 wafers/h are available on the market today. Further improvements in this field will depend strongly on the progress made with the screen printing technology that currently focuses on smaller line width and lower paste consumption. A maximum of about 10000 wafers/h is expected by 2027 for front- and back-end tool sets.

Wet chemical processing is today leading the throughput development with new machines enabling >7800 wafers/h. The color coding in Fig. 23 describes throughput capabilities by today. Technical solutions are available for chemical processing tools with throughputs of up to 10000 wafers/h as discussed above and indicated by the grey/yellow marking. For new thermal processes and metallization/testing tools technical solutions are available for up to 5400 and 6000 wafers/h respectively, indicated by the grey/yellow coding. For higher throughputs exist solutions, but not yet suitable for production. The purple bar for metallization/testing tools indicates that no solutions are available so far to realize throughputs above 8000 wafers/h.

Two scenarios are considered for a discussion of this topic in more detail. The standard scenario reflects the evolutional optimization approach, which is suitable for batch as well as in-line equipment (the evolutionary scenario). The progressive scenario also enables in-line or cluster line layouts but combines this with fairly new automation concepts and potentially higher process throughputs. Both scenarios are based on the achievement of substantial improvements through new tools, which are necessary to reduce depreciation and labor costs. More optimistic forecasts in previous editions have been offset by the current investment cycle. New "high throughput" equipment is about to be installed on a large scale in mass production during the current investment cycle. Nevertheless, manufacturers are also working in existing lines on continuous process improvements by improving existing tool sets. In addition, they realize process technology upgrades like for PERC as well by implementing new machines.

Single tools with increased throughput in chemical and thermal processing can be implemented, especially in cluster lines as replacements or upgrades as for PERC. New lines will be equipped from the beginning with the new tool concepts that were evaluated during the last years for their mass production capability.

In order to reduce the floor space and hence the cost of module manufacturing, the equipment should occupy less floor space and achieve higher throughput. This should be possible by combining continuous improvements and new developments, particularly for connection and encapsulation processes. For the latter process, new encapsulation materials with shorter processing times would be desirable. The throughput of stringing and lamination tools is expected to increase continuously reaching 130% of the 2016 throughput in 2027.

5.2.2. Processes – technology

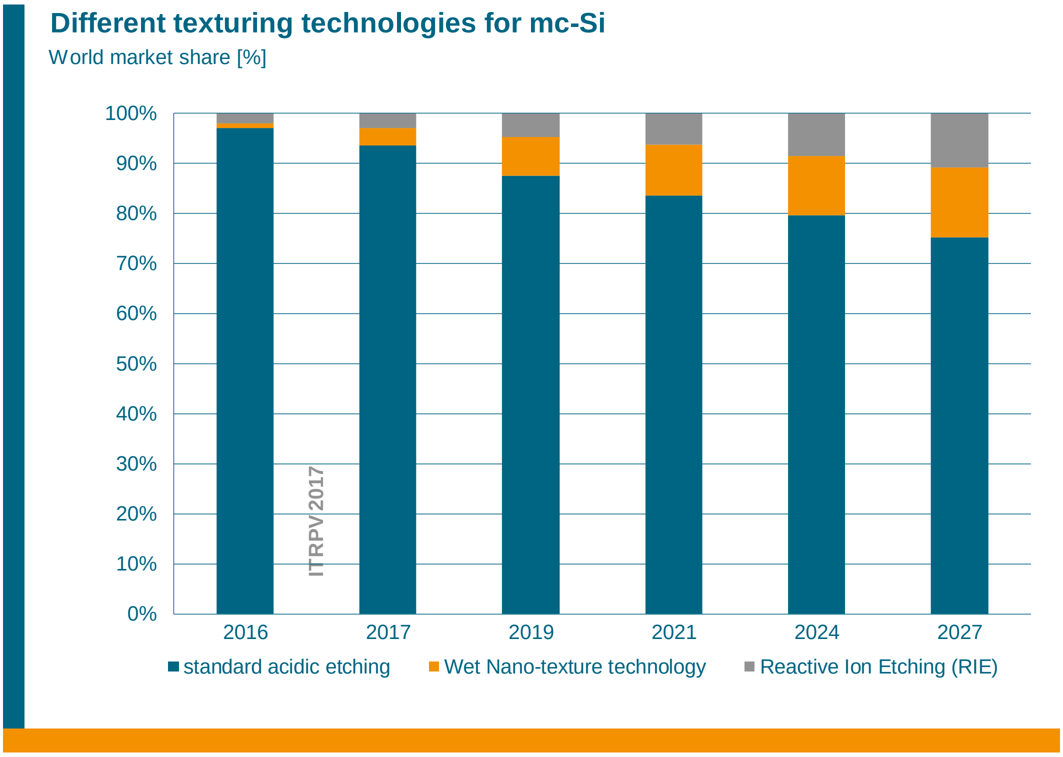

Fig. 24: Expected market share of different texturing methods for mc-Si.

The first production process in cell manufacturing is texturing. Reducing the reflectivity is mandatory to optimize cell efficiency. The expected market share of different texturing methods for mc-Si is shown in Fig. 24. Acidic texturing, a wet chemical process, is mainstream in current mc-Si cell production and is expected to stay mainstream. Wet chemical processing is a very efficient and cost optimized process especially due to its high throughput potential as discussed in Fig. 23. Wet nano-texturing is expected to be an improvement step with increasing market share over the next years. Reactive ion etching (RIE) will only slowly gain market share. The further development of wet chemical etch processes especially for diamond wire sawed mc-Si wafer is mandatory.

Solar cell recombination losses on the front and rear sides of the cell, as well as recombination losses in the crystalline silicon bulk material, must be reduced in line with high-efficiency cell concepts. The recombination currents J0bulk, J0front, J0rear, indicating the recombination losses in the volume, on the cell's front and rear side respectively, are a reasonable way to describe recombination losses. Fig 25 shows that all recombination currents need to be reduced. The values are in line with the assumptions of former ITRPV editions.

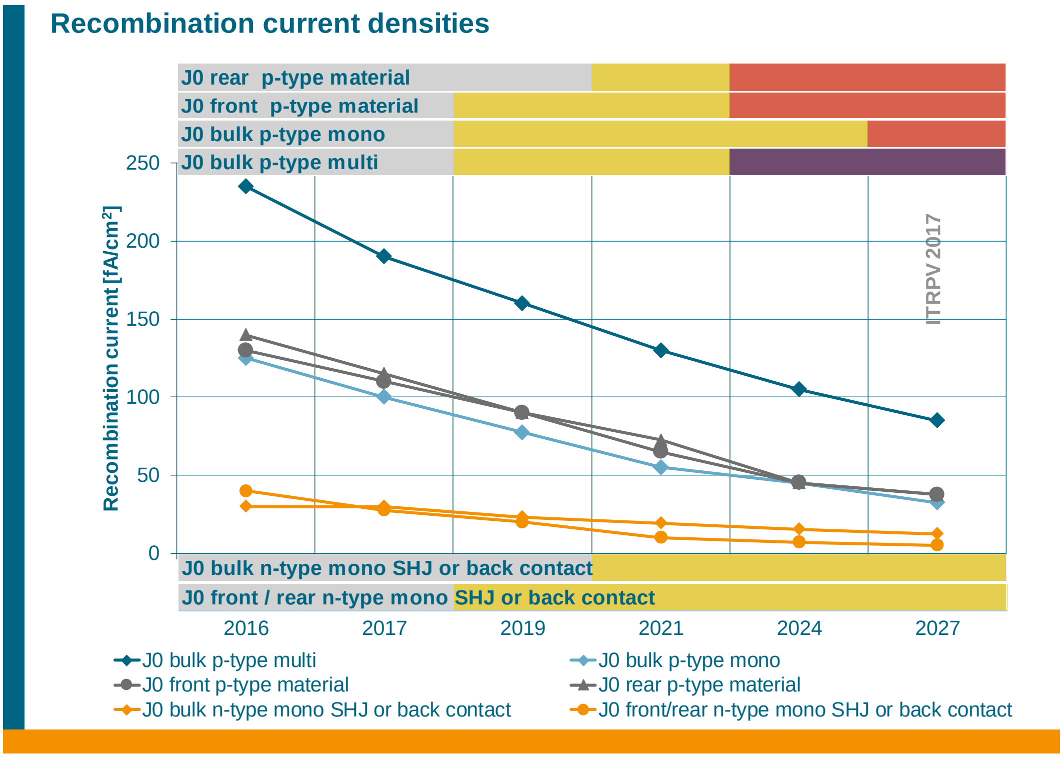

Fig. 25: Predicted trend for recombination currents J0bulk, J0front, J0rear for p-type and n-type cell concepts.

Recombination currents can be measured as described in the literature [17], or they can be extracted from the IV curve if the other J0 components are known.

Color coding in the case of n-type J0 values clearly indicates that technical solutions for lowest recombination current densities are available by today in contrast to the p-type J0 maturity. Here we see that for beside rear side and front side J0 improvements, the development of industrial solutions is required. Technical solutions are not known by today for p-type bulk multi material to reach J0 values below 130fA/cm² – indicated by the purple bar.

The improvement of the silicon material quality for both mono and multi will continue. This should result in a reduction of the J0bulk value to 85fA/cm² for multi and around 30fA/cm² for mono. N-type mono wafers display a J0bulk value of 30fA/cm², which is expected to be further reduced to 5fA/cm² within the next 10 years.

Reductions of J0bulk will result from improvements to the crystallization process (see 5.3). The introduction of improved casted silicon materials (e.g. HPmc-Si, monolike-Si) resulted in lower bulk recombination currents for this material type.

J0 values of front and rear surfaces are similar for different bulk materials. This J0 values are expected to be reduced by up to 70% of the current values by 2027.

Rear-side recombination current values below 200 fA/cm² cannot be attained with an Al Back Surface Field (BSF). Therefore, J0back improvement is linked directly to cell concepts with passivated rear side.

Since 2012, several cell concepts using rear-side passivation with dielectric layer stacks have been introduced to production processes (PERC technology). Fig. 26 shows the predicted market shares of different rear-side passivation technologies suitable for n-type and p-type cell concepts.

PECVD Al2O3 in combination with a capping layer is the most widely used technology for this purpose and is currently rolled out on mass production lines. Other technologies, such as ALD Al2O3 deposition in combination with capping layers are not expected to reach large market-penetration. PECVD SiONx/SiNy will disappear.

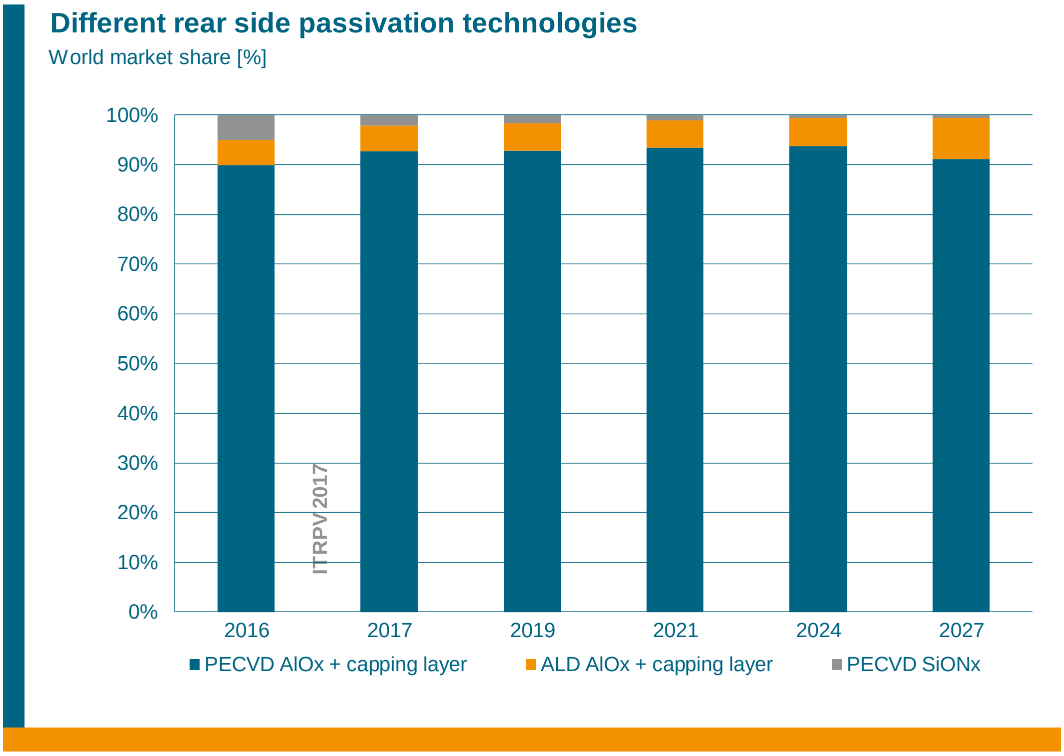

Fig. 26: Predicted market shares for AlOx-based rear-side passivation technologies.

One parameter that influences recombination losses on the front surface is emitter sheet resistance. The predicted trend for n-type emitters is shown in Fig. 27. It can be seen that an emitter sheet resistance between 90 and 100 ohm/square became mainstream in today's industry.

Increased sheet resistances above 100 Ohm/square are realized with and without selective emitters. If a selective emitter is used, sheet resistance shall refer only to the lower doped region, whereas J0front includes all relevant front-side parameters (emitter, surface, contacts).

Sheet resistances equal or exceeding 120 Ohm/square and up to 135 Ohm/square are expected to be in production starting in 2021. However, those emitters will require further improvements in terms of contact formation. Nevertheless, technical solutions for higher emitter sheet resistances are available by today as the grey/yellow marking indicates.

Fig. 28 shows the expected world market share of different technologies for phosphorous doping in p-type cell processing. Homogenous gas phase diffusion is a mature, cost efficient doping technology and will remain the mainstream for the years to come, despite the availability of other technologies.

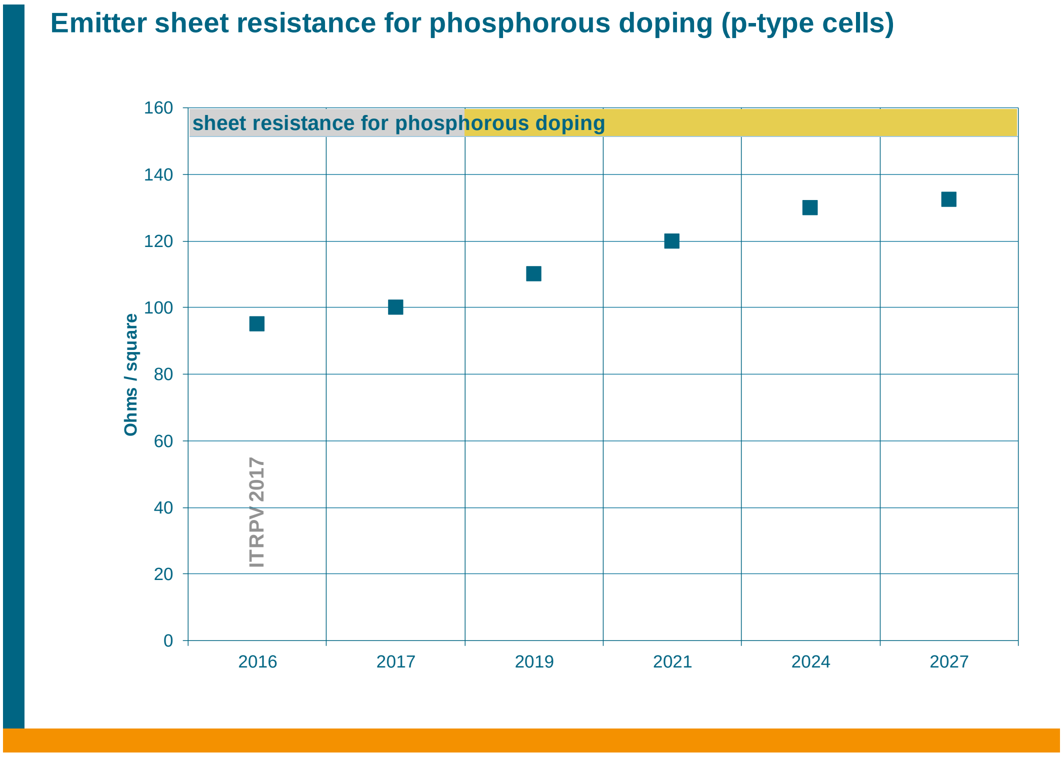

Fig. 27: Expected trend for emitter sheet resistance.

