
Source: www.siemens.com/presse

Recent Results of the International Technology Roadmap for Photovoltaics (ITRPV)

8th Edition, March 2017

A. Metz, M. Fischer, J. Trube

PV seminar at UNSW
Sydney, March 23rd, 2017

Outline

1. ITRPV Introduction

2. PV Learning Curve and Cost Considerations

3. ITRPV – Results 2016

   - Wafer - Materials, Processes, Products

   - Cell - Materials, Processes, Products

   - Module - Materials, Processes, Products

   - Systems

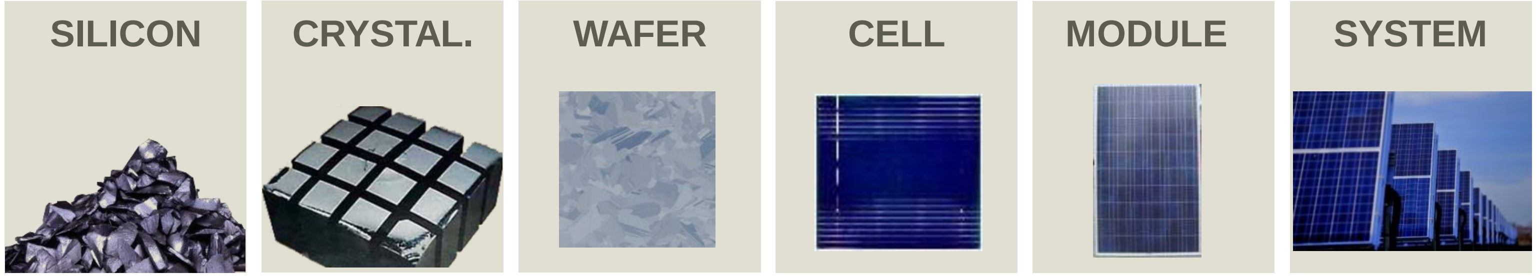
4. Summary and Outlook

Outline

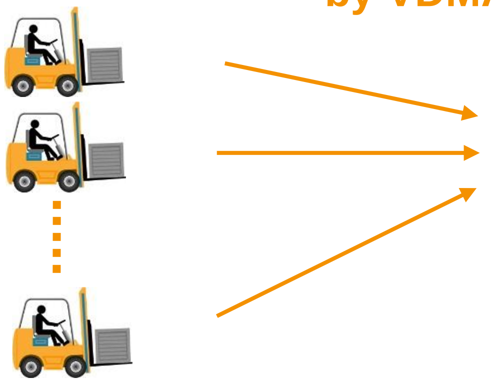
1. ITRPV Introduction
2. PV Learning Curve and Cost Considerations
3. ITRPV – Results 2016
   - Wafer - Materials, Processes, Products
   - Cell - Materials, Processes, Products
   - Module - Materials, Processes, Products
   - Systems
4. Summary and Outlook

ITRPV – Methodology

Working group today includes 40 contributors from Asia, Europe, and US

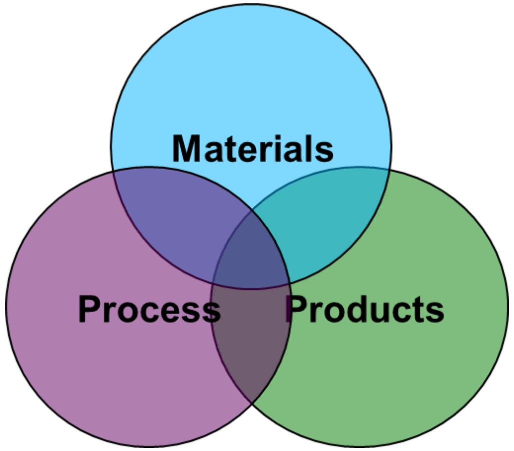


Participating companies → **Independent data collection / processing by VDMA** → **Review of data Preparation of publication → regional chairs** → **Next ITRPV edition**



Photovoltaic Equipment

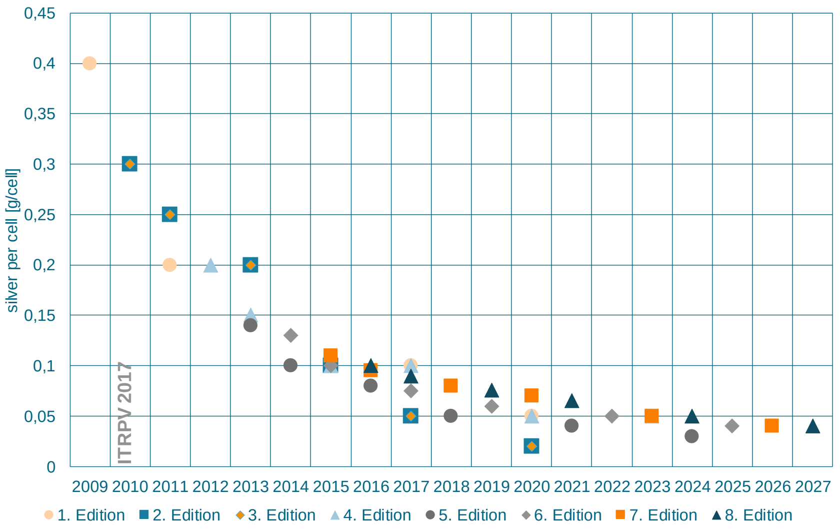
Chairs EU
Chairs PRC
Chairs TW
Chairs US



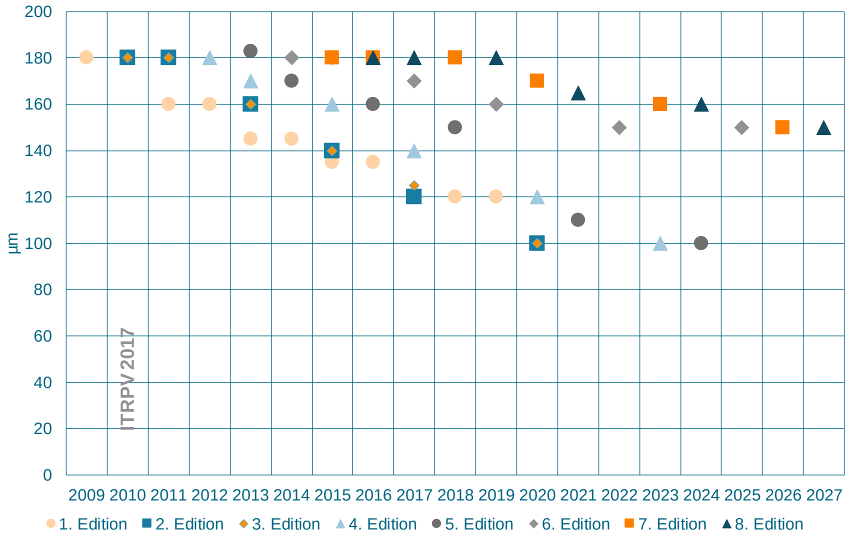
Parameters in main areas are discussed → Diagrams of median values

ITRPV 8th Edition 2017 – some statistics

Silver amount per cell



Wafer thickness (multi)



Edition	**8th**	**7th**
Contributors	40	33
Figures	60	50

Prediction quality since 2009:

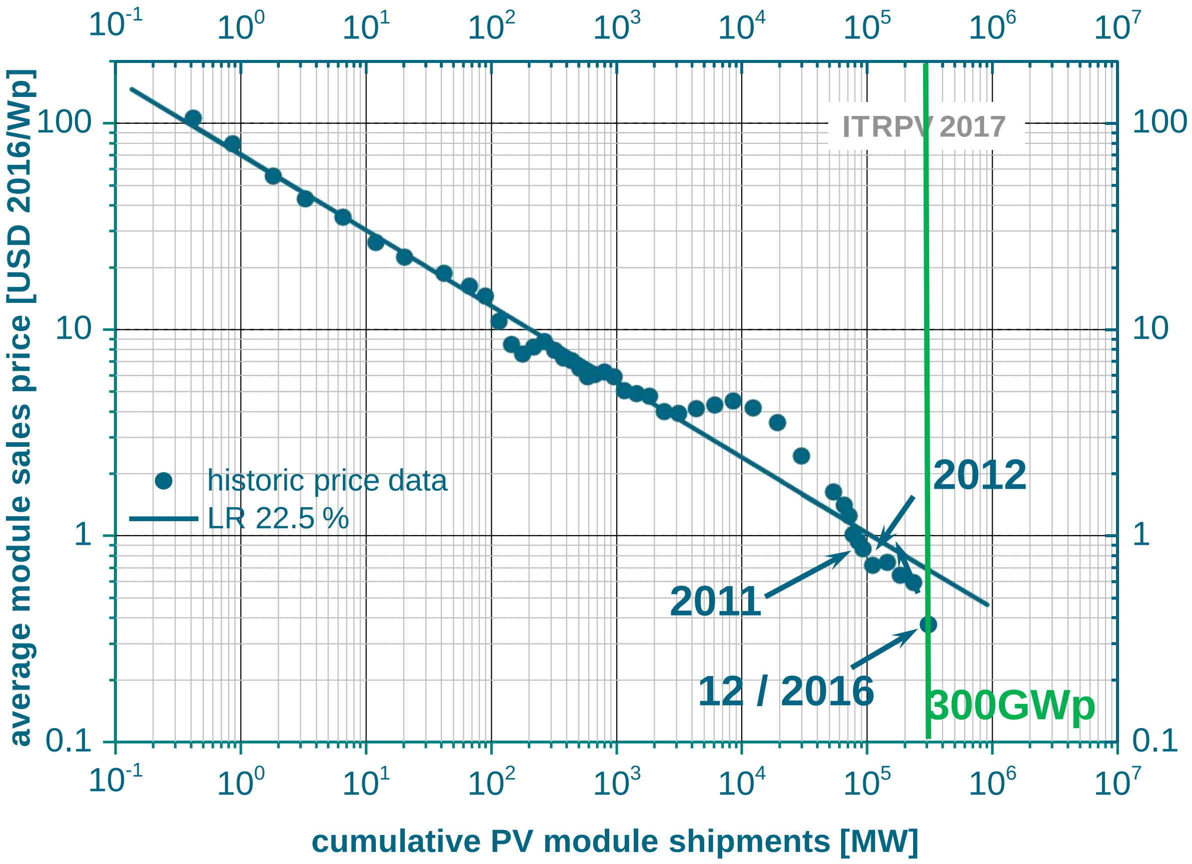
Silver consumption trend → well predicted and realized
(Silver availability depends on **world market**)

Wafer thickness trend → bad predicted and no progress
(Poly-Si price depends on **PV market** development)

Outline

1. ITRPV Introduction
2. PV Learning Curve and Cost Considerations
3. ITRPV – Results 2016
   - Wafer - Materials, Processes, Products
   - Cell - Materials, Processes, Products
   - Module - Materials, Processes, Products
   - Systems
4. Summary and Outlook

PV learning Curve



Shipments /avg. price at years end:

2016: 75 GWp / 0.37 US$/Wp

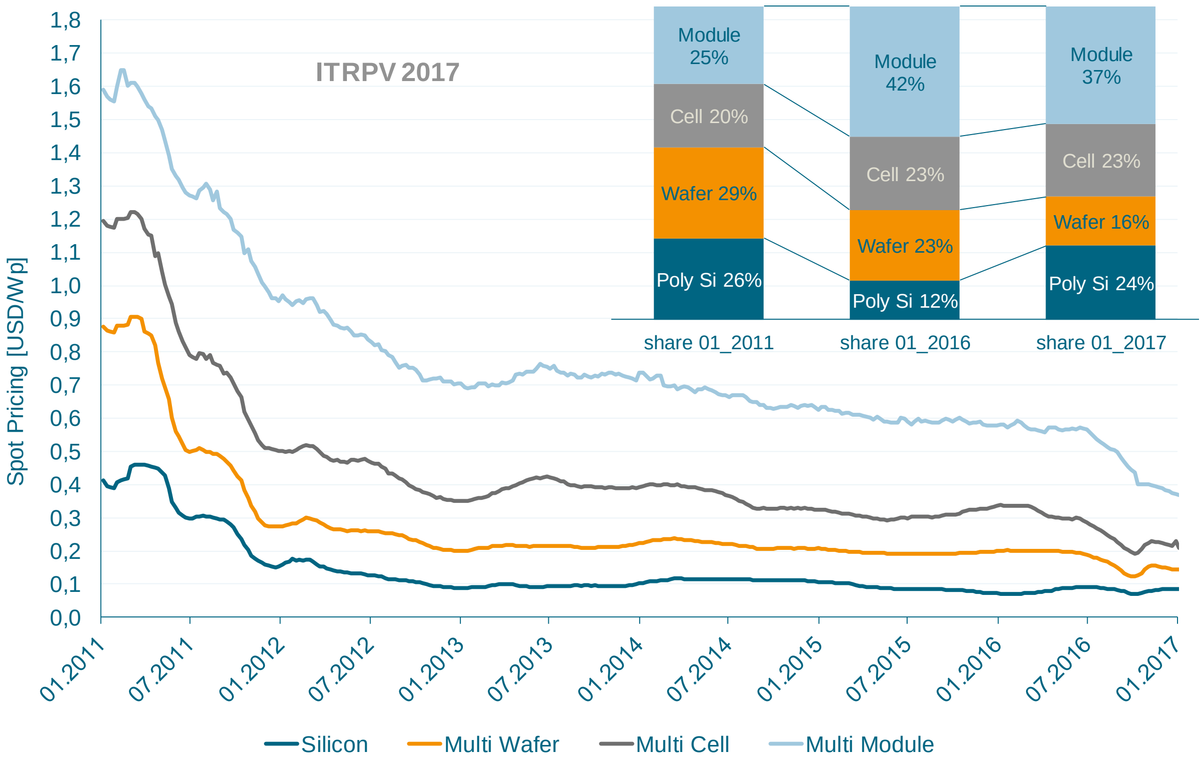
o/a shipment: ≈ 308 GWp
o/a installation: ≈ 300 GWp

300 GWp landmark was passed!

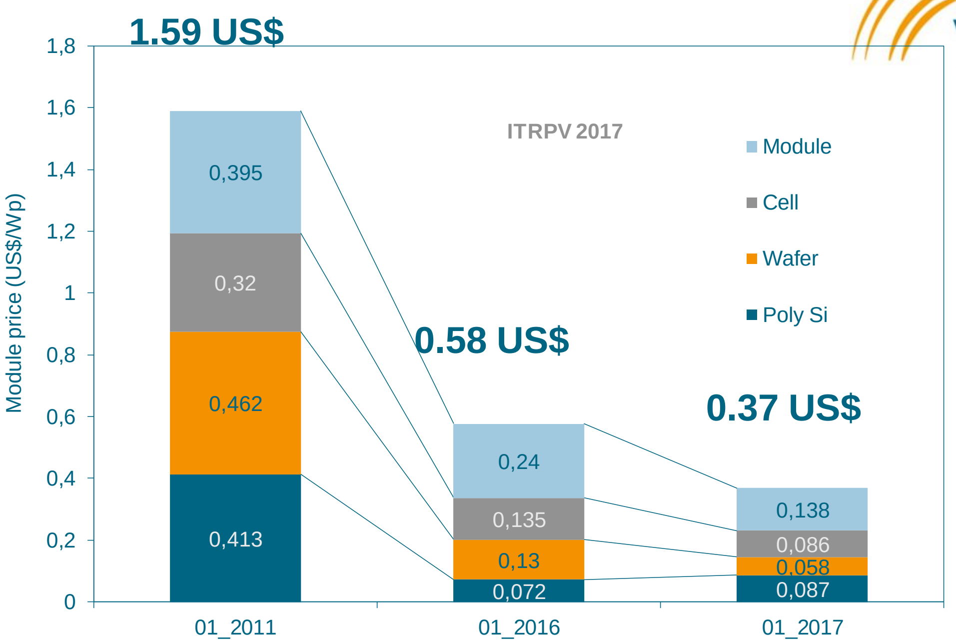
LR 21.5% (1976 …. 2016)

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

Price considerations



Module price break down [US$/Wp]



→ reduction 01/2011 → 01/2016: ≈ 64 %
→ reduction 01/2016 → 01/2017: ≈ 36 %
(reduction 01/2011→ 01/2012: ≈ 40 %)

Dramatic price drop during 2nd half of 2016

→ **Market driven drop**

→ **Poly-Si share increased again**

→ **High pressure on module manufacturers**

Outline

1. ITRPV Introduction

2. PV Learning Curve and Cost Considerations

3. ITRPV – Results 2016

   - Si / Wafer - Materials, Processes, Products

   - Cell - Materials, Processes, Products

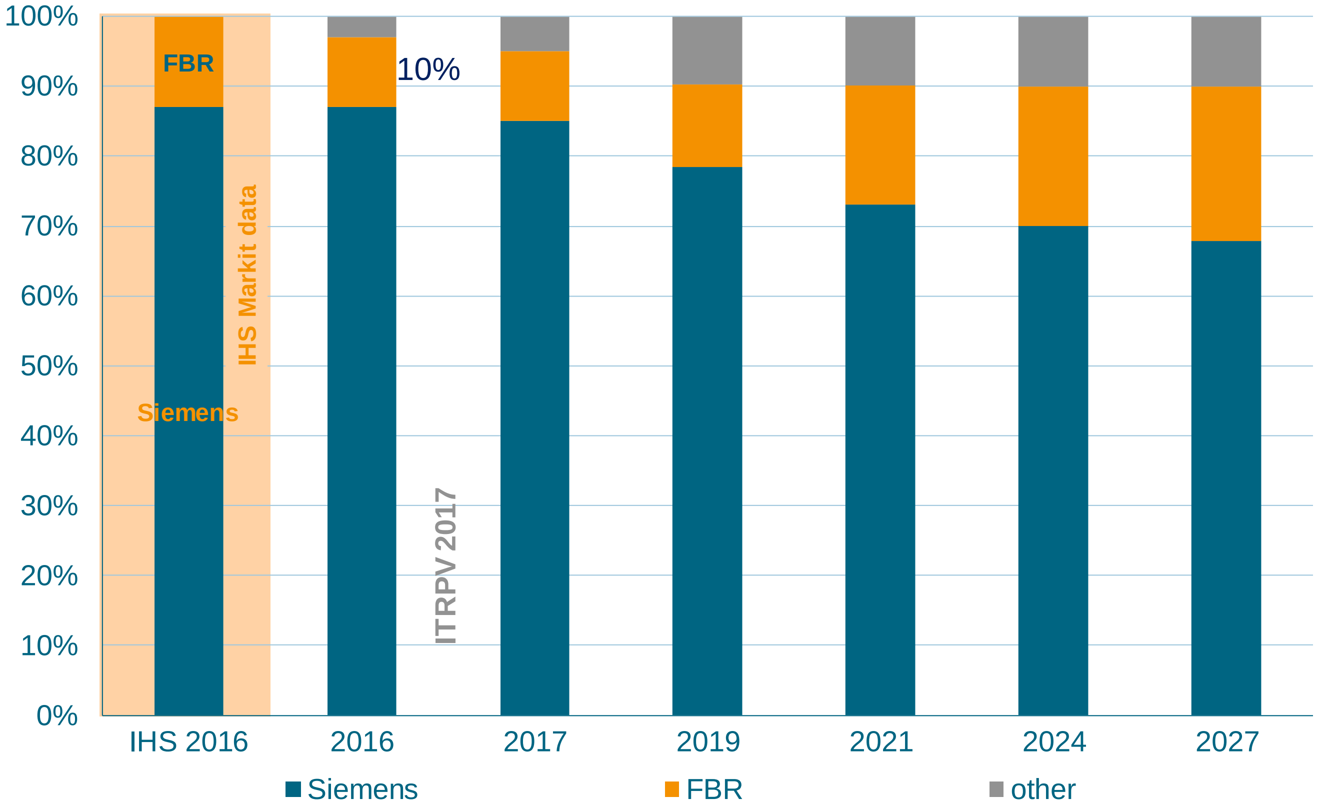
   - Module - Materials, Processes, Products

   - Systems

4. Summary and Outlook

Silicon – Materials: Poly Si Feedstock Technology

Trend: Share of poly-Si feedstock technology



Poly Si price trend:

E 2012: 20 US$/kg

02/ 2016: ≈14 US$/kg

02/ 2017: ≈16 US$/kg

→ oversupply situation of 2016 relieved

→ Siemens process will remain mainstream
FBR shows potential for cost reduction

→ **FBR share will be increased moderately w/ new capacity**
(2016 values in line w/ IHS Markit)

Other technologies (umg, epi growth, ..)

