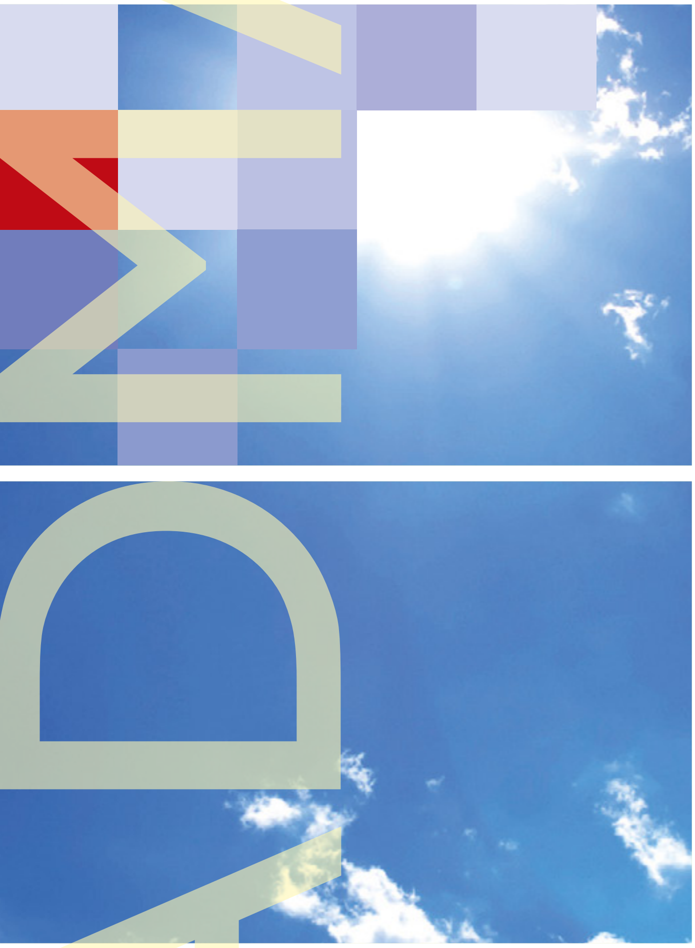
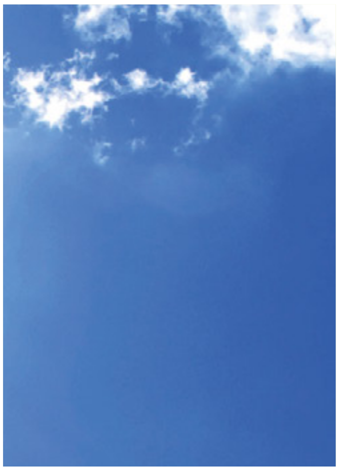
# ITRPV

International Technology Roadmap for Photovoltaic

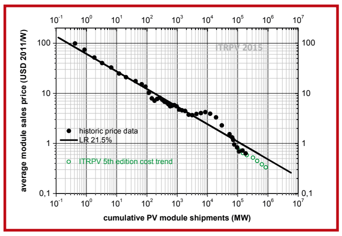




**Sixth Edition**

April 2015







# International Technology Roadmap for Photovoltaic (ITRPV)

## 2014 Results

Revision 1, July 2015

Supported by:

semi

# Acknowledgement

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# 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 identify trends and define requirements for any necessary improvements. The aim of the SEMI 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, sixth edition of the ITRPV was jointly prepared by 26 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. 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 in 2014 is estimated to have been between 45 and 55 GWp; the market share of around 90% for the c-Si market and under 10% for thin-film technologies is assumed to be unchanged [1, 2]. Technological developments and trends for this c-Si module production capacity are described in this roadmap.

The module-price decrease continued in 2014 after a short period of stabilization during 2013.

The implementation of advanced cell technologies and the use of improved materials resulted in higher average module power. Continued efforts to reduce the cost per piece along the value chain were part of the reason why several manufacturers reported making a profit in 2014. The price experience curve continued with its historic learning rate of about 20%. This learning rate can be maintained over the next few years by introducing new double and single-sided contact cell concepts with improved Si-wafers, improved cell front and rear sides, and improved module technologies. This aspect will be discussed in this revision of the ITRPV. Improvements in these areas will result in standard multi crystalline silicon (mc-Si) modules with an average output power in excess of 310 Wp (60 cell modules) by 2025. The combination of increased cell and module performance and significantly lower manufacturing costs will support the reduction of PV system costs and thus ensure the long-term competitiveness of PV power generation.

Roadmap activity will be continued in cooperation with SEMI, and updated information will be published annually to ensure good 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 were divided into three areas: materials, processes, and products. Data was collected from the participating companies and processed anonymously by SEMI. All companies jointly agreed that the results would be reported in this roadmap publication. As shown in Table 1, color marking was used for selected parameters in order to describe the maturity of a technology: Green indicates that the technology is in use, yellow means that an industrial solution is known but is not yet used in mass production, orange means that an interim solution exists, but it is too expensive, and red indicates that there is no known industrial solution available. All plotted data points of the parameters are median values generated from the input data.
As stated above, the topics are split into three areas: materials, processes, and products. Here, we addressed issues connected with crystallization, wafers, cells, modules, and PV systems for each of these areas respectively.

| | |
|---|---|
| **Green** | Industrial solution exists and is being optimized in production |
| **Yellow** | Industrial solution is known but not yet used in mass production |
| **Orange** | Interim solution is known, but too expensive or not suitable for production |
| **Red** | Industrial solution is not known |

***Table 1:*** *Color marking to depict 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. Replacing some materials will be necessary in order to safeguard availability, avoid environmental risks, reduce costs, and increase efficiency. Price development plays a major role in making PV-generated electricity competitive with other renewable 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 also 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.

# 3. PV learning curve

It is obvious that cost reductions in PV production processes should also result in price reductions [3]. Fig. 1 shows the price experience curve for PV modules, displaying the average module sales price (in 2011 US$/Wp) as a function of cumulative module shipments from 1976 to 12/2014 (in MWp) [4]. Module shipments have been ahead of PV system installations for years [5]. Displayed on a log-log scale, the plot becomes approximately linear until the shipment value of 3.1 GWp (shipments at the end of 2003), despite kinks at around 100 MWp. This indicates that for every doubling of cumulative PV module shipments, the average selling price decreases with a learning rate (LR) of about 21%. The large deviations from this LR plot in Fig.1 are caused by the tremendous market fluctuations between 2003 and 2013.

The last two data points indicate the average prices and the assumed corresponding shipment volumes at the end of the past two years, – i.e. 34 GWp / 0.72 US$/Wp in 2013 and 39.3 GWp/ 0.62 US$/Wp in 2014 [6, 7]. The 100 GWp landmark was clearly exceeded in 2012 [8] and the current shipped module power is estimated to be approximately 184 GWp. As is usual, this is a bit higher than the actual worldwide installed module power of about 177 GWp, as announced by the IEA [9].

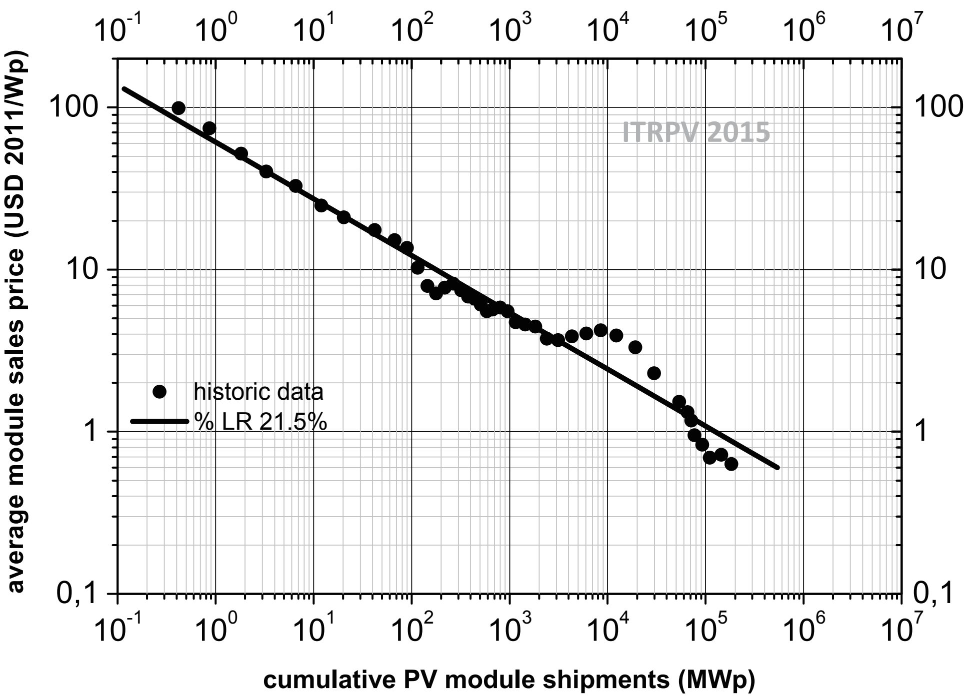


***Fig.1*** *Learning curve for module price as a function of cumulative PV module shipments.*

# 4. Cost considerations

Fig. 2 shows the price development of mc-Si modules from January 2010 to February 2015 with separate price trends for poly-Si, multi crystalline (mc) wafers, and cells [7]. The price erosion in 2011/2012 was mainly caused by huge overcapacities along the PV value chain, which led to module prices that fell short of the cost of c-Si modules [10]. The inset of Fig 2 shows the comparison of the proportion of prices attributable to silicon, wafer, cell, and module price. The overall price level decreased by 10% from 12/2013 to 02/2015 and the share of the different cost elements shifted as well. Poly-Si remains the most expensive particular material, and the module-conversion price share corresponds to around 50% of the module price.

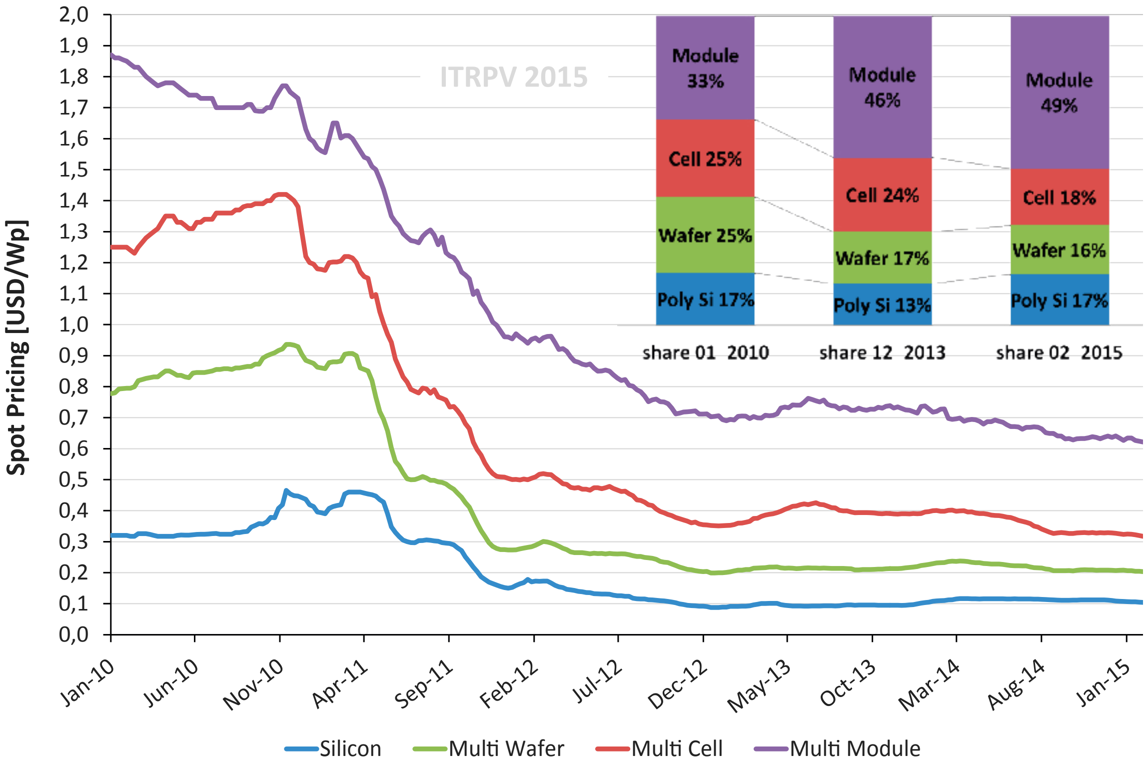


***Fig. 2*** *Price trends for poly-Si, mc-Si wafers, cells, and c-Si modules (assumption: 44.1 Wafers per kg with ~22.7g/wafer, average mc-Si cell efficiency of 17.3% {4,21Wp}); inset: comparison of the proportion of the price attributable to different module cost elements between 01/2010 ,01/2013, and 02/2015 (1.86, 0.72, and 0.62 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. If we take into account the fact that the anticipated global PV module production capacity in 2015 of >60 GWp [2] will still exceed the global market demand of about 50 GWp, then prices will not compensate for any cost increases — in other words, the pressure on PV module manufacturing will persist. Achieving cost reductions in terms of consumables and materials will therefore remain a major task.