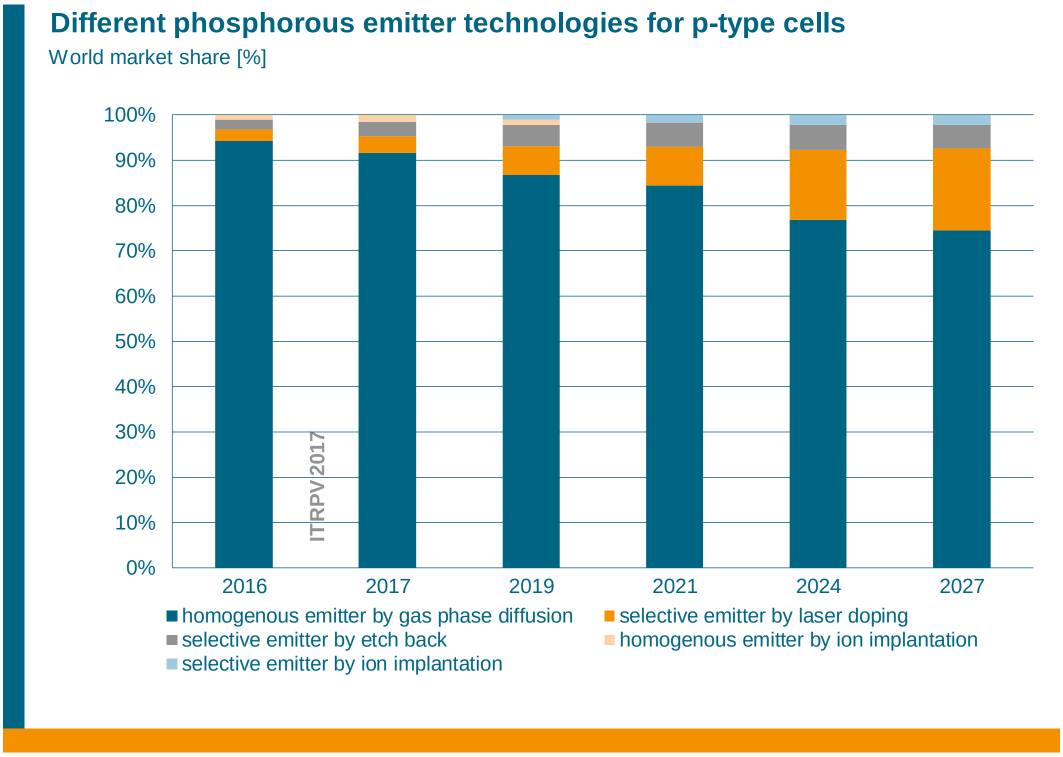

Fig. 28: Expected world market share for different phosphorous emitter technologies for p-type cells.

Nevertheless, selective emitter processes are expected to be used in mass production with shares of >10% by 2019. Ion implantation for homogeneous doping will disappear. Like in the 7th edition of the ITRPV, we discuss below technologies for boron doping, especially for n-type cells. Fig 29 shows the expected market share for the different boron doping technologies.

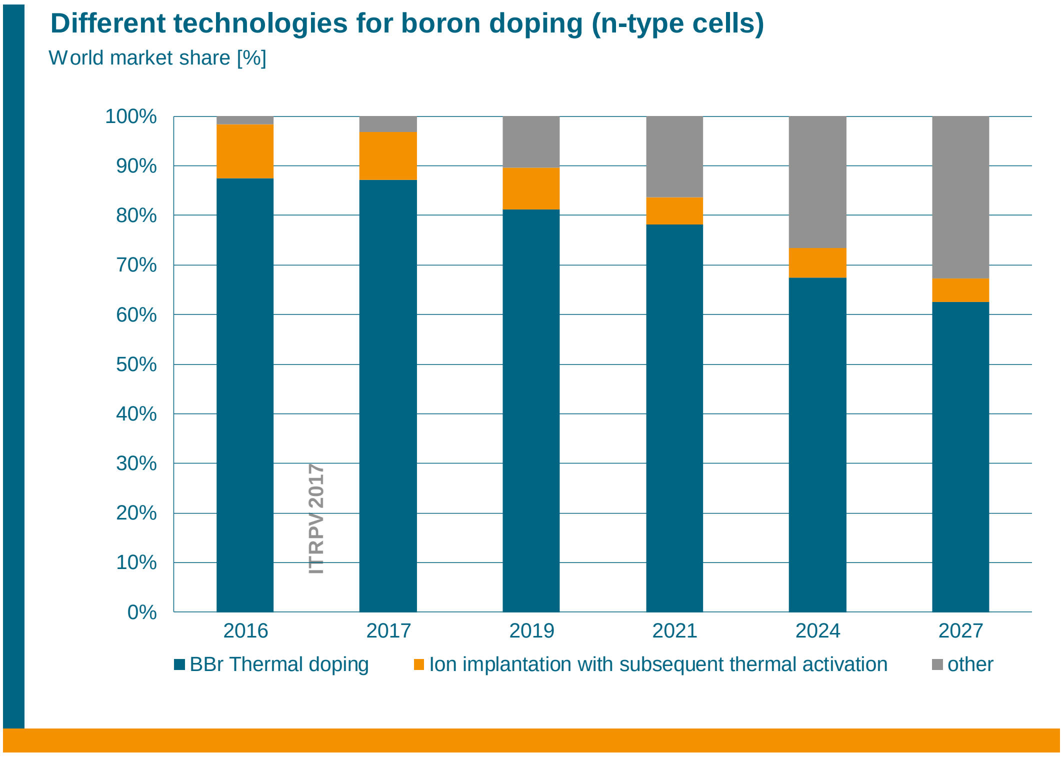

Fig. 29: World market share for different technologies for boron doping (n-type cells).

In line with the findings of the 7th edition we expect that the currently most widely used BBr thermal diffusion technique is expected to stay mainstream. Ion implantation is supposed to be applied in production but significantly reduced. Alternative doping technologies such as APCVD/PECVD of doped layers in combination with thermal diffusion are expected to have a high potential for implementation until 2027.

Front metallization is a key process in the production of c-Si solar cells. New front-side metallization pastes enable the contacting of the previously discussed low-doped emitters without any significant reduction in printing process quality.

A reduction in finger width is one method yielding in efficiency gain and cost reduction, but only if it is realized 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 a selective emitter structure, preferably without increasing processing costs. Fig. 30 shows that finger widths of 48 µm are currently applied in production processes. Widhts of down to 30 µm are ready for the industrial implementation and may be rolled out faster than indicated. A further reduction to 25 µm appears possible over the next 10 years but needs further development from today's point of view as indicated by the red bar. Reducing finger width increases efficiency, but a trade-off has to be made if the roadmap for silver reduction as discussed in 5.1.2 will be followed. Different approaches for improving the printing quality are possible. Single print technology is currently the mainstream technique used, followed by double printing. Double printing requires an additional printing step and good alignment. A third, more robust technology — the dual print — separates the finger print from the busbar print, enabling the use of busbar pastes with less silver. New busbar less cell interconnect techniques can even omit the bus bars completely. These techniques were discussed in the 5th edition. Therefore, and for reliable module interconnection a good alignment accuracy is important in metallization — an alignment accuracy of about 10 µm (@+/- 3 sigma) will be required from 2019 onwards as shown in Fig 30.

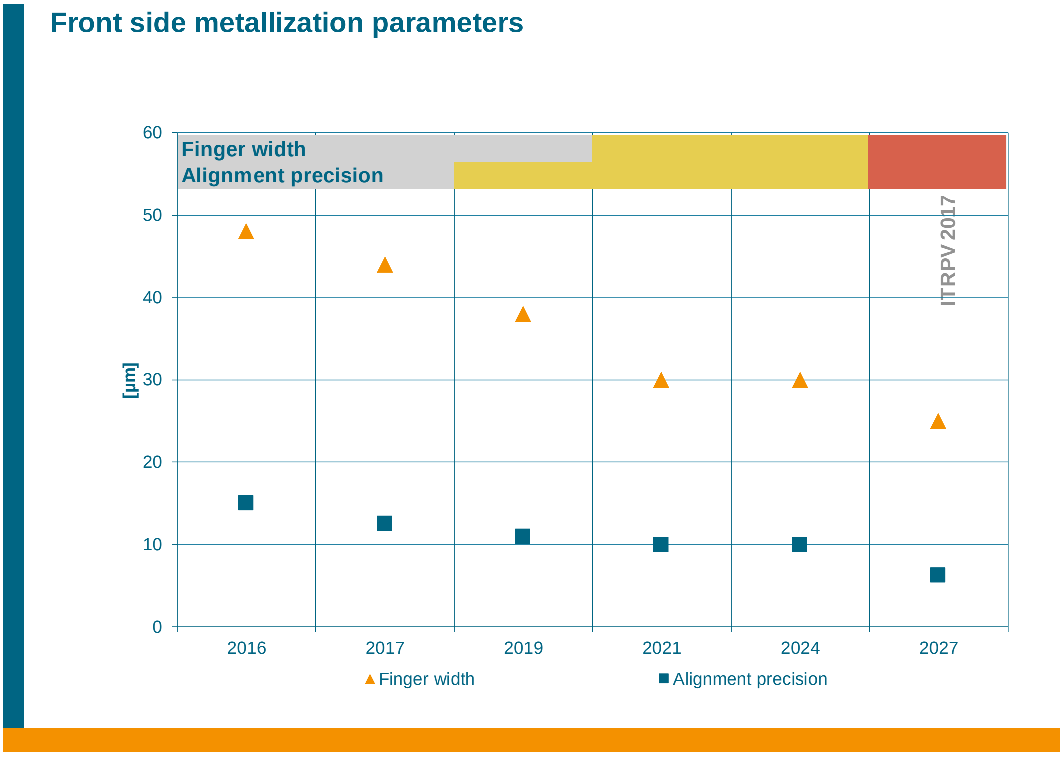

Fig. 30: Predicted trend for finger width and alignment precision in screen printing. Finger width needs to be reduced without any significant reduction in conductivity.

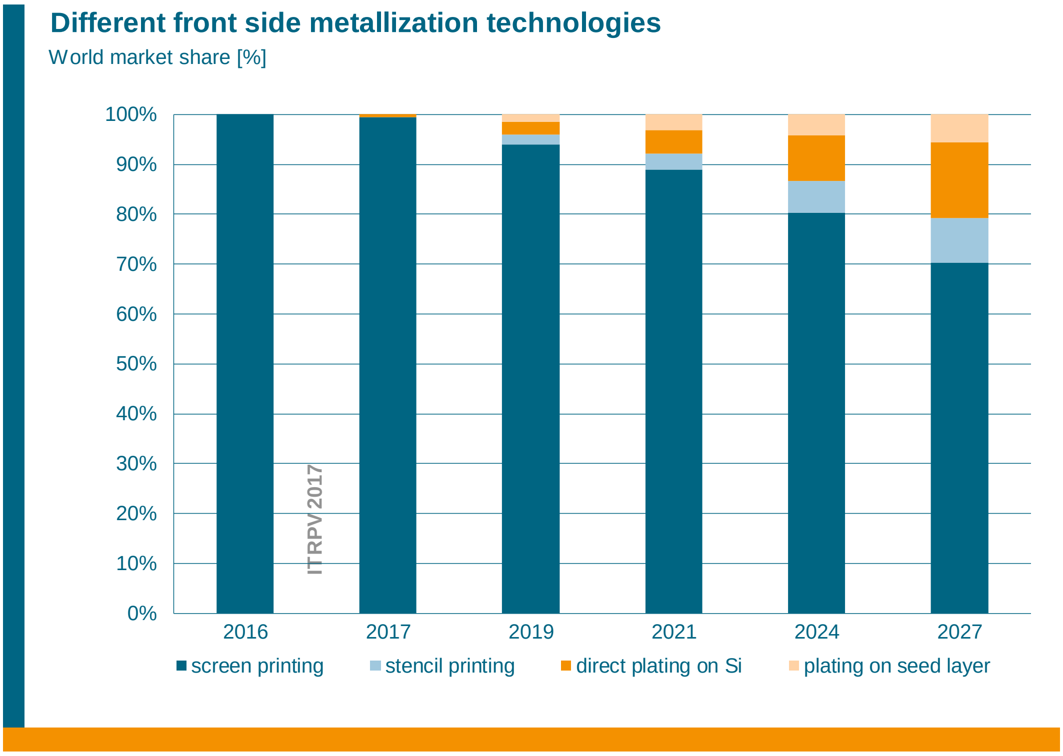

Fig. 31a: Predicted trend for different front side metallization technologies.

The expected share of different technologies for front side and rear side metallization are shown in Fig. 31a and 31b respectively. Fig. 31a shows that classical screen printing is expected to remain the mainstream technique for the years to come in front side metallization. Stencil printing, which can be used with existing screen printing equipment, is expected to be introduced in mass production starting in 2018. Plating technologies are expected to attain a market share of about 20% in 2027.

Screen printing as well is expected to remain the mainstream technology in rear side metallization for the next years as shown in Fig. 31b. Plating, especially used for rear side contact cells, is expected to gain slowly market share of around 10% in 2027. Physical vapor deposition (PVD) by evaporation or sputtering is expected to appear as niche application.

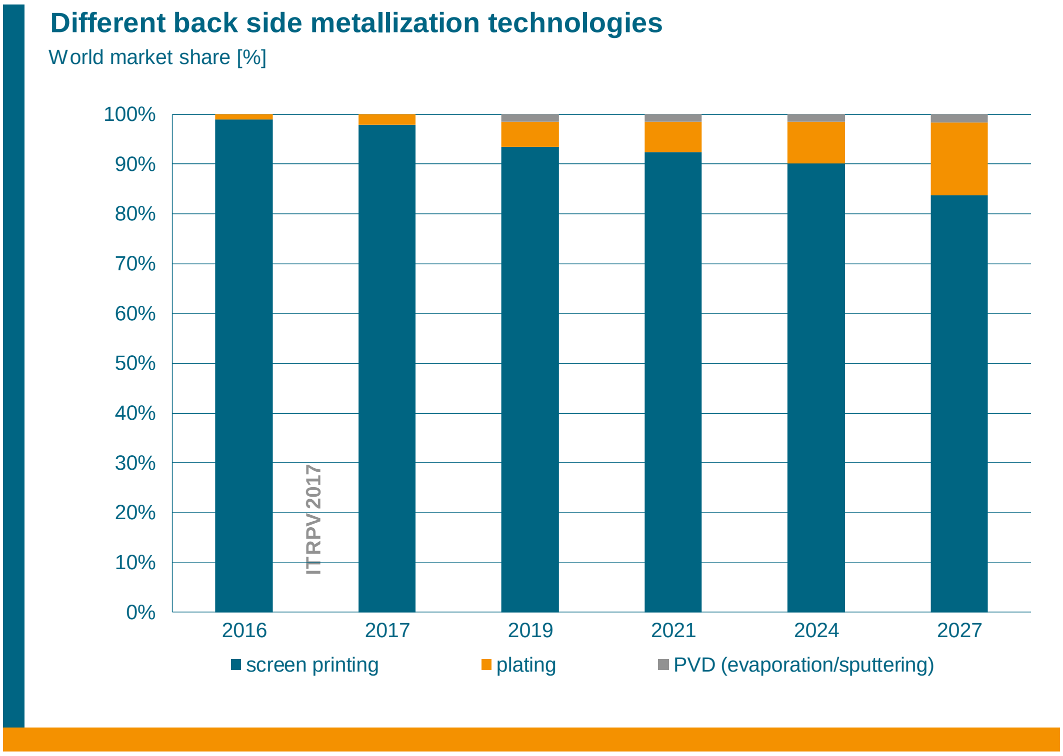

Fig. 31b: Predicted trend for different rear side metallization technologies.

A current trend in metallization relates to the number of busbars (BB) used in the cell layout. Fig. 32 shows the expected trend. We see that the 3-BB layout, still dominating in 2016, will be fast replaced over the next years by 4- and 5/6-BB - and by BB-less layouts. BB-less technologies support minimum finger widths as shown in Fig. 30. Nevertheless, this will require new interconnection technologies in module manufacturing that cannot be implemented by upgrading existing production tools.