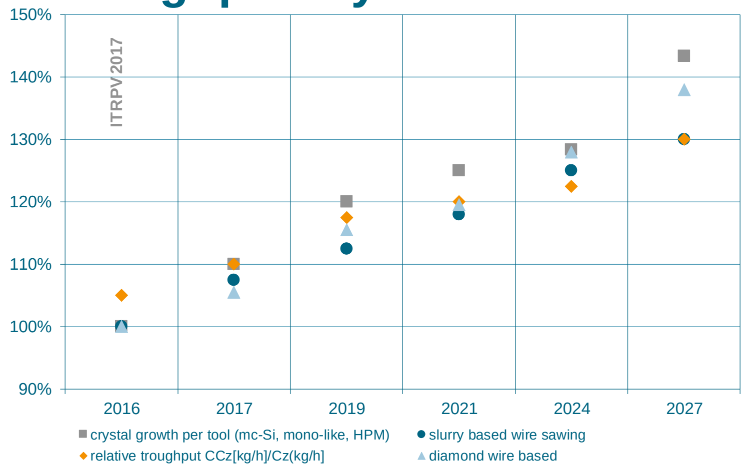
→ Not yet mature but available

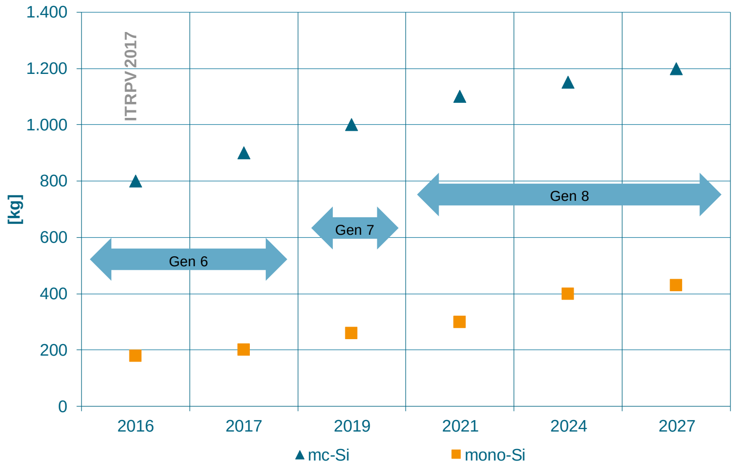
Wafer – Processes: wafering technology (1)

Trend: Kerf loss / TTV

diamond wire sawing **advantage**:
→ enable faster kerf reduction
No big change in thickness variation is expected

Trend: throughput crystallization/ wafering

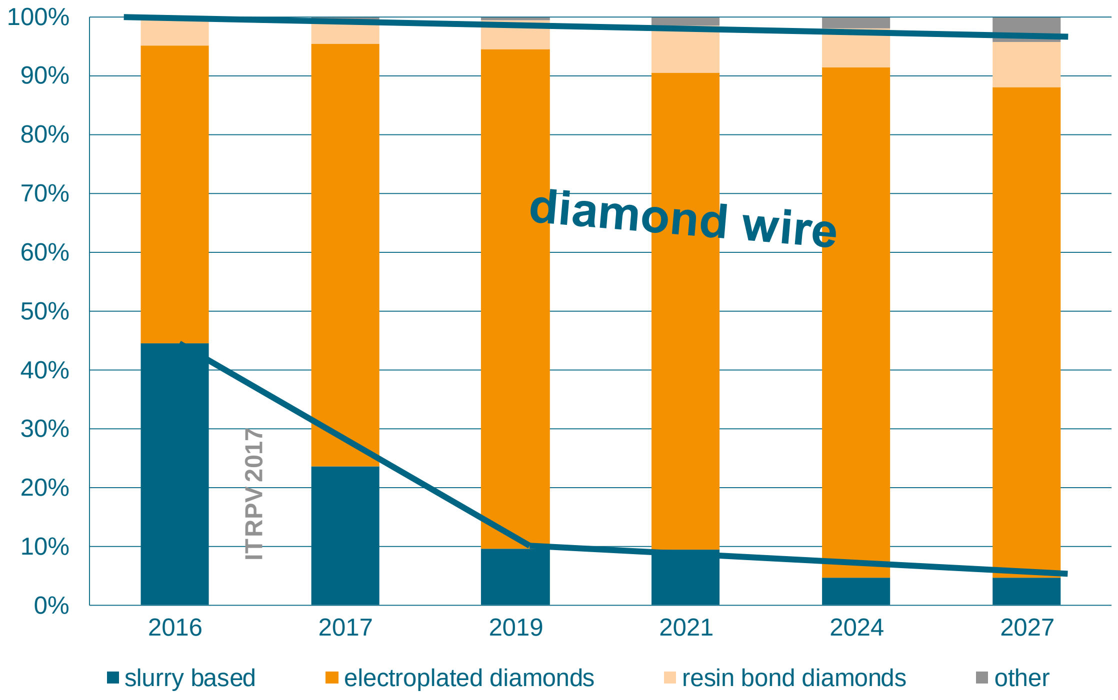




→ Throughput increase in crystallization/wafering will continue

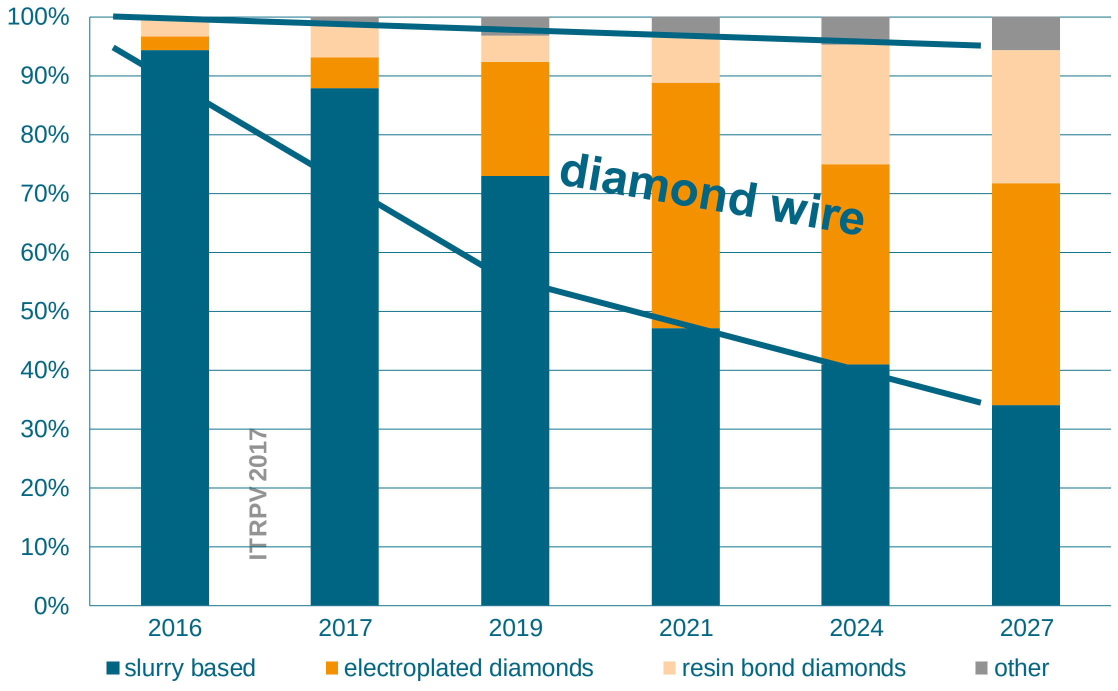
Wafer – Processes: wafering technology (2)

For mono-Si



diamond wire wafering now mainstream for mono-Si
→ Throughut 2x – 3x faster than slurry based

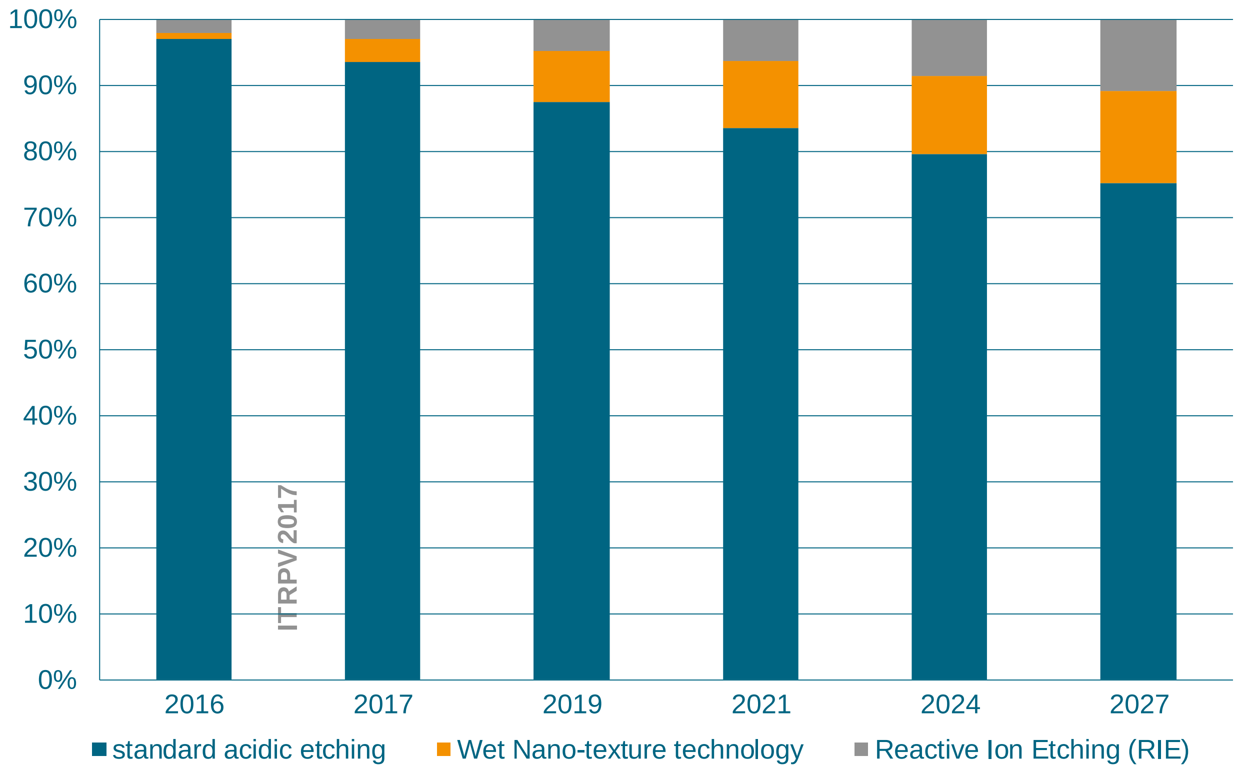
For mc-Si



For mc-Si change to diamond wire is ongoing
→ **main challenge: texturing**

Wafer – Processes: texturing of mc-Si wafers

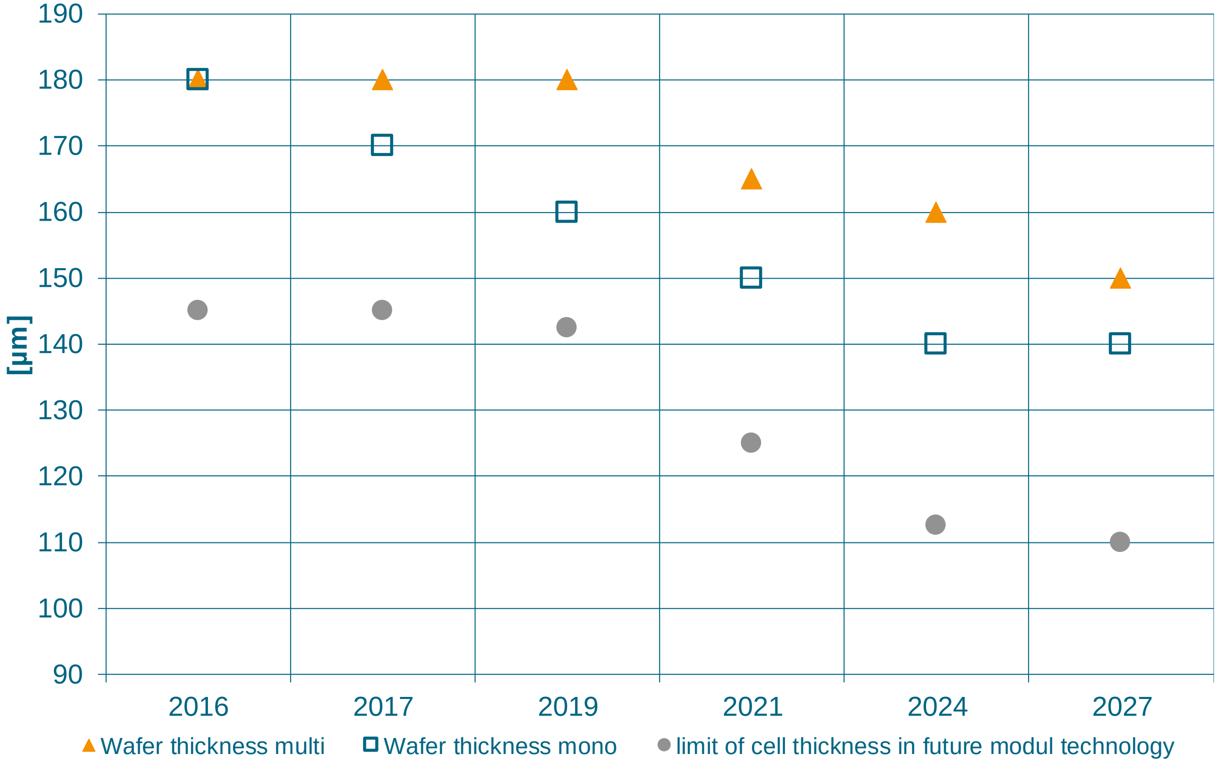
Trend: market share of mc-Si texturing technologies



- Acidic texturing is:
  → mature and high throughput process
  → changes in "standard" will apear
- Next step:
  → wet nano texturing, esp. for diamond wire
- RIE share is expected to increase **"but"**
  → no cost efficient alternative

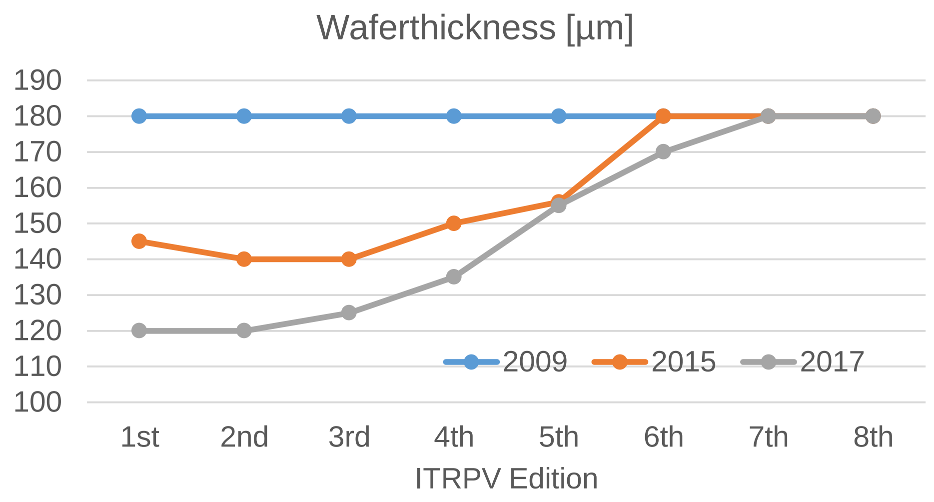
→ Wet processing remains mainstream in mc-Si texturing

