C-Si PV:
Manufacturing Trends & Challenges
- ITRPV 8th edition update
(incl. maturity report)

World Solar Congress | Shanghai, September 5-6, 2017

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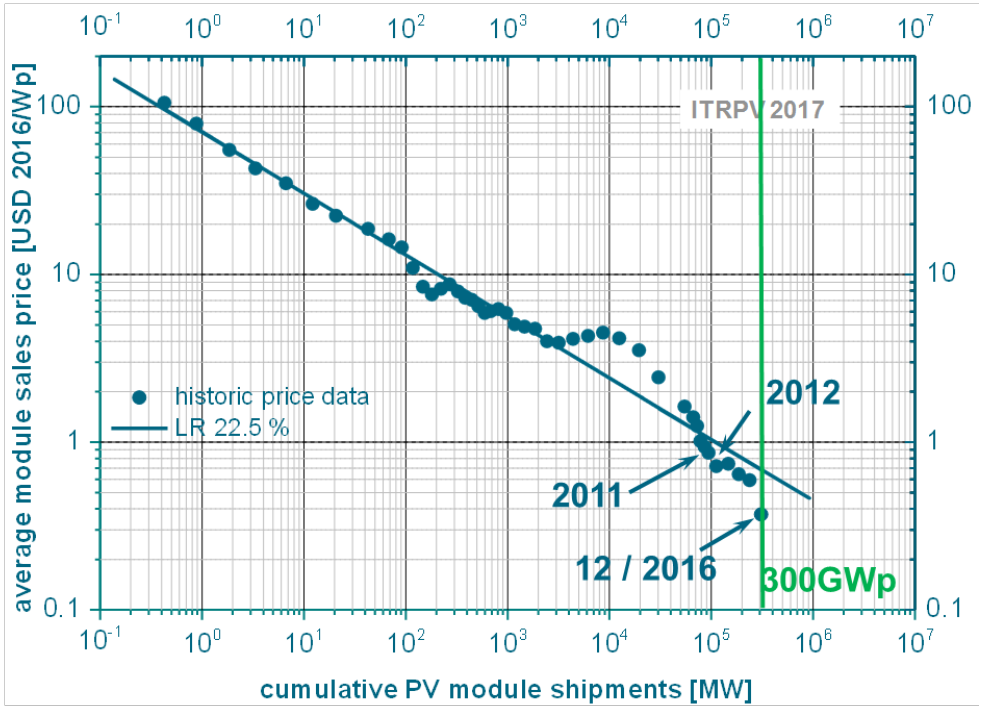
Module Price learning Curve



Shipments /avg. price at years end:

2016: 75 GWp / 0.37 US$/Wp
08/2017: 0.35 US$/Wp

o/a shipment: ≈ 308 GWp
o/a installation: ≈ 300 GWp

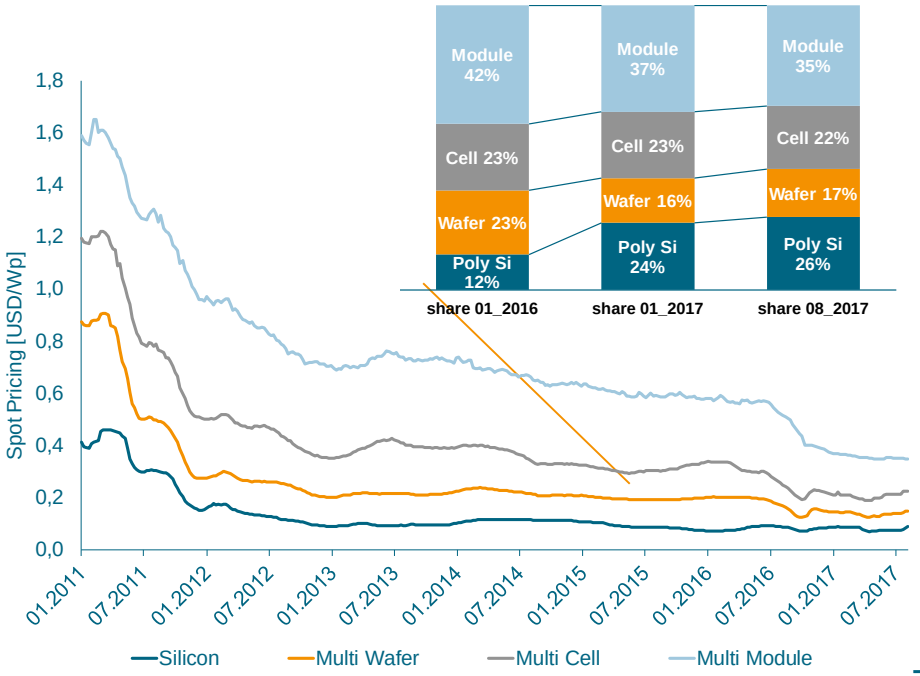
2017expectation: ≈ 380 GWp

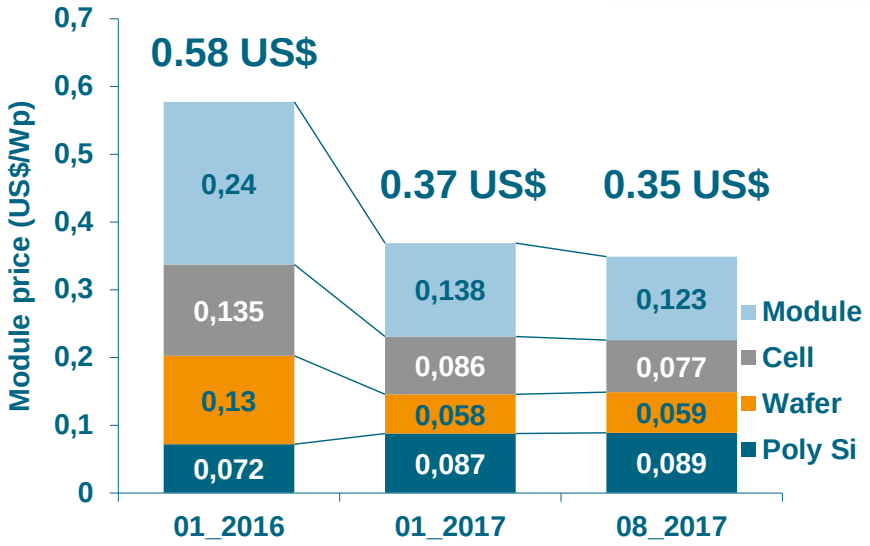
300 GWp landmark was passed!