Three strategies can help address this challenge:

i) Continue the cost reduction per piece along the entire value chain by optimizing the utilization of the installed production capacity and by using Si and non-Si materials more efficiently.
ii) Introduce specialized module products for different market applications (i.e. tradeoff between cost-optimized, highest volume products and fully customized niche products).
iii) 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. 2014 Results

## 5.1 Materials

### 5.1.1 Materials – crystallization and wafering

Poly-Si is the most expensive particular material of a c-Si module as discussed in Chapter 4. It also displays potential for cost reduction. We expect FBR technology to increase its share in relation to Siemens processing, as shown in Fig. 3. Other technologies such as umg-Si are not expected to yield significant cost advantages as compared to conventional poly-Si technologies over the coming years, but they are expected to remain available on the market.

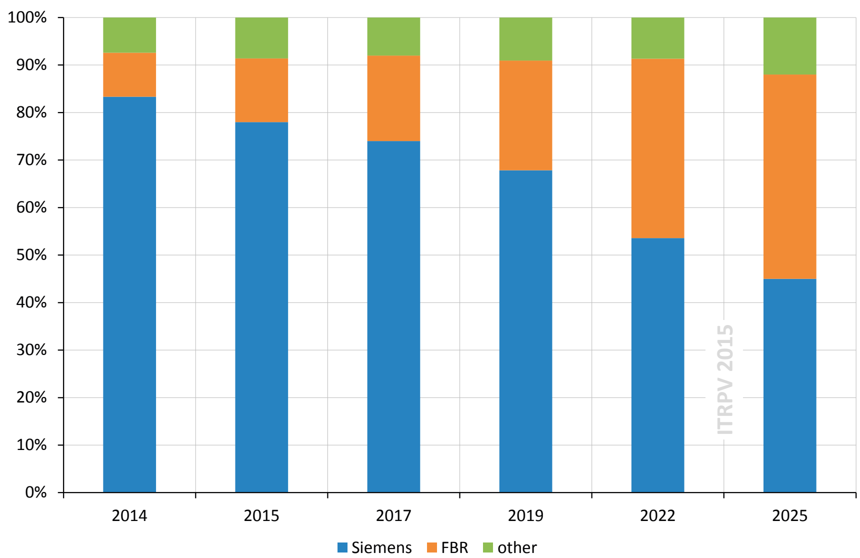


***Fig. 3***
*Expected change in the distribution of poly-Si production technologies.*

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. Diamond wire sawing is maturing today in mono-Si wafering and is thus becoming more widespread.

Fig. 4 shows the expected share of different wafering technologies for mc-Si in volume production. Diamond wire sawing is expected to gain market shares at the expense of slurry-based wafering over the next 10 years. Other new wafer manufacturing techniques, especially kerfless technologies, are not expected to gain market shares above 5%, this being due to the maturity of the established sawing technologies.

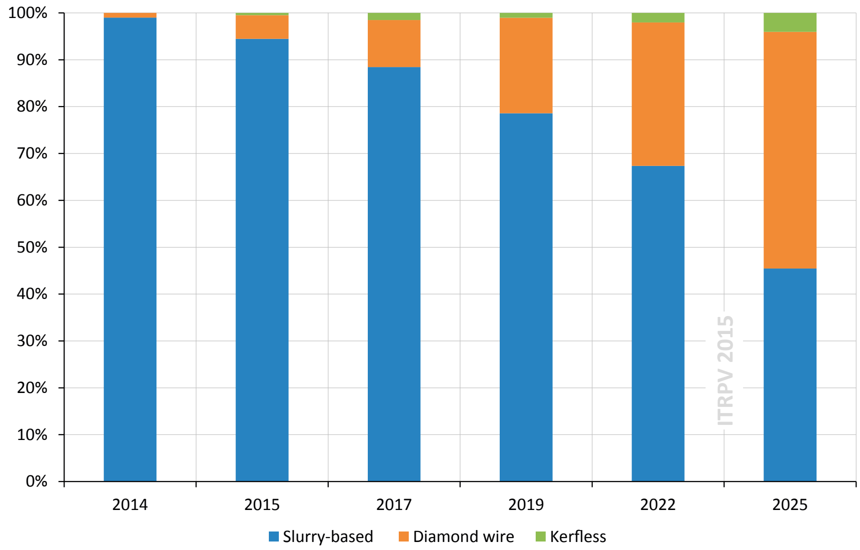


***Fig. 4***
*Market share of wafering technologies for mc-Si.*

Savings can be achieved by producing thinner wafers, reducing kerf loss, increasing recycling rates, and reducing the cost of consumables. Wire diameters will be reduced continuously over the next few years, and there will be more recycling of Si and diamond wire. The SiC recycling rate is expected to stay constant at around 80%.

## 5.1.2 Materials – cell processing

Si wafers account for approximately 51% of today's cell price, as shown in Fig. 2. Reducing as-cut wafer thickness would lead to more efficient use of silicon. The developments anticipated in previous editions of the roadmap did not materialize as predicted due to declining market prices. Instead of thinner wafers, 180µm is the preferred thickness of wafers used on cell and module production lines, this being mainly due to reduced breakage. Fig. 5 shows the predicted trend for minimum as-cut wafer thickness for mass production of the c-Si wafers addressed in the current study. It is assumed that the thickness of mc-Si wafers will approach a minimum value of 150µm within the next seven years. Mono-Si wafer thickness will follow more the minimum thickness requirement of the module technology and reach a minimum thickness of 120µm in 2025. Future module technology is expected to enable a further reduction of thickness to 100µm.

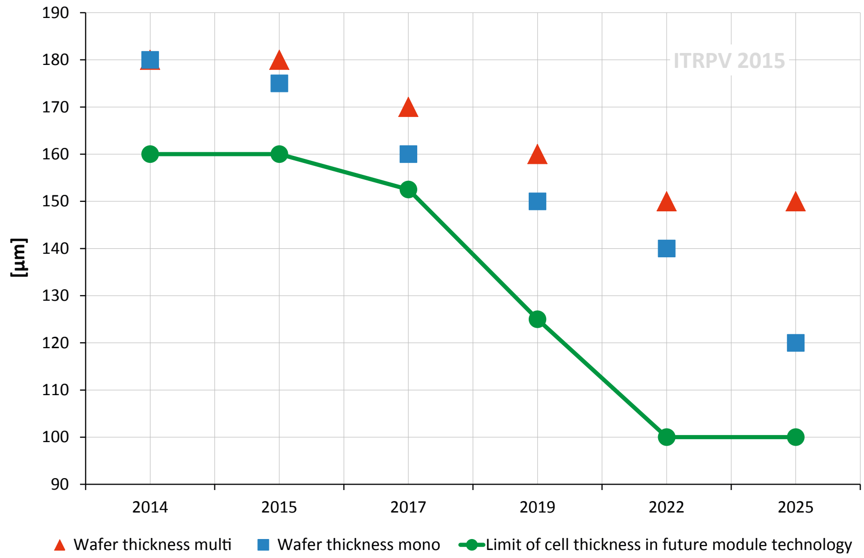


***Fig. 5***
*Predicted trend for minimum as-cut wafer thickness for mass production of c-Si solar cells.*

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. 6 shows our estimations regarding the future reduction of the silver that remains on a 156x156 mm² cell after processing. Silver consumption per cell is expected to further decrease, as has been demonstrated over the past few years. A reduction from currently about 100mg down to 40mg per cell will be achieved by 2025. New developments in pastes and screens will enable this reduction, and this clearly shows the reaction of suppliers to the needs of cell manufacturers. The average price of silver of 581 US$/kg in April 2015 resulted in costs of 5.8 US$ cents/cell (1.3 US$ cents/Wp, for 18.3% mc-Si cell), or still about 10% of the non-Si cell price, as shown in Fig. 2.

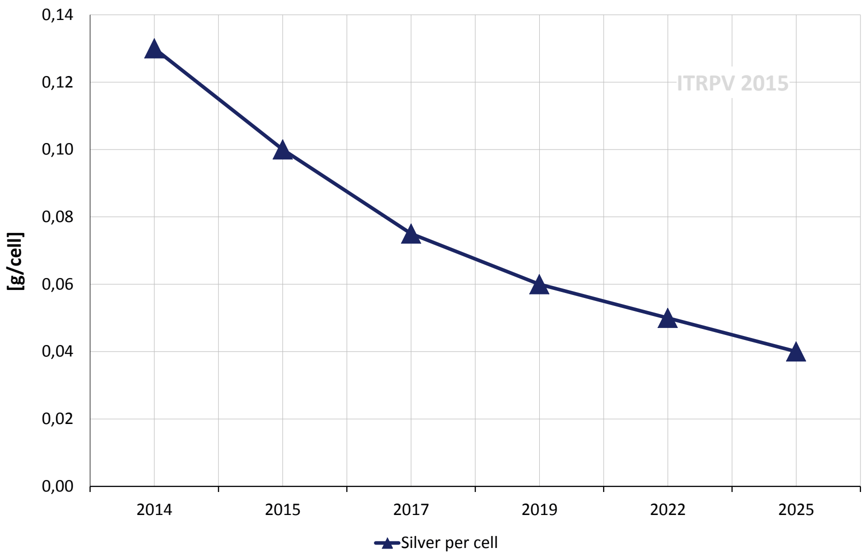


***Fig. 6***
*Trend for remaining silver per cell (156x156mm²).*

Because the price of silver is expected to remain high, it is extremely important to continue efforts to lower silver consumption as a means of achieving further cost reductions.
Despite a continual 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 assumed that the anticipated introduction of mass production of Cu will not start before 2018 at any significant volume, and it is then expected to account for around 30% of the market in 2020. 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 therefore expected to remain the most widely used metallization material for c-Si cells in the years to come.
Lead-free pastes are expected to become widely used in the mass production of c-Si cells beginning in 2017.
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 mid-2021 at the latest.[2] Cell manufacturers should tread carefully, however, 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.

[1] *Article 2(i) of the RoHS Directive [2011/65/EU] excludes "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" from the scope of the Directive.*

[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.*

### 5.1.3 Materials – modules

Module add-on costs are clearly dominated today by material costs. Both improvements in module performance as shown in Chapter 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. absorption and reflection of front cover glass) and the reduction of interconnector losses.

Approaches for reducing material costs include:
- i) Reducing material volume, e.g. material thickness.
- ii) Replacing (substituting for) expensive materials.
- iii) Reducing waste 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. 7, 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 80%. In the long term, other materials such as polymer-based front cover materials could gain a market share of > 10%.

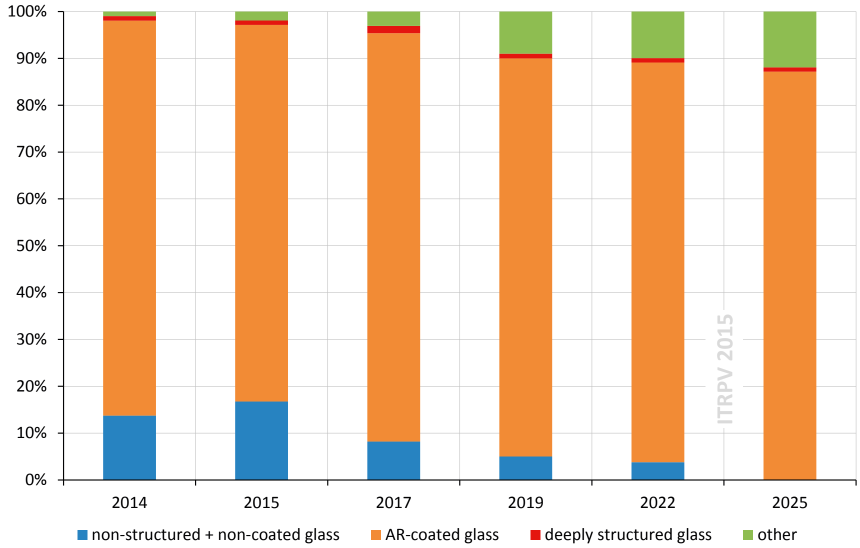


***Fig. 7***
*Expected relative market share of different front cover materials.*

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. However, there is a clear trend indicating that the average service life of these coatings will improve over the next five years to a level in the range of the anticipated module service life (as can be seen in Fig. 8).