Wafer – Product: Wafer thickness trend



Mono-Si wafer: thickness reduction starts

Still no progress in mc-Si thickness reduction



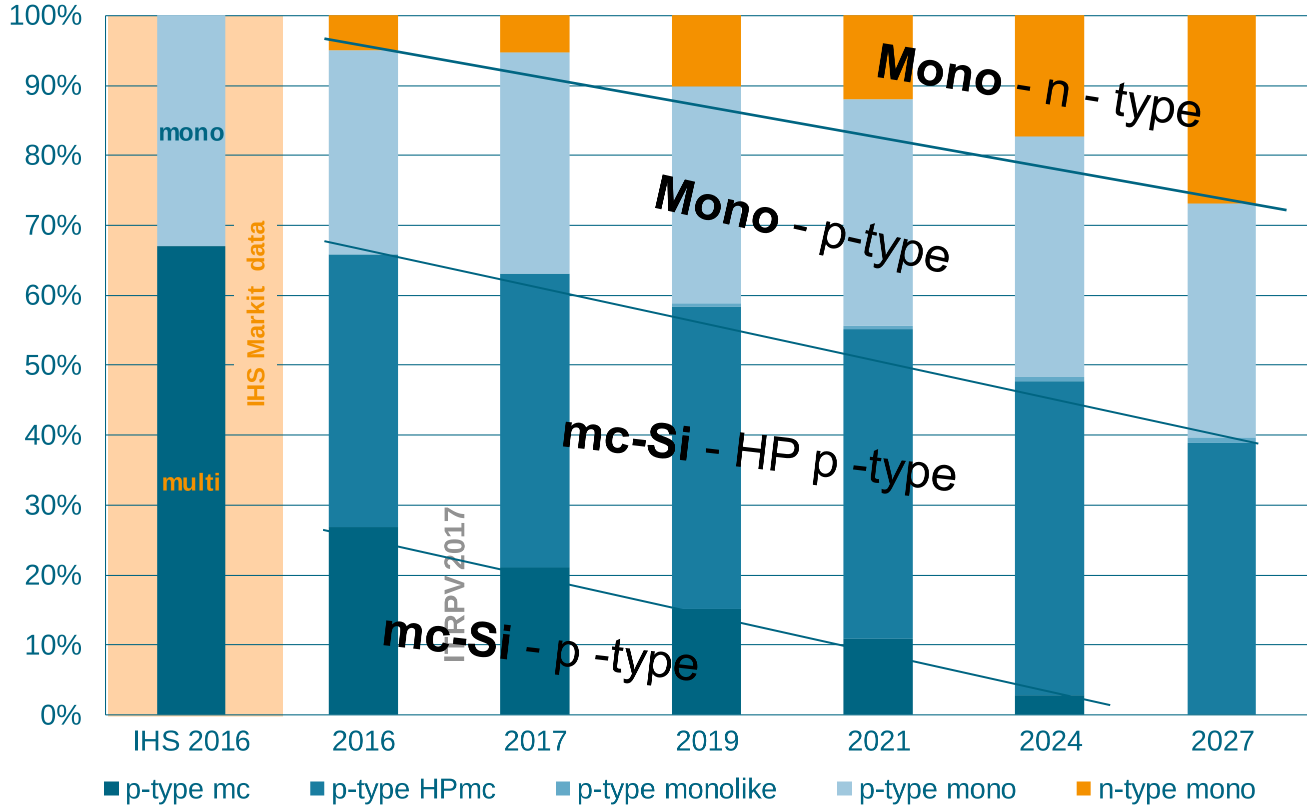
→180 µm mc-Si preferred thickness since 2009

→Thickness reduction expected to start for mono-Si
- cost reduction potential
- diamond wire will support

New module technologies should enable thickness reduction

Wafer – Product: market share of material types

Trend: share of c-Si material types



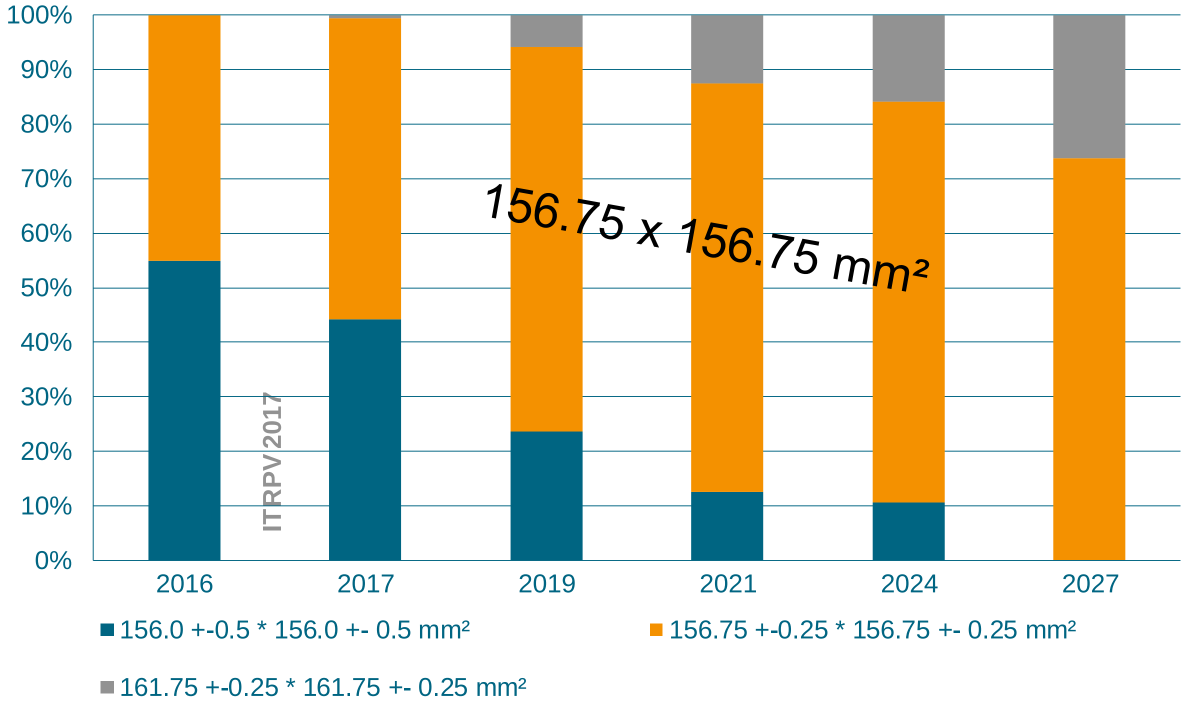
→ **Casted material is still dominating** today with > 60%
→ **Mono share is expected to increase** (driven by n-type)

casted-Si domination is not for ever:
→ Trend of last years will continue

- **Casting technology:**
  → HP mc-Si will replace standard mc-Si
  → no "come back" of mono-like expected
- **Mono technology:**
  → n-type material share will increase
  → n- + p-type market share today ≈ 35%
  (2016 values are in line w/ IHS Markit)
- **p-type material is expected to stay dominant**
  → mainly due to progress in LID regeneration

Wafer – market share of wafer dimensions (new)

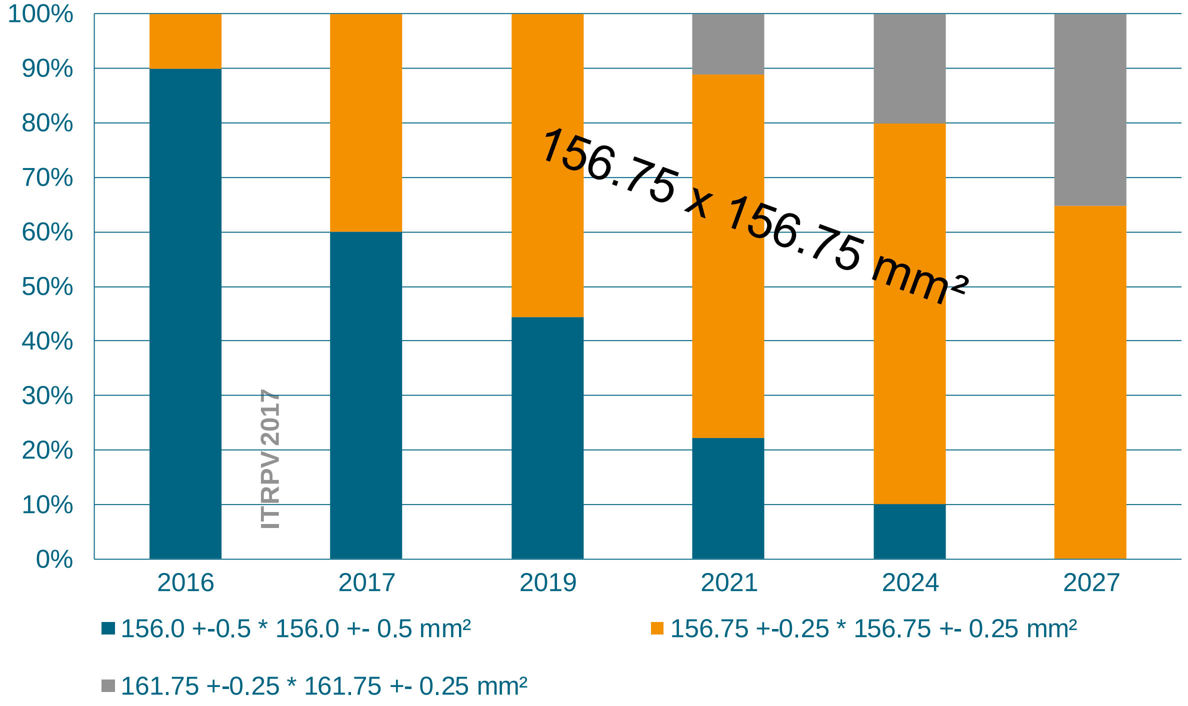
Trend: mono-Si



Fast switch to new format:

→ **New mainstream: 156.75 x 156.75 mm²**
→ **Larger formats are upcoming**

Trend: mc-Si



Transition to new format in 2017

→ Expected new mainstream: 156.75 x 156.75 mm²
→ Larger formats may occur after 2020

Outline

1. ITRPV Introduction

2. PV Learning Curve and Cost Considerations

3. ITRPV – Results 2016

   - Si / Wafer - Materials, Processes, Products

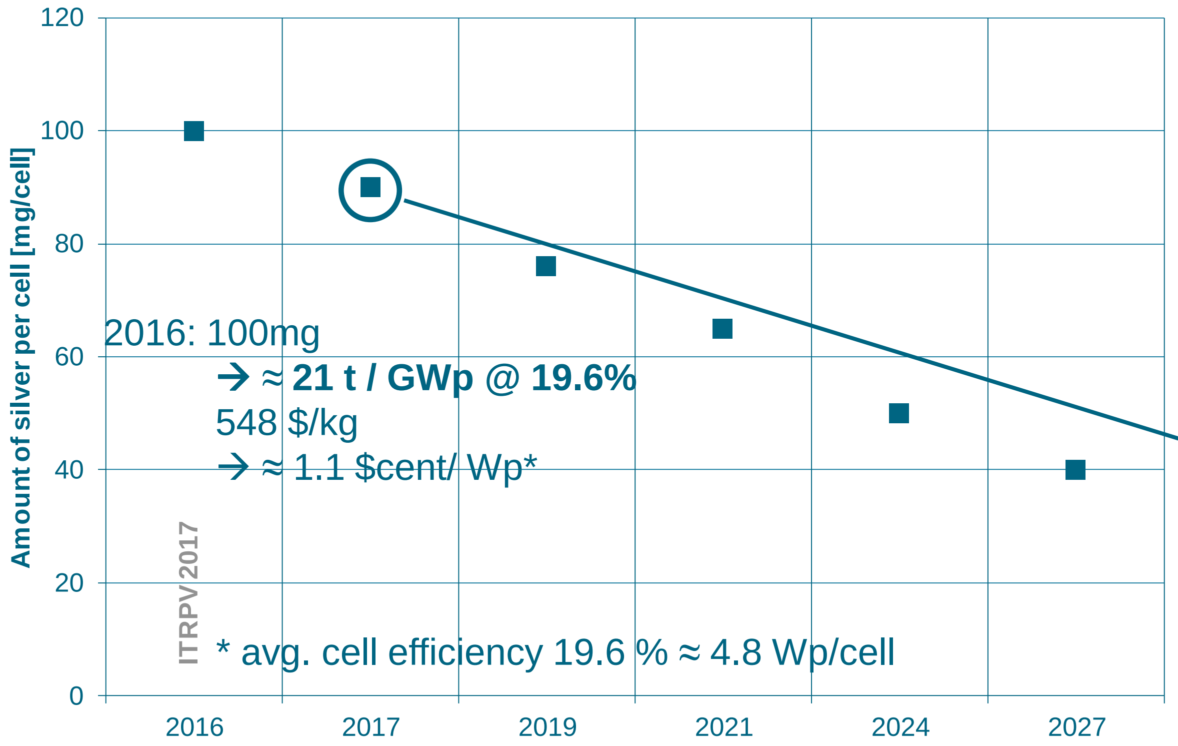
   - Cell - Materials, Processes, Products

   - Module - Materials, Processes, Products

   - Systems

4. Summary and Outlook

Cell – Materials: Silver (Ag) per cell

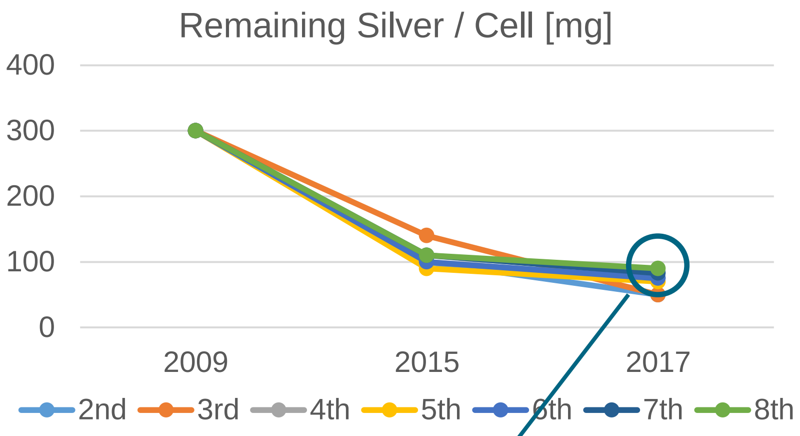


2016: 100mg
→ ≈ **21 t / GWp @ 19.6%**
548 $/kg
→ ≈ 1.1 $cent/ Wp*

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

Ag will stay main metallization in c-Si technology

Good prediction of Ag reduction continues



2009 300 mg
2016 100 mg reached
2017 90 mg expected

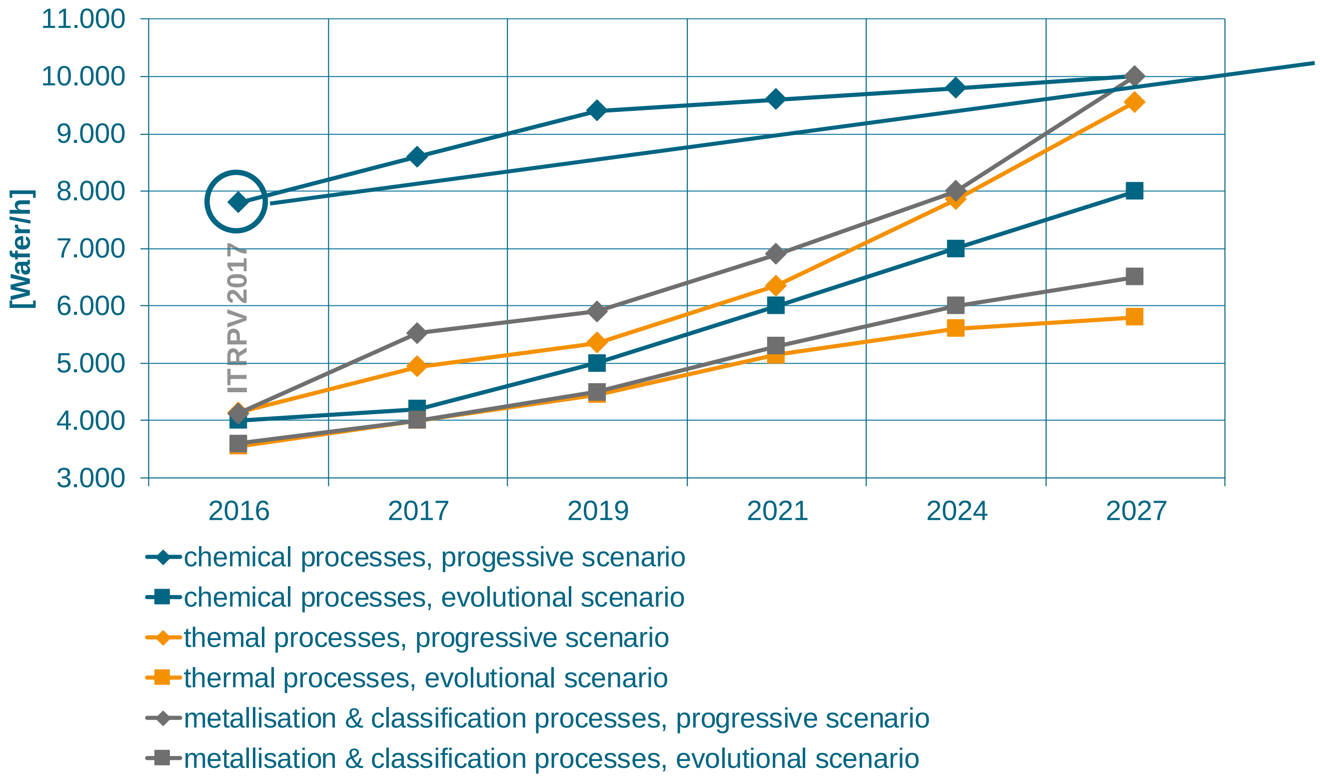
→ Ag accounts in 2016 for ≈ 8% of cell conversion cost