LR 22.5 % (1976 …. E 2016)

dramatic price drop due to market situation
→ Comparable to 2011/2012, but faster

Module Price development





→ reduction 01/2011 → 01/2016: ≈ 64 %
→ **reduction 01/2016 → 01/2017: ≈ 36 %**
(reduction 01/2011→ 01/2012: ≈ 40 %)
→ reduction 01/2017 → 08/2017: ≈ 5% → 0.35US$

Result:

High cost pressure PV - manufacturers

Dramatic price drop in 2016

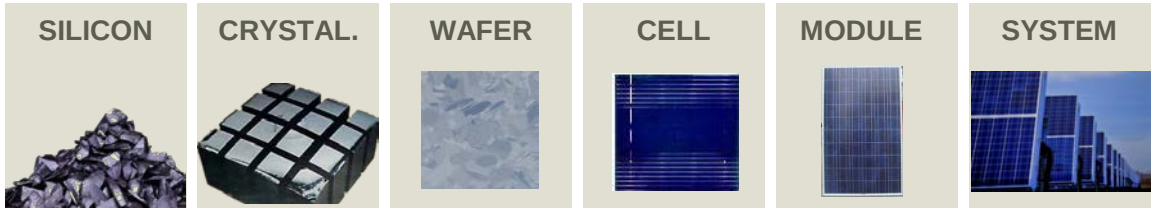
→ Market driven drop

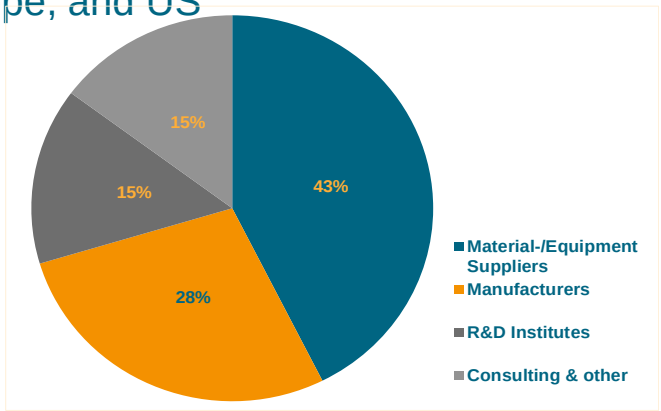
→ Poly-Si share increased again (temporary shortage)

→ Next price drop expected

ITRPV – Methodology

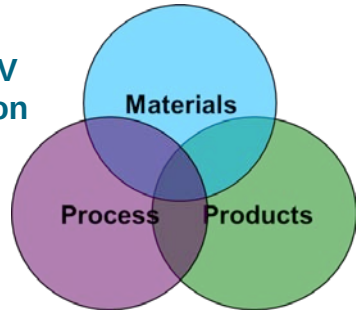
Working group today includes >50 contributors from Asia, Europe, and US





Participating companies → **Independent data collection / processing by VDMA** → **Review of data Preparation of publication → regional chairs** → **Next ITRPV edition**

Chairs EU
Chairs PRC
Chairs TW
Chairs US



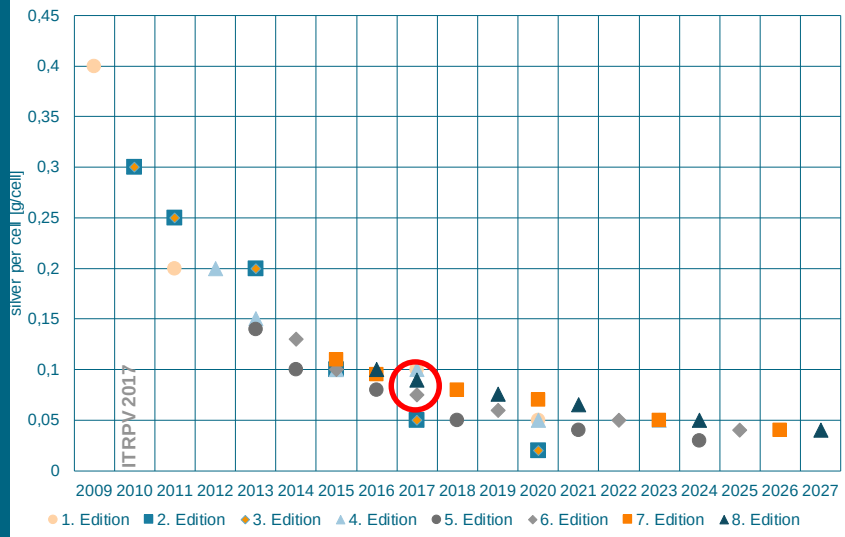
Grey	Industrial solution exists, and is being optimized in production
Yellow	Industrial solution is known but not yet in mass production
Red	Interim solution is known, but too expensive or not suitable for production
purple	Industrial solution is not known

Parameters in main areas are discussed → Diagrams of median values + maturity

Cell – Materials Example: Ag reduction

ITRPV Trend:

Prediction of remaining Ag on c-Si Solar cells → from 2009 to today



Ag reduction will continue

Challenge: increase efficiency, keep quality

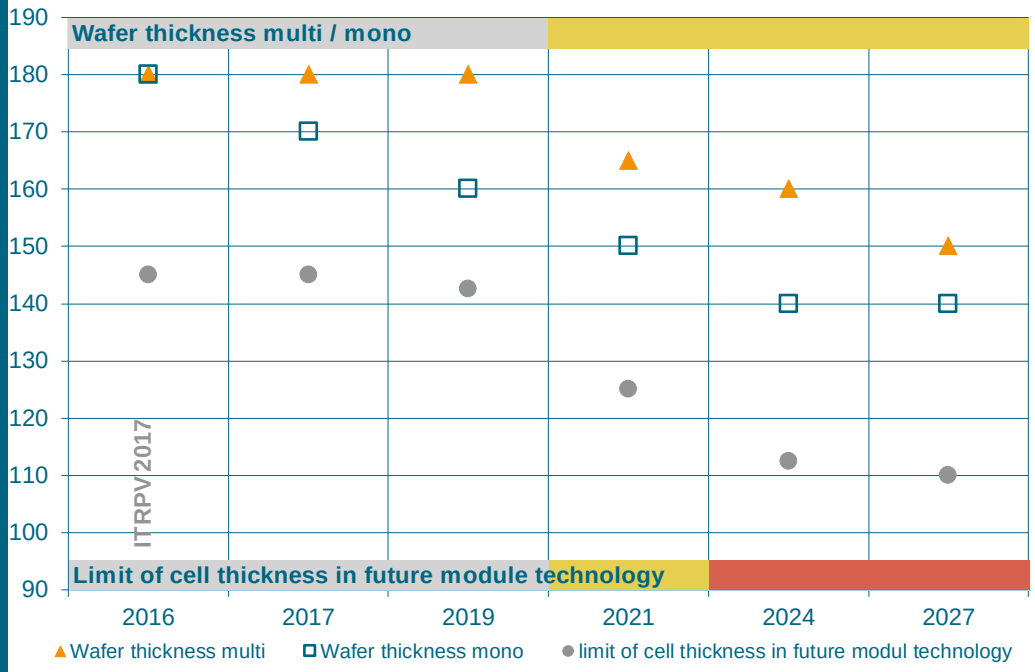
90mg remaining Ag are reality
50mg will be reached within 5 years

Measures (new pastes, thinner fingers, multi bus bars, bus bar less, etc…)

→ **Cost reduction will continue**
→ **Material suppliers have to provide innovation**
→ **Tool suppliers have to support implementation**

Material: Minimum as-cut wafer / cell thickness

Trend: wafer thickness reduction will materialize



- Reduction to 160µm may appear faster

→ Indicated by grey /yellow marking!

