DuraMAT
Durable Module Materials Consortium

# Technology Scouting Report: Reliability Implications of Recent PV Module Technology Trends

Jarett Zuboy, Martin Springer, Elizabeth Palmiotti, Teresa Barnes, Joe Karas, Brittany Smith, and Michael Woodhouse

May 9, 2022

# The importance of module reliability

PVTECH

NEWS

**Built solar assets are 'chronically underperforming' and modules degrading faster than expected, research finds**

Stoker (2021a)


PV module hotspot (Image by Dirk Jordan / NREL)

nature

**Build solar-energy systems to last – save billions**

Jordan et al. (2021)

PV modules damaged by hail (Photo by Dennis Schroeder / NREL)

pv magazine

**The weekend read: The financial risk of investing in PV systems and the 'Peter PAN' files**

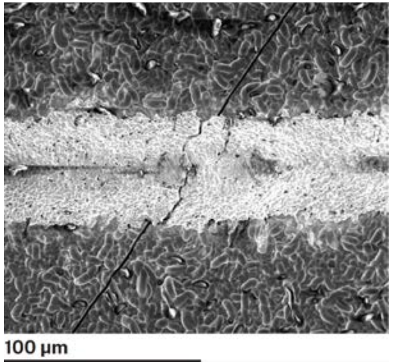
Willuhn (2022)

PVTECH

NEWS

**Solar module failure rates continue to rise as record number of manufacturers recognised in PVEL Module Reliability Scorecard**

Stoker (2021b)



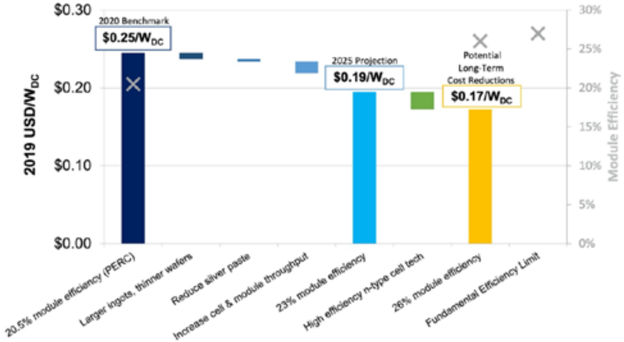

PV cell metallization cracking (Image by Tim Silverman / NREL)

# Reliability-related trends

## Accelerating Solar Deployment

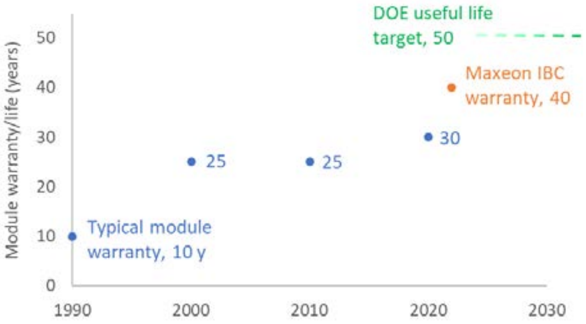

DOE (2021)

## Price and Performance Pressure



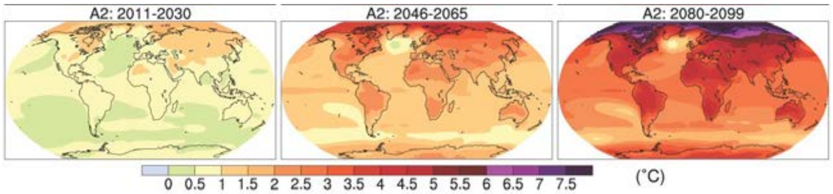

Smith et al. (2021)

## Longer Module Lifetimes




Modified from Jordan et al. (2022)