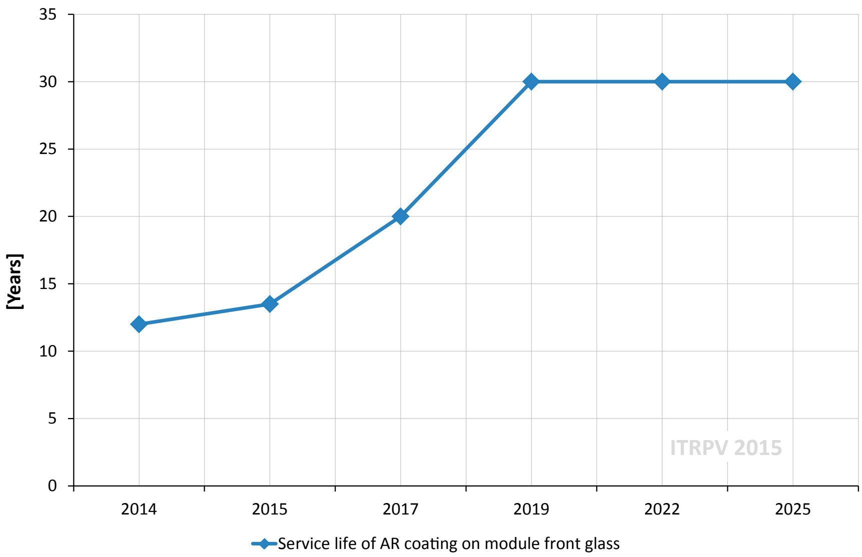


***Fig. 8***
*Predicted trend for the average service life of AR coatings on front glass.*

For a long period of time, solders that contain lead have served as the standard connection technology for solar cells in module manufacturing. Due to environmental and other considerations, more and more PV manufacturers are now examining lead-free alternatives, as can be seen in Fig. 9.

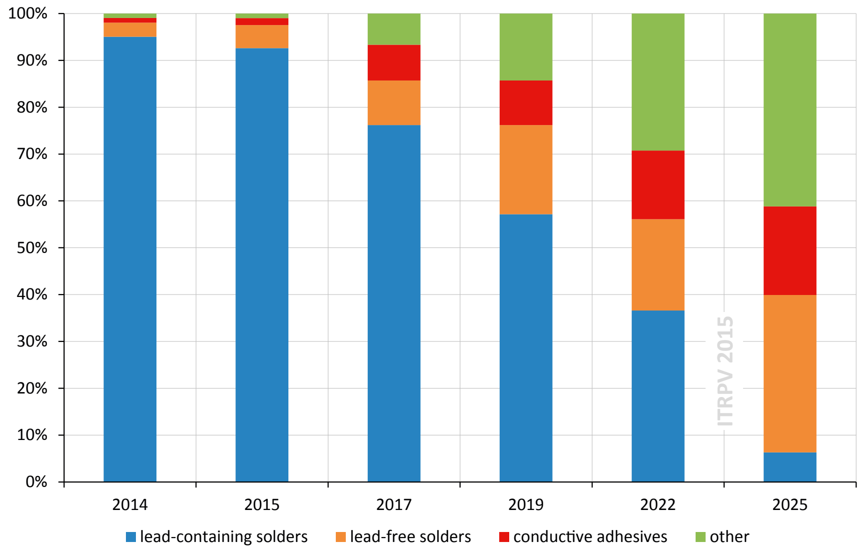


***Fig. 9***
*Expected market shares for different cell connection technologies.*

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, other (e.g. wire-based) connection technologies are expected to advance to become the leading connection technologies. It is important to note that the up-and-coming connection technolgies 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. The trend shows that there is a need for new technologies, but no clear favorite.
Because the encapsulant material and the backsheet 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. 10 and Fig. 11 for encapsulants and backsheets, respectively.

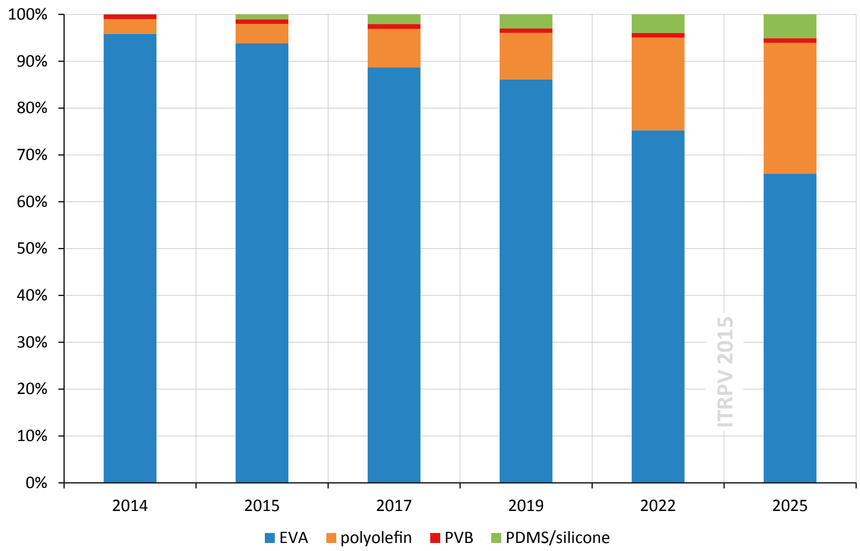


***Fig. 10***
*Expected market shares for different encapsulation materials.*

As can be seen in Fig. 10, it is expected that the market share of polyolefines will increase from 2% in 2014 to around 30% in 2025. However, it is also predicted that EVA will remain the dominant encapsulant with a marktet share still greater than 60% over the ten-year time frame of this survey.

There is an even stronger trend toward alternative materials for backsheets. The market share of TPA is expected to decline, while glass and APA are expected to make corresponding gains and thus reach around 25% and 20%, respecitvely, in 2025 (see Fig. 11). PET-based backsheets are predicted to remain at their current market share of around 40%.

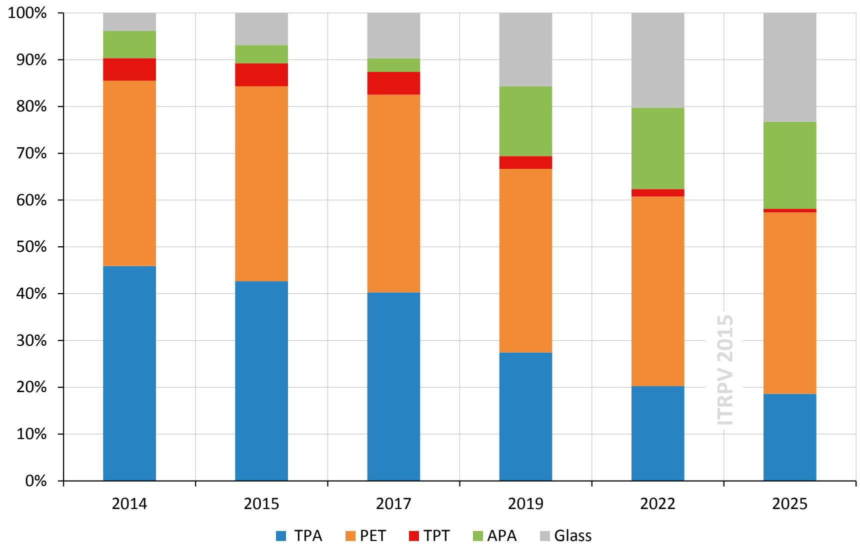


***Fig. 11***
*Market shares for different module backsheet materials.*

It is expected that the mounting of the module frame to the laminate will increasingly be carried out using silicone as a replacment for adhesive tapes. More specifically, the current market share of silicone of 75% is expected to increase to around 90% in 2025.

In order to maintain quality (for thinner cells as well), the solar cells used for module assembly should be free of microcracks. 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.

At the same time, there is no industry-wide accepted and applied definition of microcracks, nor does a standardized test method exist for either microcracks or PID testing. A common (standardized) agreement would certainly reduce testing costs. The ITRPV authors suggest using IEC testing standards, for example, on an industry-wide basis for PID testing on the module level. This would eliminate “over testing”.

## 5.2 Processes

### 5.2.1 Processes – manufacturing

It is possible to increase the throughput of the crystallization process by changing the common sizes of the ingots. Fig. 12 shows the increase in ingot mass for casted silicon materials and for Czochralski / Continuous Czochralski (Cz/CCz) growth of monocrystalline silicon (mono-Si), as predicted by the roadmap. The overlap of the arrows indicating the different generation lines show that G6/G7 ingoting with masses of up to 1,000 kg is already being done in production operations today. Casted ingot mass will increase towards 1,200 kg by the time of the transition to Gen8 within the next 4 years. The ingot mass of mono is expected to double within the next 10 years (driven by CCz technology).

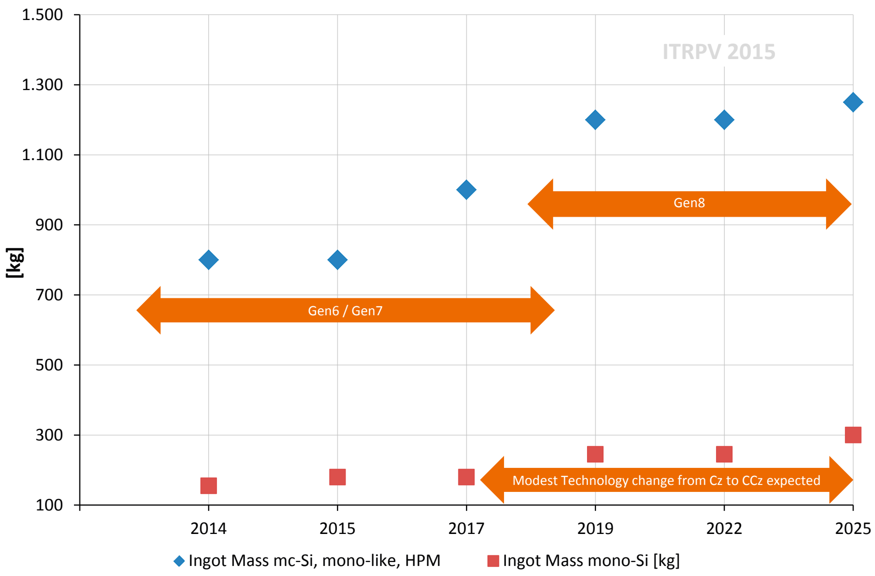


***Fig. 12***
*Predicted trend for ingot mass for mc-Si, mono-like, and HPmc-Si, as well as for mono-Si.*

The throughput of crystal growth for both types, casted and mono, will be continuously increased by 40%–50% over the next 10 years, as predicted in Fig 13.

The throughput trend for sawing technologies is also summarized in Fig. 13. Similar trends are predicted for the throughput of both sawing technologies – however, throughput is expected to increase by 20%–25% between now and 2025.

Yield enhancement through the optimization of the kerf loss will improve productivity in wafering above and beyond the effect of the increased throughput.