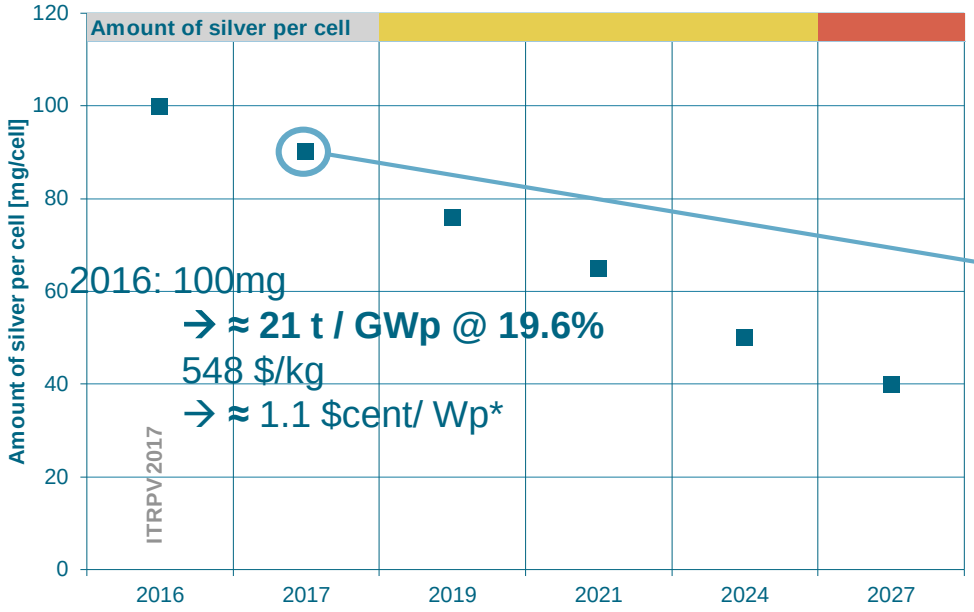
→ Down to 140µm will be possible

- Module technology

→ Requires development for < 120µm **(red)**

Materials – Silver (Ag) per Cell

Ag will remain dominating in c-Si metallization



2016: 100mg
→ ≈ **21 t / GWp @ 19.6%**
548 $/kg
→ ≈ 1.1 $cent/ Wp*

* avg. cell efficiency 19.6 % ≈ 4.8 Wp/cell

Ag price is very volatile

→ 2016 100 mg
→ 2027 40 mg

Maturity report:

90 mg are in mass production (Grey)

Technical solutions for < 90 mg are ready (Yellow)
→ Faster reduction might be possible

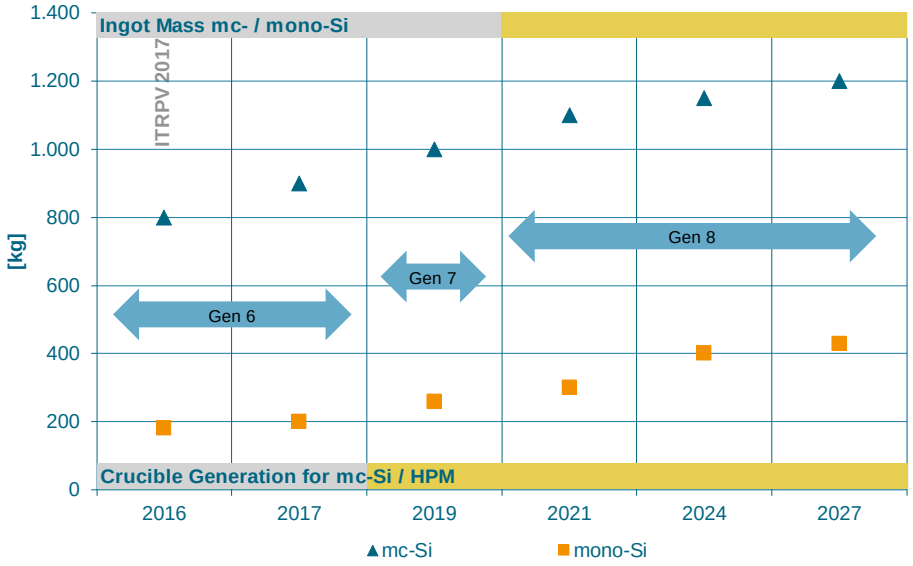
No good solutions so far for <50mg (**Red**)

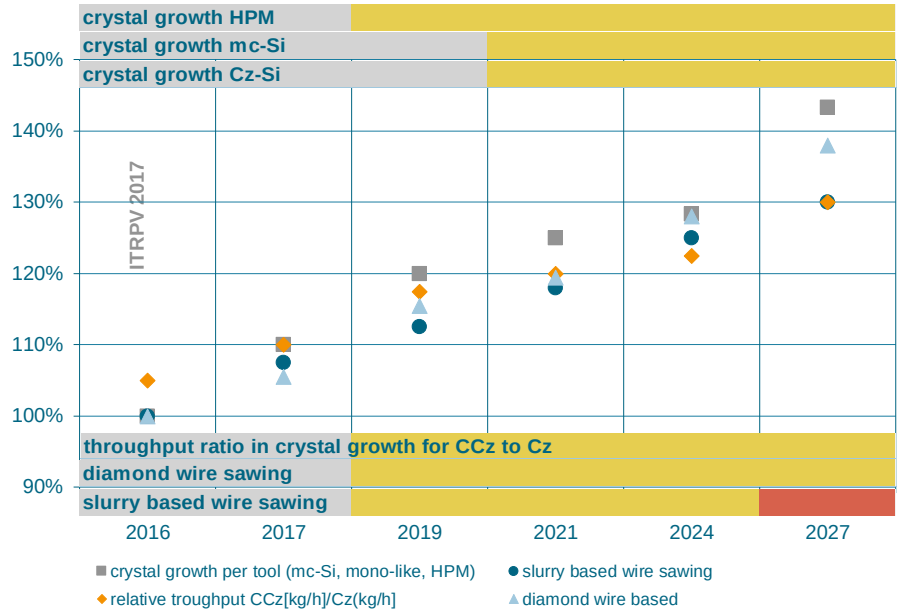
2016:
Ag accounted for ≈10% of cell conversion price
→ Ag reduction is mandatory and will continue
→ Cu is expected to have 5% market share in 2019

Lead free pastes in production → 2019

Processes manufacturing. Ingot mass / throughput

Trend: crystallization ingot size / tool throughput



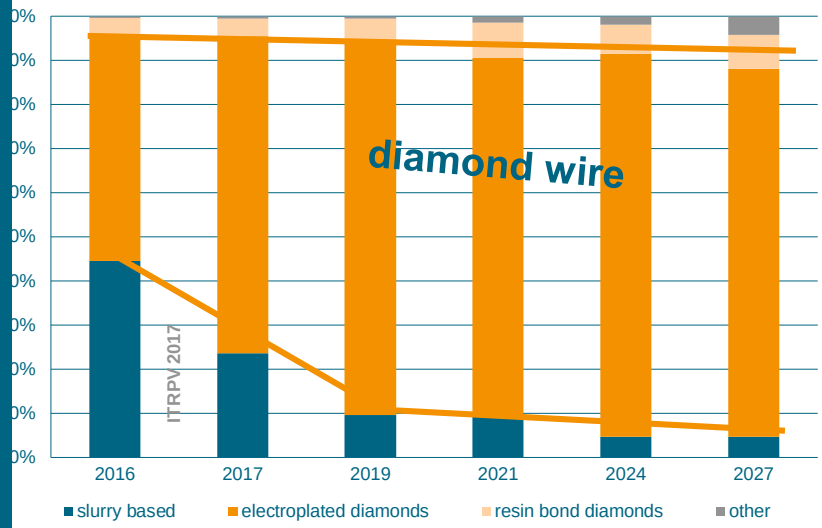


Casting G6 is standard
→ move to G7/8 may occur faster (yellow coding)
Mono ingot mass 200kg = standard
→ move to 400kg may occur faster (yellow coding)