It is crucial to get as much power out of the assembled solar cells as possible. The cell-to-module power ratio is a good parameter to describe this behavior. It is defined as module power divided by cell power multiplied by the number of cells (module power / (cell power x number of cells)). This ratio was 2016 at 99.5% for mc-Si cell technology (acidic texturing) and about 98% for mono-Si cell technology (alkaline texturing), as shown in Fig. 23.

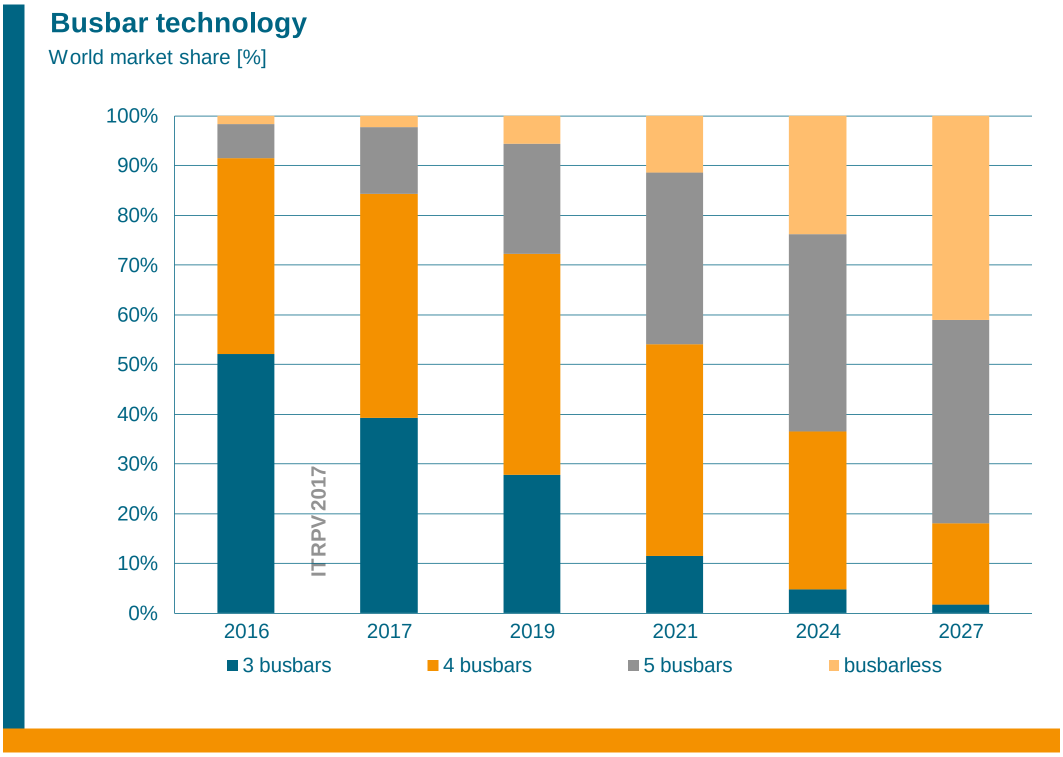

Fig. 32: Worldwide market share for different busbar technologies.

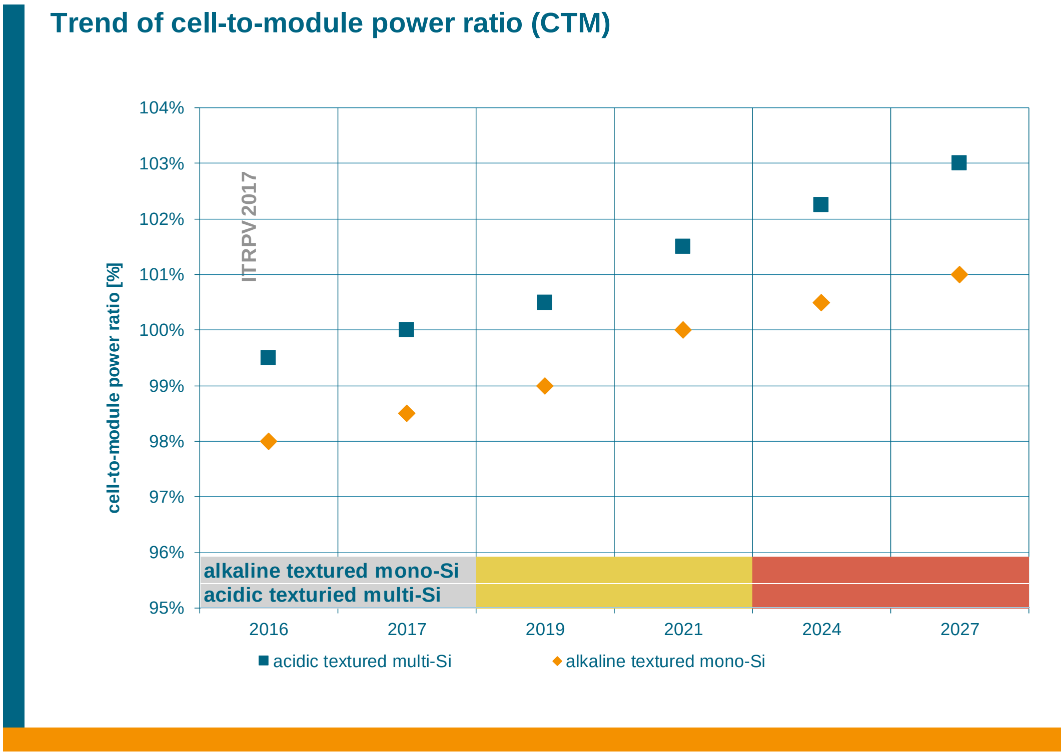

Fig. 33: Expected trend for the cell-to-module power ratio.

The cell-to-module power ratio is expected to exceed 100% for both cell types but not as fast as expected in the 7th edition. This implies that the power of the finished module will exceed the power of the cells used in the module. Such effects will be enabled by further improvements of light management within the module as a means of redirecting light from inactive module areas onto active cell areas. The introduction of new interconnection and encapsulation technologies (e.g. narrower ribbons, encapsulants with improved UV performance, etc.) will result in further improvements that will enable additional power gains. Technical solutions are available by today for alkaline and acidic texturing to reach CTM values of 100% and 101.5% respectively and may be rolled out even faster than assumed as the grey/yellow coding indicates. Solutions to go beyond this limits are currently not suitable for production and require further development as indicated by the red color coding.

The junction box is the electrical interface between the module and the system. We found that the internal electrical connection of the bypass diodes will be done mainly by soldering and welding, clamping will be used less. Also, we found that the current single junction box concept is expected to shift to multiple junction box as mainstream from 2019 onwards.

In line process control becomes more and more important to ensure high production yields and long-time product reliability. Fig.34 and Fig. 35 summarize the assumptions about in-line cell process control of important process parameters. The quality control of the front side antireflective (AR) layer is very common in the industry while wafer incoming inspection and sheet resistance measurement will be deployed more widely during the next years.

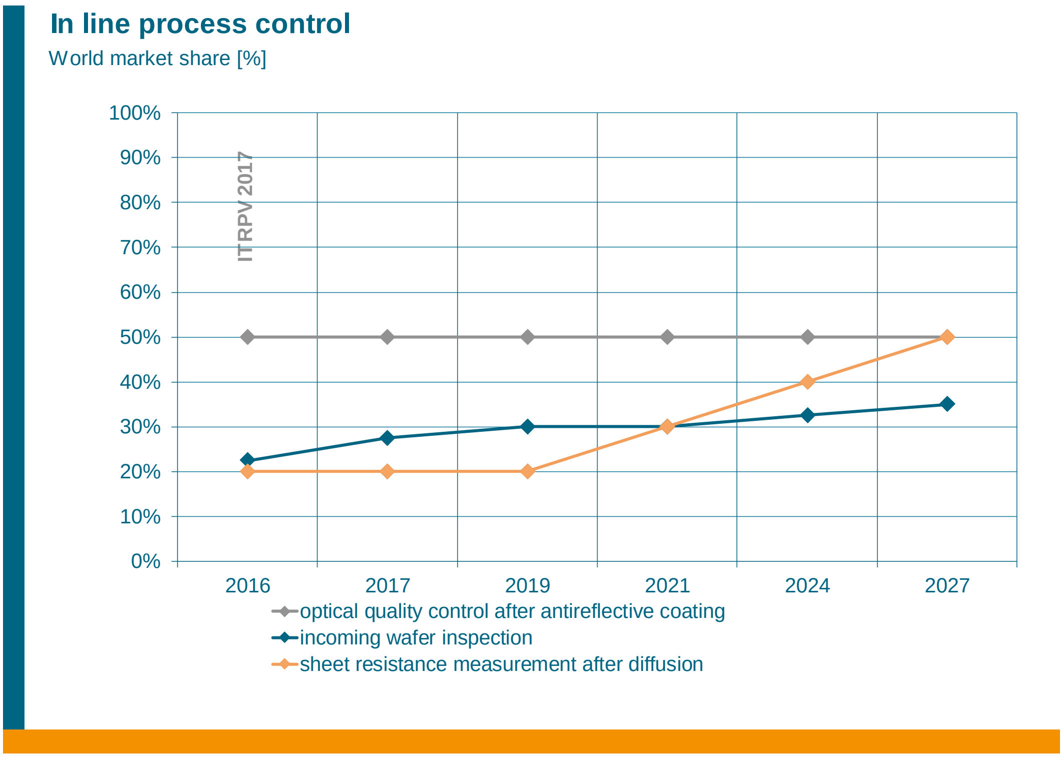

Fig. 34:. Market share of in line process control for sheet resistance, incoming wafer quality, and cell front side antireflective coating quality.

Fig. 35 shows that in printing, automatic optical inspection (AOI) of printing quality is widely used and that the share will even increase. For cell test parameters like EL and infrared imaging the current market share is about 5% but it is expected that the share will increase to 65% and 20% respectively.

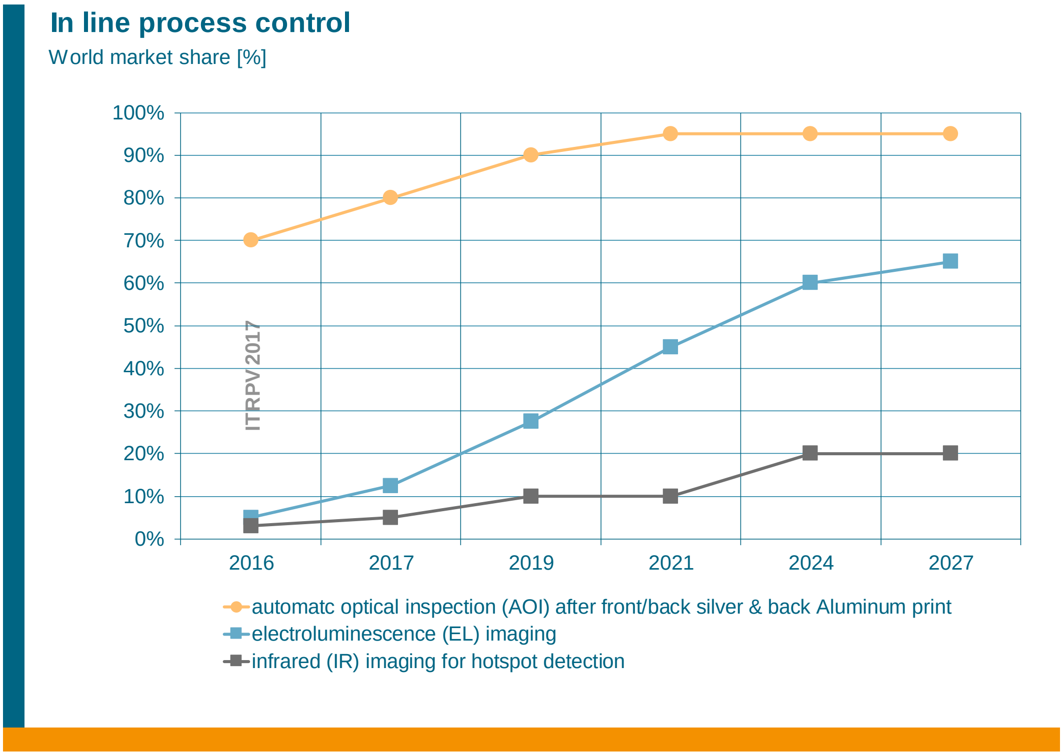

Fig. 35: Market share of in line process control for printing, electroluminiscence (EL) imaging, and infrared (IR) imaging at cell test.

5.3. Products

Casted materials dominate today's wafer market for c-Si silicon solar cell manufacturing and it had an assumed market shares 65%. This is in line with the IHS Markit assumption [15]. However, this market share will eventually shrink to below 40% in 2027. Simply distinguishing between mono-Si and mc-Si, as was done some years ago, is insufficient. The c-Si materials market is further diversifying, as shown in Fig. 36. High-performance (HP) mc-Si material dominates the casted silicon market. Due to its excellent performance, this material is about to replace conventional mc-Si completely. Monolike-Si will stay present at a negligible share.

Mono-Si will make gains over casted material and will attain a share of 60% in 2027. The overall trend of increased mono-Si market share is in line with the assumptions of the 7th edition. We predict a market share of p-type mono-Si of about 30% for the years to come and a slower increase of n-type mono-Si compared to the 7th edition of >25% in 2027. This is mainly due to the tremendous progress in stabilizing p-type mono.

Fig. 37 and Fig 38 show the ITRPV analysis of the market share of different wafer dimensions for mc-Si and mono-Si wafers respectively. The new wafer formats first appeared in 2015. The move from 156x156mm² to the slightly larger format of 156.75x156.75mm² in mass production started 2016. The transition to 156.75x156.75mm² is faster for mono-Si as can be seen by the predicted 2019 share of 70% for mono vs. 56% for mc-Si. An even larger format was introduced by one cell and module manufacturer in 2016. We assume that a larger format of 161.75x161.75mm² will also be introduced in the market for mc-Si and mono-Si. Standardization of wafer dimensions is highly recommended in order to enable tool manufacturers to provide the right tools and automation equipment. The dimension change for mono-Si is assumed to go in parallel with an increase in diameter of the pseudo square wafers from the old 200mm to mainly 210 mm as new mainstream.

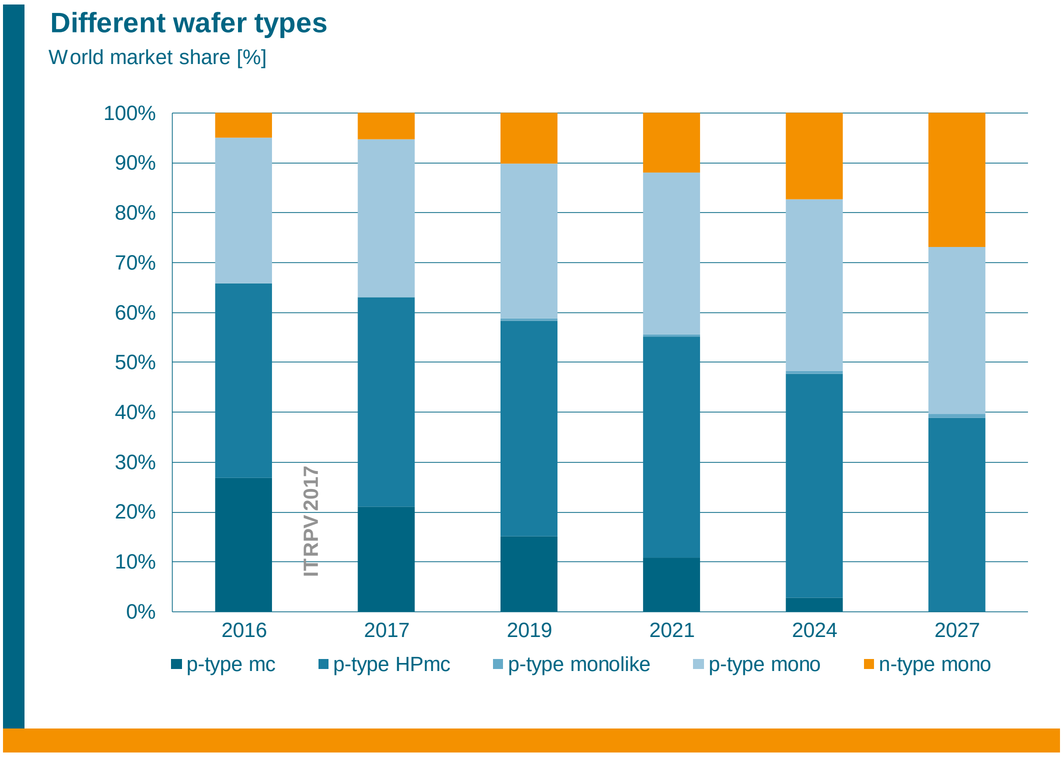

Fig. 36: World market shares for different wafer types.