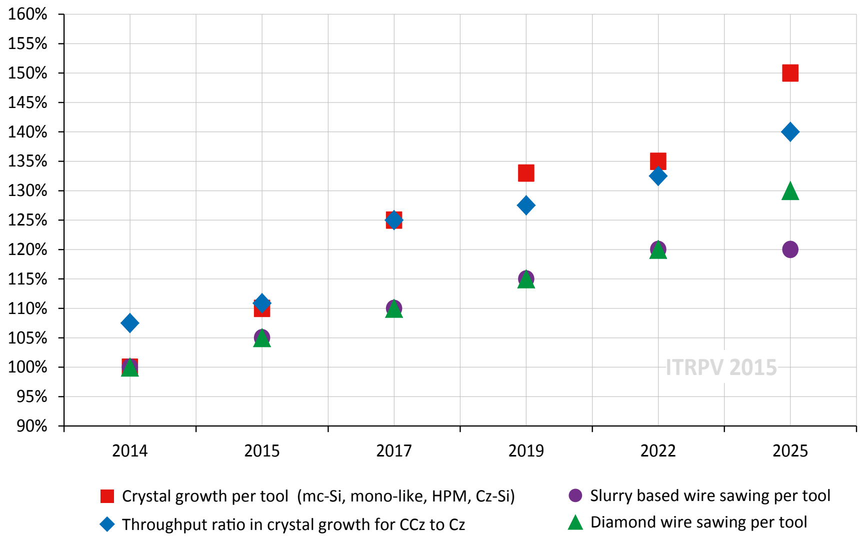


***Fig. 13***
*Predicted trend for throughput per tool for ingot growth of casted Si materials and mono Si, and for wafer sawing technology.*

The kerf loss of slurry-based sawing is generally about 20µm higher than for diamond wire -based sawing. Nevertheless, today's kerf loss of 150 µm for slurry-based and 130 µm for diamond wire-based sawing is predicted to decline by around 25 µm within the next 10 years for both technologies. This underscores the long-term advantages of diamond wiring technology, which will lead to a higher market share for diamond wiring, as shown in Fig. 4.

Optimizing productivity is essential in order to remain cost competitive. Increasing the throughput of the equipment in order to achieve maximum yield figures is therefore a suitable way to reduce tool-related costs per cell. In order to match the throughput on a cell production line both front-end (chemical and thermal processes) and back-end (metallization and classification), processes should have equal capacity. Table 2 summarizes the expected throughput of cell production equipment, with synchronized front-end and back-end throughput processes anticipated by 2025.

Metallization tools with throughputs of 3,200 wafers per hour are currently available on the market. 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.

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. No new "high throughput" equipment has been installed on a large scale in mass production. Manufacturers are still focusing on continuous process improvements and the upgrading of existing machinery.

Single tools with increased throughput in chemical and thermal processing can be implemented, especially in cluster lines as replacements or upgrades. New tool concepts for the next investment cycle can now be implemented on a small scale in order to test mass production capability.

| | Front-end [wafer/h] (chemical + thermal) | | Single line back-end [wafer/h] (metallization + classification) | |
|---|---|---|---|---|
| Year | Evolutional scenario (collected data) | Progressive scenario | Evolutional scenario (collected data) | Progressive scenario |
| 2015 | 3400 | 3800 | 3200 | 3200 |
| 2017 | 3600 | 4000 | 3200 | 3700 |
| 2019 | 4400 | 5400 | 4000 | 4300 |
| 2022 | 5000 | 6600 | 4800 | 6000 |
| 2025 | 5200 | 7200 | 5200 | 7200 |

***Table 2:*** *Expected throughput of production tools. Front and back-end tool throughput is expected to be 1:1 by 2025. All numbers are to be viewed as minimum requirements for a high-end production environment.*

In order to reduce the floor space and hence the costs 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 (see Fig. 14). For the latter process, new encapsulation materials with shorter processing times would be desirable. A significant improvement to the connection process is expected after 2019 through the advent of new connection technologies and back-contacted cell concepts. As tool throughput in module production increases, the relative number of operators relative to line output will decrease.

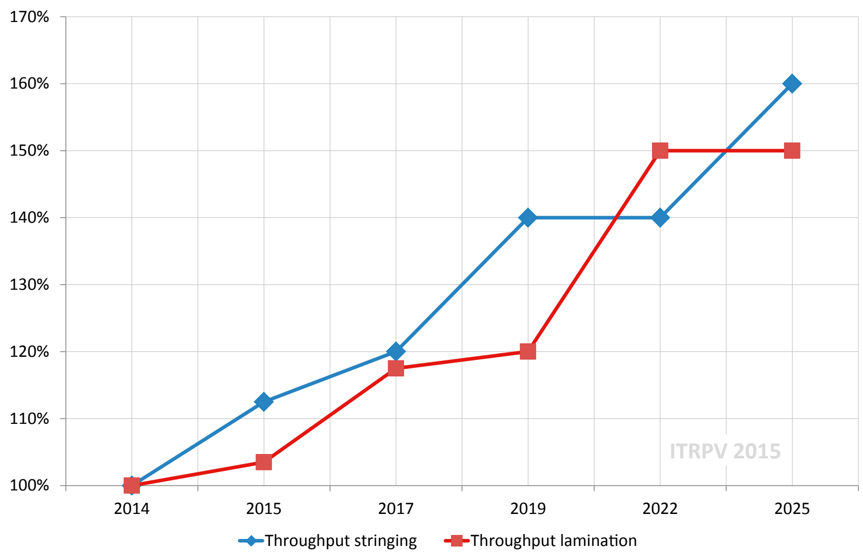


***Fig. 14***
*Predicted trend for throughput per tool for stringing and lamination in c-Si module manufacturing.*

## 5.2.2 Processes – technology

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 volume, on the cell's front and rear sides, are a reasonable way to describe recombination losses. Fig. 15 shows that all recombination currents need to be reduced.

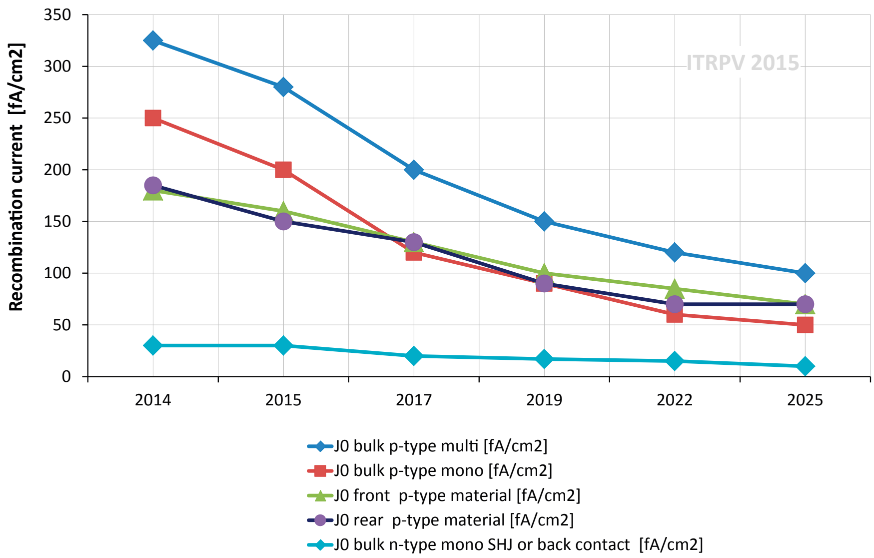


***Fig. 15***
*Predicted trend for recombination currents J0bulk, J0front, J0rear for p-type and n-type cell concepts.*

Recombination currents can be measured as described in the literature [11], or they can be extracted from the IV curve if the other J0 components are known.

The silicon material quality for both mono and multi will be improved, whereby this will result in a reduction of the J0bulk value to 100fA/cm² for multi and 50fA/cm² for mono. N-type mono wafers display a J0bulk value of around 30fA/cm², which will be further reduced to 10fA/cm² within 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) has led to lower bulk recombination currents for this material type.

J0 values of front and rear surfaces are also similar for different bulk materials. The J0 values are expected to be reduced to 50% of the current values by 2025.
Rear-side recombination current values below 200 fA/cm² cannot be attained with an Al Back Surface Field (BSF). Since 2012, several new cell concepts using rear-side passivation with dielectric layer stacks have been introduced to production processes (PERC technology). Fig. 16 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 set to be rolled out on mass production lines. Other technologies, such as ALD Al2O3 deposition or PECVD SiONx, in combination with capping layers, are expected to make slight market-share gains.

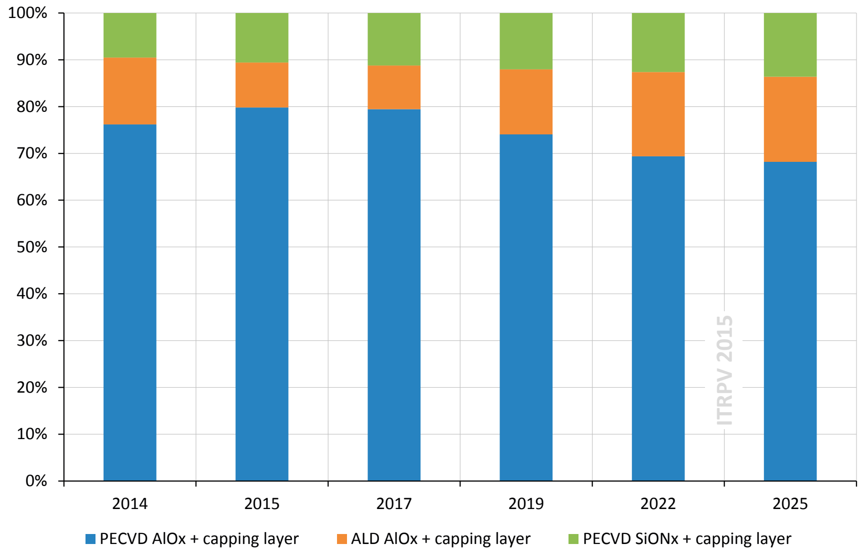


***Fig. 16***
*Predicted market shares for rear-side passivation technologies.*

One parameter that influences recombination losses on the front surface is emitter sheet resistance. Proposals made in earlier ITRPV editions to increase emitter sheet resistance have been implemented. The predicted trend of the values for n-type emitters is shown in Fig. 17.

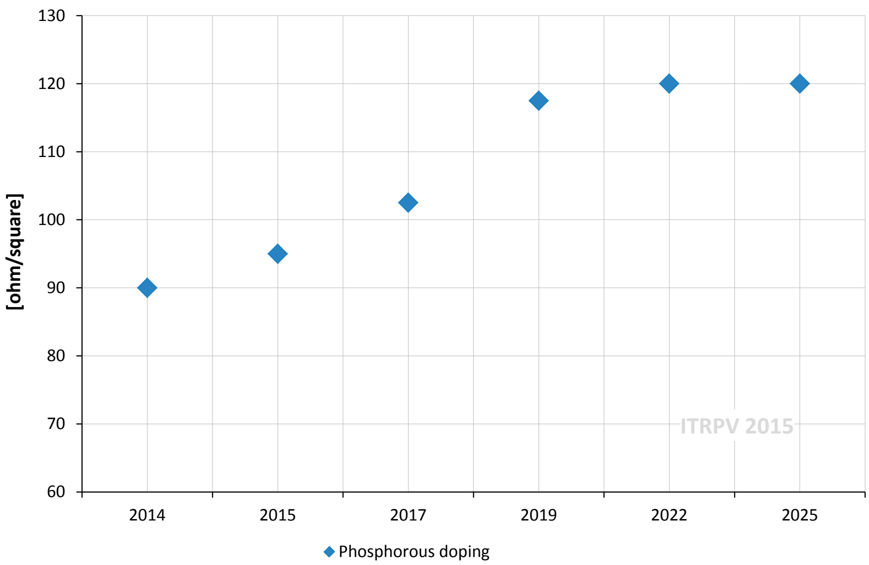


***Fig. 17***
*Expected trend for emitter sheet resistance.*

Increased sheet resistances of 100 Ohm/square have been achieved in production with and without selective emitters and will become standard. 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).

Higher sheet resistances of up to 120 Ohm/square are expected to be achieved starting in 2022. However, the emitters involved will need to be further improved in terms of contact formation.
Fig 18 shows the expected world market share of different technologies for phosphorous doping in p-type cell processing. Homogenous phase diffusion will remain the mainstream for the years to come as well, despite the availability of several technologies such as homogenous ion implantation, and various selective doping techniques.