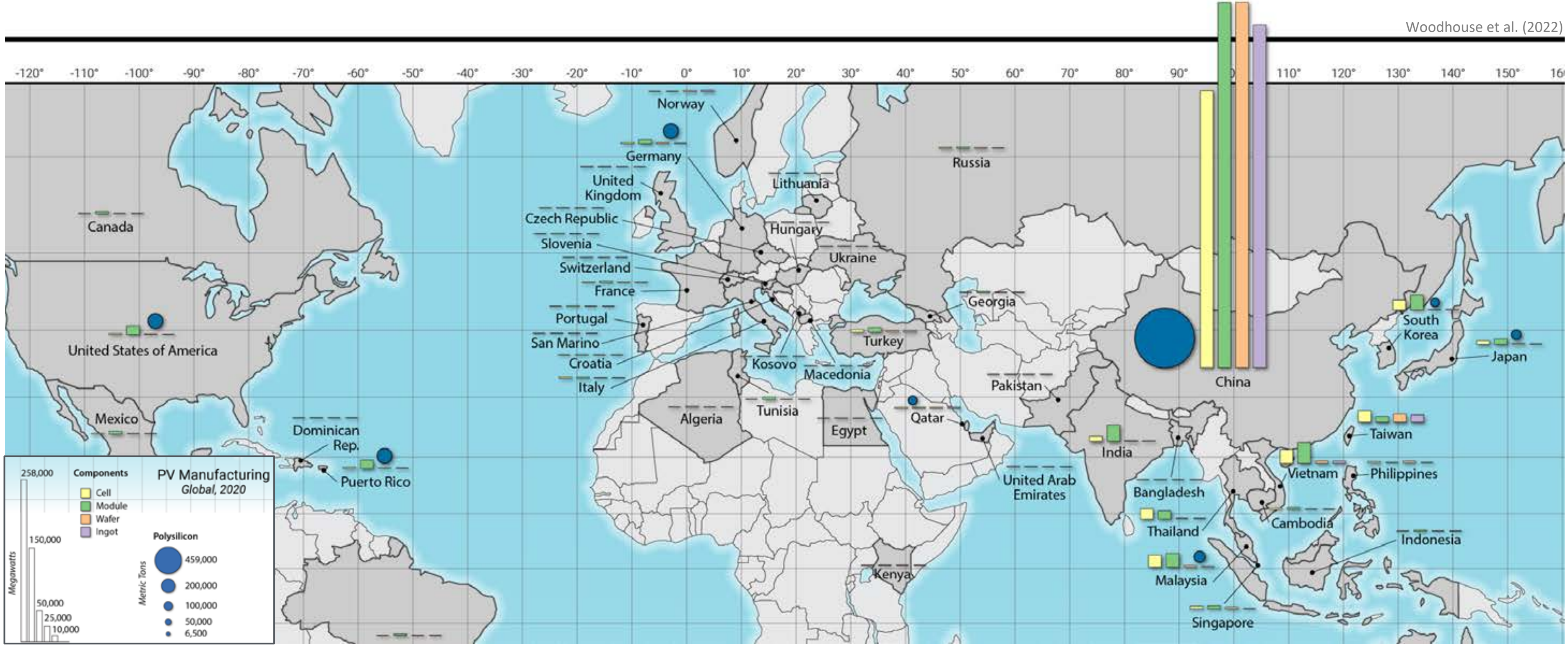
## Changing Environments




IPCC (2007)

# Supply chain impacts

Woodhouse et al. (2022)



# Goals of the DuraMAT Technology Scouting Report

- Track technology changes that could affect PV module reliability
- Assess changes in module reliability risks over time
- Identify the need for new research related to reliability

*"PV moves pretty fast. If you don't stop and look around once in a while, you could miss it." – Inspired by* Ferris Bueller's Day Off