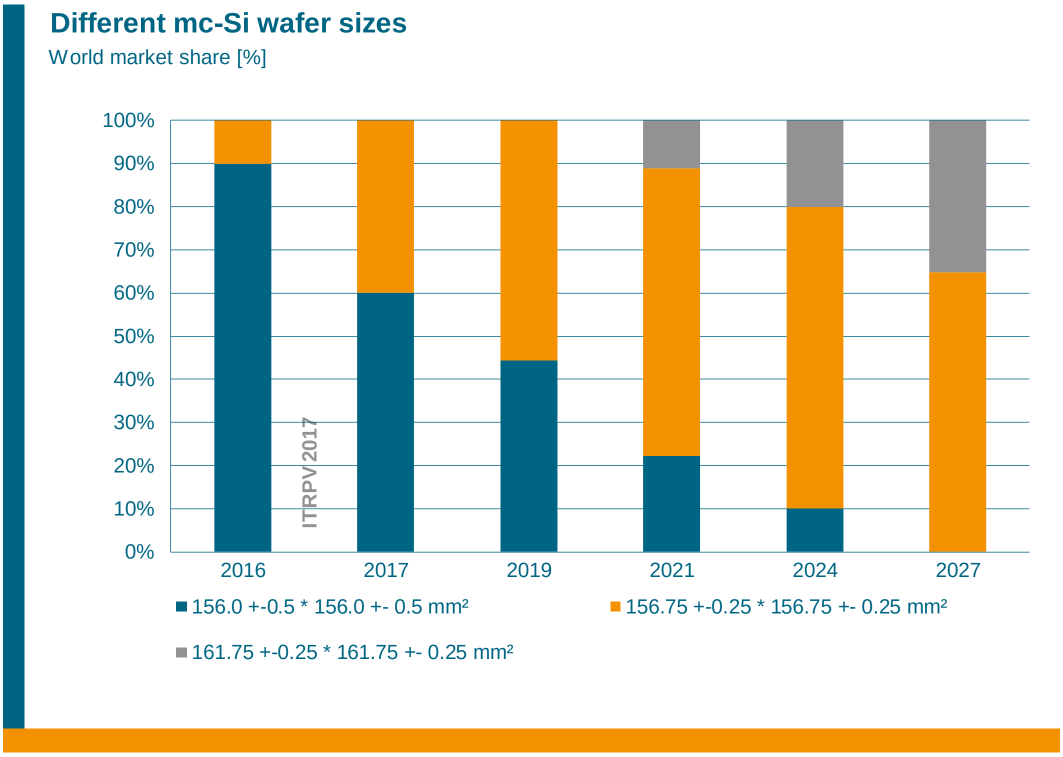

Fig. 37: Expected trend of mc-Si wafer size in mass production.

The roadmap also confirms that pseudo square wafers will dominate the market over full square wafers. Nevertheless, we expect that the share of full square wafers will increase to about 5% from 2019 onwards.

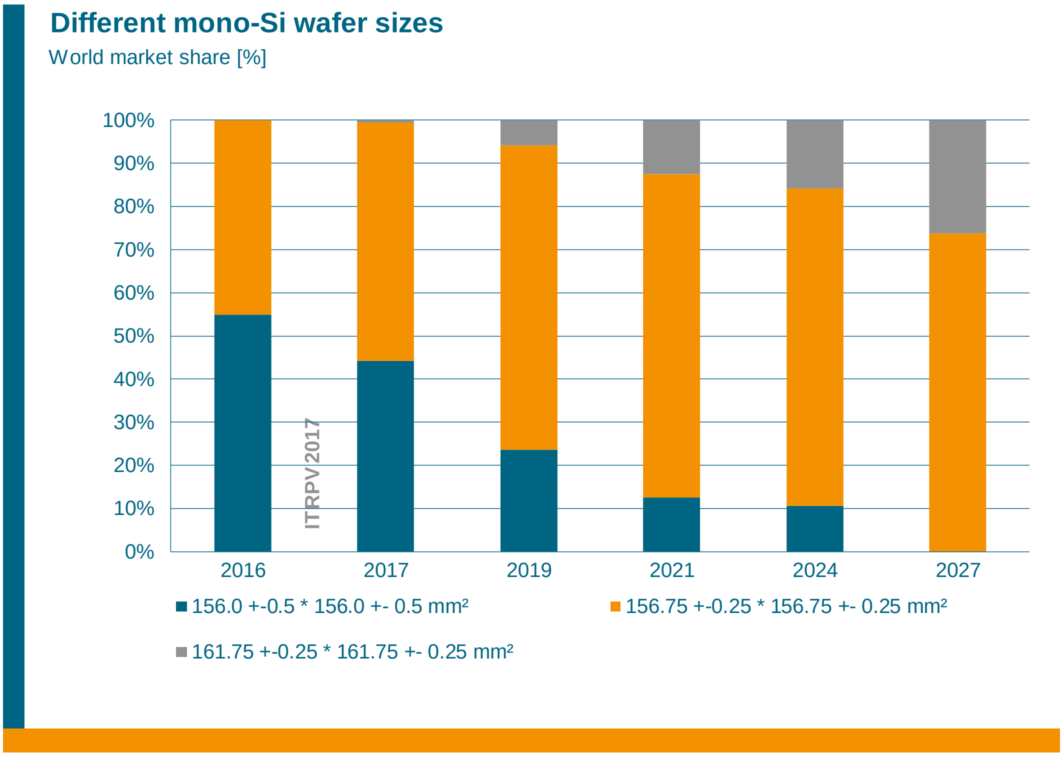

Fig. 38: Expected trend of mono-Si wafer size in mass production.

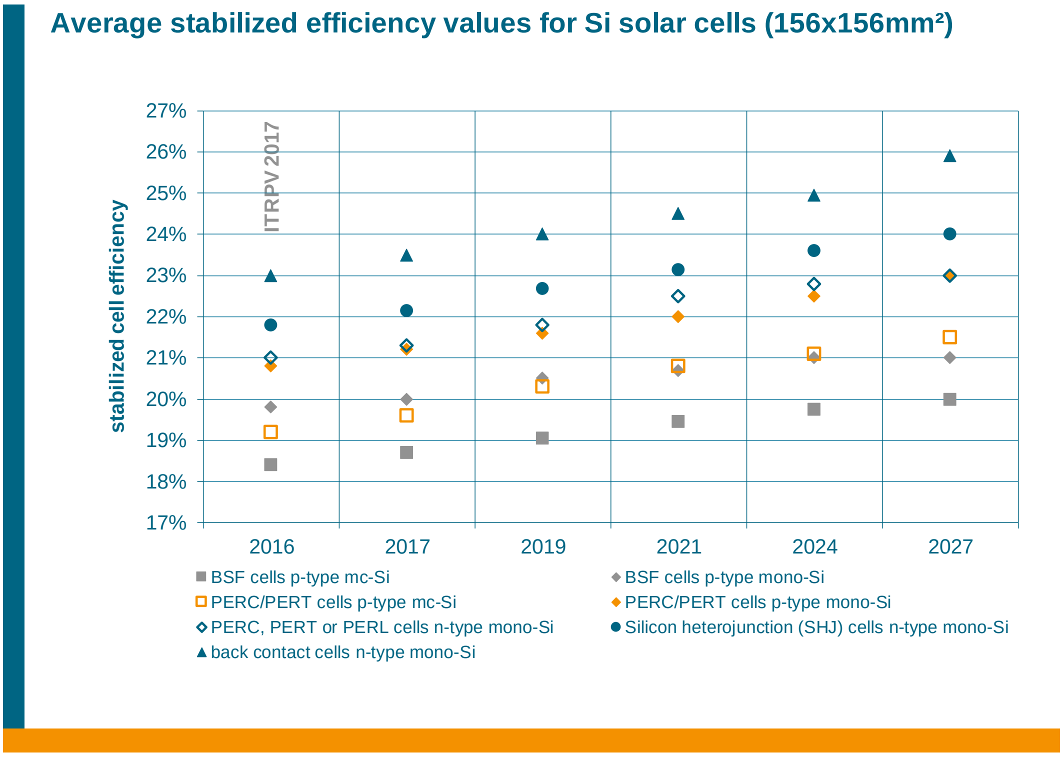

Fig. 39: Average stabilized efficiency values of c-Si solar cell in mass production (156 x 156 mm²).

Fig. 39 shows the expected average stabilized efficiencies on 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 big potential for all technologies to improve their performance. N-type cells show the highest efficiency potential. Nevertheless, there will be nearly no efficiency delta for double-side contacted mono n- and p-type cells in the future. It is expected that p-type mono cells will reach 23%. N-type-based cell concepts like HJT and back-contact cells, will reach higher efficiencies.

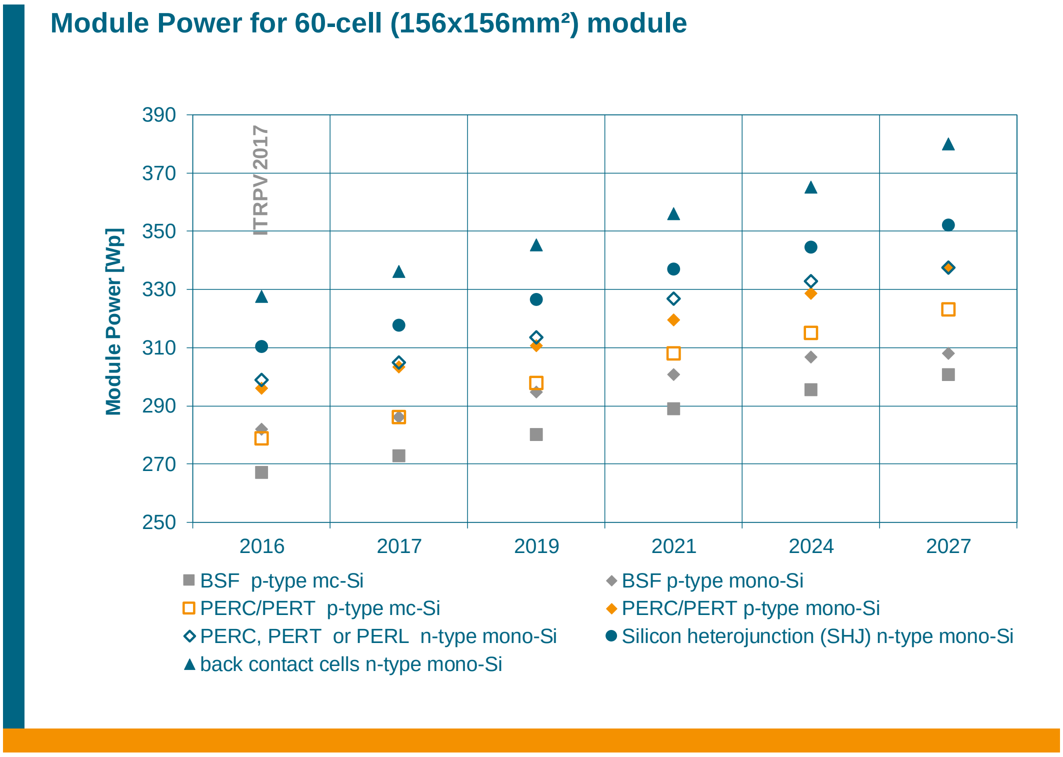

Fig. 40: Predicted trend curve for module power of 60-cell modules for different c-Si cell types.

Fig. 40 shows the corresponding development of module power for typical 60-cell modules with 156 x 156 mm^2 cells, considering the cell efficiencies shown in Fig. 39 and the cell-to-module power ratio trend shown in the previous Section (Fig. 33). We assume acidic texturing for mc-Si and HP mc-Si and alkaline texturing for mono-Si. We consider pseudo-square wafers with diagonals of 210 mm as mono-Si material.

It should be noted that for modules with high efficiency back-contact cells, which are not yet available on 156 x 156 mm^2 wafers, the module power values given in Fig. 40 represent equivalent values in order to enable a better comparison with double-side contact technologies.

Modules with 60 cells based on HP mc-Si will achieve module power above 320 W by 2027. Modules with p-type mono-Si will surpass 300 W in 2017 and will achieve a power output in the range of nearly 340 W by 2027, as shown in Fig. 40.

The current edition of the ITRPV confirms a mainstream market for double-sided contact cell concepts; within this market, PERC/PERT/PERL cells will gain significant market share over BSF cells, as can be seen in Fig. 41. Secondly, heterojunction (HIT/HJT) cells are expected to gain a market share of 10% in 2024 and 15% by 2027. The share for rear-side contacted cells is not expected to exceed 10% within the next ten years. Si-based tandem cells are expected to appear in mass production operations after 2019.

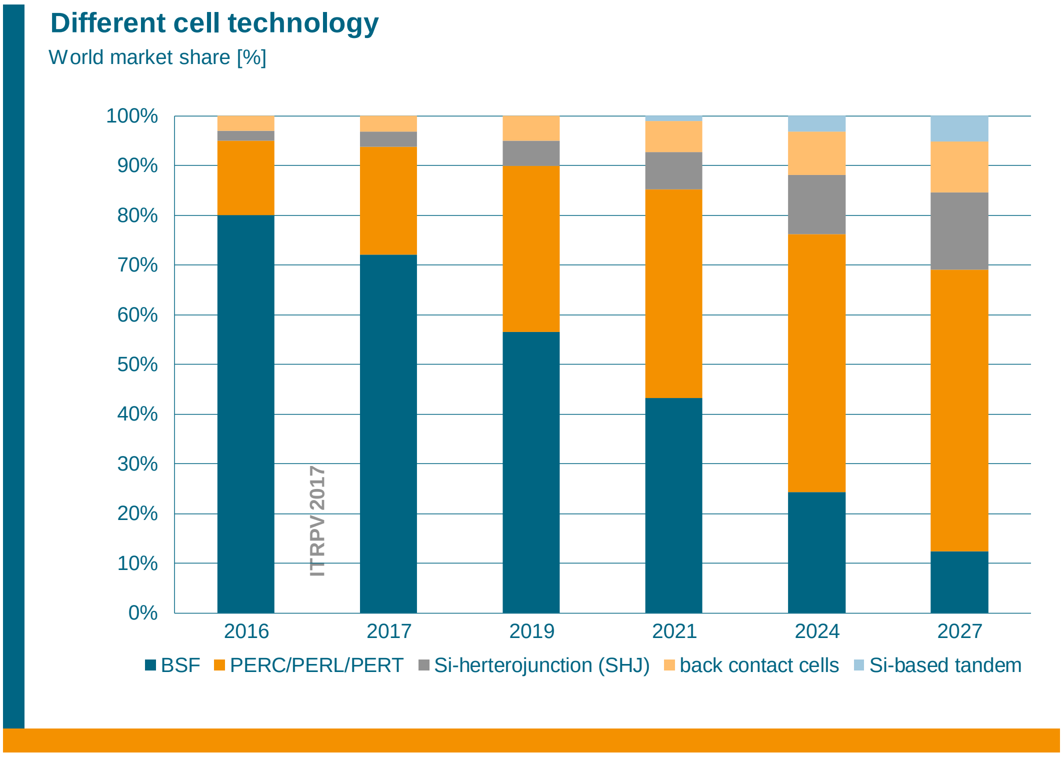

Fig. 41: Worldwide market shares for different cell technologies.