- Ag reduction is mandatory and continues
- delays substitution by Cu or other material

No break through for lead free pastes so far
→ Market introduction depends on performance

Cell – Processes: cell production tool throughputs

Trend: tool throughput increase + synchronization of frontend/backend



Wet benches are leading today with > 7800 wf/h
→ Throughput increase continues

Challenge: increase throughput + Improve OEE

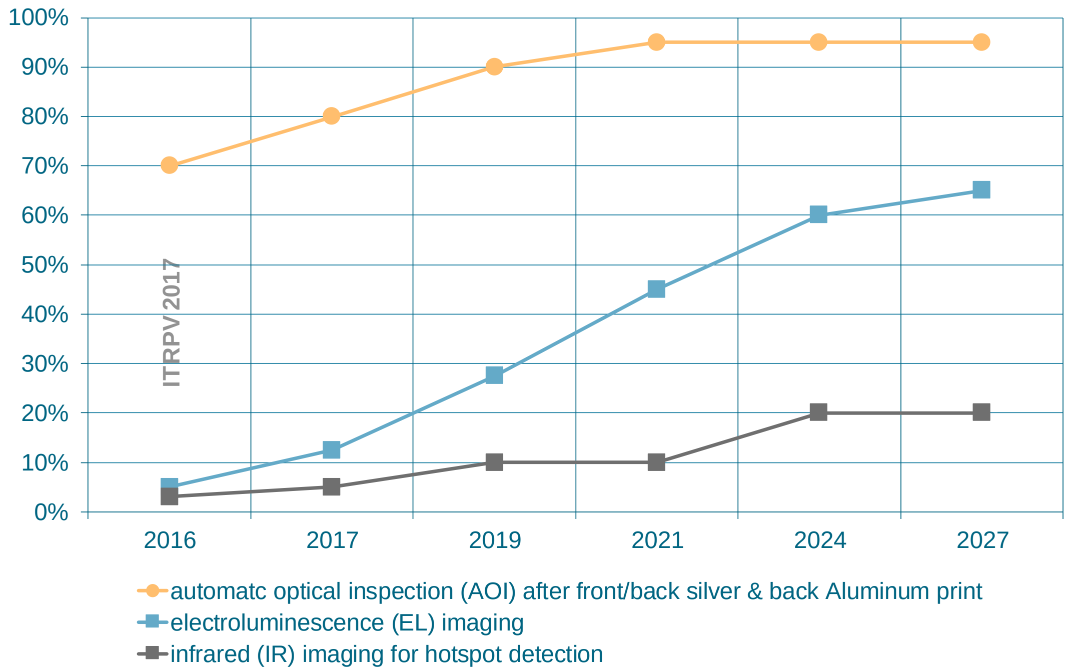
Two throughput scenarios:

Progressive = new high throughput tools

Evolutionary = continuous improvement of existing tools (debottlenecking, upgrades…)

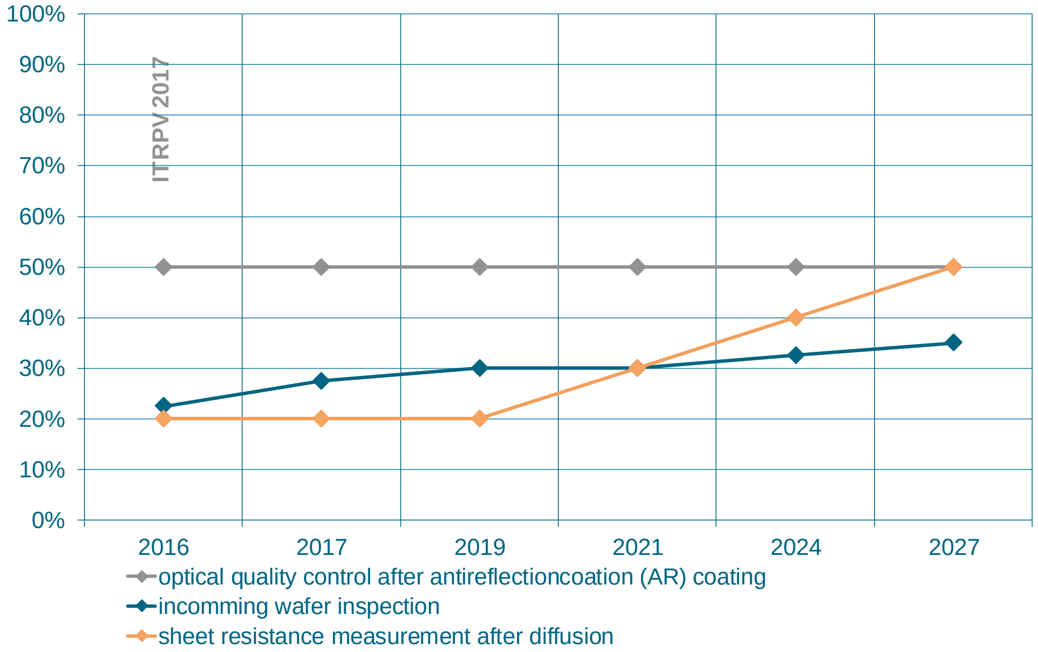
Cell – Processes: in line monitoring in cell production (new)

Trend: in-line process control backend/test



AOI is widely used in printing 2016: 70%
Inspection at cell testing:
→ EL use will expand (currently 5% only)
→ IR inspection is not widely used

Trend: in-line process control frontend

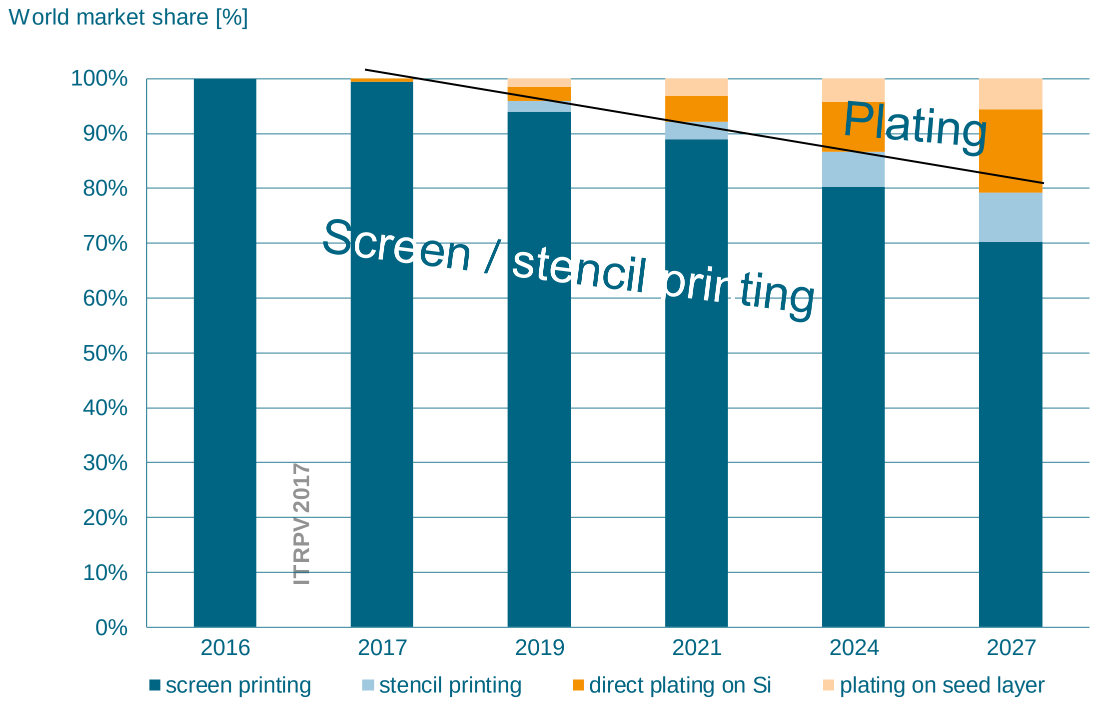


SiNx quality control has constant share – 50%

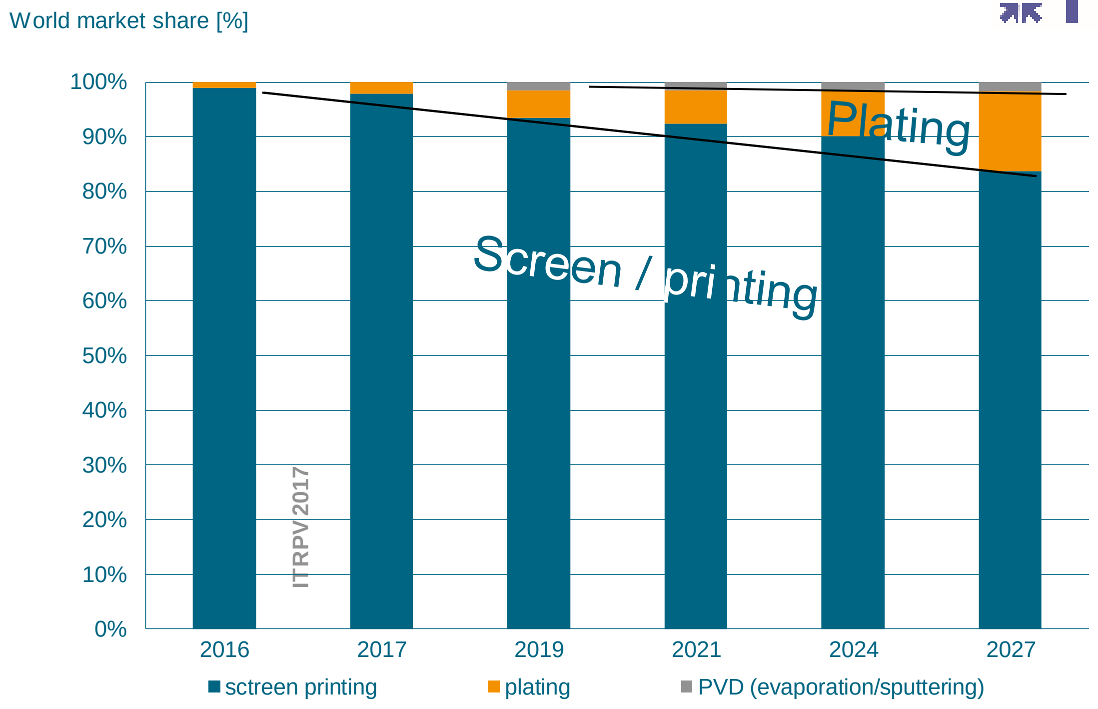
→ Incoming wafer inspection will exceed 30% after 2021
→ Emitter sheet rho in-line control will increase

Cell – processes: c-Si metallization technologies

Front side metallization technologies



Rear side metallization technologies



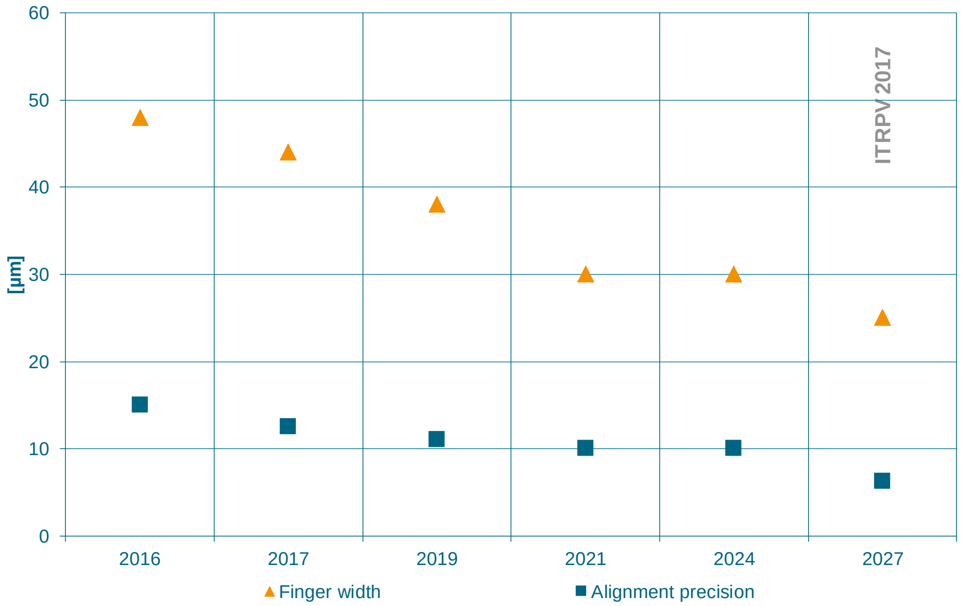
Screen printing remains main stream metallization technology

→ Plating is expected for rear and front side

→ For rear side PVD methods may appear

Cell – processes: finger width / number of bus bars / bifaciality

Trend: Finger width / alignment precision



Front side grid finger width reduction continues

2016: < 50µm reached!

→ Enables Ag reduction, requires **increase of number of busbars**

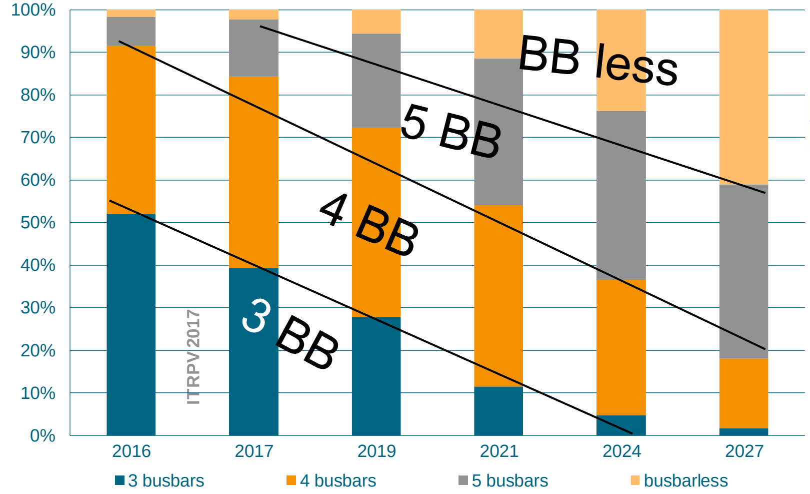
→ 4BB are mainstream – 3 BB will disappear

Alignment precision will improve to <10µm @3 sig.

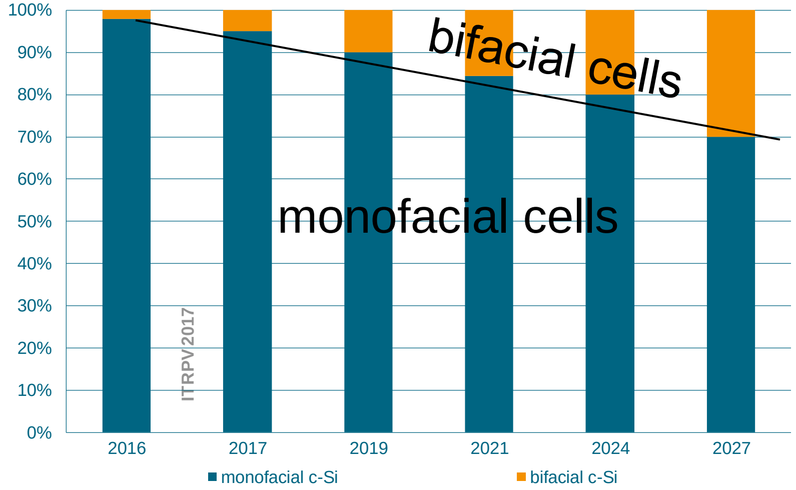
→ Selective emitters + Bifacial cells require good alignment

→ **Bifacial cells will increase market share**

Trend: number of bus bars (BB)

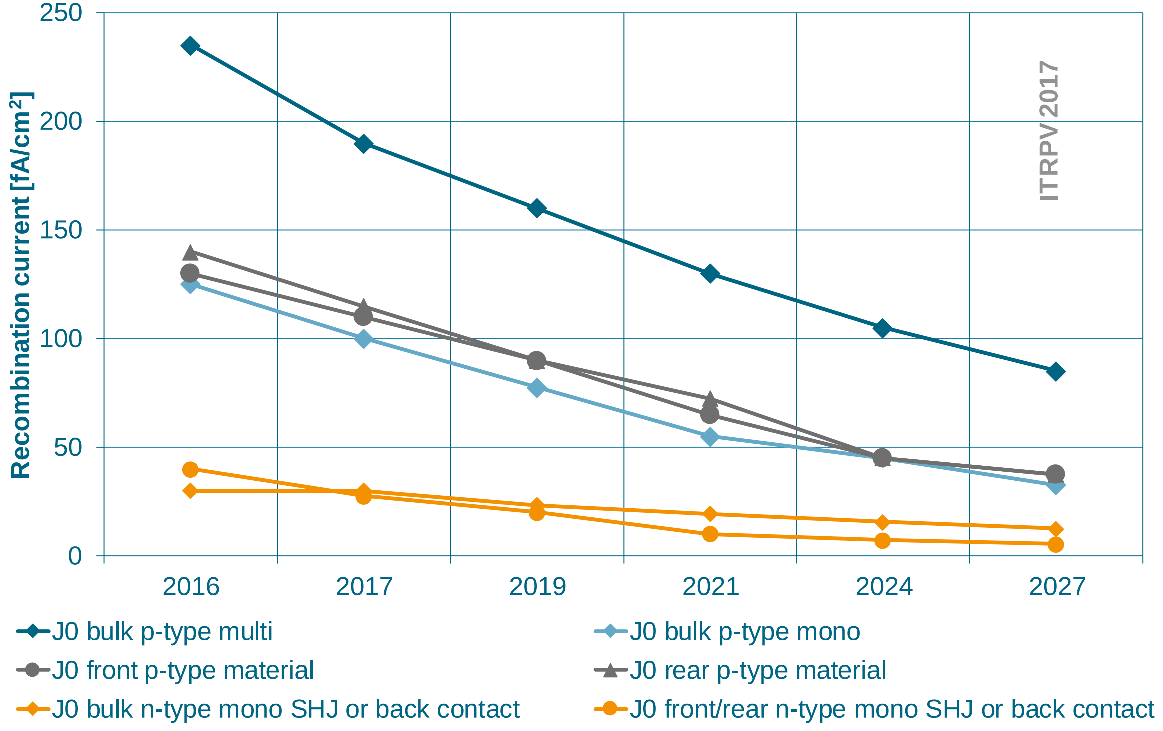


Trend: market share of bifacial cells



Cell – processes: recombination current densities

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



$J0_{bulk}$

will be further reduced by optimizing crystallization

	2010		2016
→ p-type mc-Si:	650	→	240 fA/cm²

- further reductions will appear:

	2016		2017		2027
→ p-type mc-Si:	240	→	180	→	32 fA/cm²
→ p-type mono-Si:	125	→	100	→	30 fA/cm²
→ n-type mono-Si:	25	=	25	→	15 fA/cm²

$J0_{front}$ / $J0_{rear}$

→ Further reductions by > 50% to < 50 fA/cm²

→ p-type improvements are limited at the front side (i.e. need of improved diffusion / new pastes)

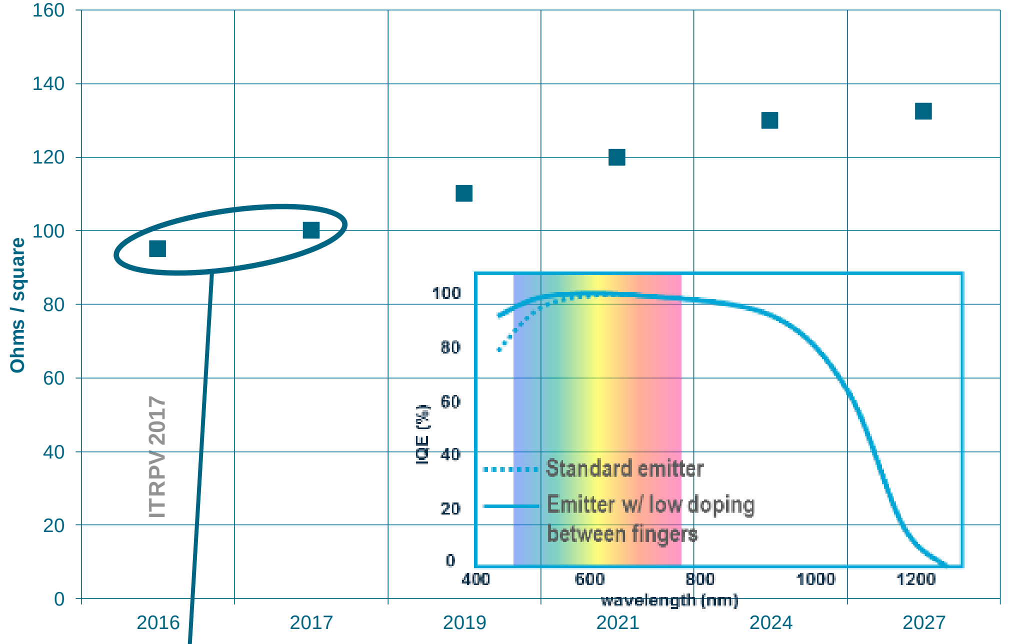
→ Wide use of rear side passivation concepts

→ 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



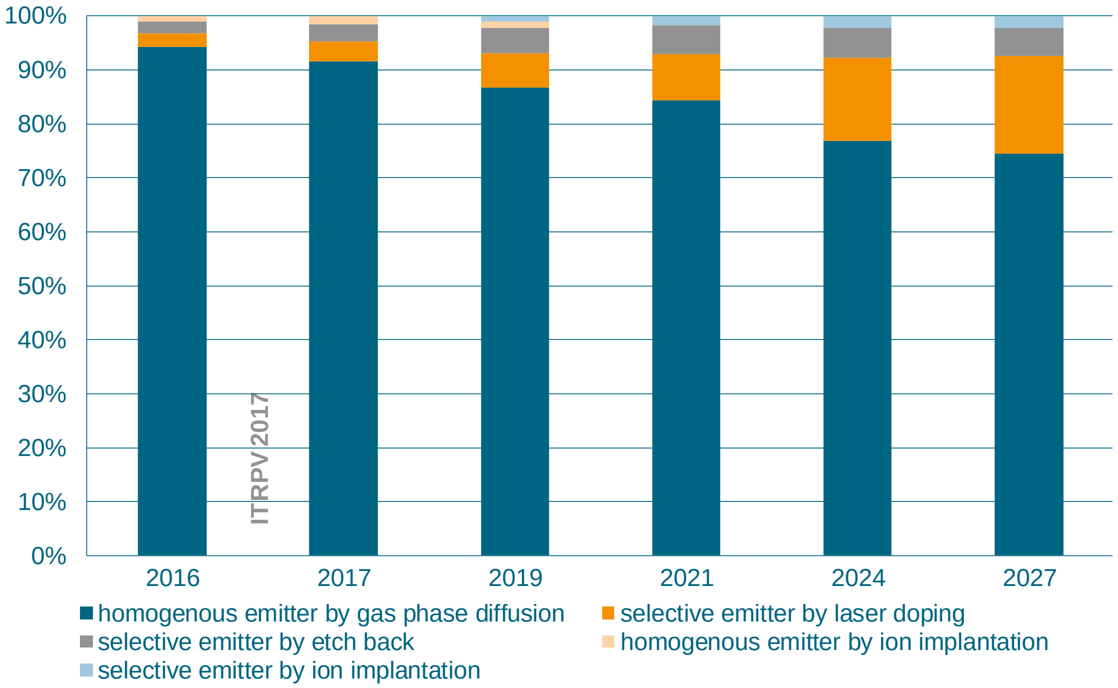
Essential parameter for J0front

→ **95…100 Ω/□** are standard today

→ Increase to 135 Ω/□ is predicted

→ **Challenge for tools and front pastes**

Trend: emitter formation technologies



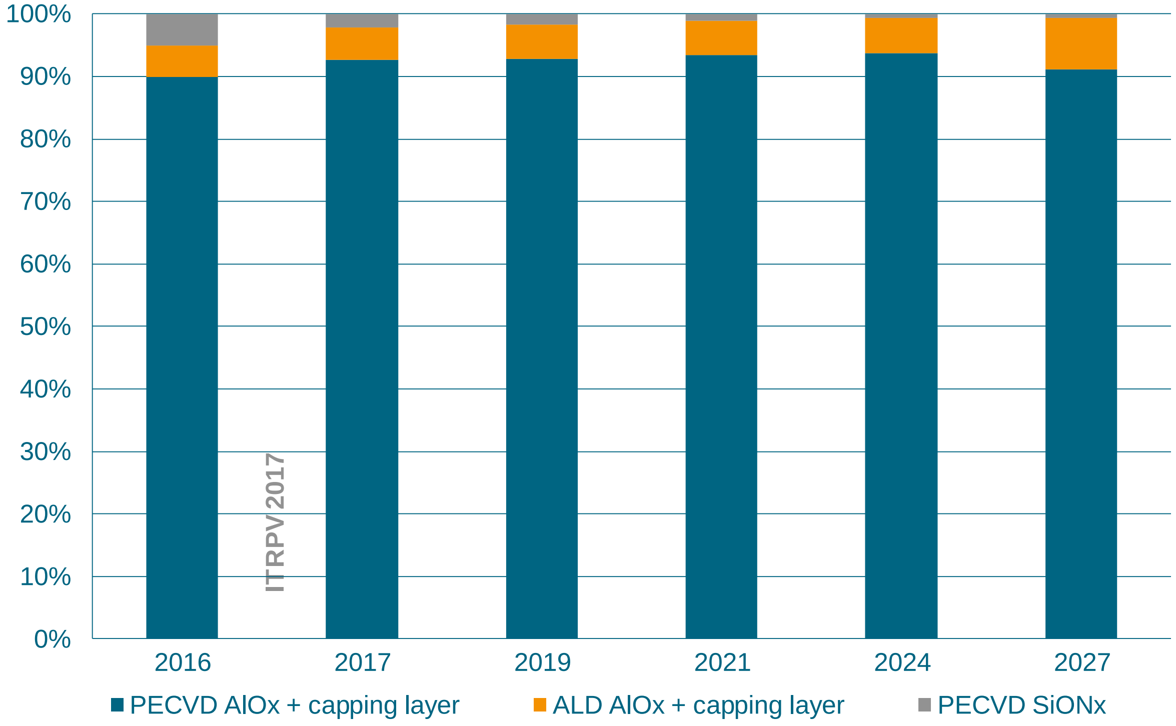
Mainstream: homogenous gas-phase diffusion

→ selective doping: etch back or laser doping

→ Ion implant stays niche

Cell – processes: technology for low $J0_{rear}$

Trend: rear side passivation technologies



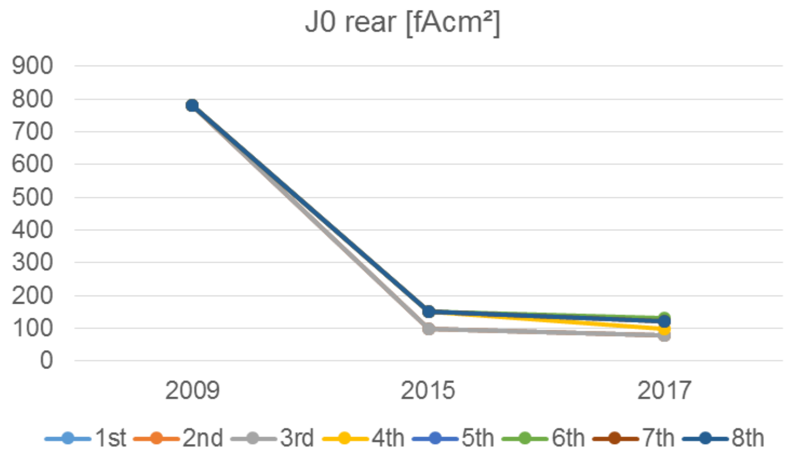
Rear side passivation is mandatory for PERC

→ PECVD AlOx will stay mainstream

→ ALD will hold up to 10 %

→ SiONx will disappear

ITRPV prediction for $J0_{rear}$ were good



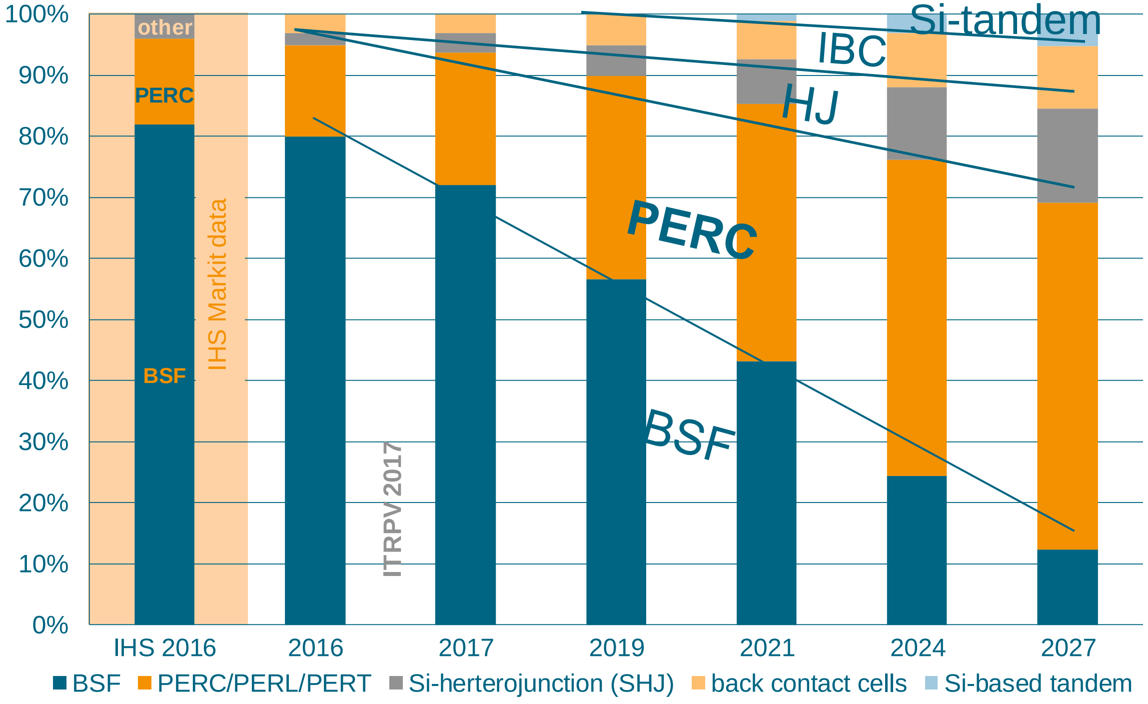
2009 2017
780 → 120 fA/cm²

- BSF cannot deliver required low $J0_{rear}$
- PERC takes over
- competing technologies in PERC
  → PECVD Al2O3 + capping
  → Al2O3 ALD + capping
  → PECVD SiONx/SiNy etc.

Cell – Products: cell technologies / cell efficiency trends

Trend: market share of cell concepts

2016: PERC ≈15% (in line w/ IHS Markit)



PERC is gaining market share (20% 2017)

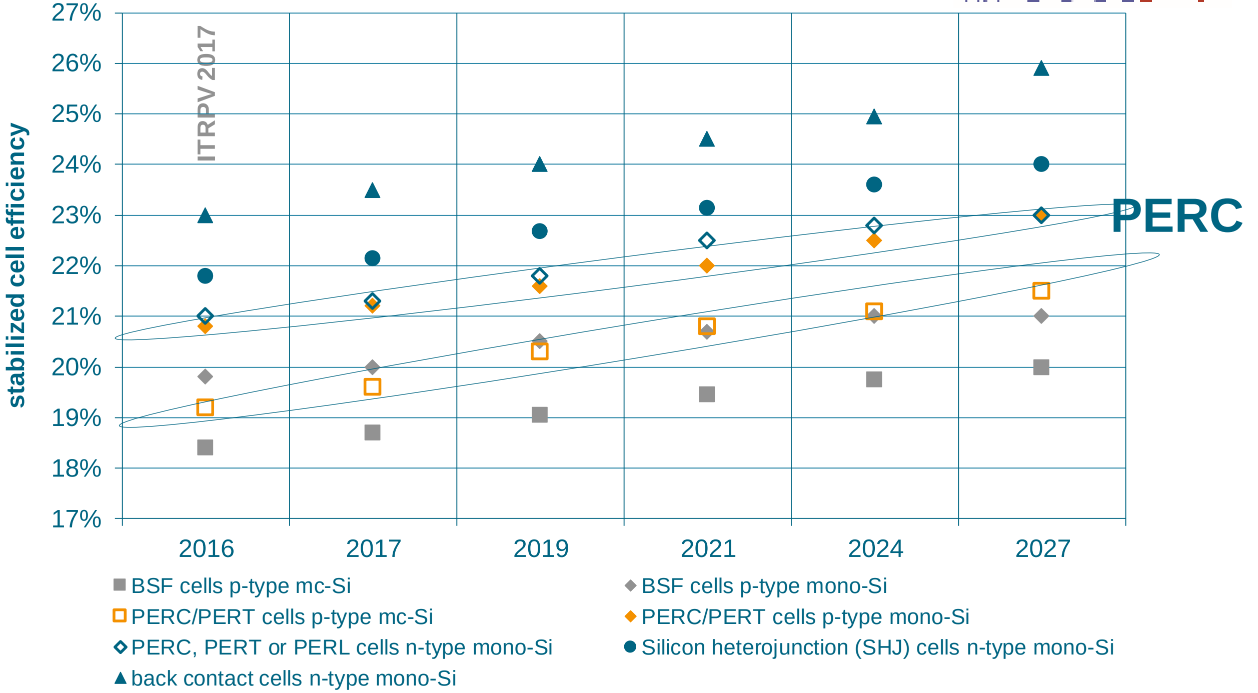
→ **BSF share is shrinking**

→ Back contact + HJ: slow increasing share

→ Si tandem: under development

Trend: stabilized cell efficiencies;

→ p-type PERC outperforms



p-type mono PERC will reach n-type performance

mc-Si PERC is about to outperform mono BSF

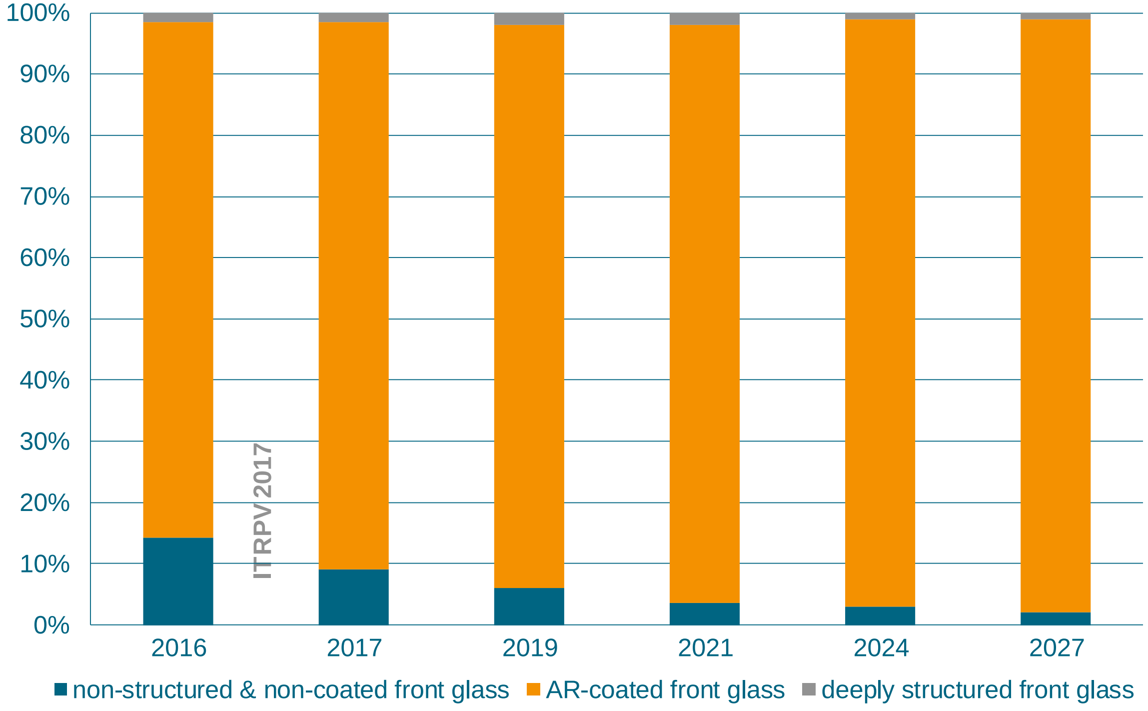
→ n-type IBC + HJ for highest efficiency applications