Crystal growth speed:
→ increase by >30% expected fast (yellow coding)
Wiring throughput DWS:
→ Fast increase by >30% expected (yellow coding)
→ Slurry sawing will drop behind

Processes: wafering technology

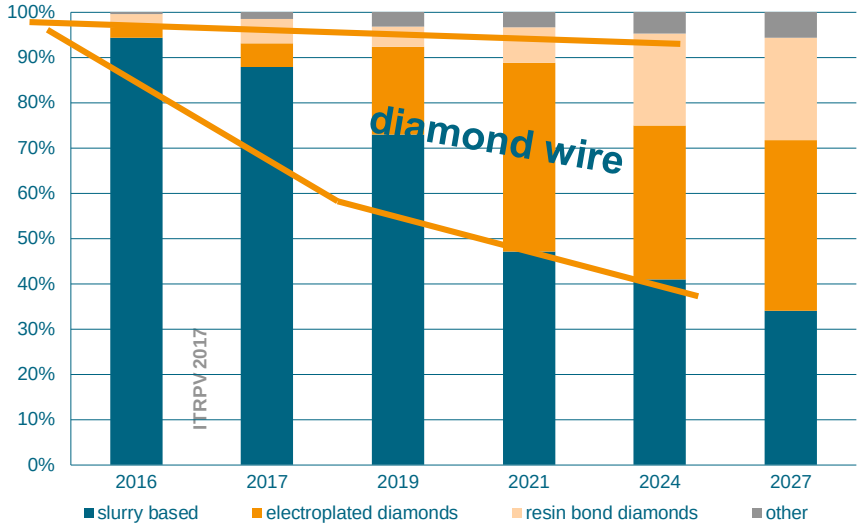
Trend: wafering technology for mono-Si



diamond wire wafering: now mono mainstream

→ Electroplated diamond wire is mostly used

Trend: wafering technology for mc-Si



Slurry based wafering will disappear

→ change to diamond wire is ongoing

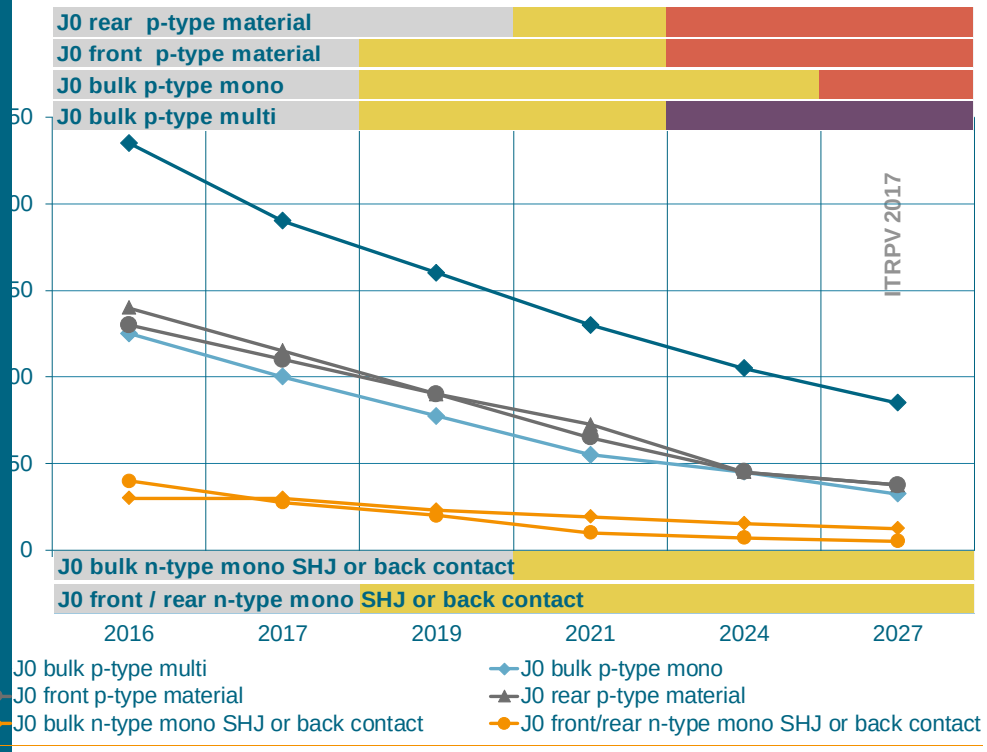
→ main challenge: texturing

→ Big progress in wet texturing

Different Solutions compete: MCCE, Additives,….

Cell Processes - recombination current densities

Trend: $J0_{bulk}$, $J0_{front}$, $J0_{rear}$



- **$J0_{bulk}$:**

will be further reduced
optimizing requires R&D (not yet usable)

	yellow		purple
→ p-type mc-Si:	130	→	**<130fA/cm²**
	yellow		**red**
→ p-type mono-Si:	60	→	**<45 fA/cm²**

N-type bulk is ready
→ n-type mono-Si: **15 fA/cm²**

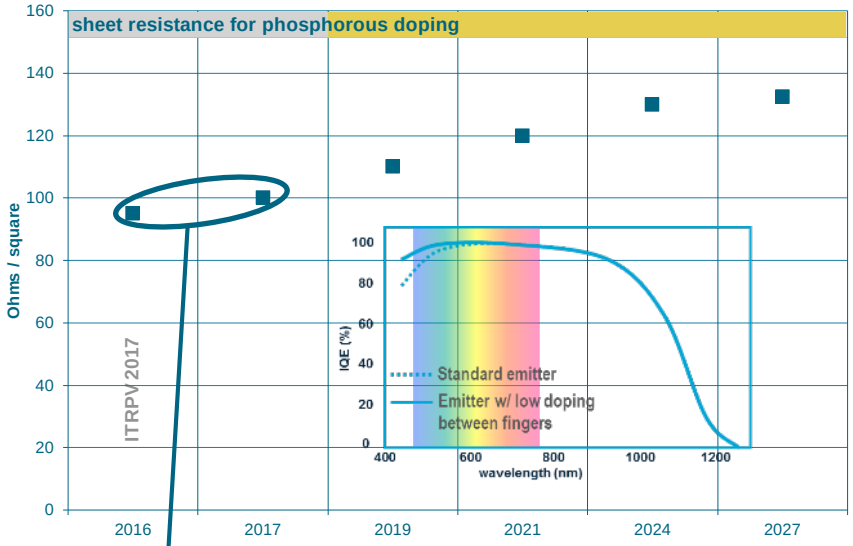
- **$J0_{front}$ / $J0_{rear}$**

→ Further reductions by >50%
But R&D required **(red coding)**
→ p-type is limited at the front side
(i.e. need of improved diffusion / new pastes)
→ Wide use of rear side passivation concepts