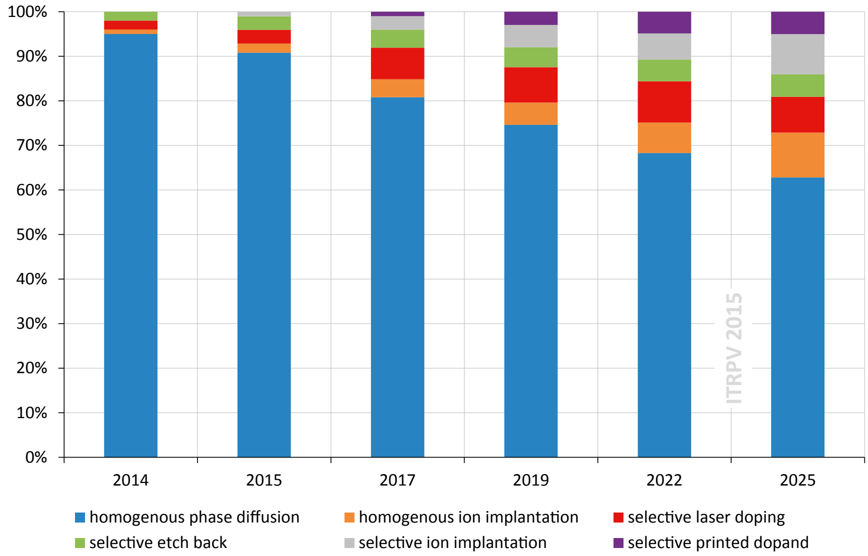


***Fig. 18***
*Expected world market share for different phosphorous emitter technologies for p-type cells.*

In this edition of the ITRPV, we discuss for the first time the various technologies for boron doping, especially for n-type cells. Fig 19 shows the expected market share for the different boron doping technologies. The currently most widely used BBr thermal diffusion technique will be displaced by ion implantation or alternative doping technologies such as APCVD.

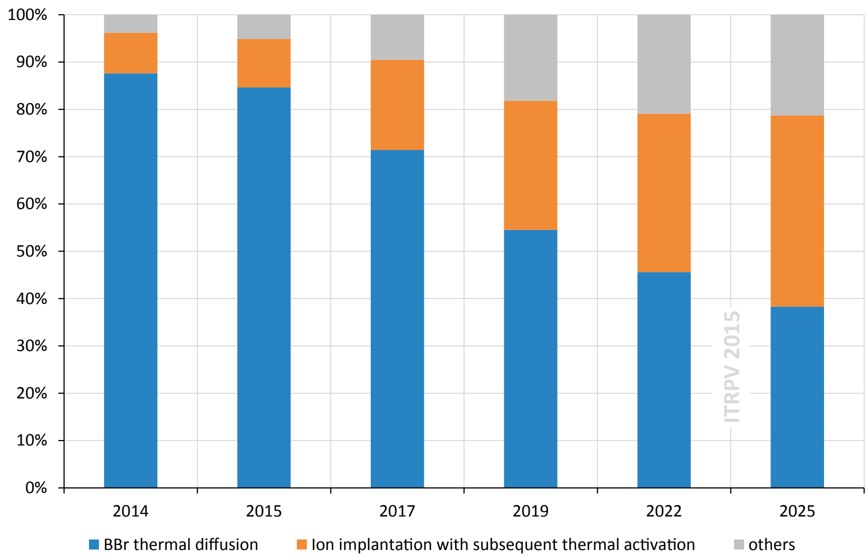


***Fig. 19***
*World market share for different technologies for boron doping (n-type cells).*

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 needed, but without significantly increasing finger resistance. Furthermore, contact with a shallow emitter needs to be reliably established. One possible way to achieve these goals is to use a selective emitter structure, preferably without increasing processing costs. Fig. 20 shows that finger widths between 50-60µm are currently possible in production processes. A further reduction to below 30µm appears possible over the next 10 years. However, finger-width reduction also seems to have slowed down recently as compared to previous years.

Reducing finger width increases efficiency, but a trade-off will have to be made if the roadmap for silver reduction as discussed in 5.1.2 is to be followed. Different approaches for improving 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 bus bar print, enabling the use of bus bar pastes with less silver. These techniques were discussed in the 5th edition. The alignment accuracy is important in metallization — an alignment accuracy of 10µm (@+/- 3 sigma) will be required from 2019 onwards.

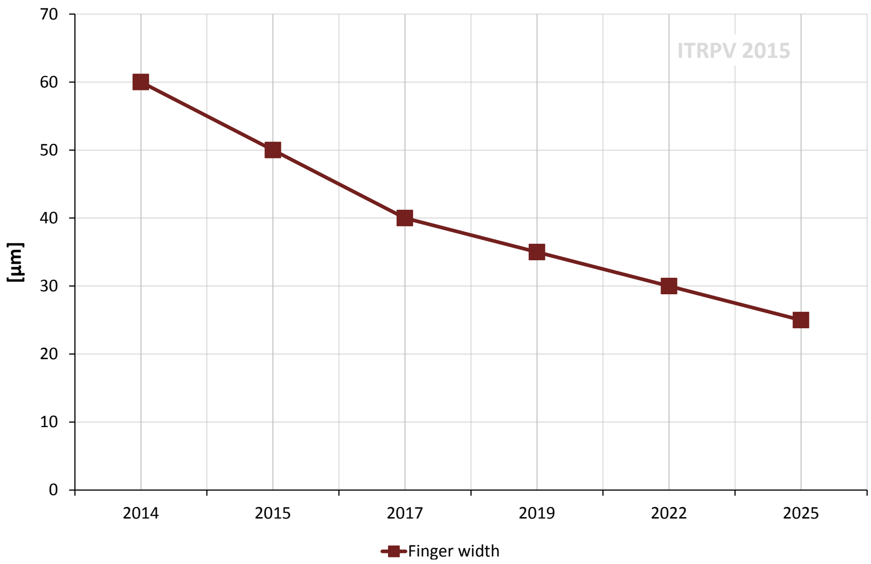


***Fig. 20***
*Predicted trend for finger width in screen printing. Finger width needs to be reduced without any significant reduction in conductivity.*

The expected share of different metallization technologies is shown in Fig. 21. Classical screen printing is expected to remain the mainstream technique up until 2025. Stencil printing, which can be used with existing screen printing equipment, is expected to be introduced in mass production starting in 2017, and it may attain a market share of as much as 20% in 2025. Plaiting technologies are expected to attain a nearly 30% market share, as was discussed in 5.2.1. Other technologies, such as inkjet, aerosol, or dispensing, are considered to be niche applications. The elimination of busbars would enable even smaller finger widths, but this would require upgraded module connection technologies.

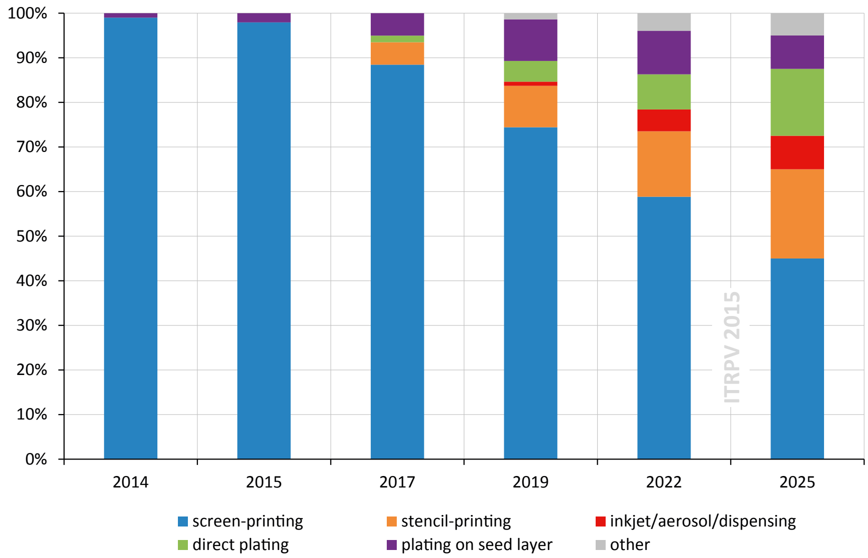


***Fig. 21***
*Predicted trend for different metallization technologies.*

Another trend in metallization relates to the number of busbars (BB) used in the cell layout. Fig. 22 shows the expected trend. We expect that the 3-BB layout dominant today will be replaced over the next few years by 4 or 5 BB — and by BB-less layouts requiring sophisticated connection technologies in module manufacturing.

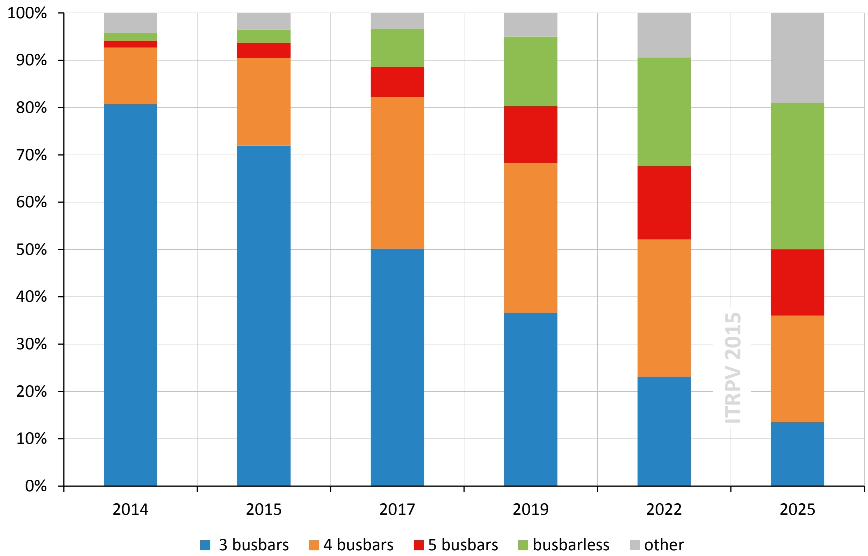


***Fig. 22***
*Worldwide market share for different busbar technologies.*

It is crucial to get as much power out of the assembled solar cells as possible. A good parameter expressing this is the cell-to-module power ratio, defined as module power divided by cell power multiplied by the number of cells (module power/(cell power x number of cells)). This ratio is currently around 99.5% for multicrystalline silicon cell technology (acidic texturing) and about 98% for monocrystalline silicon cell technology (alkaline texturing), as shown in Fig. 23.

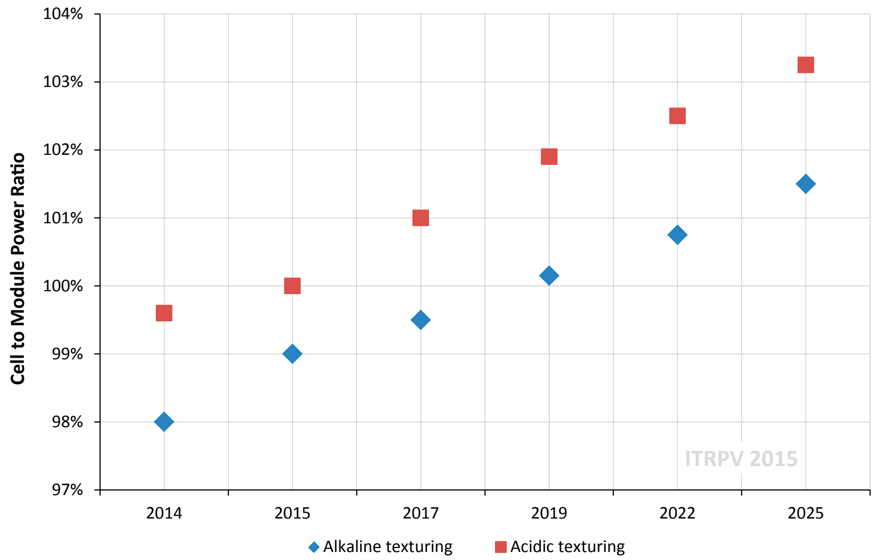


***Fig. 23***
*Expected trend for the cell-to-module power ratio.*

As can be seen in Fig. 23, the cell-to-module power ratio is expected to exeed 100% for modules with acidic textured (multicrystalline) cells, as well as for modules with alkaline textured (monocrystalline) cells. This means that eventually the power of the finished module will exceed the power of the cells used in the module. This effect will be made possbile by further improvements to light management within the module as a means of redirecting light from inactive module areas onto active cell areas. The introduction of new connection and encapsulation technologies (e.g. narrower ribbons, encapsulants with improved UV performance) will result in further improvements that will enable additional power gains.

The junction box is the electrical interface between the module and the system. We expect that the internal electrical connection of the bypass diodes currently carried out through soldering/clamping will be replaced by welding sometime between 2017 and 2019.