# Thank you

- DuraMAT Industry Advisory Board
- Nick Bosco (NREL)
- David Feldman (NREL)
- Peter Hacke (NREL)
- Al Hicks (NREL)
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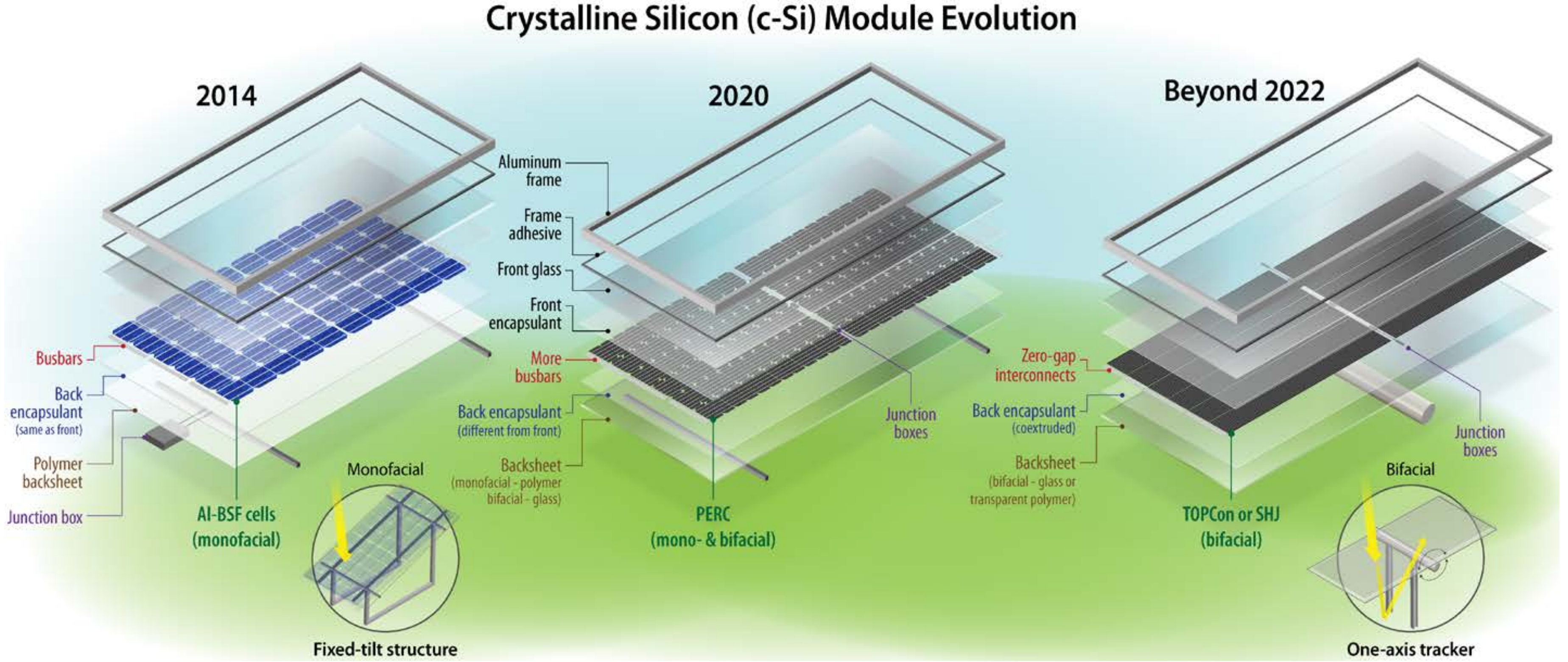
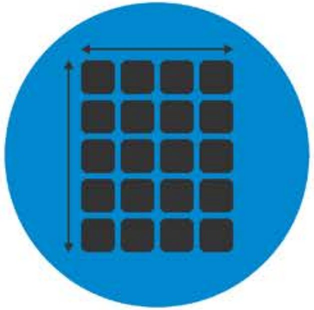
- Dirk Jordan (NREL)
- Mike Kempe (NREL)
- David Miller (NREL)
- Heather Mirletz (NREL, Colorado School of Mines)
- Ingrid Repins (NREL)
- Tim Silverman (NREL)