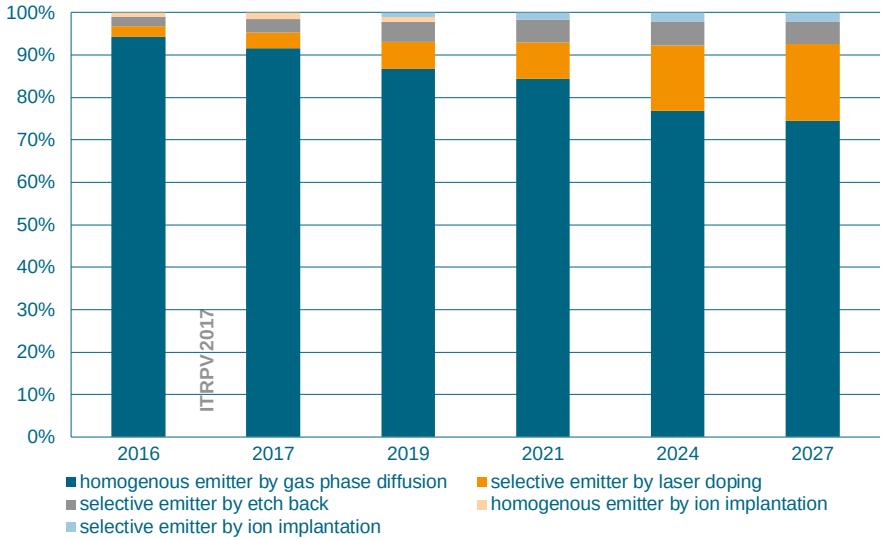
→ p- type: reducing recombination losses is on a good way
→ n-type: overcomes p-type bulk material limitations

Cell – processes: emitter formation for low $J0_{front}$

Trend: emitter sheet resistance



Trend: emitter formation technologies



Essential parameter for J0front

→ **95…100 Ω/□** are standard today

→ Increase to 135 Ω/□ is predicted

→ **Challenge for tools and front pastes**

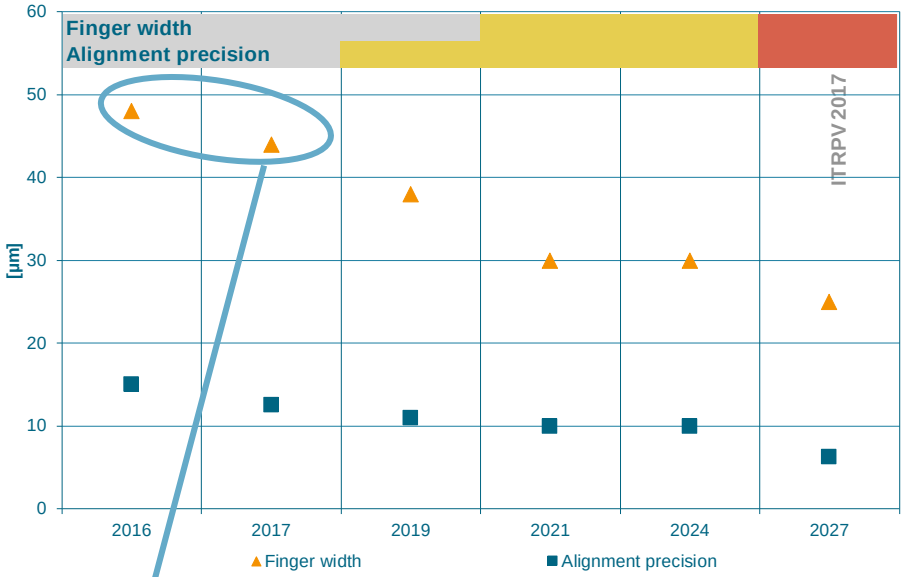
Mainstream: homogenous gas-phase diffusion

→ selective doping: etch back or laser doping

→ Ion implant stays niche

Cell Processes:
finger width / number of bus bars / bifaciality

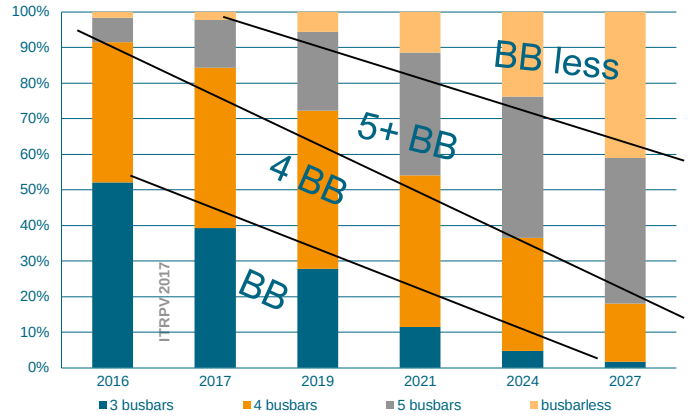
Trend: Finger width reduction + alignment precision



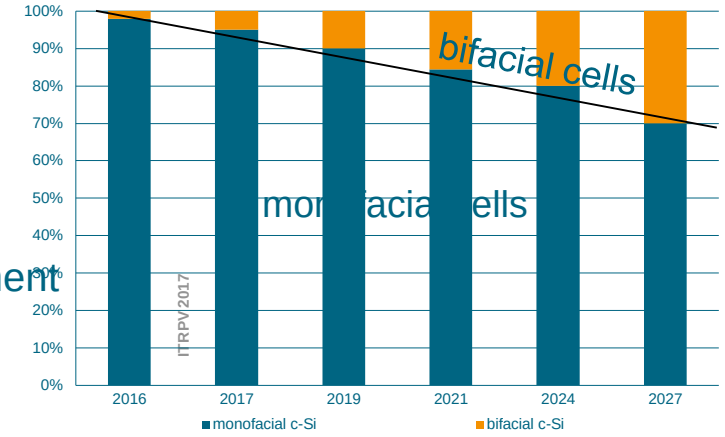
Front side grid finger width reduction continues
2017: <50µm reached!
→ Enables reduction of BBs + Ag reduction
→ **4BB are mainstream – 3 BB will disappear**
Alignment precision will improve to <10µm @3 sig.
→ Selective emitters + Bifacial cells require good alignment
→ Bifacial cells will increase market share

Improvements may proceed faster (Grey + Yellow)

Trend: number of bus bars (BB)