## 5.3 Products

Today's wafer market for c-Si silicon solar cell manufacturing is dominated by casted materials, which will achieve a market share in excess of 60% in 2015. However, this market share will eventually shrink to below 50%. 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. 24. High-performance (HP) mc-Si material now dominates the casted silicon market. Due to its excellent performance, this material is expected to replace conventional mc-Si completely by 2022. Monolike-Si has disappeared today but is expected to come back with a market share of up to 8% in 2025.

Mono-Si is expected to make significant gains over casted material and will attain a share of more than 47% in 2025. The roadmap confirms the predicted shift from p-type to n-type mono-Si within the mono-Si material market, as described in former editions. Considerable volumes of Si material produced by other technologies such as kerfless or ribbon will appear after 2020.

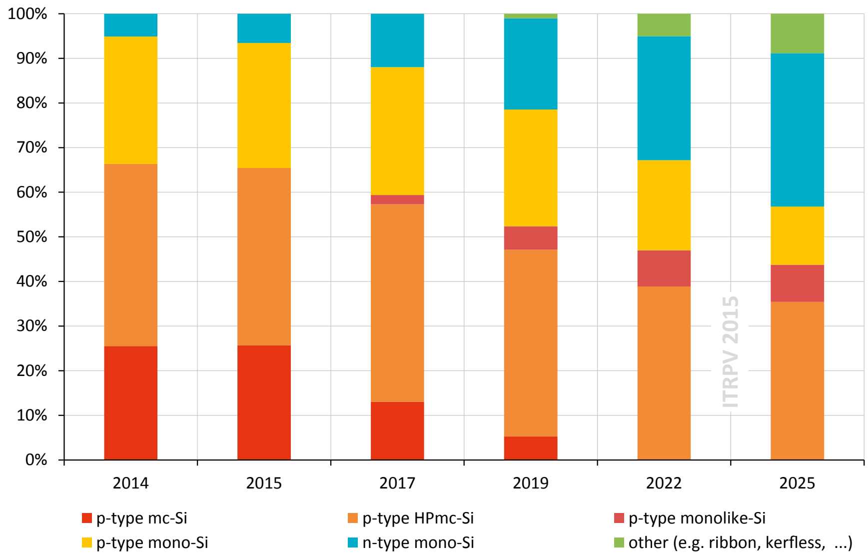


***Fig. 24***
*World market shares for different wafer types.*

Fig. 25 shows the different technologies that will be used for mono-Si crystallization. CCz will make significant gains in market share over classical Cz due to the former's cost advantages. Float zone (FZ) material for producing cells of the highest efficiency is also expected to appear on the mono Si market with a share of nearly 20% by 2025.

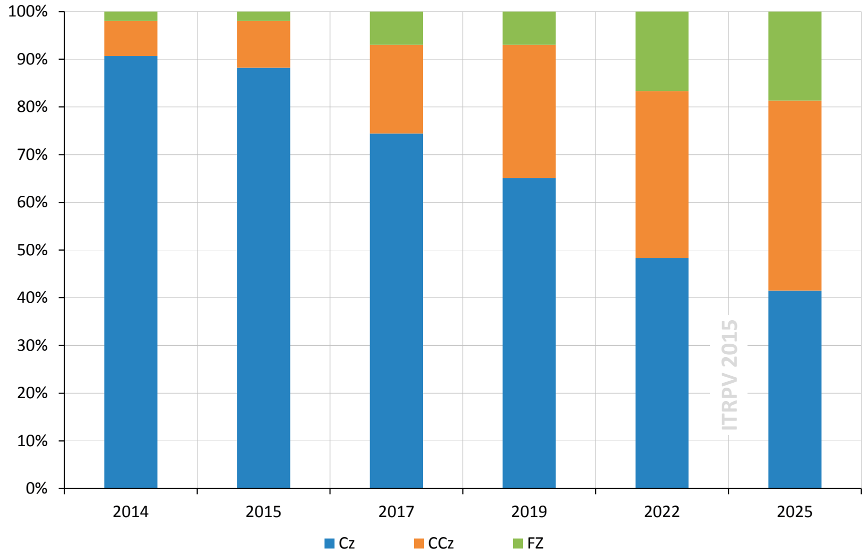


*Fig. 25*
*World market shares for different mono crystallisation methods.*

The roadmap also predicts that pseudo square wafers will dominate the market over full square wafers. Nevertheless, it is expected that the share of full square wafers will increase from the current 2% to 20% in 2025.

Fig. 26 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 still major potential for all technologies to improve their performance.

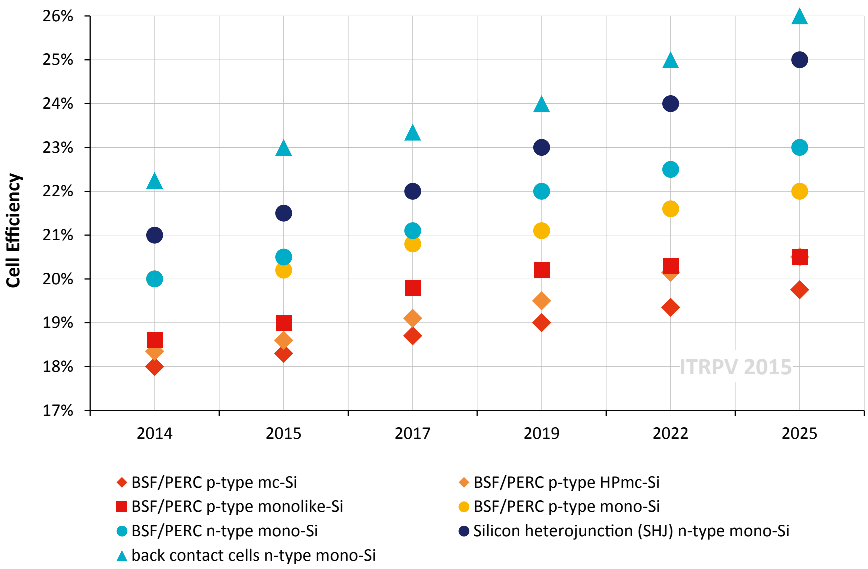


*Fig. 26*
*Average stabilized efficiency values for Si solar cells (156x156mm²).*

N-type cells show a noticeably higher efficiency increase over the time as compared to p-type cells. No significant efficiency delta is expected for double-side contacted mono n- and p-type cells during the next two to three years.

It is notable that for the first time, the efficiency of mc-Si cells is expected to surpass the 20% efficiency landmark in mass production.

Significantly higher efficiencies are expected for n-type-based cell concepts, including HJT and back-contact cells, which are also predominantly based on n-type wafers.

Fig. 27 shows the corresponding development of module power for typical 60-cell modules with 156 mm cells, with consideration of the cell efficiencies shown in Fig. 26 and the cell-to-module power ratio trend shown in the previous chapter (Fig. 23). Acidic texturing is assumed for mc-Si and HP mc-Si, while alkaline is assumed for mono and mono-like Si material. Pseudo-square wafers with diagonals of 200-205 mm are assumed for mono wafers.

It should be noted that for modules with high efficiency back-contact cells, which are not yet available on 156x156 mm² wafers, the module power values given in Fig. 27 represent equivalent values in order to enable a better comparison with double-side contact technologies.

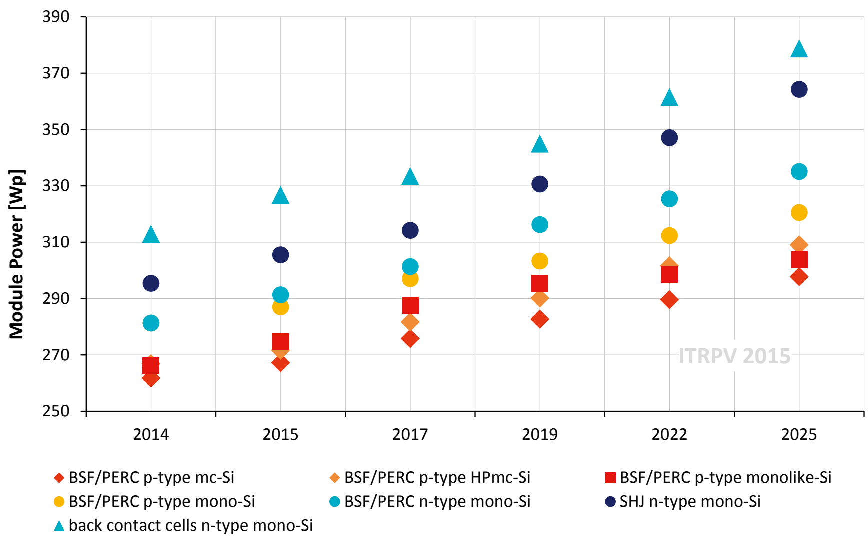


***Fig. 27***
*Predicted trend curve for module power for different c-Si cell types.*

Modules based on HP mc-Si are expected to achieve module power of nearly 310 W, and modules with n-type mono-Si will perform in the range above 360 W in 2025, as shown in Fig. 27.

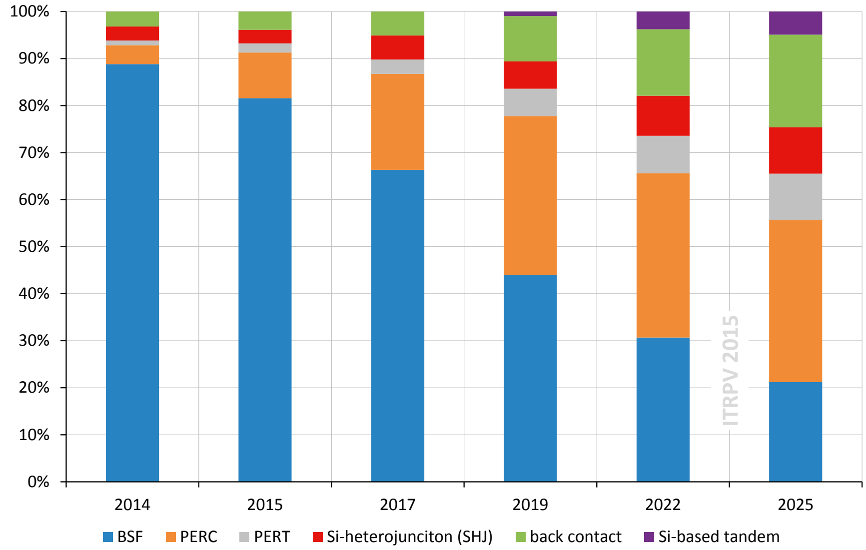


*Fig. 28*
*Worldwide market shares for different cell technologies.*

The current edition of the ITRPV predicts a mainstream market for double-sided contact cell concepts; within this market, PERC cells will gain significant market share over BSF cells, as can be seen in Fig. 28. Additionally, heterojunction (HIT/HJT) cells are expected to gain a market share of up to 10% by 2025. The share for rear-side contacted cells is not expected to exceed 20% by 2025. Si-based tandem cells are expected to appear in mass production operations in 2019.

Furthermore, it is expected (see Fig. 29) that an increasing number of cells will be light-sensitive on both sides and will therefore be bifacial cells. Our research predicts that beginning in 2014, the percentage of bifacial cells will steadily increase to a value of about 20% by 2025. Since not all bifacial cells will be integrated into bifacial-type modules with transparent backsheets or double glass, the proportion of bifacial modules will be smaller than that of cells.

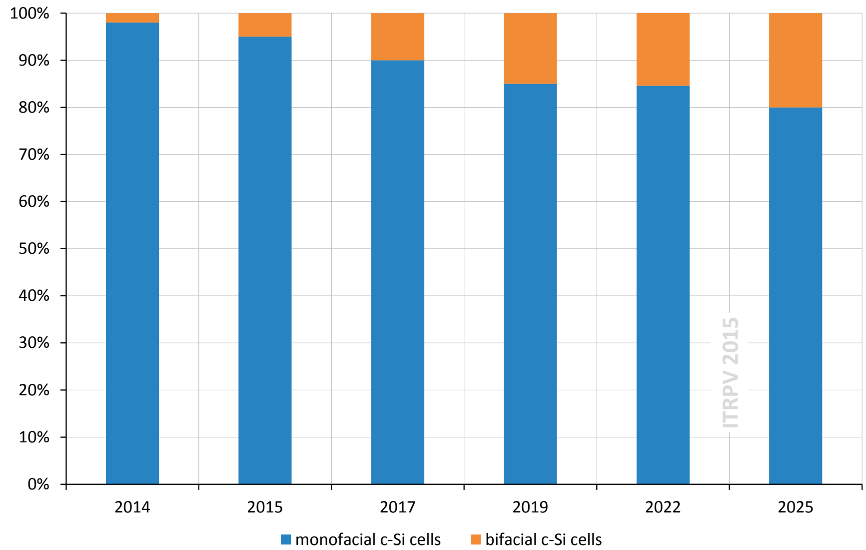


*Fig. 29*
*Worldwide market shares for bifacial cell technology.*

Modules that use half-sized cells rather than full-sized cells have recently been introduced to the market in order to reduce connection 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. 30, it is expected that the market share of half cells will grow from 2% in 2015 to around 30% in 2025.