→ **stabilized >21% p-type mono PERC is in production**

Outline

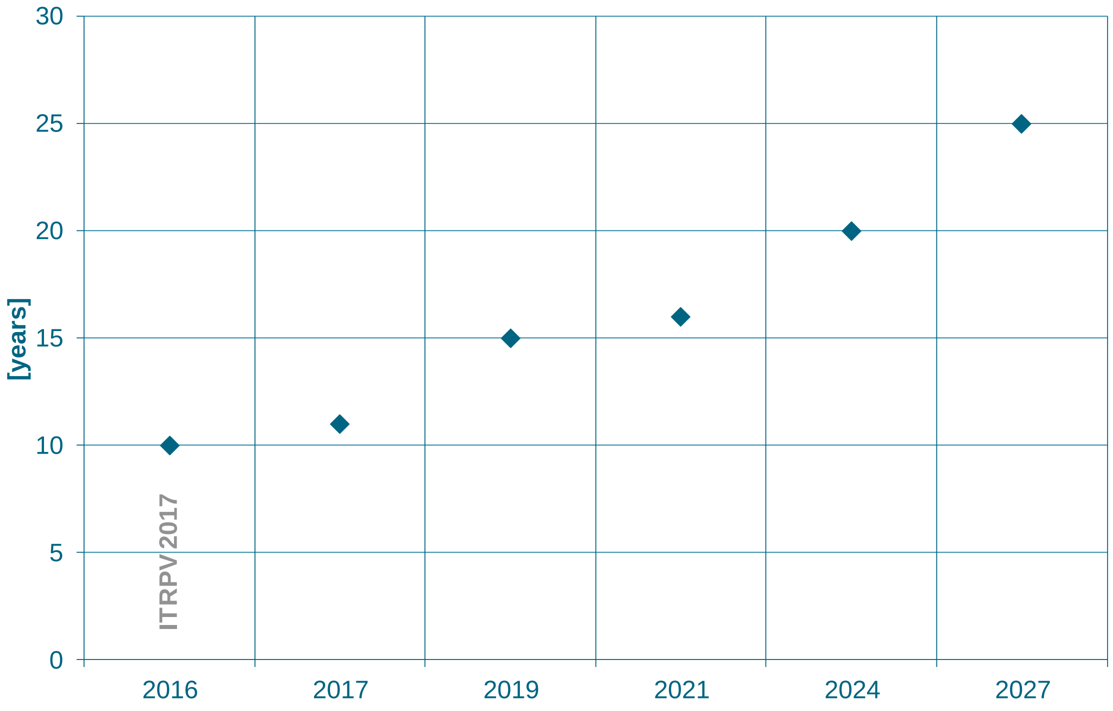
Module – Materials: front cover material

Trend: market share of front cover material



AR coated glass is mainstream

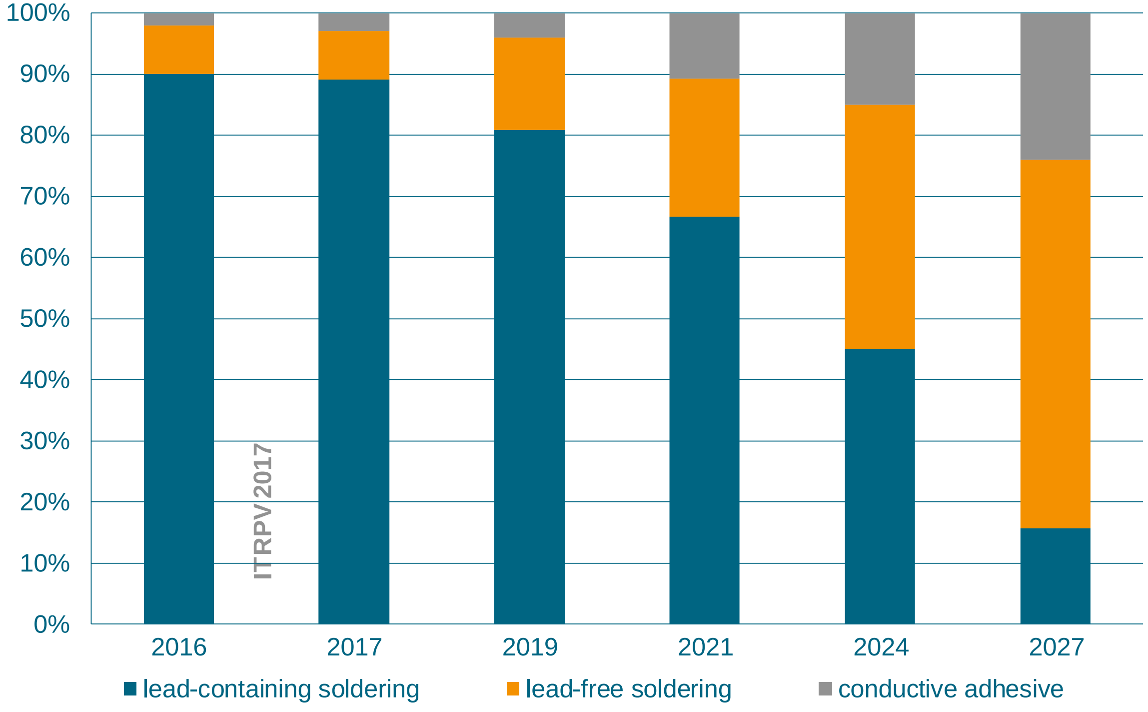
Trend: lifetime of AR coating



AR coating lifetime will increase to 25 years

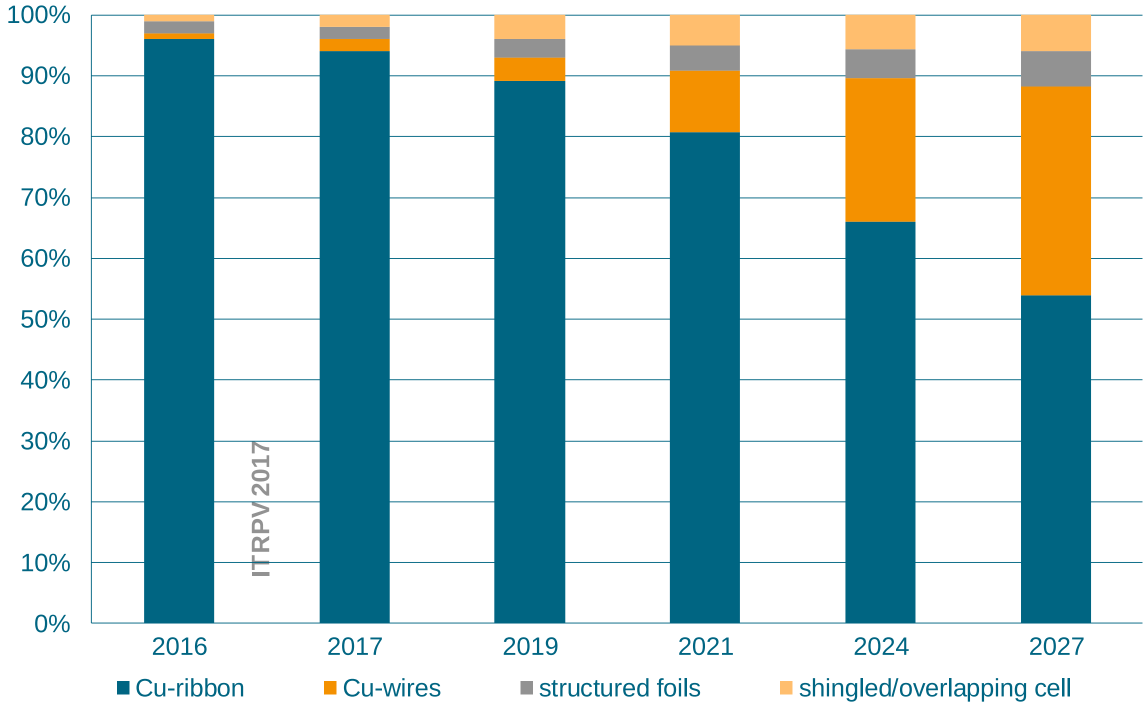
Module – Processes: interconnection technology

Trend: cell interconnection technology



**Expanding market share:
lead free soldering + conductive adhesives**

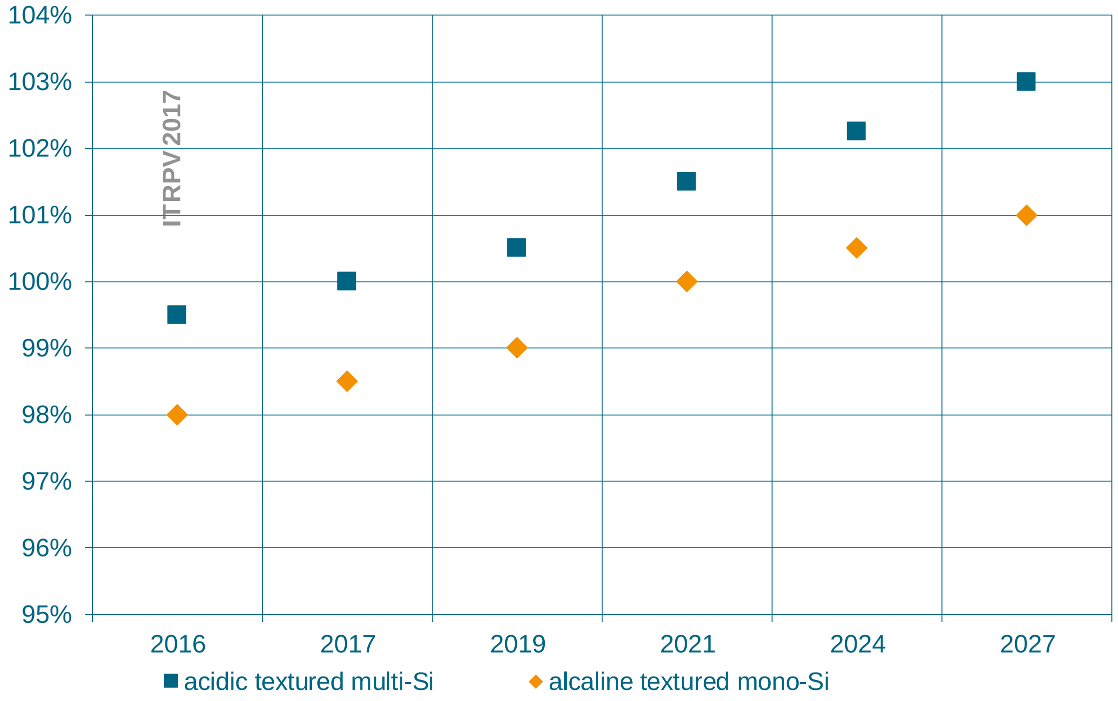
Trend: cell connection material



Ribbons/wires will remain most widely used cell connection material

Module – Products: module power outlook

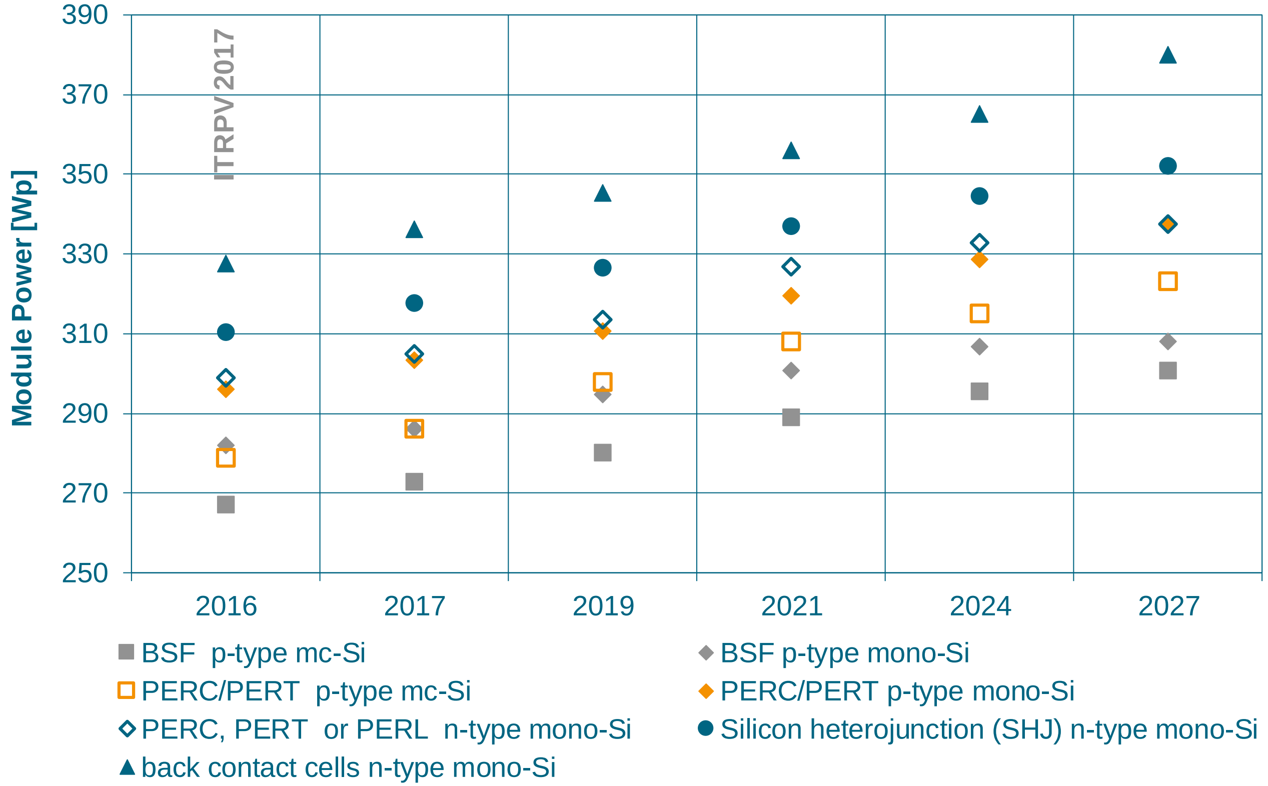
Trend: cell to module power ratio (CTM)



CTM will increase to > 100%

→ Acidic texturing has higher CTM

Trend: module power of 60 cell (156x156mm²)



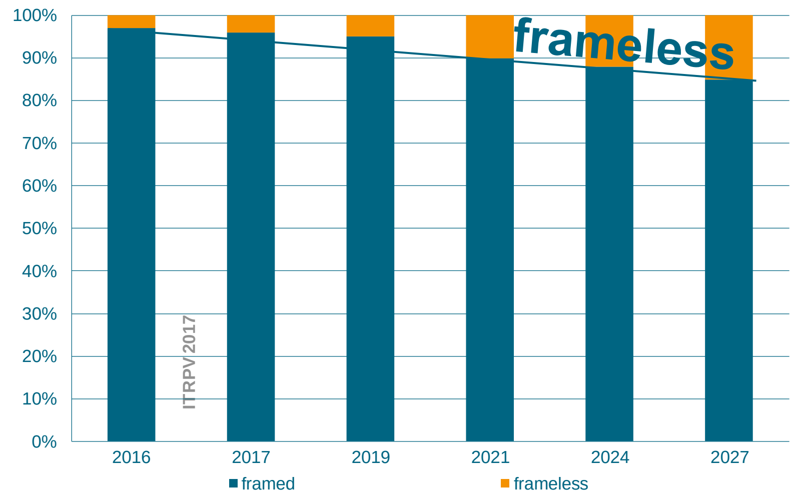
60 cell modules 2017:

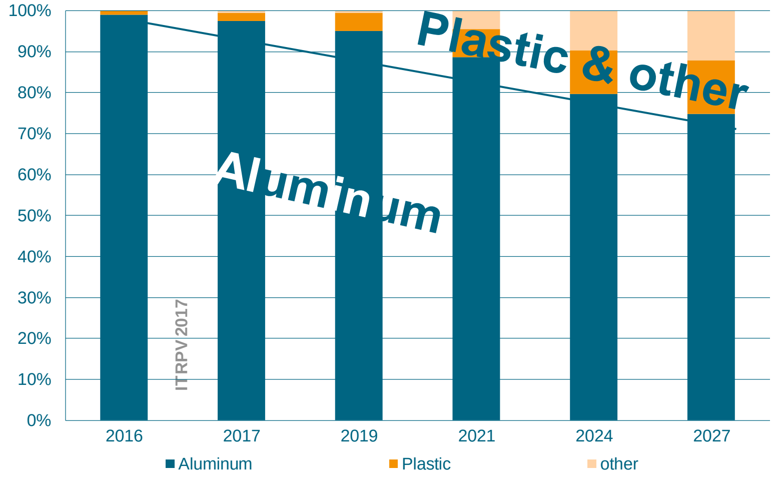
Mono p-type PERC: 300 W are standard

Multi p-type PERC: 285 W are common

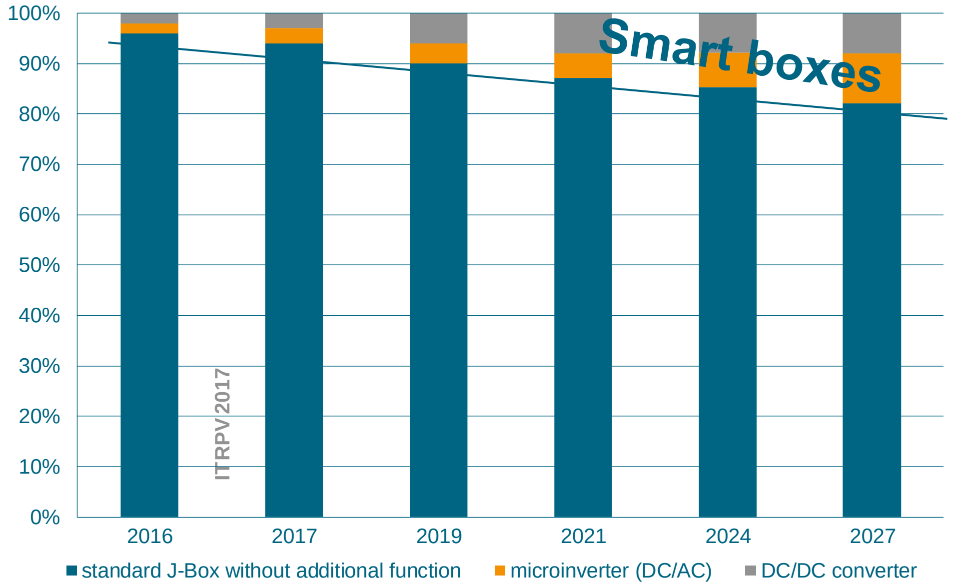
Module – Products: framed modules and J-Boxes

Trend: share of frameless c-Si modules





Trend: share of smart J-Boxes

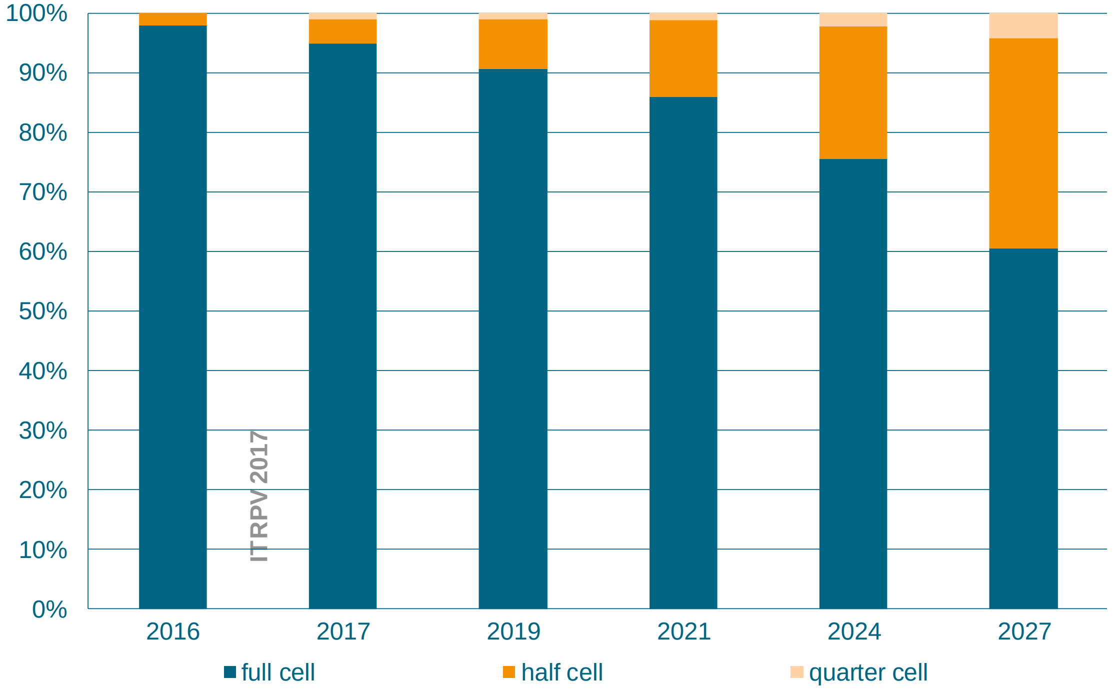


Al-frames will stay mainstream
→ frameless for niche markets

Standard J-Box remains mainstream
→ Smart J-Boxes for niche applications

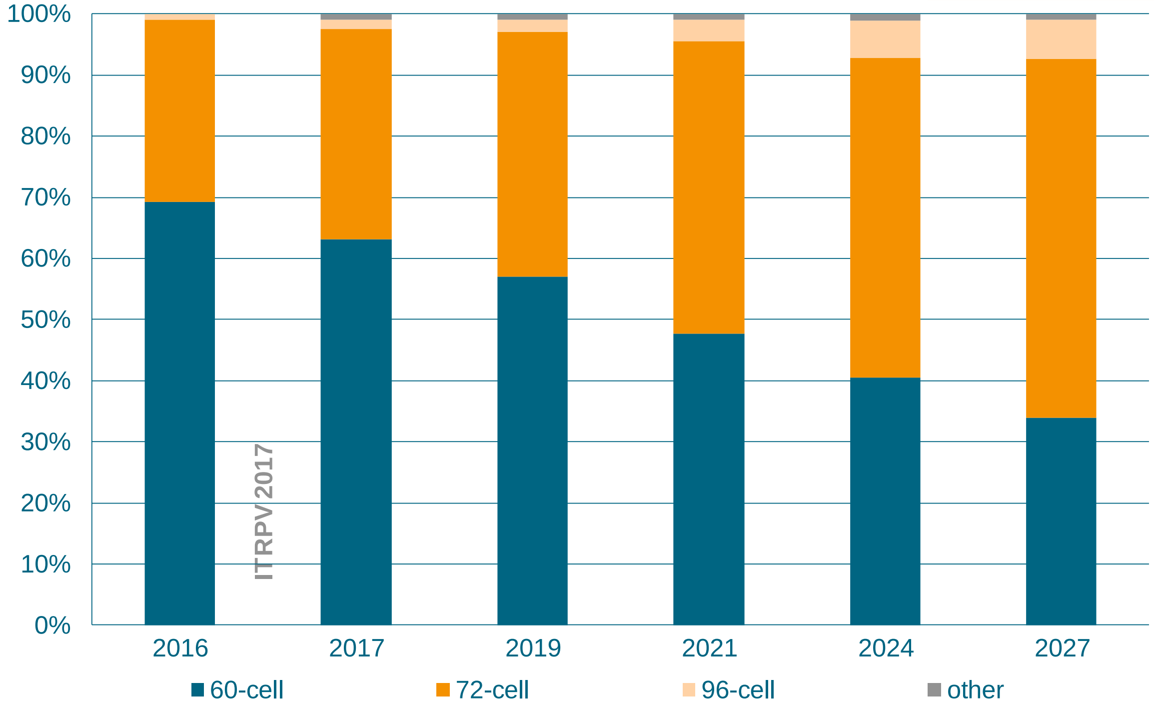
Module – Products: module size

Trend: share of cell dimensions



Full cell will remain main stream
half cell implementation started!
quarter cells – currently a niche

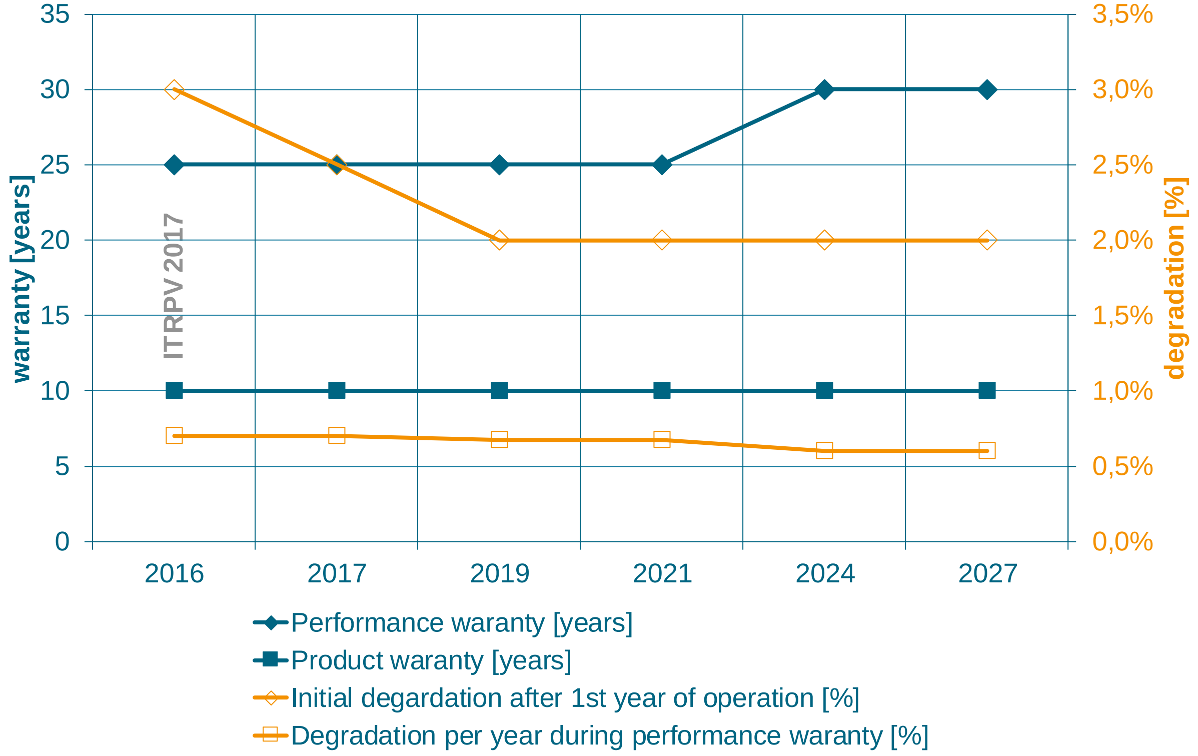
Trend: share of module size (full cell)



Big is beautiful: **72 cell module share will increase**
60 cell modules → mainstream until 2020

Module – Products: module reliability (new)

Trend: warranty conditions and degradation for c-Si modules



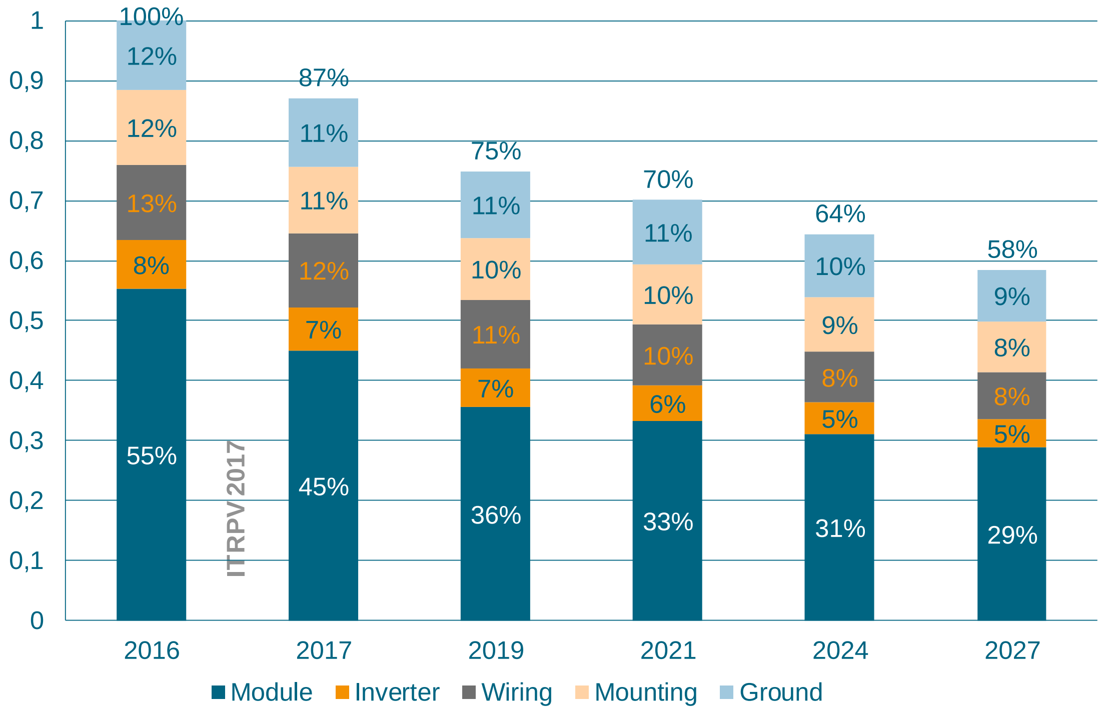
Product warranty will remain 10 years
Performance warranty 2024+: 30 years

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

Outline

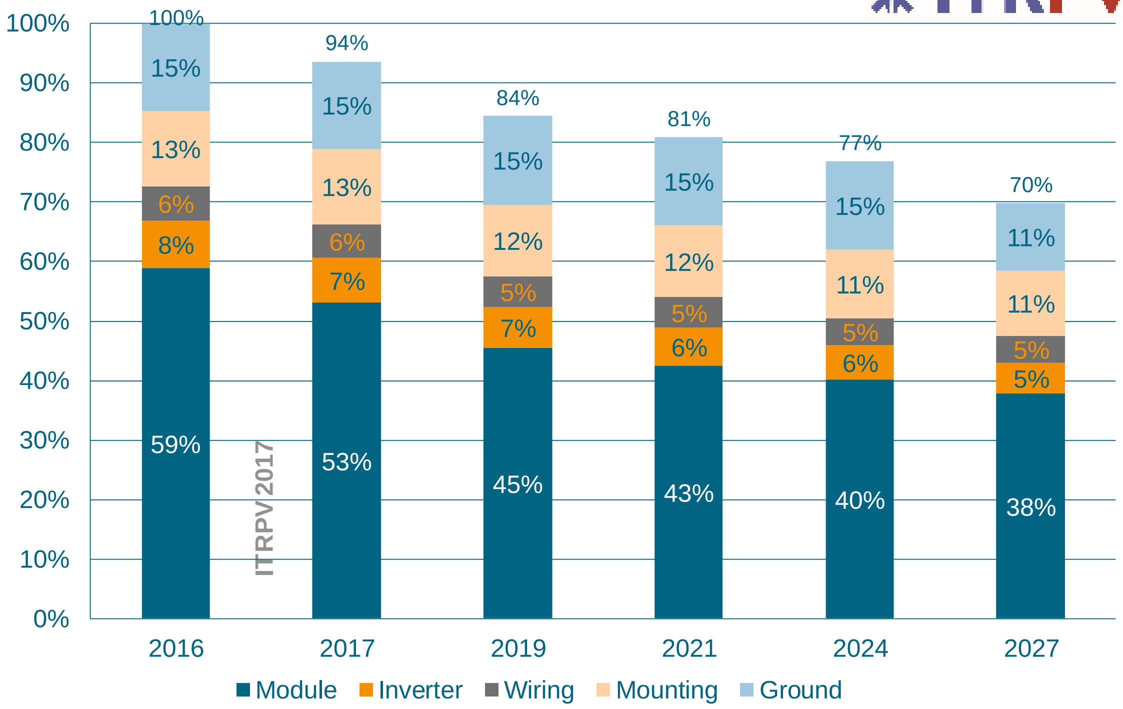
Systems – Balance of system (BOS) for power plants

Trend: BOS in Europe and US



Module costs still significant

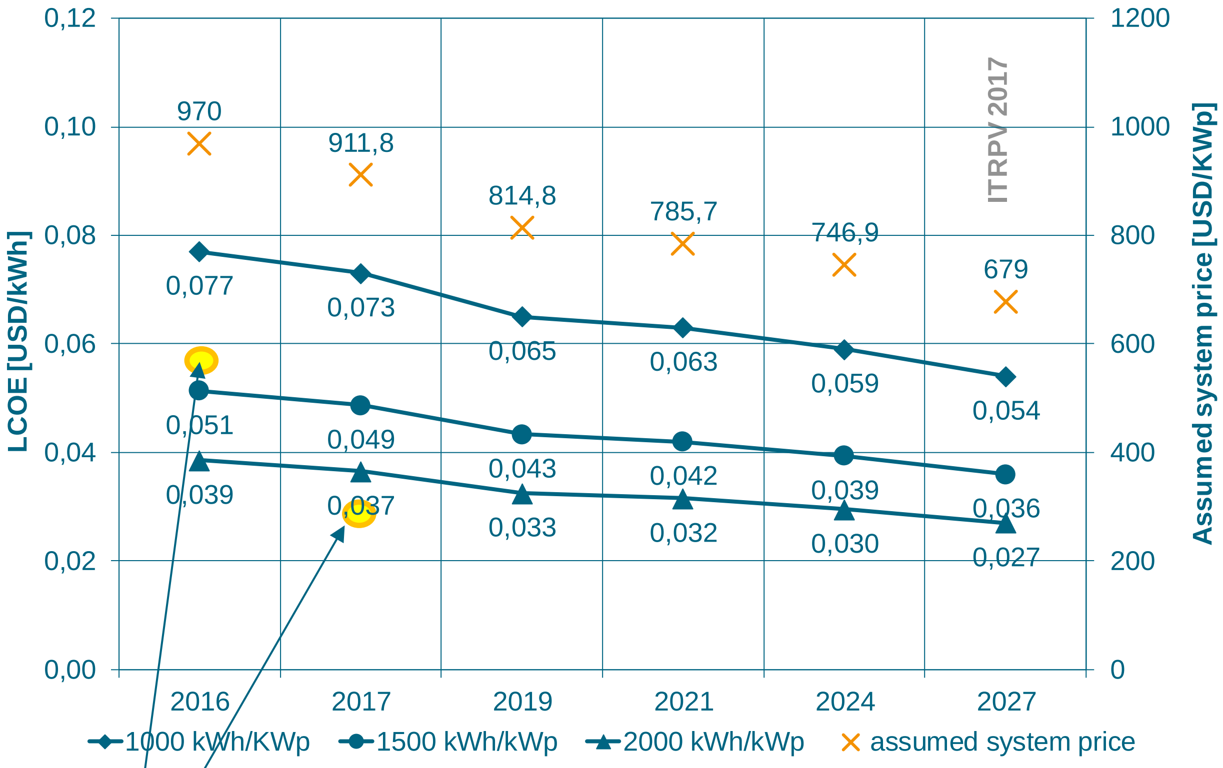
Trend: BOS in Asia



Costs in Asia are assumed to be significant lower

Systems – Levelized Cost of Electricity (LCoE)