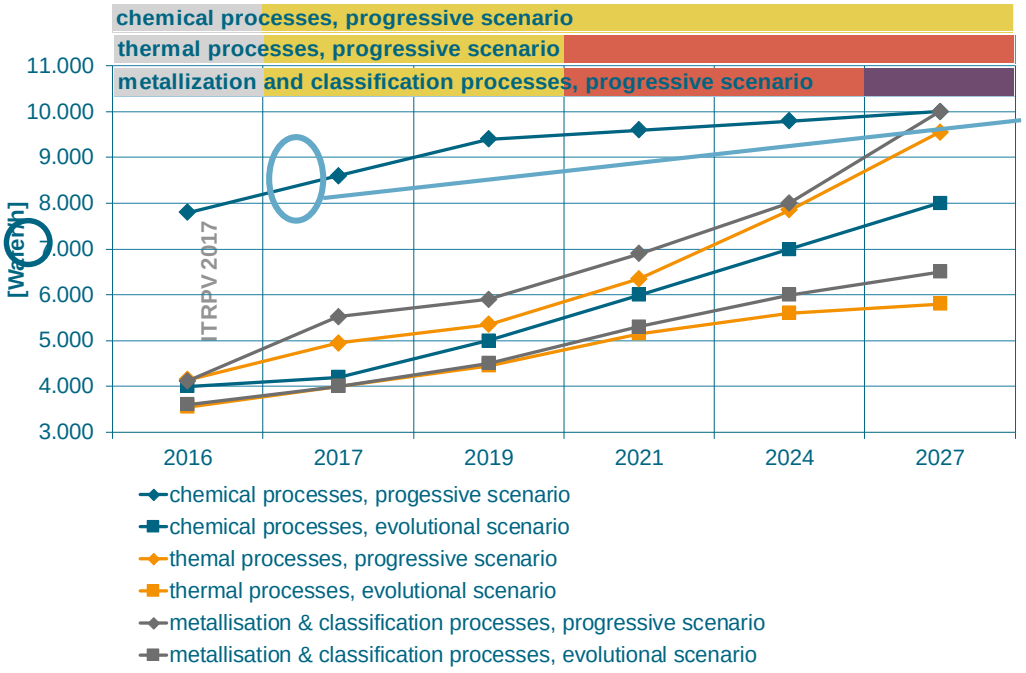
Trend: market share of bifacial cells



Cell – Processes: cell production tool throughputs
→ Tool throughputs will increase

ITRPV Trend:

tool throughput increase + synchronization of frontend/backend



Wet benches are leading w/ >8000 wf/h
→ Throughput increase will continues
→ Easy to implement **(**Grey **/** Yellow **coding)**

Challenge:
increase throughput + Improve OEE

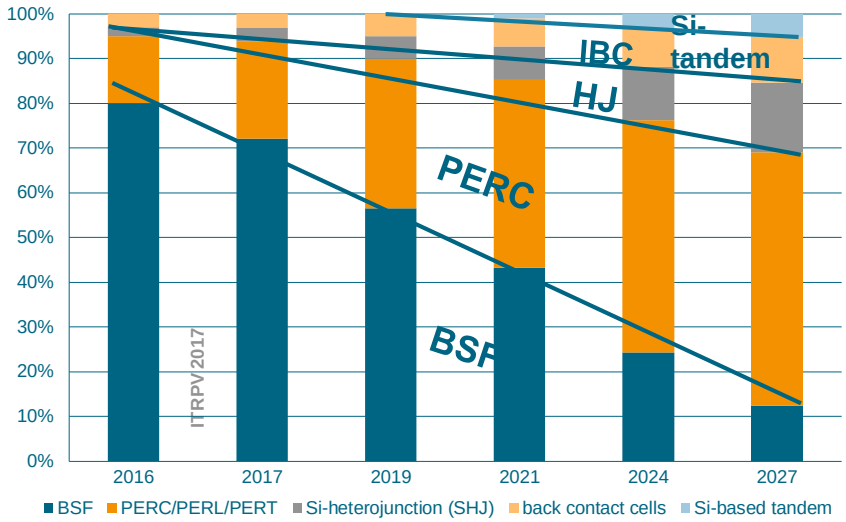
Two throughput scenarios:

Progressive = new high throughput tool

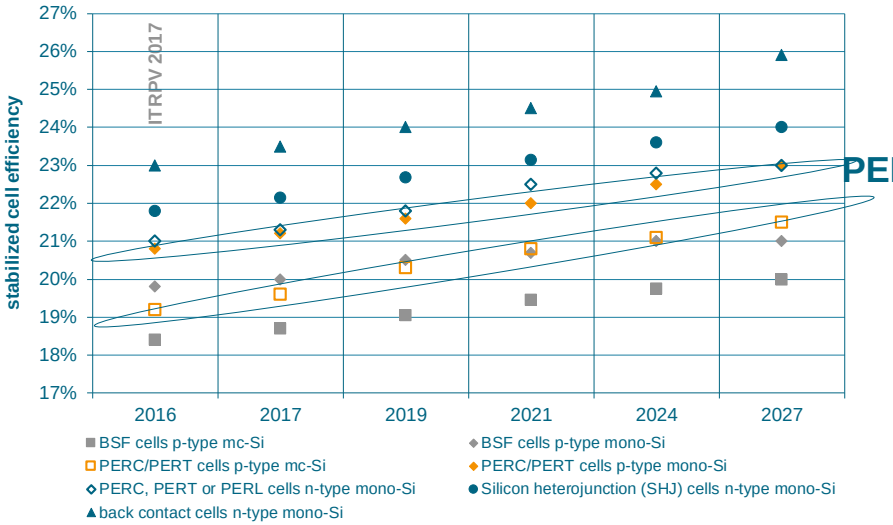
Evolutionary = Cont. improvement of tools (debottlenecking, upgrades…)

Products: cell technologies / cell efficiency trends

Trend: market share of cell concepts
2016: PERC ≈15%



Trend: stabilized cell efficiencies;
→ p-type PERC outperforms

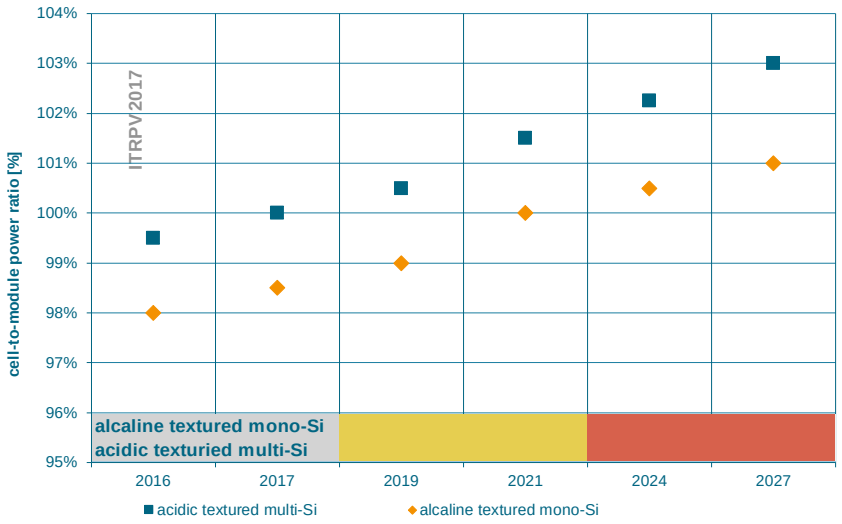


PERC is gaining market share (20% 2017)
→ BSF share is shrinking
→ Back contact + HJ: slow increasing share
→ Si tandem: under development

p-type mono PERC will reach n-type performance
mc-Si PERC is about to outperform mono BSF
→ n-type IBC + HJ for highest efficiency applications
→ stabilized >21% p-type mono PERC is in production