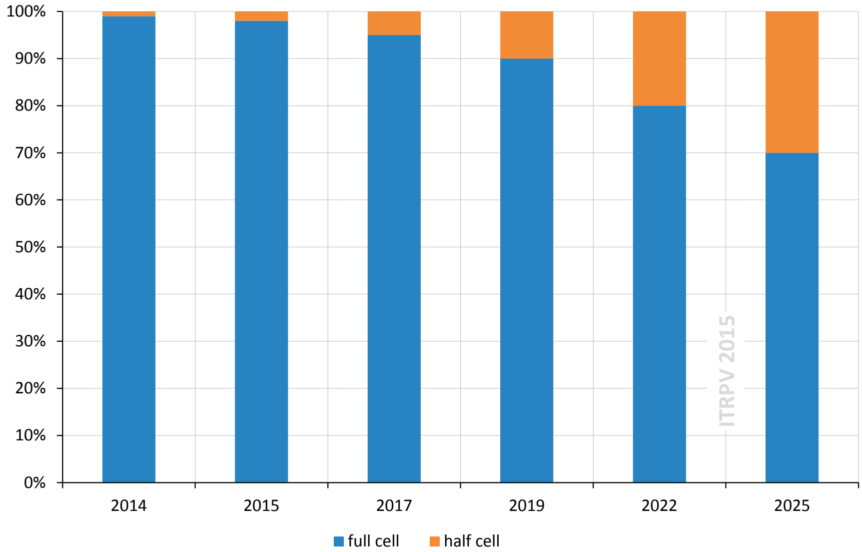


*Fig. 30*
*Predicted market shares for modules with full and half cells.*

With regard to module sizes, it is becoming clear that the market will be split into different applications: 60-cell modules, 72-cell modules, and 80-cell modules for utility scale applications with market shares of > 40% for the first two types and around 2% for the 80-cell types; other module sizes for niche markets (e.g. 32, 36, 48 cells) are expected to account for less than 10% of the market by 2025 (see Fig. 31). Today's mainstream modules (60-cell) should still have a market share of around 50% in 2025.

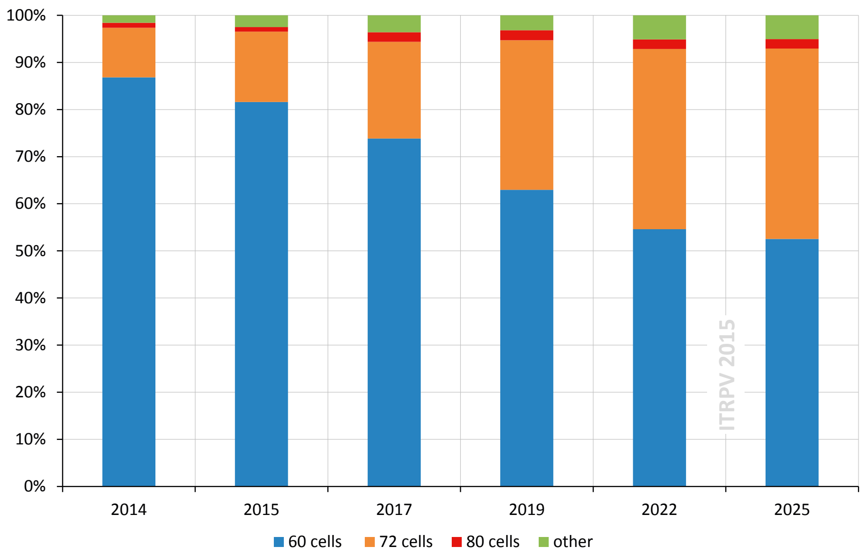


*Fig. 31*
*Market shares of different module sizes.*

So-called smart J-Box technologies have been developed in recent years to improve the power output of PV systems. In this year's ITRPV edition, we wanted to determine whether these technologies are becoming a major trend. As can be seen in Fig. 32, 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.

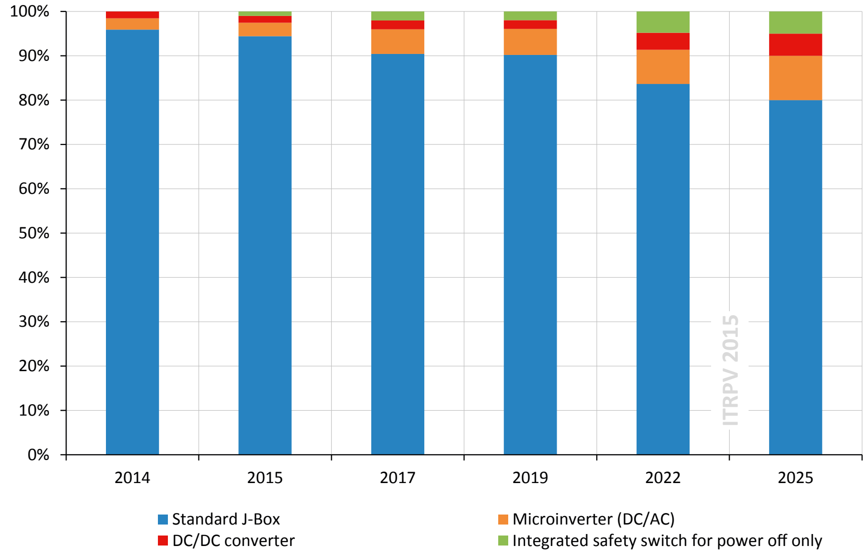


***Fig. 32***
*Market trend for different J-Box functionalities.*

DC/AC micro-inverters are expected to increase their market share to around 10% by 2025. Integrated safety switches for power off (e.g. in case of fire) and DC/DC converters (so- called power optimizers) are both expected to attain a market share of around 5% during the same time frame.

# 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. In Figures 33 and 34, we show the relative development of system costs for large systems > 100 kWp in the U.S., Europe, and Asia. It should be noted that no "soft costs," such as costs for permits or costs for financing, are included, as these costs can vary greatly from country to country. Excluding the "soft costs," the distribution of system costs as well as the development over time is expected to be very similar in the U.S. and Europe.

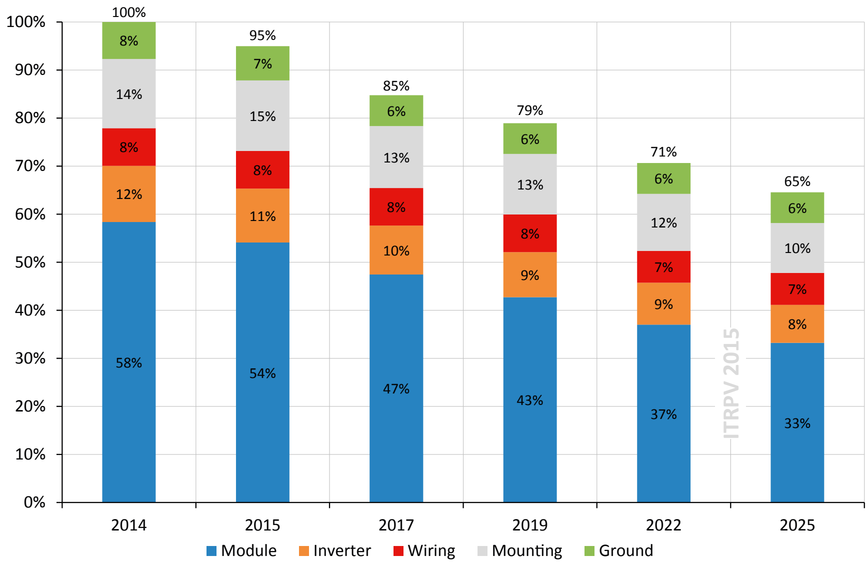


***Fig. 33***
*Relative system cost development for systems > 100kW in the U.S. and Europe (2014 = 100%).*

As can be seen from Fig. 33 and Fig. 34, the overall trend for a system cost reduction of approximately 30% over the next ten years is expected to be very similar for Asia, Europe, and the 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 development of the share of the module costs as compared to the system costs. Whereas this share is expected to decline to 50% in the U.S. and Europe, it appears it will stay constant at around 60% in Asia.

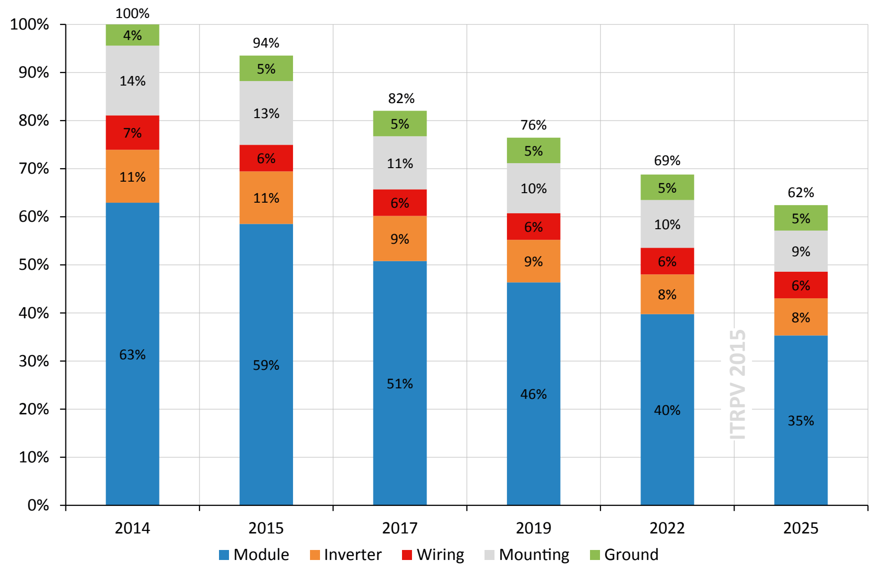


***Fig. 34***
*Relative system cost development for systems > 100kW in Asia (2014 = 100%).*

One trend to be expected on the system level is that toward an increase of system voltage from 1,000 V to 1,500 V — becoming discernible from 2017 onwards and attaining a market share of around 30% in 2025. 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.

Furthermore, the average module power class for systems > 100 kWp is expected to increase from the current 255 Wp to 310 Wp for 60-cell modules, and from 310 Wp to 365 Wp for 72-cell modules. This also should support the reduction of the area-dependent BOS costs.

The participants in the current ITRPV are predicting another long-term trend on the system level: The market share for large-scale crystalline silicon-based PV-systems built using 1-axis tracking will increase from approximately 6% today to more than 20% in 2025. By contrast, 2-axis tracking will remain negligable for c-Si technology (market share of less than 2% during the same time frame).

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, we calculated the LCOE in USD for large PV systems under different insolation conditions (see Fig. 35). As the actual system price is strongly dependent on the location of the system, we assumed for our calculation 1300 USD/kWp in 2014 [12], which is typical for large-scale systems in China. Taking into account the system-cost trends depicted in Fig. 34, the system costs will decline to a value of around 810 USD in 2025.