Trend: LCoE progress – a minimum approach



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

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 of 25 years are assumed

Next steps to further reduce LCoE:

→ extended **service live** to **30 years** (supported by performance warranty trend)

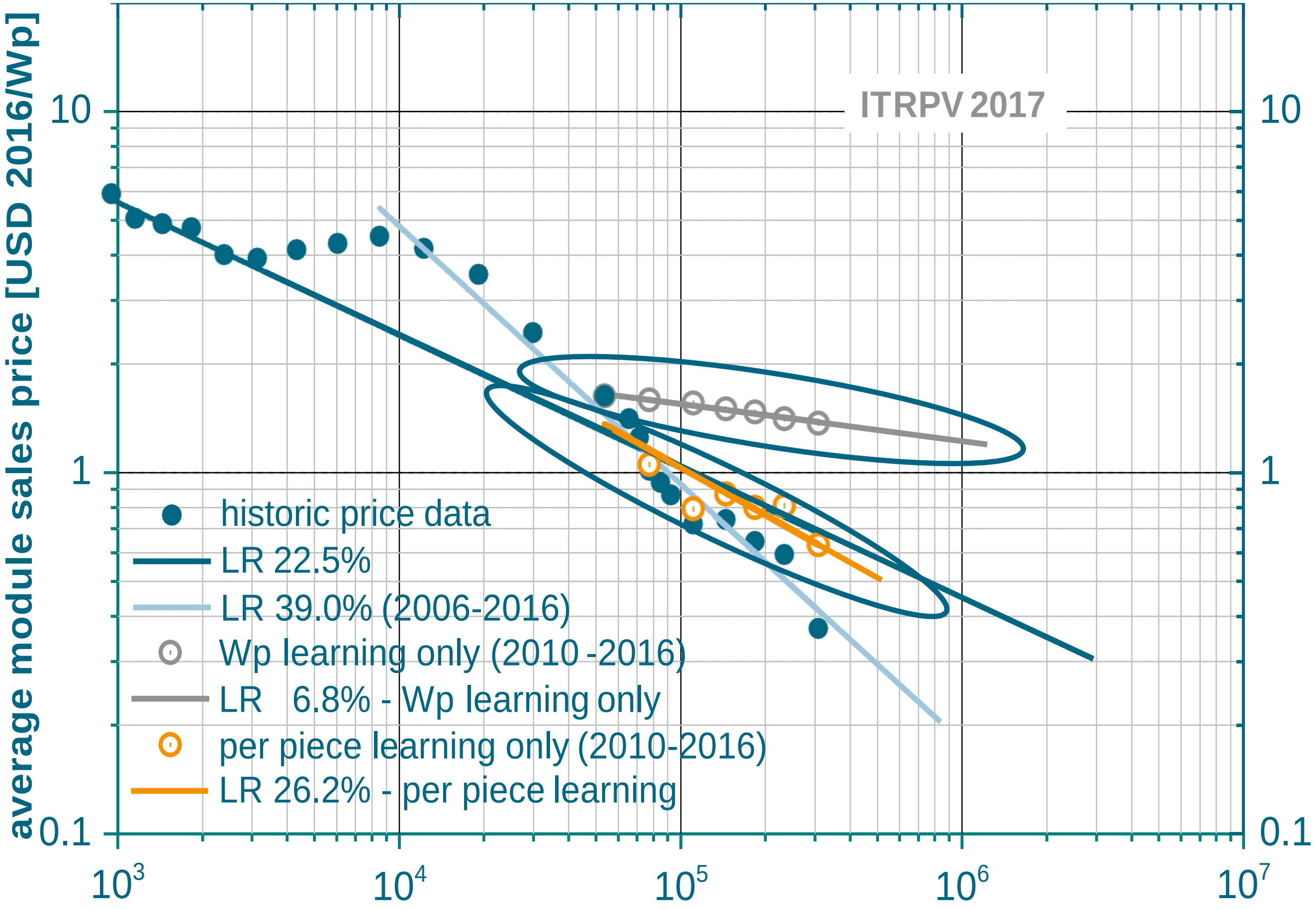
→ further efficiency improvements + cost down measures

Outline

1. ITRPV Introduction
2. PV Learning Curve and Cost Considerations
3. ITRVP – Results 2016
   - Si / Wafer - Materials, Processes, Products
   - Cell - Materials, Processes, Products
   - Module - Materials, Processes, Products
   - Systems
4. **Summary and Outlook**

Outlook: in detail view at PV learning curve

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



ITRPV finding 2010-2016:

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

→ Learning was and will always be a combination of:

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

But how will PV proceed in future?

Approach: **logistic growth**

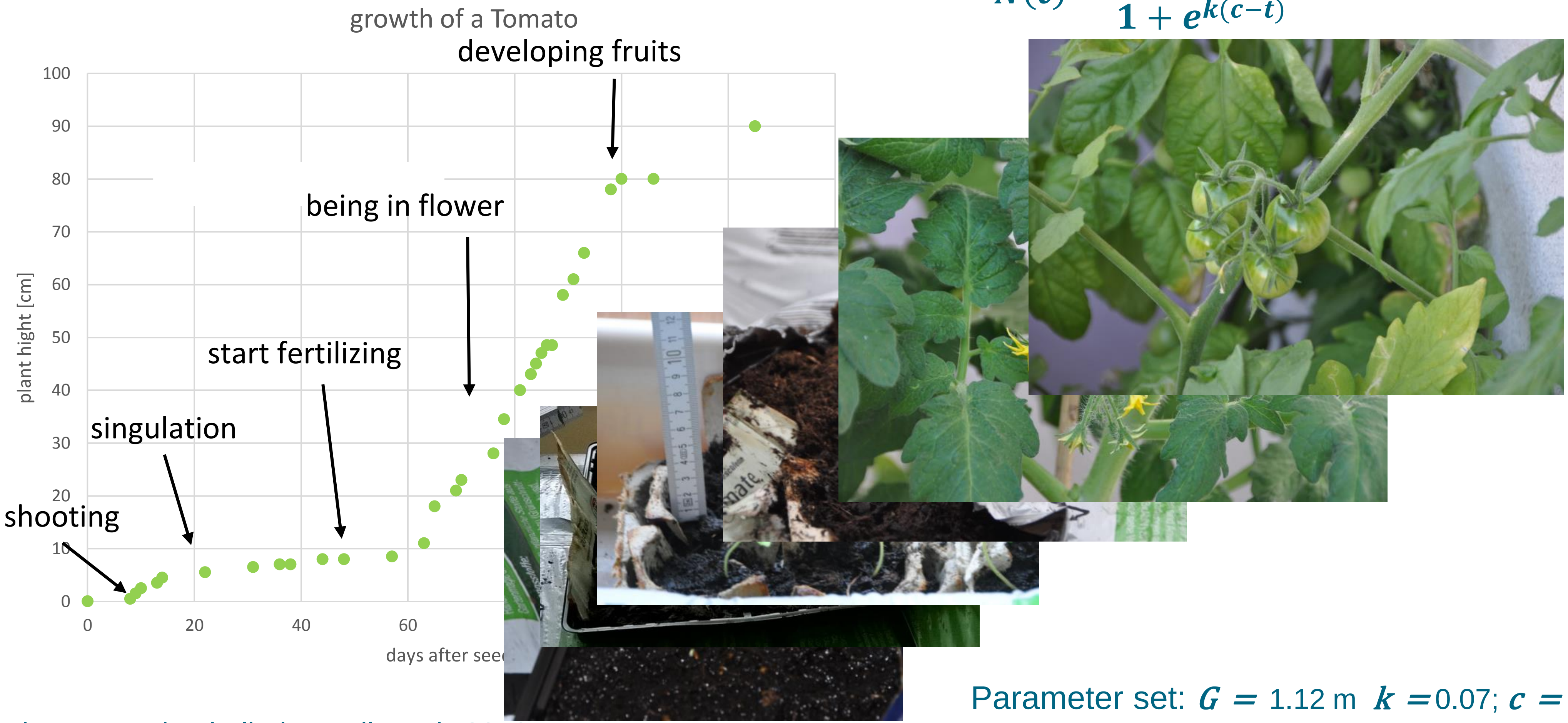
→ exemplified by nature:

Spreading of PV – like a plants life: An Experiment

PV experiment: Investigation of the growth of a Tomato plant*

→ watching milestones in a tomato plant's live

$$N(t) = \frac{G}{1 + e^{k(c-t)}}$$



Parameter set: $G = 1.12$ m $k = 0.07$; $c = 67$ d

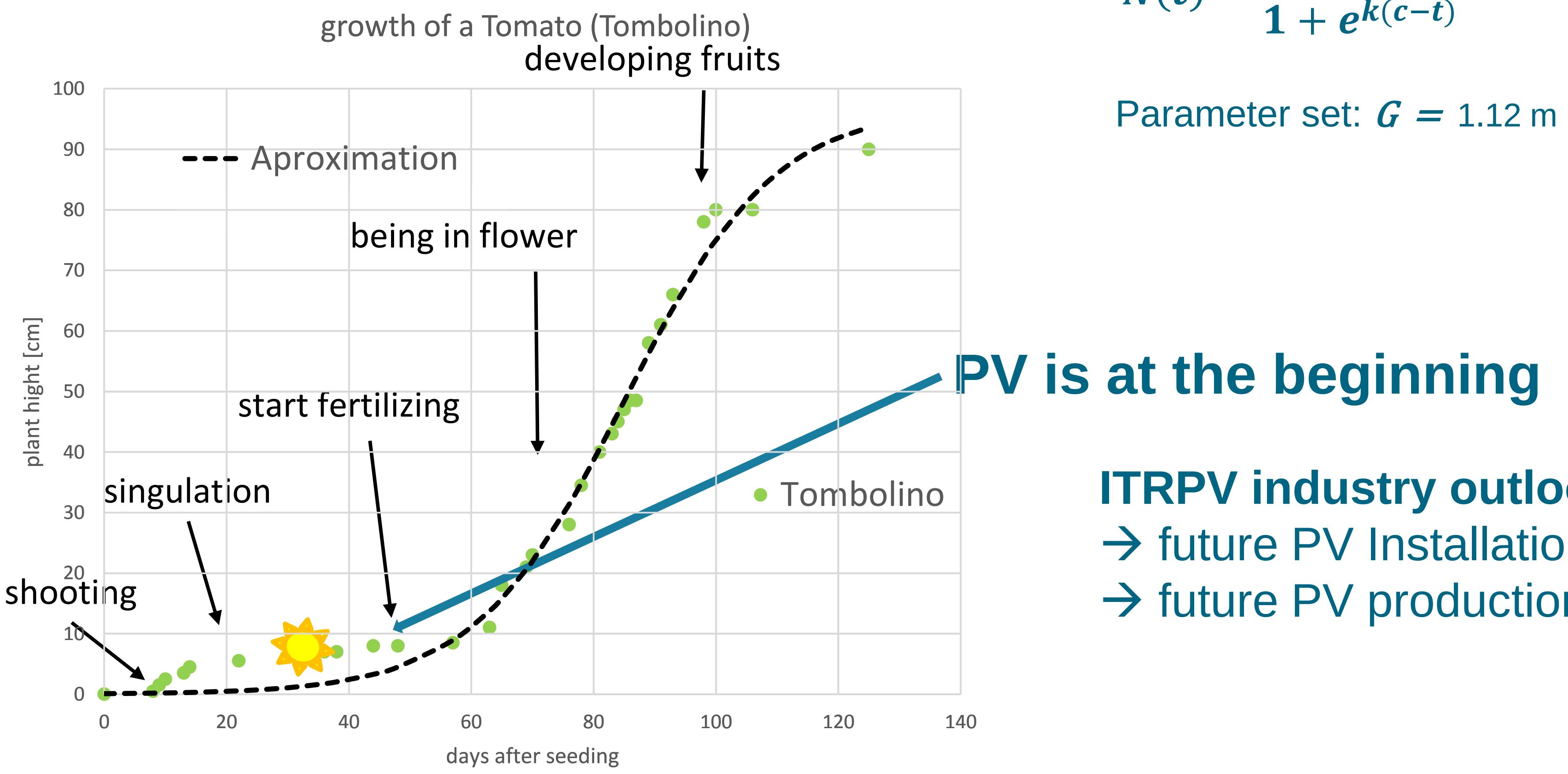
* Plant grown in Thalheim April – July 2016

Spreading of PV – like a plants life: An Experiment

PV experiment: Investigation of the growth of a Tomato plant*
→ PV is starting

$$N(t) = \frac{G}{1 + e^{k(c-t)}}$$

Parameter set: $G = 1.12$ m $k = 0.07$; $c = 67$ d

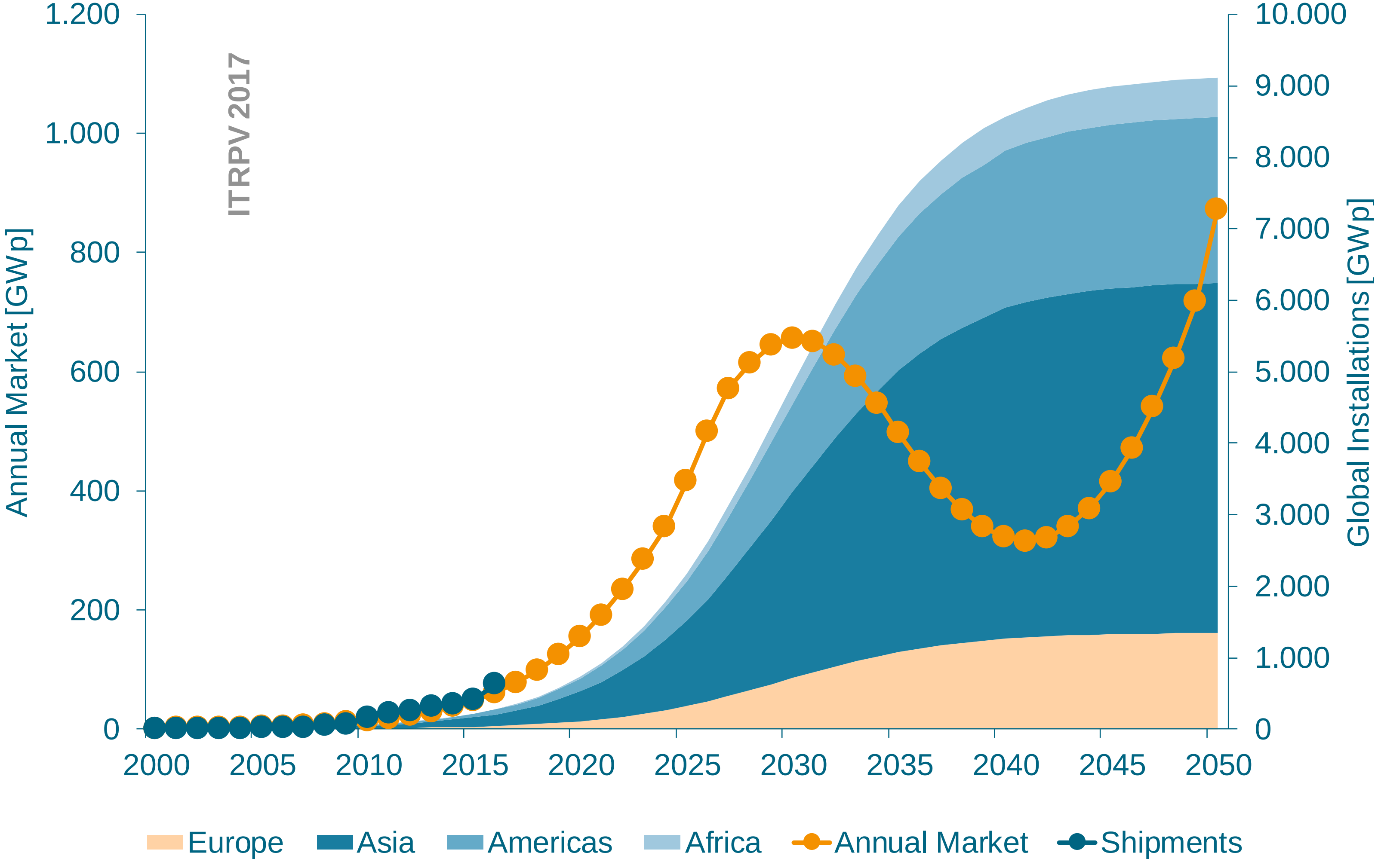


ITRPV industry outlook:
→ future PV Installation and
→ future PV production requirements

* Plant grown in Thalheim April – July 2016

PV market trend until 2050: logistic growth

Scenario 3 “high”: 9.2 TWp/ 14.3 PWh (< 10 % primary energy)



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

ITRPV finding:

- Shipments until 2016 slightly above all scenarios
- Annual PV market: **335 GWp/a to 800 GWp/a**

→ **Replacement rate = key to overcome down cycles**

→ **Evolutionary technology development works for all scenarios**

Summary

- **Silicon PV will remain a fast developing technology**

- **Further reductions of c-Si PV manufacturing cost are possible**

  → without sacrificing quality and reliability
  → cell efficiency improvements will support the cost reduction

- **Silicon PV will significantly contribute to future power supply**

- **We are just at the beginning of PV-market development**

Source: www.siemens.com/presse

Thank you
for your attention!

Contact us:

jutta.trube@vdma.org

Full version of 7th edition available at:

www.itrpv.net