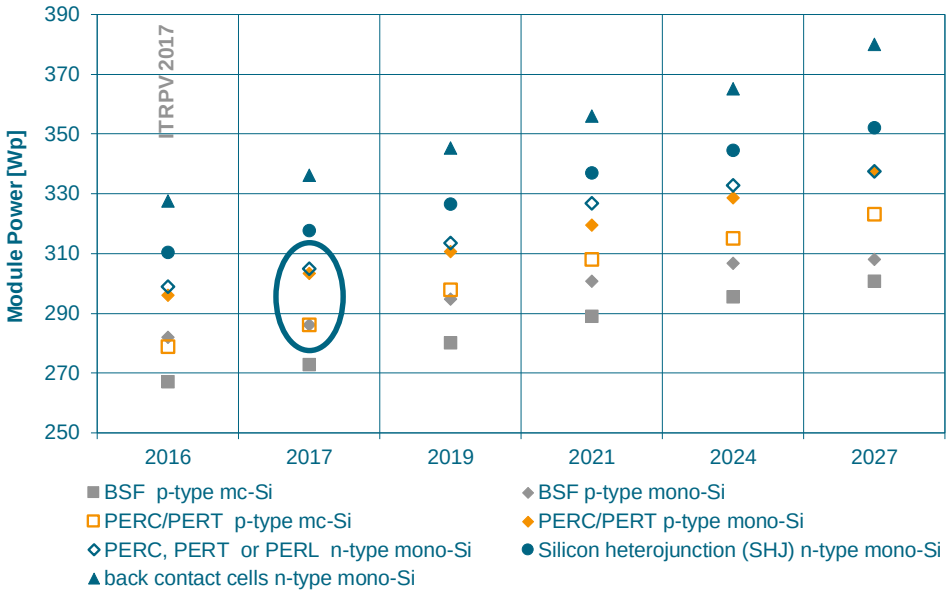
Products: module power outlook

Trend: cell to module power ratio (CTM)



CTM will increase
→ Acidic texturing has still higher CTM

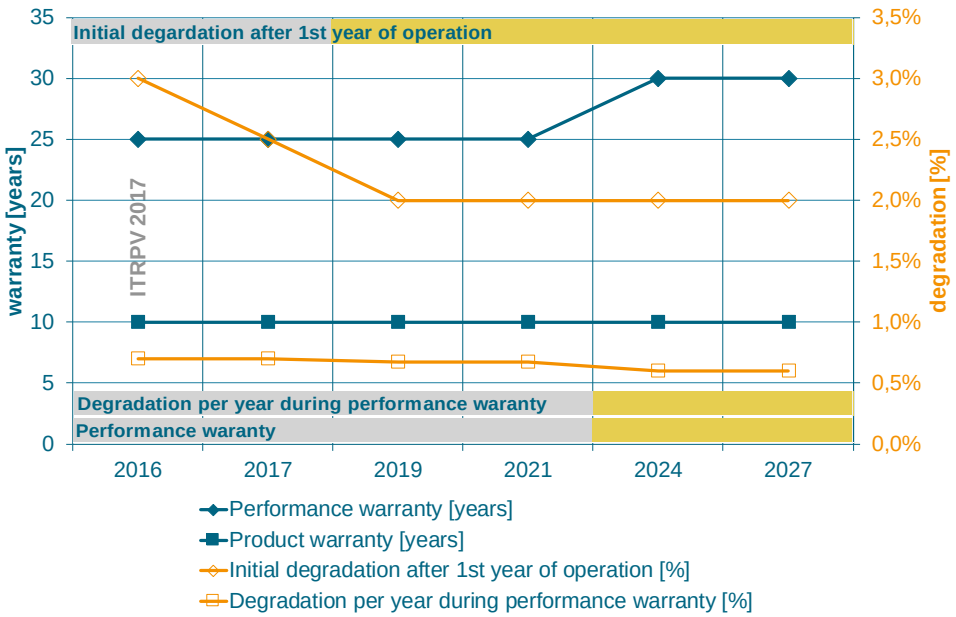
Trend: module power of 60 cell (156x156mm²)



60 cell modules 2017:
Mono p-type PERC: 305 W are standard
Multi p-type PERC: 285 W are common

Products: Warranty / degradation trend

Warranty requirements & degradation for c-Si PV modules

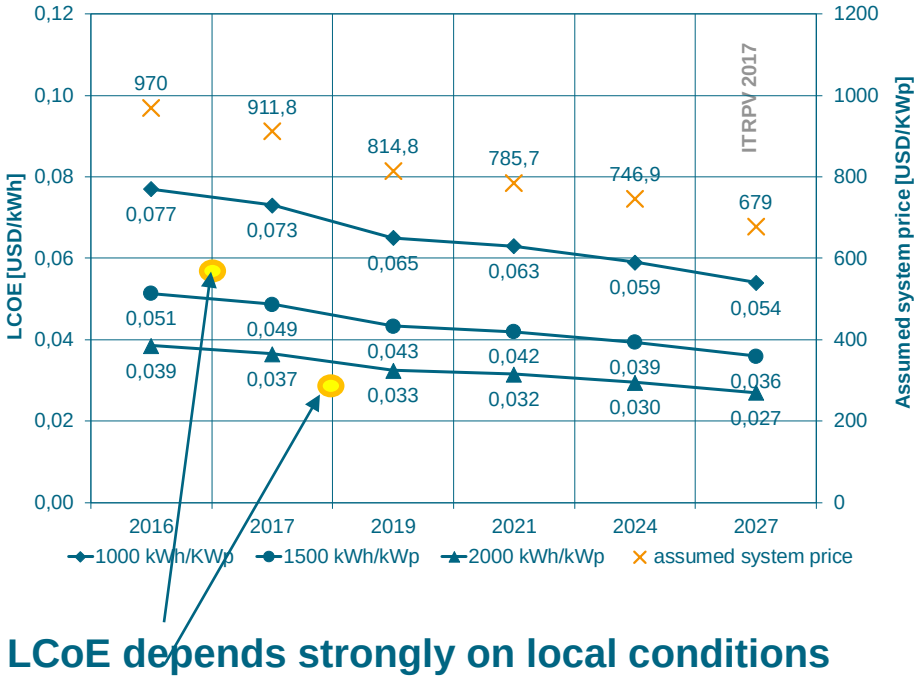


degradation:	Initial / linear/year
2016:	3.0 % / 0.7%
2017:	2.5 % / 0.68%
2019+:	2.0 % / 0.68%
2021+:	2.0 % / 0.60%

Product warranty will remain 10 years
Performance warranty 2024+: 30 years

Systems – Levelised Cost of Electricity (LCoE)

Trend: LCoE progress – a minimum approach



- System prices:
  → 2016: 970 $ / kWp
  → 2027: <680 $ / kWp
- LCoE
  → 2016: 3.9 ….. 8 $ct/kWh (GER avg. 7.7 $ct**)
  → 2027: 2.7 ….. 5 $ct/kWh are ralistic
- System live times 25 years are assumed
- Next steps to further reduce LCoE:
  → extended service live to 30 years
  (supported by performance warranty trend)
  → further efficiency improvements
  + cost down measures

LCoE depends strongly on local conditions

→ **~5.7 US$ct/kWh** lowest auction bidder in GER 2016** (avg. 7.7$ct)