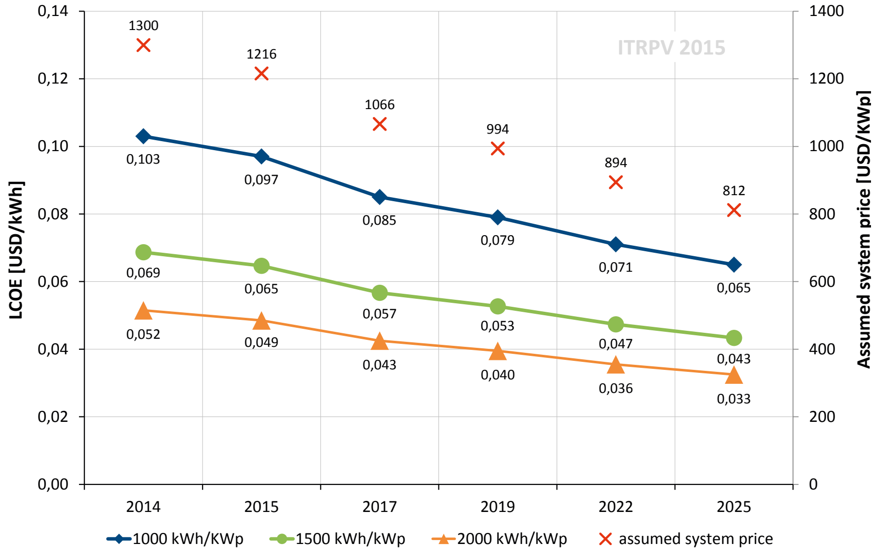


***Fig. 35***
*Calculated LCOE values for different insolation conditions. Financial conditions: 80% debt, 5%/a interest rate, 20-year loan tenor, 2%/a inflation rate, 25 years usable system service life.*

As can be seen in Figure 35, LCOE values of between 0.05 and 0.10 USD are already feasible today, depending on the insolation level. Considering the system price trend anticipated by the ITRPV, PV electricity costs in the range of 0.03 to 0.06 USD are predicted for the year 2025. It should be noted that along with the system price and the insolation level, the LCOE is also strongly dependant 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 or more, which would make it possible to reduce LCOE levels even further. This clearly makes PV power generation a clean and cost-competitive energy source that will play a major role in future global energy supply.

# 7. Outlook

In earlier editions of the roadmap, we discussed possible trends related to c-Si PV module production costs. We highlighted the fact that increasing module power while simultaneously lowering the cost per piece is the most promising scenario for the future of PV.

Table 3 combines this ITRPV cost-trend assumption of the 5th edition (module cost / assumed shipments) with module prices / shipments over the last few years.
The assumed volumes for 2013 / 2014 are higher than what was finally achieved – the actual values are between the “EPIA Policy-Driven” and “EPIA Business-as-Usual” scenario [13]. This reflects the fact that PV is now an attractive business and no longer a subsidized niche. However, predictions regarding PV trends can only be made with a high degree of uncertainty. Nevertheless, the combined plot of the historic price learning curve and the ITRPV cost trend in Fig. 36 shows that costs can be below the average sales prices. This will enable profitable business operations in the years to come. The future cost reductions for c-Si modules will significantly support the PV-system cost reductions as discussed in Chapter 6.

| | 06/ 2012 | 12/ 2012 | 12/ 2013 | 12/ 2014 | 12/ 2016 | 12/ 2018 | 12/ 2021 | 12/ 2024 |
|---|---|---|---|---|---|---|---|---|
| **Cum. volume shipped** | **92** | **110** | **144** | **184** | | | | |
| **Price at end of period (US$/Wp)** | 0.95 | 0.69 | 0.72 | 0.63 | | | | |
| **Assumed cum. volume shipped (GW)** | **92** | **110** | **150** | **200** | **320** | **440** | **630** | **850** |
| Avg. Wp increase (period to period) | | | 3% | 3% | 3% | 4% | 5% | 5% |
| Cost reduction (period to period) | | | 6% | 6% | 8% | 10% | 10% | 10% |
| **ITRPV 5th edition cost trend (US$/Wp)** | **0.83** | **0.73** | **0.64** | **0.58** | **0.52** | **0.45** | **0.38** | **0.33** |

***Table 3:*** *Comparison of the ITRPV 5th edition cost scenario with price and shipment data .*

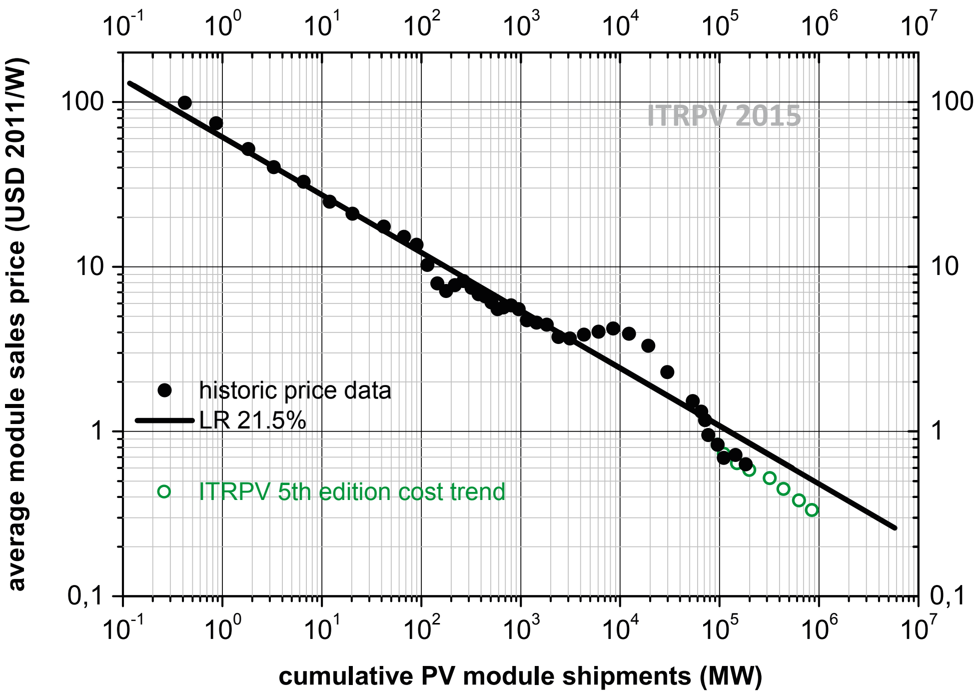


***Fig. 36*** *Learning curve of module price as a function of cumulative PV module shipments with historic price data and the ITRPV 5th edition cost trend shown in Table 3.*

The most widely publicly discussed PV-related topics are installed module power and module shipments. A look at the supplier side, especially at the installed capacities for PV modules, cells and polysilicon, is less spectacular, but it is essential for planning current and future production capacities. In the following section, we attempt to provide an outlook for future production capacity growth.

An interesting outlook for the worldwide development of PV-generated electricity up until 2050 is provided by the IEA Solar Photovoltaic Energy Technology Roadmap [14]. The IEA assumes in this roadmap that by 2050 about 16% of global electricity consumption will be covered by PV installations with about 4.68 TWp, generating about 6.3 PWh of electricity.
We utilized these figures and deduced the annual installed PV power $P_{PV}(t)$ as the sum of the installed PV power in $j$ different regions $N_i(t)$:

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

The installed module power in each region was calculated with the logistic growth approach, in which $G_i$ is the maximum installed power in the market, $k_i$ is the growth slope, and $c_i$ is the time constant for the market in question:

$$N_i(t) = \frac{G_i}{1 + e^{k_i\,(c_i - t)}}$$

The simplified model considers four different growth regions with different growth parameters as summarized in Table 4 – Europe and Japan (EU /JP), PRC / India / Asia, U.S., and rest of world (ROW).

| **Region(s)** | $G_i$ (market 2050+) | $k_i$ (growth slope) | $c_i$ (time constant) |
|---|---|---|---|
| ROW | 1400 GW | 0.20 | 2030 |
| U.S. | 600 GW | 0.19 | 2025 |
| PRC/India/Asia | 2300 GW | 0.30 | 2019 |
| EU /JP | 380 GW | 0.39 | 2015 |

*Table 4: Logistic growth parameter of the four key regions in the world.*

The annual addressable market $AM\ (n)$ corresponds to the installed module power in year n. It is calculated by subtracting $P_{PV}(n-1)$ from $P_{PV}(n)$ and adding the replacement capacity of the worn-out installations $P_{PV}(n-30)$, assuming a wear-out period of 30 years. $AM\ (n)$ is therefore calculated as:

$$AM\ (n) = P_{PV}(n) - P_{PV}(n-1) + P_{PV}(n-30)$$

Fig. 37 shows the plot of the cumulated installations, historic PV shipment data (up until 2014), the ITRPV outlook (for 2013–2024), and the annual market. The annual market is plotted with a different scale (right y axis).

Fig.37 shows as well that based on the IEA roadmap, the addressable PV market and the corresponding production capacity require no urgent expansion beyond 60 GWp over the next three years. The market should expand to above 80 GW beginning in 2022, with a peak of around 220 GWp in 2030. After this peak, demand should decline again to below 150 GWp until 2040, with a minimum of 100 GWp around 2050. This up-and-down development will repeat itself due to the replacement of old systems after 30 years of operation from today's point of view. This fact emphasizes the importance of PV-module reliability.

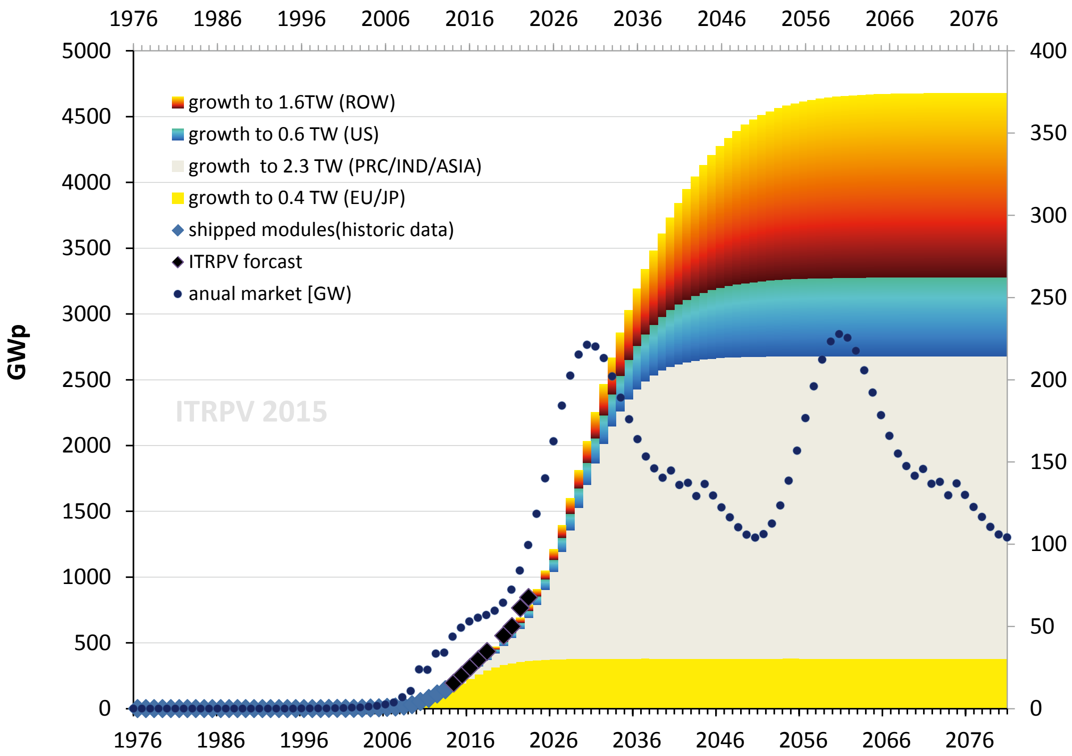


***Fig. 37*** *Cumulative installed module power calculated with a logistic growth approximation for different regions based on the IEA predictions of approx. 4.7 TWp installed PV module power in 2050.*

This simple model shows that there will be no "endless" market for PV modules, nor will "endless" production capacity be needed. However, there will be a considerable market with possible critical demand peaks. The failure to limit such peaks might lead to superheated markets with subsequent production overcapacities similar to the situation roughly four years ago (2009–2012).

Progressive tool concepts in cell manufacturing for production lines with matched throughput between front and back end, as discussed in Chapter 5, support >100 GW production capacity scenarios. Such tool sets are already available today.

PV equipment suppliers can now focus on supporting an upgrade of existing production capacities for new technologies such as PERC. The continued replacement of worn-out equipment and support for moderate capacity expansions will also constitute a considerable business segment over the next few years. All of this is good news for the c-Si PV industry.

Current 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 this 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.

The data used in this roadmap was collected at the beginning of 2015 from leading international PV manufacturers, companies along the c-Si value chain, PV equipment suppliers, production material providers, and PV institutes. Plans call for this information to be updated annually. Topics such as wafer thickness require cooperation between tool suppliers, cell manufacturers, and other companies along the value chain. A version of this document for downloading, 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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