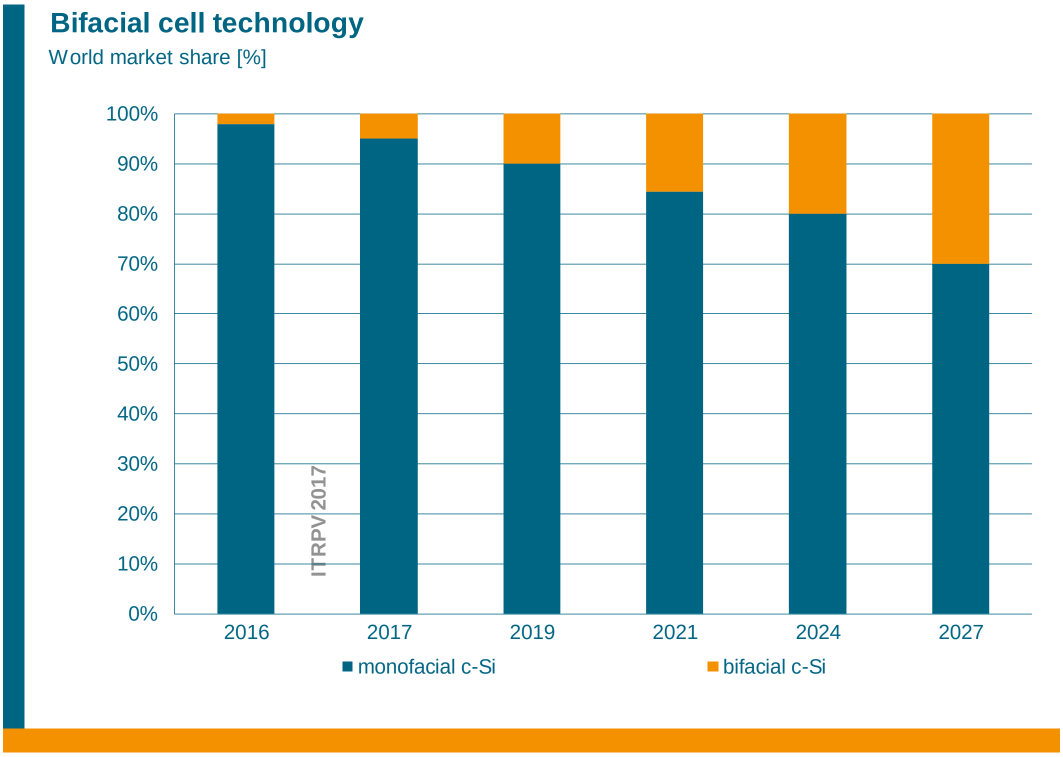

Fig. 42: Worldwide market shares for bifacial cell technology.

Furthermore, it is expected that an increasing number of cells will be light-sensitive on both sides, so called bifacial cells. Our research predicts that the percentage of bifacial cells will steadily increase to about 30% by 2027 as shown in Fig. 42.

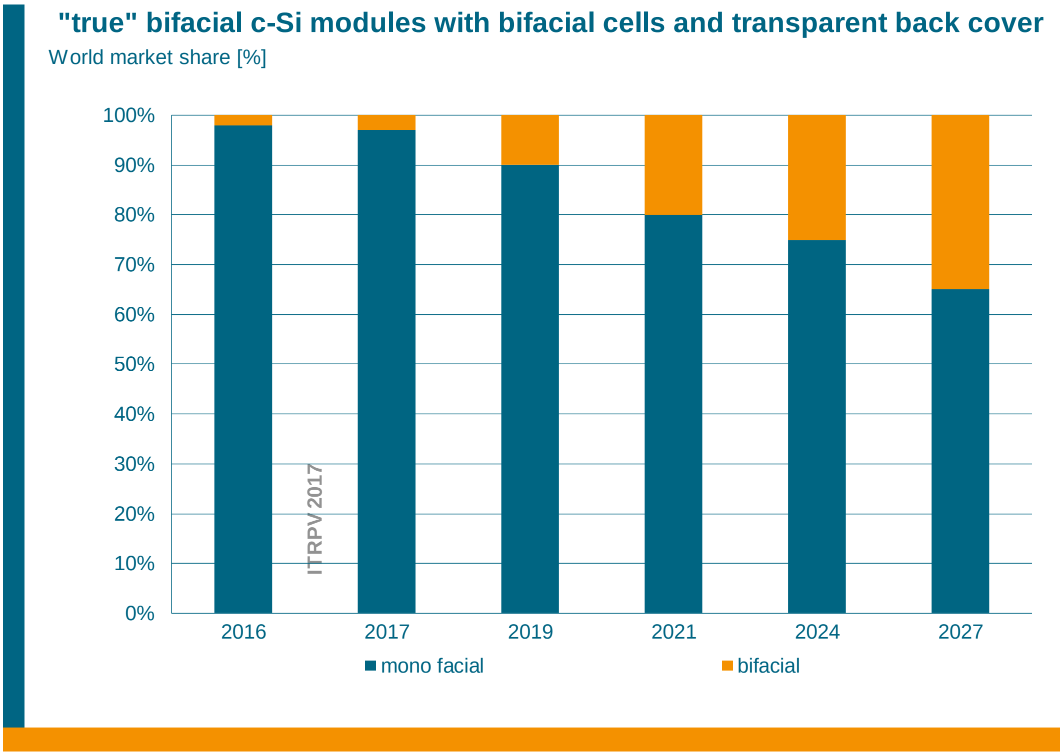

Fig. 43: Worldwide market shares for monofacial and “true” bifacial modules.

In addition, Fig. 43 shows the expected share of “true” bifacial modules with transparent back sheet or glass as back cover. Bifacial modules are more and more appearing in the market. Their share in the market after 2020 appears to be slightly higher than that of bifacial cells shown in Fig. 42. Nevertheless, the expected trend towards a higher market share is similar to that of bifacial cells.

Modules that use half-sized cells rather than full-sized cells were recently introduced in the market in order to reduce interconnection losses. Since this technology requires the additional process step of cutting the cells, as well as a modification of the stringer equipment, it has an impact on cell and module manufacturing. As shown in Fig. 44, it is expected that the market share of half cells will grow from 2% in 2016 to about 35% in 2027

Fig. 45 shows that the module market splits into two main sizes: 60-cell and 72-cell modules. 96-cell modules are appearing in special markets. The larger module sizes are mainly used in utility applications. Other module sizes for niche markets (e.g. 48 and 80 cells) are expected to account for 2% of the market during the next years. Today’s mainstream modules (60-cells) will have a market share of only about 30% in 2027.

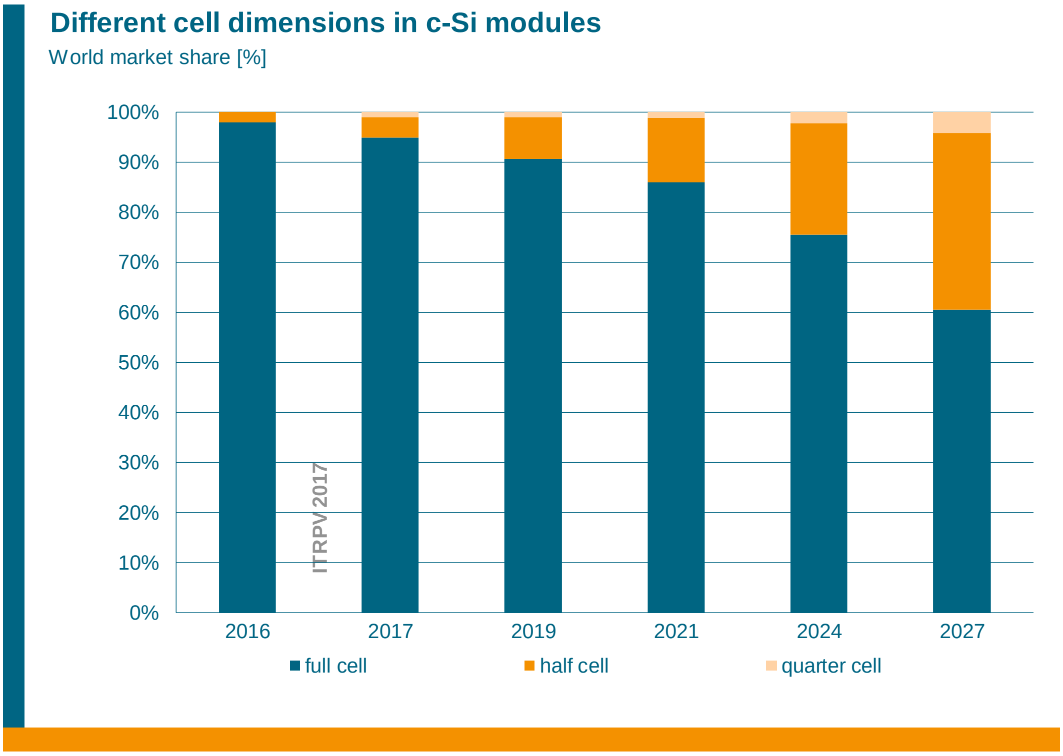

Fig. 44: Predicted market shares for modules with full and half cells.

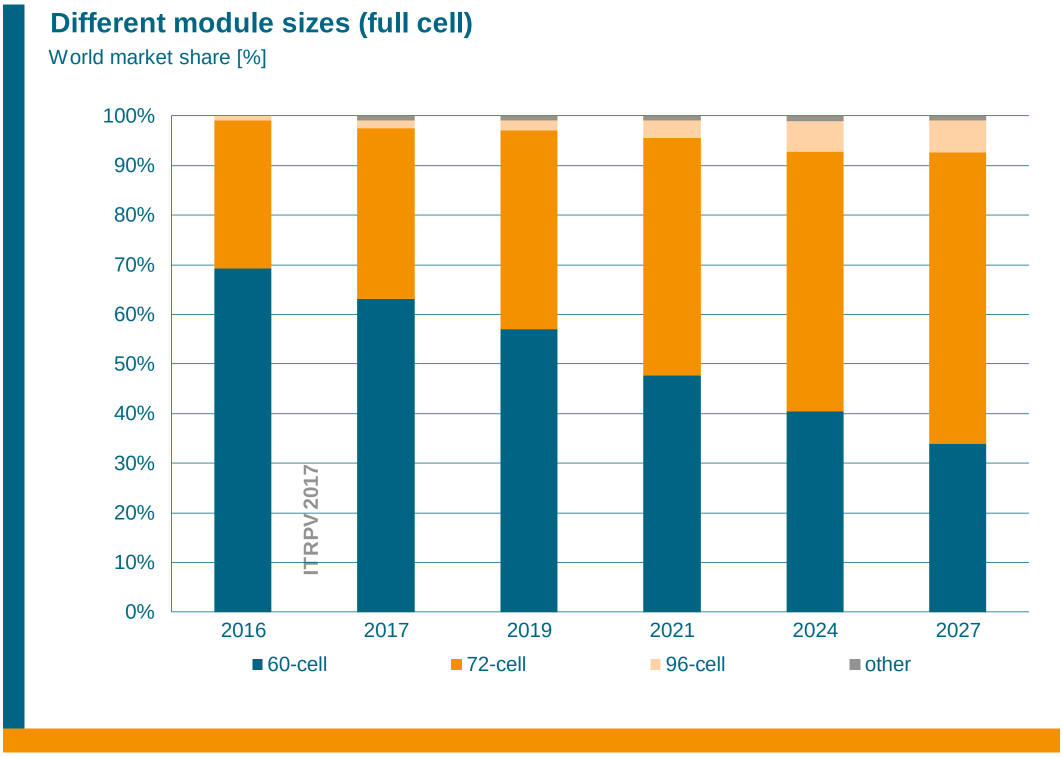

Fig. 45: Market shares of different module sizes with 156x156mm² cells.

One option to save costs on module level is to move to frameless modules.

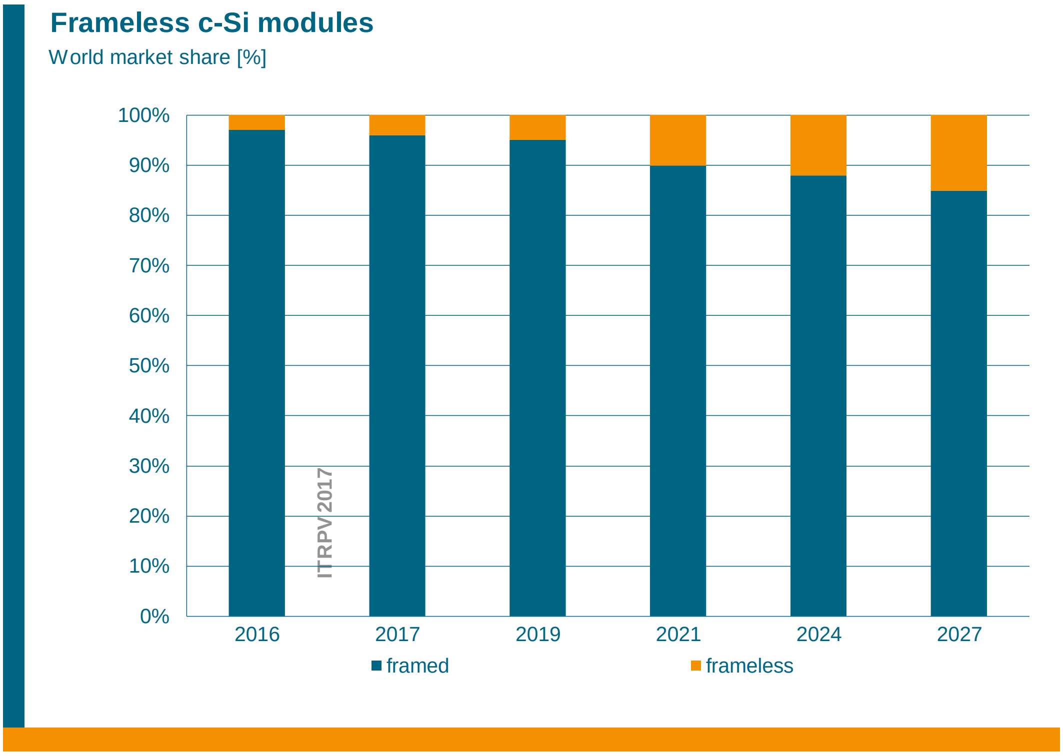

Fig. 46: Market share for framed modules.

As can be seen in Fig. 46 it is expected that the fraction of frameless c-Si modules will increase from around 3% in 2016 to 15% in 2027. As the frame is an important element to ensure the mechanical stability of the module, frameless modules most likely will be double glass modules with glass as

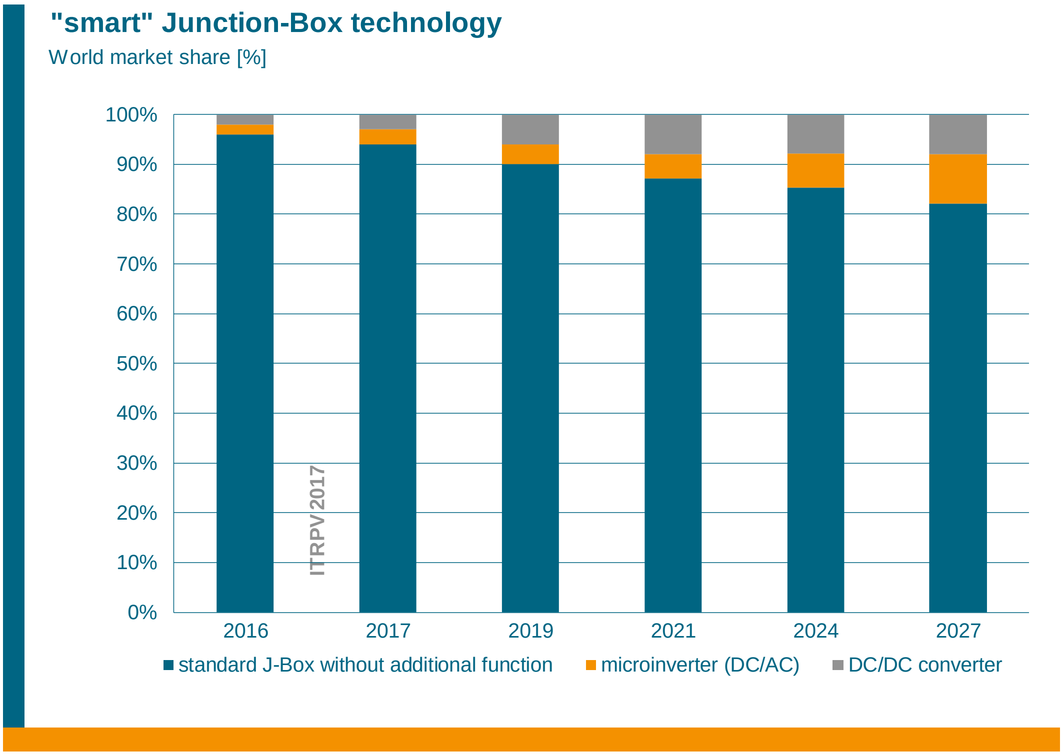

Fig. 47: Market trend for different J-Box functionalities.

front and as rear cover. It should be noted, that with increasing module size the requirements for the mechanical elements such as glass and frame, which predominantly determine the mechanical stiffness become more and more demanding. This could be one of the reasons, why the fraction of frameless modules remains relatively small during the next decade, despite a noticeable cost saving potential for frameless modules.