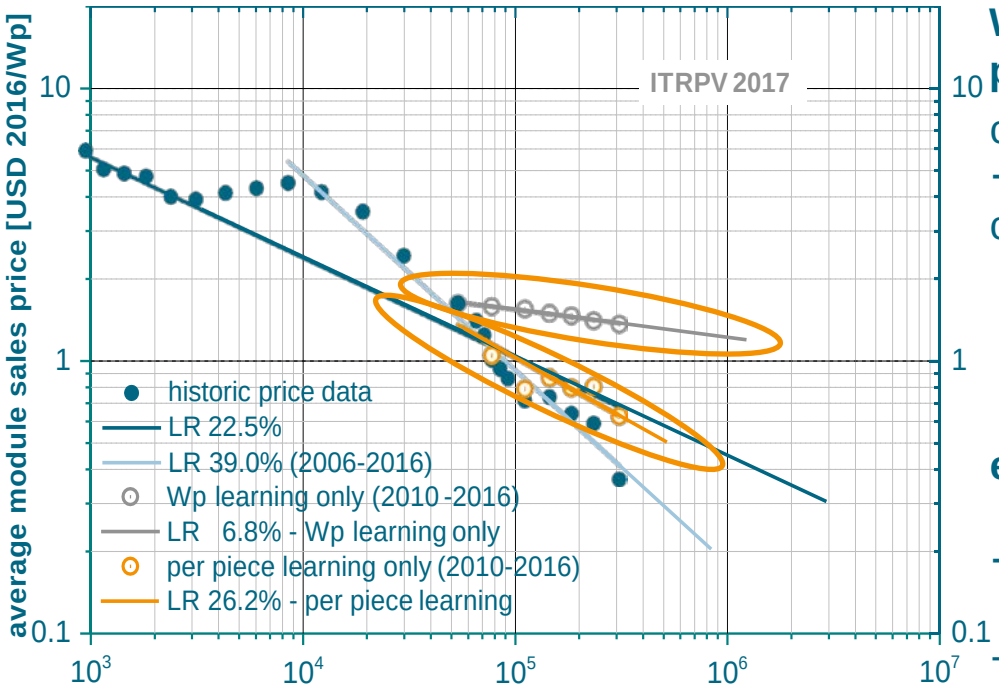
→ **~2.42 US$ct/kWh** possible near Abu Dhabi* today

* http://www.pv-tech.org/news/jinkosolar-in-deal-to-build-1.2GWp-solar-plant-in-Abu-Dhabi

** http://www.sunwindenergy.com/photovoltaics/danish-bidders-win-cross-border-pv-tender

Outlook: in detail look at PV learning curve

1976-2016: LR= 22.5%
2006-2016: LR= 39.0%



ITRPV finding:

2010-2016 Wp and per piece learning analysis revealed:

Wp learning ~ 7% (continually)
per piece learning ~26% (market driven)

conclusion:

→ Learning was and will be always a combination of

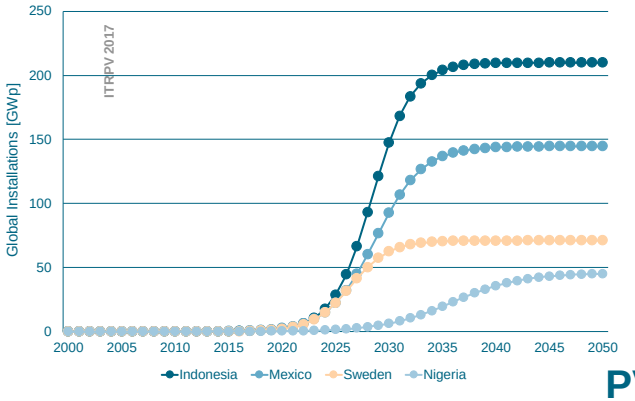
efficiency increase
+ continues cost reduction per piece
= cost reduction of PV generated electricity

→ Wp increase w/o cost increases /Wp

→ But how will PV proceed in future?
Approach: logistic growth

PV market trend until 2050: logistic growth

Approach: 3 cases for 190 different countries in 4 regions Asia / America / Africa / EU



ITRPV finding:

- Shipments until 2016: slightly above all scenarios
- Yearly PV market: 335 GWp …. 600 GWp

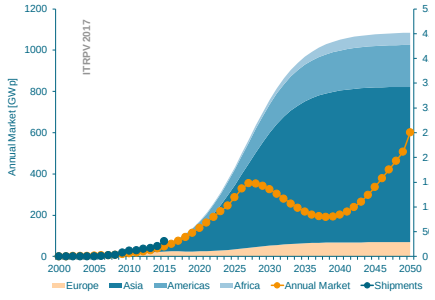
→ Current technology may run all scenarios

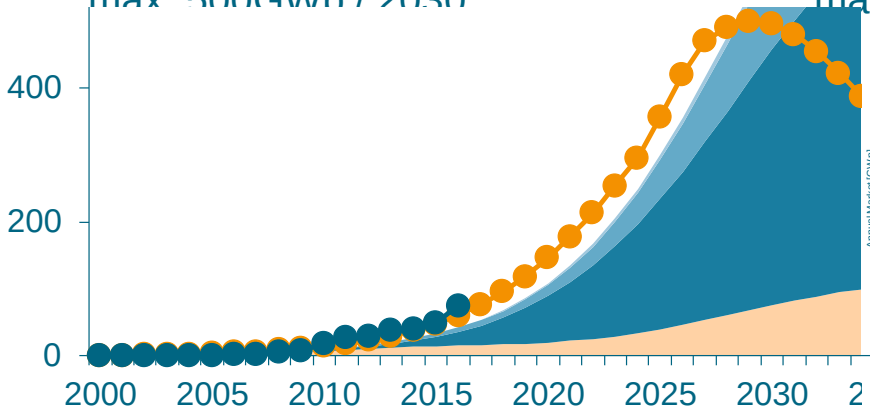
→ Replacement rate = key to overcome down cycles

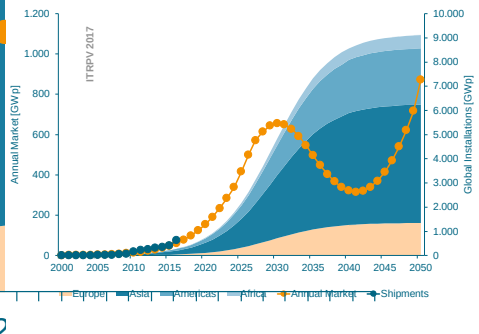
PV has a bright future – ITRPV provides a guideline

low: 4.5 TWp/7 PWh (16% of el. energy) medium: 6.8 TWp/10.6 PWh (+ prim. en.) high: 9.2 TWp/ 14.3 PWh (++ prim. en.)

Max:355GWp / 2027 max: 500GWp / 2030 max:600GWp / 2025







Summary

Talk provided:

- Idea about market expectations and status
- Discussion of ITRPV 8th edition findings and maturity report update

Outlook:

- PV market is and will remain extremely cost sensitive
- PV market will further increase (turbulently) in the years to come!
- Silicon-PV will stay dominant during the next years
- Production capacities will (and have to) increase further
- Quality is key for continued success of PV

→ **Manufacturers, Suppliers and Customers will benefit from growing PV market**
→ **But all players have to be flexible and innovative**