So-called smart J-Box technologies are anticipated to improve the power output of PV systems. As can be seen in Fig. 47, the participants in our survey believe that the standard J-Box without any additional function except the bypass diodes will clearly dominate the market over the next 10 years. DC/AC micro-inverters are expected to increase their market share to around 10% by 2027. DC/DC converters (so- called power optimizers) are expected to attain a market share of around <10% in the same period.

6. PV systems

Due to the significant reduction of PV module prices over the last few years, balance of system (BOS) costs have become a crucial factor in overall system costs and thus the levelized cost of electricity (LCOE) as well. Warranties for the product and the product performance as well as the degradation of the modules during the operation lifetime are important parameters to reduce LCOE.

Figure 48 shows the estimated trend of these parameters for the next years. The degradation after the 1st year of operation will be reduced from 3% in 2016 to 2.5% in 2017 and to 2% from 2019 onwards. Yearly degradation is expected to be reduced slightly from 0.7% today to 0.6% over the next years. Product warranty will stay at 10 years for PV modules whereas the performance warranty is considered to increase to 30 years from 2024 onwards. Degradation and product / performance warranty may improve faster as anticipated as technical solutions are known by today – indicated by the grey/yellow color coding.

In Figures 49 and 50, the relative development of system costs for large systems >100 kWp in the U.S., Europe, and Asia is shown. It should be noted that no "soft costs," such as costs for permits or costs for financing, are included, as these costs may vary significantly from country to country. Excluding the "soft costs," the distribution of system costs as well as the development over time are expected to be comparable in the U.S. and Europe.

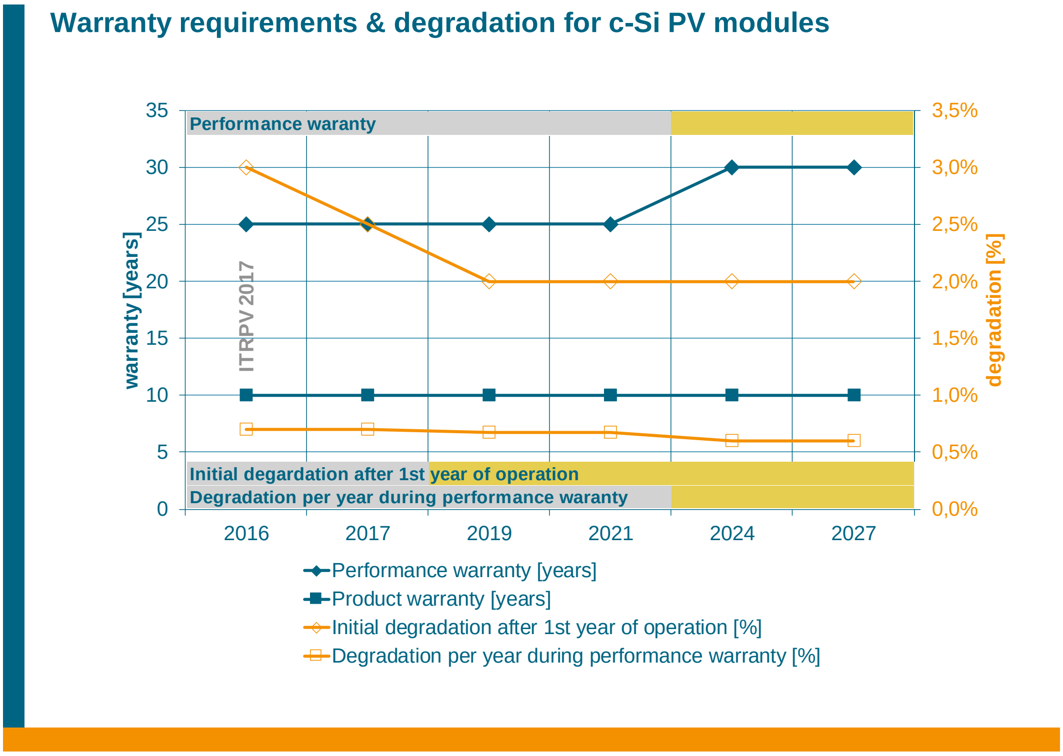

Fig. 48: Expected trend for product warranties and degradation of c-Si PV modules

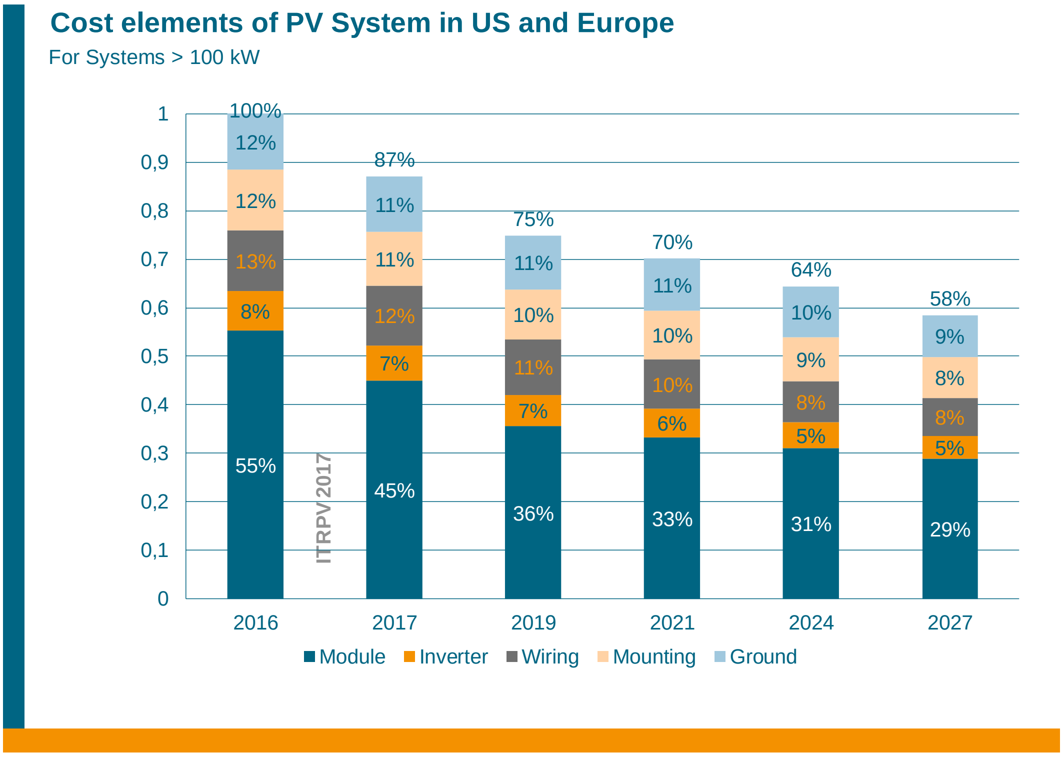

Fig. 49: Relative system cost development for systems > 100kW in the U.S. and Europe (2016 = 100%).

As can be seen by comparison of Fig. 49 and Fig. 50, the overall trend for system cost reduction during the next ten years is expected to be similar for Asia, Europe, and the U.S. with a slightly higher decrease for Europe and U.S. Due to differences in absolute system costs, the relative distribution between the cost components of module, inverter, wiring, mounting, and ground is expected to be slightly different. The only major difference can be seen in the share of the module costs as compared to the system costs. It is expected that the module share will constantly stay higher in Asia compared to U.S. and Europe. This could possibly be explained by the lower overall system costs in Asia.

One trend to be expected on system level is the trend toward an increase of system voltage from 1,000 V to 1,500 V - becoming noticeable from 2019 onwards and attaining a market share of >50% from 2021 onwards (see Fig. 51). The increase in system voltage represents an important measure for lowering resistive losses and/or BOS costs by reducing the required diameter of the connection cables within a PV system.

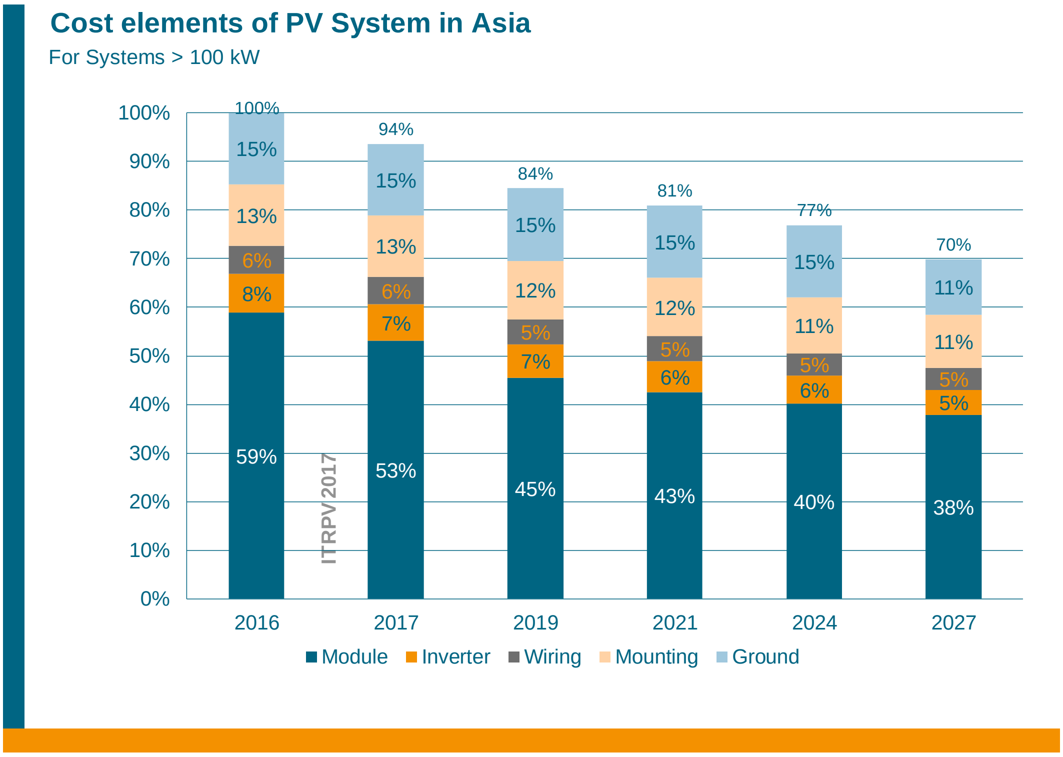

Fig. 50: Relative system cost development for systems > 100kW in Asia (2016 = 100%).

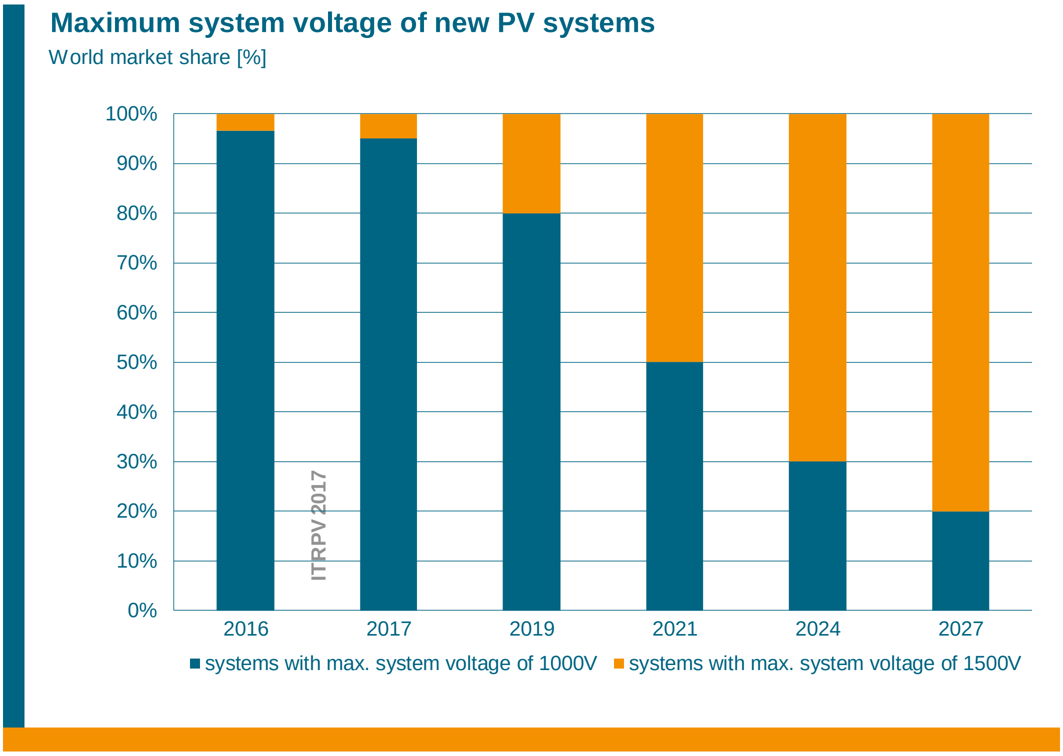

Fig. 51: Trend of maximum system voltage for systems >100kW.

Furthermore, the average module power class for systems >100 kWp is expected to increase from the current 270 Wp to above 330 Wp for 60-cell modules, and from 320 Wp to 380 Wp for 72-cell modules (see Fig. 52). This also should significantly support the reduction of the area-dependent BOS costs.

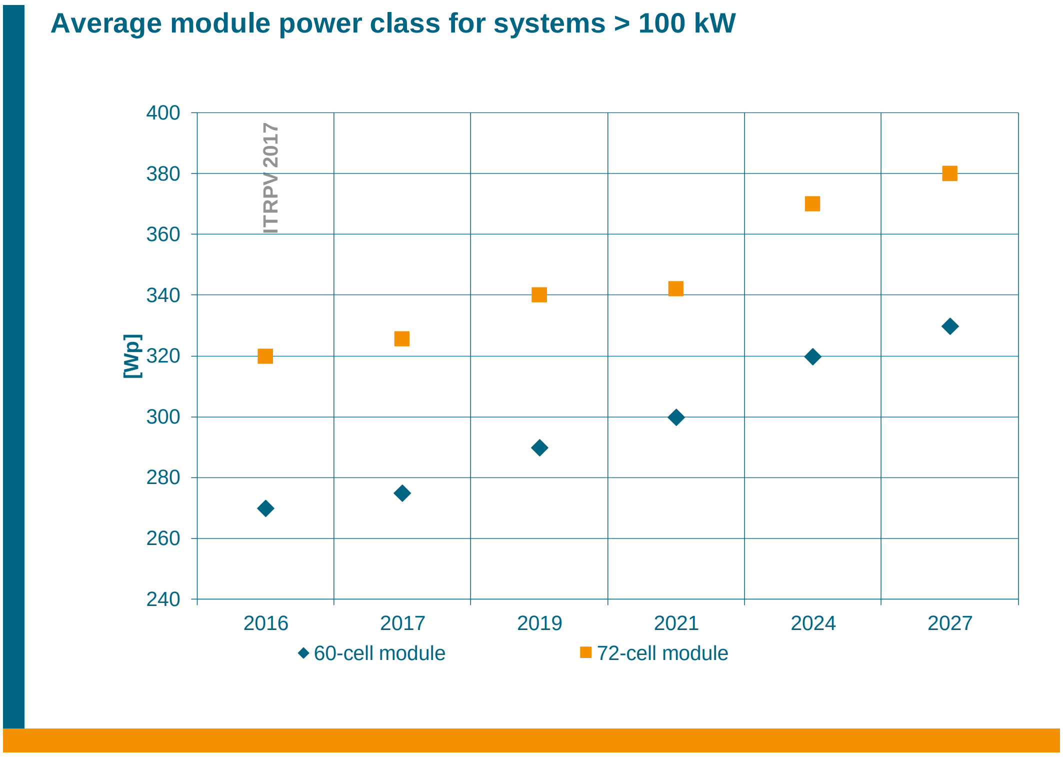

Fig. 52: Trend of average module power class for utility applications with >100kW.

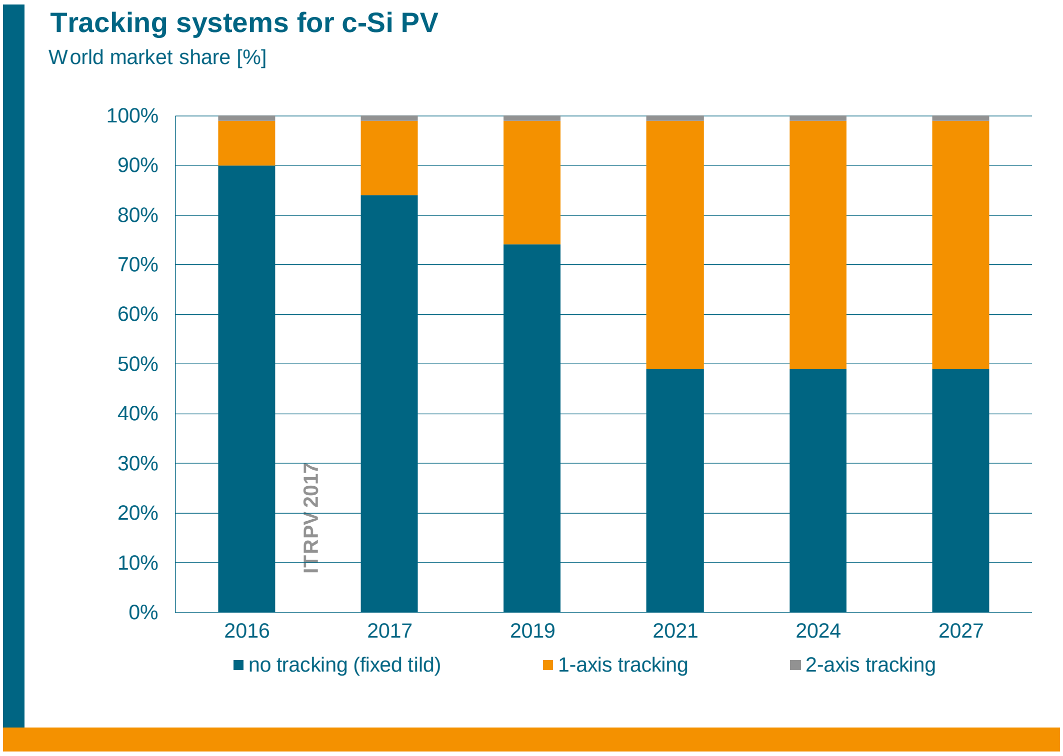

Fig. 53: Market share of tracking systems for c-Si PV installations.

Another long-term trend on the system level is included in the current version of the ITRPV: The market share of tracking systems in large scale c-Si based PV-systems is shown in Fig. 53. 1-axis tracking systems will increase the market share from approximately 10% in 2016 to 50% from 2021 onwards. By contrast, 2-axis tracking will remain negligible for c-Si technology with a (market share of around 1% during the next decade).

As a key figure for energy production, the levelized cost of electricity LCOE is of paramount importance when comparing different renewable and non-renewable technologies for electricity generation. In order to demonstrate the potential of PV power generation, the LCOE in USD for large PV systems under different insolation conditions has been calculated (see Fig. 54). As the actual system price is strongly dependent on the location of the system, we assumed for our calculation 970 USD/kWp in 2016, which is typical for large-scale systems in the U.S. and Europe. Taking into account the system-cost trends depicted in Fig. 49, the system cost will decline to a value of around 680 USD in 2027.

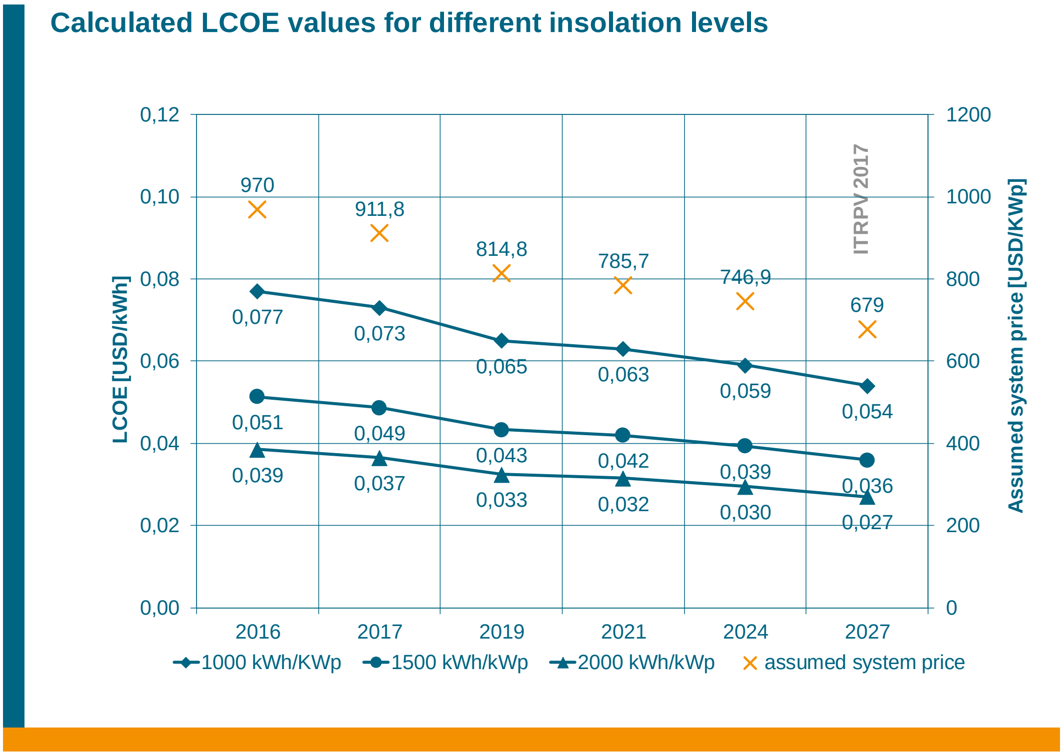

Fig. 54: Calculated LCOE values for different insolation conditions. Financial conditions: 80% debt, 5%/a interest rate, 20-year loan tenor, 2%/a inflation rate, 25 years usable system service life.

As can be seen in Fig. 54, LCOE values of between 0.039 and 0.077 USD are already feasible today, depending on the insolation level. Considering the system price trend anticipated by the ITRPV (see Fig. 49 and Fig. 50), PV electricity costs in the range of 0.03 to 0.05 USD are predicted for the year 2027. It is important to note that along with the system price and the insolation level, the LCOE is also strongly dependent on financing conditions and the usable service life of the system. For our calculations, we assumed 25 years of usable system service life. However, it is expected that advances in module technology as outlined in the ITRPV will enable an extension of the system service life to 30 years and more, which would make it possible to reduce LCOE levels even further. Improved financing, as a major contributor to the LCOE – due to PV being a low risk electrical energy generation technology – may allow the 2027 LCOE levels to be reached earlier. This clearly makes PV power generation a clean and cost-competitive energy source that will play a major role in future global energy supply. This will be discussed in the next section.

7. Outlook

7.1. PV learning curve

We discussed in Chapter 3. the current learning curve situation. Fig. 3 shows the price learning curve and the calculated price learning rate. The learning rate was calculated to be 22.5% by using all data points between 1979 and 2016. However, considering only the data points of the last 10 years, the learning rate is 39.0% as shown in Fig. 55. This seemingly higher learning rate is mainly caused by oversupply of silicon and modules after 2006 following significant capacity extensions due to scarcity situation of silicon and modules during the period 2004 to 2006.

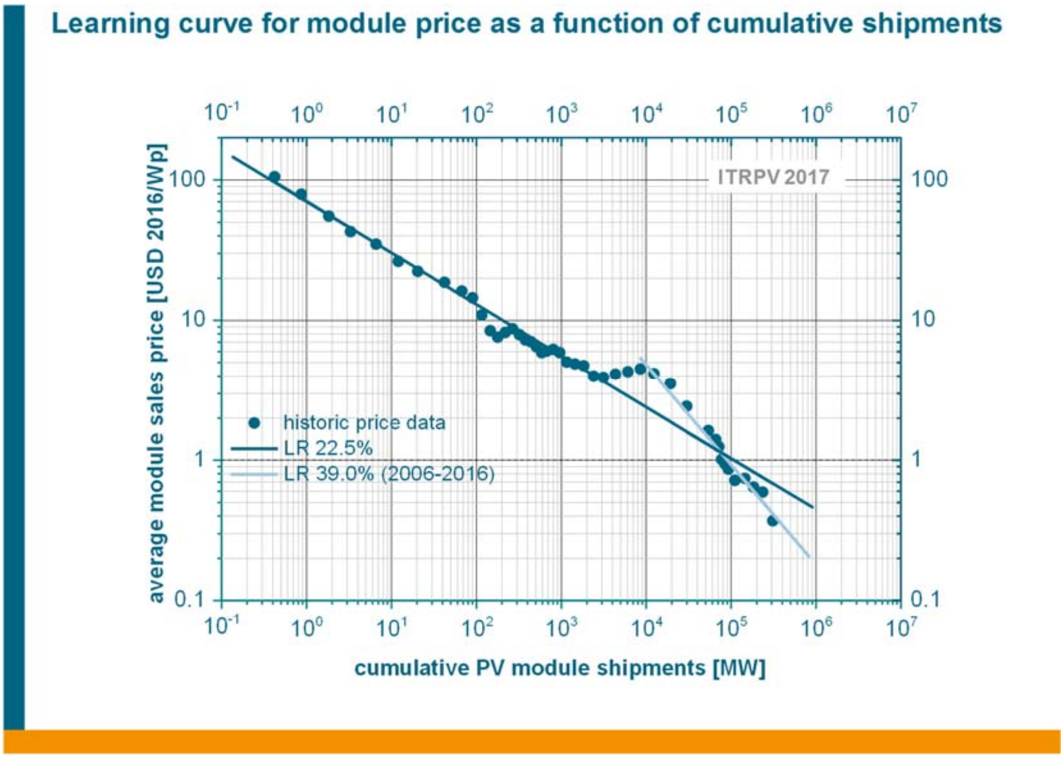

Fig. 55: Learning curve of module price as a function of cumulative PV module shipments and calculated learning rates for the period 1979 to 2016 and 2006 to 2016 respectively.

Based on the findings above it is interesting to see which contribution to the learning came from the increase of module power and which contribution results from the price reductions per piece. Table 1 summarizes average module efficiencies at different years. The price values were taken from the learning curve while module efficiencies were calculated from the average module powers of p-type mc-Si and mono-Si modules of ITRPV reports (3rd to 8th edition) the module efficiency of 1980 was found in [18]. A 64% increase in module power was realized during the 30-year period from 1980 to 2010. The yearly average power learning from 2010 to 2016 was between 2% and 4% while per-piece learning varied between -6% and up to 35% for the corresponding periods.

Year over year learning

Year	1980	2010	2011	2012	2013	2014	2015	2016
avg. Module power p-type (ITRPV-data)	147.6	241.5	248	253	262	267.5	278.5	287.5
Module efficency [%], avg. Mod. area: 1.64m²	9 [18]	14.7	15.1	15.4	16	16.3	17	17.5
Module price [US$ 2016]	34.95	1.63	1.01	0.72	0.74	0.64	0.59	0.37
Module price [USD/Wp] (Wp-increase only)		1.63	1.59	1.56	1.50	1.47	1.41	1.37
Module price [USD/Wp] (cost reduction per piece only)		1.63	1.05	0.79	0.87	0.80	0.81	0.63

Table 1: : Yearly learning for module efficiency and price per piece based on module price data (2010 = 100%) [5, 6, 7], module efficiencies calculated from ITRPV module power values (3rd to 8th edition); 1980 module power calculated from efficiency in [18].

Learning curve for module price as a function of cumulative shipments

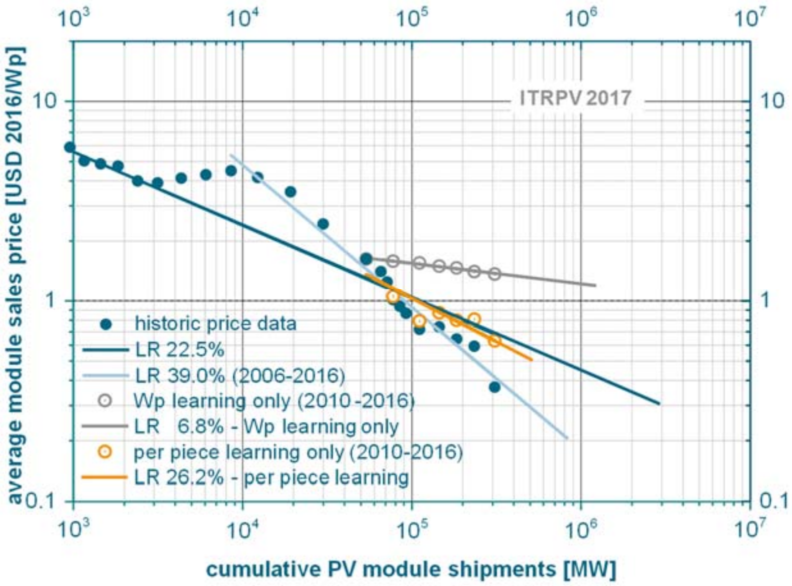

Fig. 56: Learning curve of module price as a function of cumulative PV module shipments, calculated learning rates for the period 1979 to 2016 and 2006 to 2016 respectively, calculated Wp and per piece learning including learning rates according to Table 1.

Fig. 56 shows the plot of data points for Wp learning and per piece learning according to Table 1. The calculated corresponding learning rates of 6.8% for Wp learning and 26.2% for per piece learning indicate that the main contribution of the price learning arose from per piece reductions. This is in line with the findings in [4] and emphasizes again that only the combination of Wp learning and cost reduction grants the resulting learning. Nevertheless, it can be concluded that the current price situation is not due to accelerated cost learning but is driven by a highly volatile market situation. Manufacturers are struggling with significantly reduced margins as current prices are even about to fall short of the projected 2019 manufacturing costs of 0.37$/Wp [19].

7.2. PV market development considerations

The most widely publicly discussed PV-related topics and trends are installed PV module power, module shipments, as well as scenarios about the PV generated electricity. A look at the supplier side, to follow the market development of 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 was started in the ITRPV 6th edition. In the following section, the analysis is repeated by looking at three different PV installation scenarios now - more detailed - on a country-by-country base for more than 190 countries in four regions (Americas, Africa, Europe, and Asia).

The IEA developed three scenarios for the energy consumption and generation until 2050, based on assumptions about population growth and energy consumption behavior [20]. The most optimistic scenario considers the limitation of global temperature increase to 2°C at the end of the 21st century. This scenario assumes the highest amount of PV generated electricity - sufficient to cover 16% of global electricity demand in 2050. Due to the expected competitiveness of PV, this scenario can be considered as “Low Scenario” [21]. The “High Scenario” includes contributions to the primary energy consumption by PV on top of providing electricity only. The “Medium Scenario” is a mix of High and Low. All Scenarios include a conservative wear out period of only 25 years. Power generation yield is calculated for each country in detail varying from 800 kWh/kWp in low insolation countries and >1700 kWh/kWp in high insolation countries [21].

Based on the assumptions in [21] we calculated the scenarios below:

1. Low Scenario: 4.5 TWp of installed PV in 2050, generating 7.05 PWh.
2. Medium Scenario: 6.85 TWp installed PV in 2050, generating 10.6 PWh
3. High Scenario: 9.17 TWp of installed PV in 2050, generating 14.3 PWh.

Using these figures and deducting the annual installed PV power $P_{PV}(t)$ as the sum of the installed PV power of *j* different regions $N_i\ (t)$ was calculated to be:

$$P_{PV}(t) = \sum_{i=1}^{j} N_i(t)$$

The installed module power in each region $N_i\ (t)$ was calculated as the sum of the installed power of *m* individual countries belonging to one of the four regions *l*, $L_{li}(t)$:

$$N_i(t) = \sum_{l=1}^{m} L_{li}(t)$$

Using the logarithmic growth approach, where K_{li} is the maximum installed PV power in the market of the considered country (or asymptote), Q_{li} is a scaling parameter, B_{li} is the growth slope, and M_{li} is the time constant for the country in question an v_{li} asymptote factor:

$$L_{li}(t) = \frac{K_{li}}{(1 + Q_{li}e^{B_{li}\,(M_{li}-t)})^{1/v_{li}}}$$

The global annual addressable market of year n *AM (n)* corresponds to the installed module power in year n. It was calculated by subtracting P_{PV}*(n-1)* from P_{PV}*(n)* plus adding the replacement volume of the worn-out installations P_{PV}*(n -25)*. For this approach, a conservative wear-out period of 25 years was assumed.

$$AM\ (n) = P_{PV}(n) - P_{PV}(n-1) + P_{PV}(n-25)$$

The model defines for the individual countries an individual set of growth parameters for each of the mentioned scenarios. As example, we summarize in Table 2 scenario 3 parameter sets of four countries contributing to the four regions:

Logistic growth parameter for four different countries in scenario 3

	Country	K_{li} (PV power 2050)	Q_{li} (scaling factor)	B_{li} (growth slope)	M_{li} (time of max growth)	v_{li} (asymptote factor)
Africa	Nigeria	45.67 GW	10.63	0.04	2028	0.14
Americas	Mexico	144.60 GW	7.50	0.02	2024	0.05
Asia	Indonesia	209.83 GW	0.73	0.28	2029	0.51
Europe	Sweden	71.01 GW	5.50	0.27	2023	0,49

Table 2: Logistic growth parameter for four different countries in scenario 3.

Fig. 57 shows the resulting cumulated installed PV power of the Nigeria, Mexico, Indonesia, and Sweden for scenario 3, calculated with the parameters listed in Tab. 2

Installation forecast: high

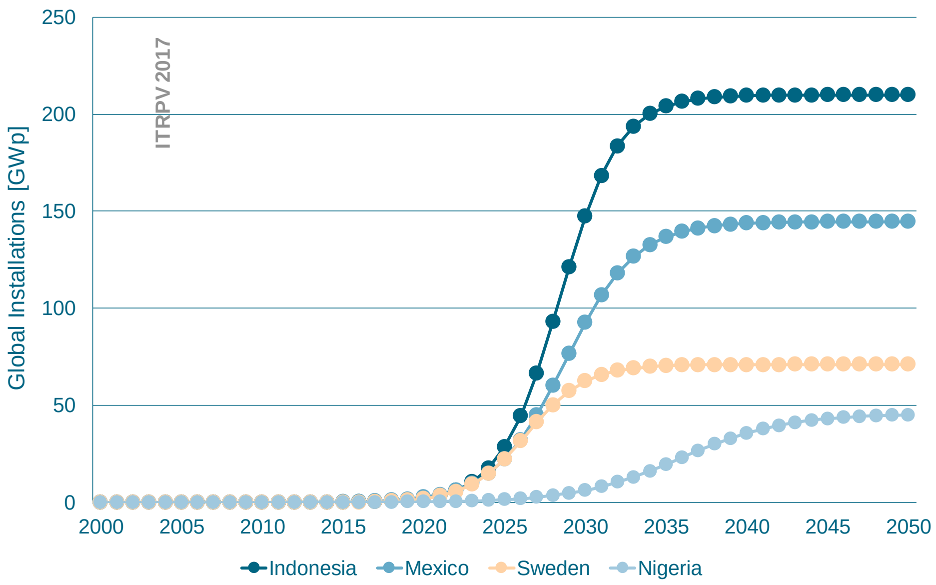

Fig. 57: Calculated cumulated installed PV power of 4 different countries for scenario 3.

Fig. 58 to 60 show for all scenarios the plots of the cumulated installations, the annual market, and historic PV shipment data (until 2016).

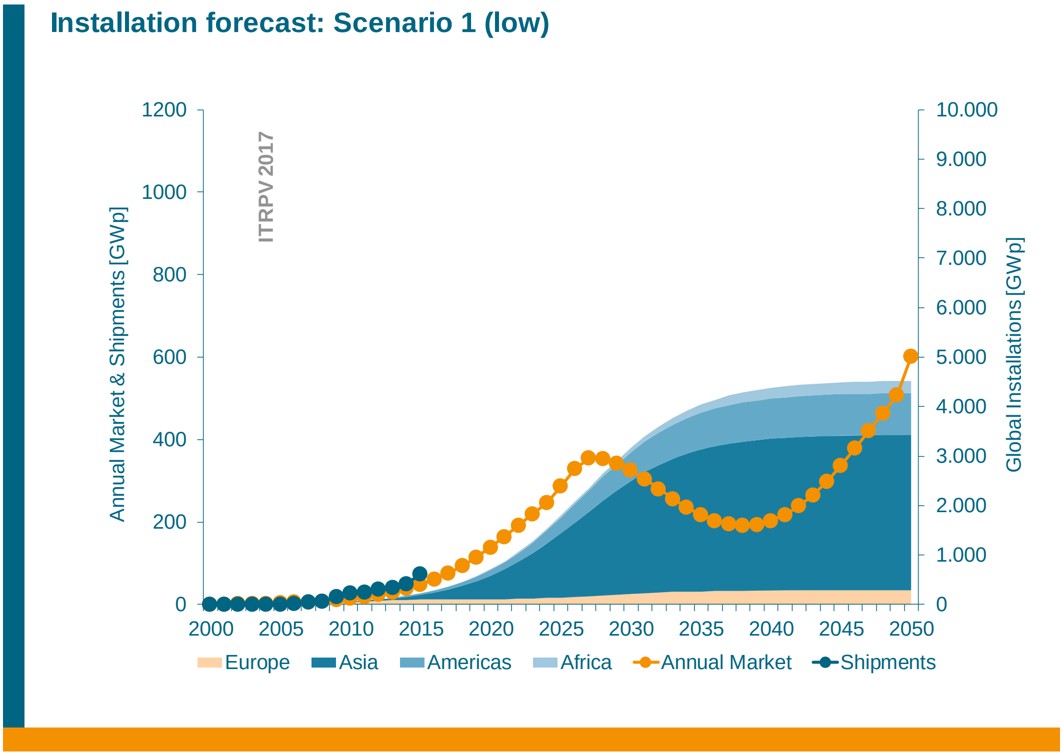

Fig. 58: Cumulative installed PV module power and annual market calculated with a logistic growth approximation for Scenario 1, assuming 4.5TWp installed PV module power in 2050.

Fig 58 shows scenario 1, the Low scenario, in line with IEA expectations [20]. The addressable PV market and the corresponding production capacity would require an expansion to 200 GWp until 2022. with a peak of 355 GWp in 2027. After this peak, demand is calculated to decline again to about 200 GWp between 2035 and 2040. This up-and-down development will repeat due to the replacement of old systems after 25 years of operation. This fact emphasizes the importance of PV-module reliability; as longer module lifetime will help to realize this development to some extent.

Fig 59 shows scenario 2, the Medium scenario. In this case, the addressable PV market and the corresponding production capacity would rapidly expand to a peak of 500 GWp per year in 2030. A repeated up-and-down development would appear as well due to the 25 years replacement cycle. The annual growth by up to 60GW per year around 2025 would be a challenge.

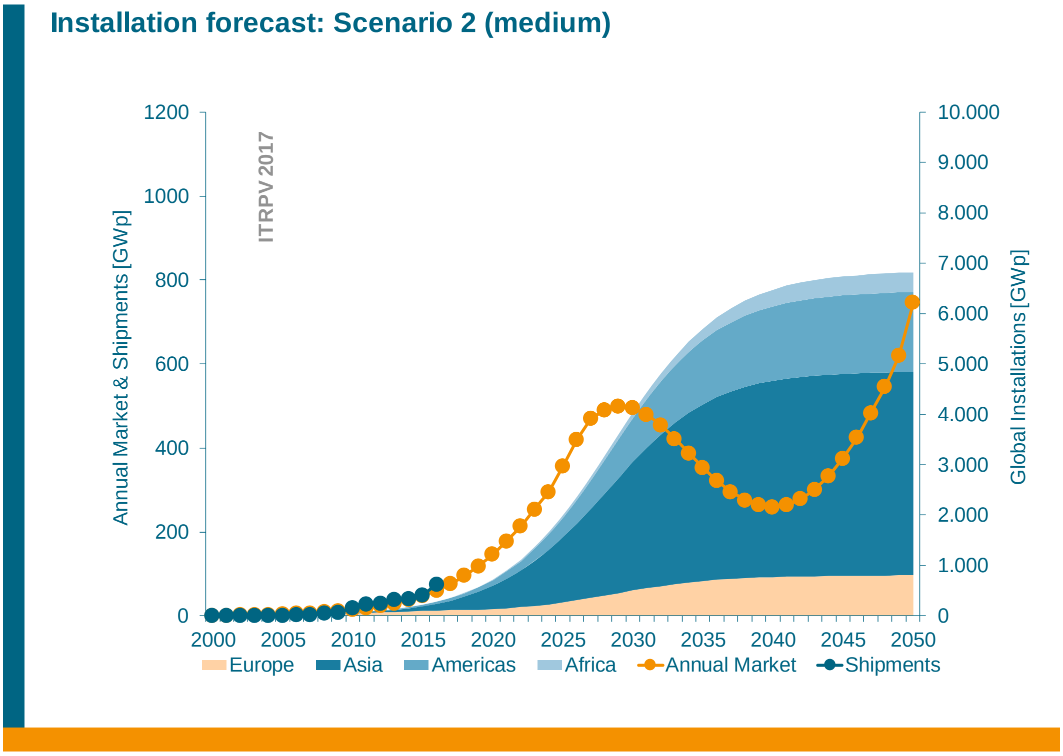

Fig. 59: Cumulative installed PV module power and annual market calculated with a logistic growth approximation for Scenario 2, assuming 6.8 TWp installed PV module power in 2050.

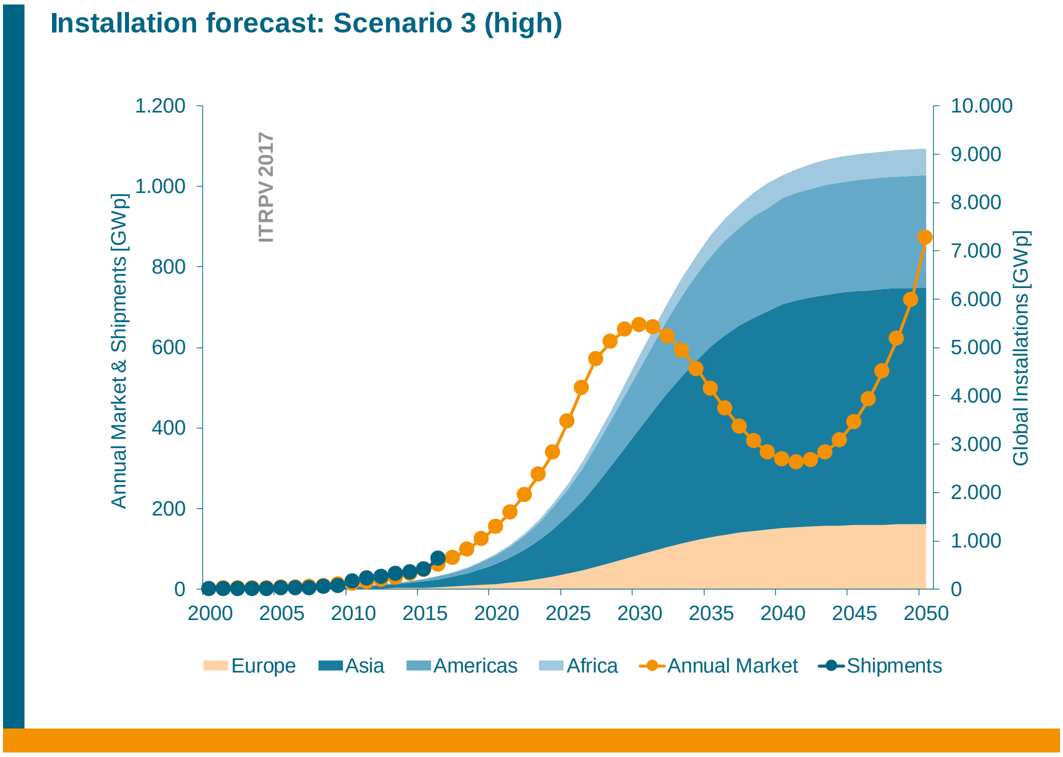

Fig. 60: Cumulative installed PV module power and annual market calculated with a logistic growth approximation for Scenario 3, assuming 9.2 TWp installed PV module power in 2050.

Scenario 3, the High scenario is shown in Fig. 60. In this case, the addressable PV market and the corresponding production capacity would expand to 660 GWp in 2030. Growth rate around 2025 would be challenging with up to 70 GWp per year in this scenario. Cycles due to module lifetime of 25 years will also occur. The intensity of the cycling may also be softened by considering changes in replacements and improved module lifetimes.

The historic shipment data are well above the market data in scenario 1 but quite in line with those of Scenario 2 and 3. All scenarios show that there will be a considerable module market in the future. The progressive scenario (2 and 3) and the more conservative scenario (1) result in different production capacity requirements.

These considerations show that, also for different growth scenarios, there will neither be an “endless” market for PV modules, nor will there be “endless” production capacity increase needed. However, there will be on the long run a large market with possible critical demand peaks. Failing to limit such peaks might lead to superheated markets with subsequent production overcapacities similar to the period the industry is currently facing.

Beside the expected increase of PV installation and production, recycling needs will become more important in the future - as well as a challenge and as a business opportunity.

Progressive tool concepts in cell manufacturing for production lines with matched throughput between front and back end, as discussed in Section 5, can support even the aggressive production capacity scenarios 3. Increase of production to this level however may still require new and lower cost production technologies.

PV equipment suppliers can now focus on supporting upgrades of existing production capacities for new technologies such as PERC. New c-Si capacities will be implemented either for PERC concepts or for HJT technologies. The continued support of depreciated production lines, the replacement of worn-out equipment and the support of upcoming capacity expansions will constitute a considerable business segment in the future. All of this is positive news for the whole c-Si PV industry.

All activities for increasing module power and cell efficiency, ensuring more efficient wafering and poly-Si usage, and achieving a higher utilization of production capacities as discussed in the current ITRPV edition will help manufacturers with their efforts to supply the market with highly competitive and reliable c-Si PV power generation products in the years to come

7.3. Final remarks

We collected all data presented in this roadmap at the end of 2016 from leading international PV manufacturers, companies along the c-Si value chain, PV equipment suppliers, production material providers, PV institutes and PV service providers listed in the Acknowledgment. Plans call for this information to be updated annually. The topics discussed require cooperation between tool and material suppliers, manufacturers, and other companies along the value chain. A version of this document for download, as well as information on how to get involved in roadmap activities, can be found at the following website: www.itrpv.net.

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VITRONIC is a leading supplier of high performance machine vision solutions. The owner-managed group of companies, founded in 1984, develops innovative products and customized solutions in the growth industries of industrial and logistics automation and traffic technology. In photovoltaics VITRONIC looks back to more than 10 years of experience. Manufacturers of solar cells and modules around the world look to VITRONIC for automated optical inspection systems (AOI) that give them a competitive edge. And with more than 2,000 successful PV installations for over 80 customers worldwide, the track record speaks for itself.

www.vitronic.de

semi™

SEMI promotes the development of the global micro and nano-manufacturing supply chain and positively influences the growth and prosperity of its members. SEMI advances the mutual business interests of its membership and promotes fair competition in an open global marketplace. SEMI initiated the ITRPV in 2009.

http://www.semi.org

VDMA (Verband Deutscher Maschinen- und Anlagenbau, German Engineering Federation) represents over 3,100 mostly medium-sized companies in the capital goods industry, making it the largest industry association in Europe. The group Photovoltaics Equipment delivers key services to the photovoltaic equipment industry in Germany. VDMA took over the organization of ITRPV in 2015.

pv.vdma.org

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. We also offer control systems for single-axis or dual-axis solar trackers. The integrated concepts and open interfaces support communication with the other components of a solar tracker farm.

www.siemens.com/solar-industry

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