# PV module technology changes



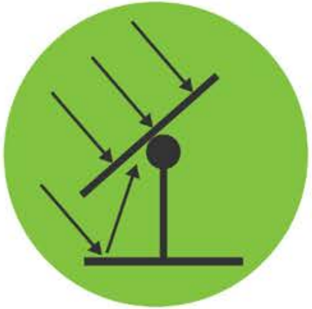
# Categories of technology change

**Large modules**

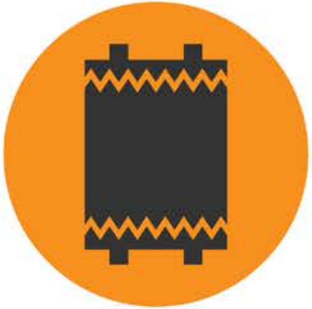


**Interconnects**

**Bifacial**

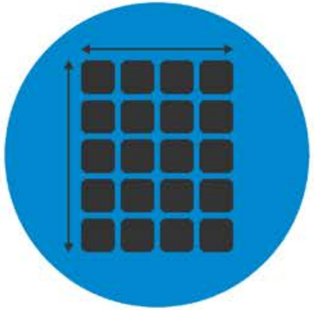


**Cell technology**



# Large modules

**Large modules**

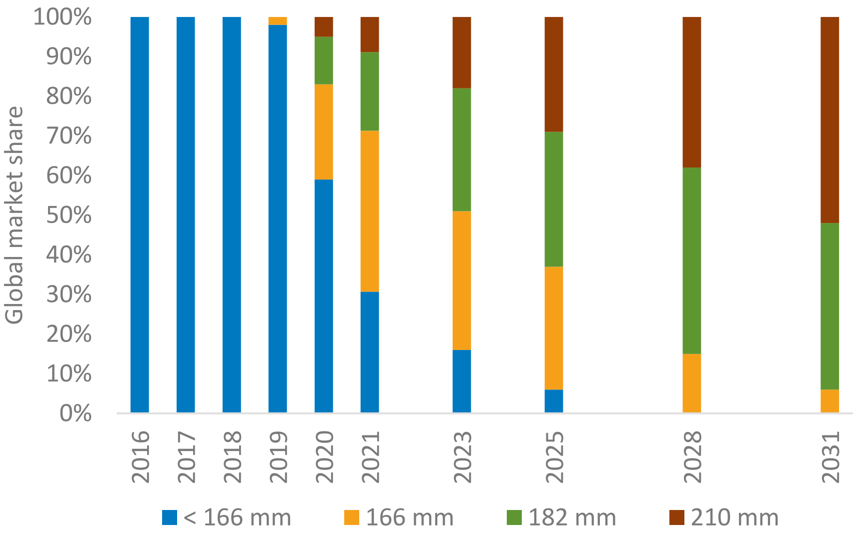


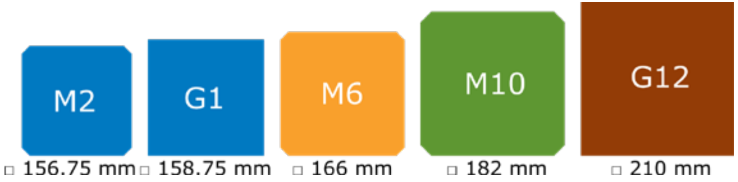
**Interconnects**

**Bifacial**

**Cell technology**

# Larger wafers




Author synthesis of mono c-Si wafer size data from ITRPV (2017–2021)

## Drivers & Benefits

**improvements in manufacturing capabilities**

- larger wafers provide potential for cost savings

**enables larger module sizes**

- large format modules – higher energy output

**efficiency gains**

- cell cutting

## Potential Risks

**requires adaptation of cell and module processes**

- significant process changes

**introduction of additional process steps**

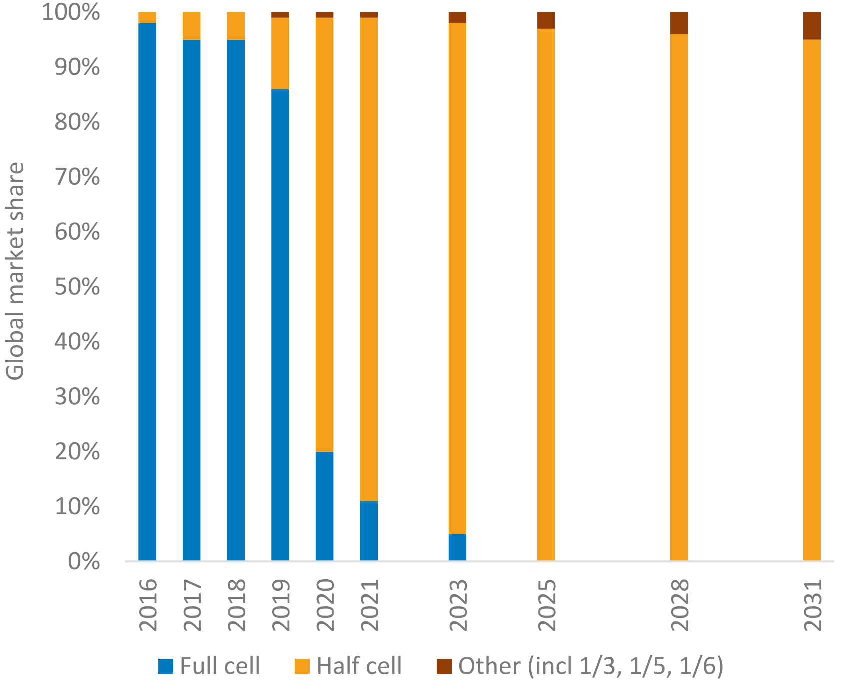
- cell cutting (see next slide) can increase reliability risks

**handling of larger wafers and cells is more complex**

- especially when coupled with thinner cells (increased fracture risk)

# Cell cutting

Bosco et al. (in review)




Author synthesis of data from ITRPV (2017–2021). The 2020–2031 values are for cells ≥ 182 x 182 $mm^2$. Cell dimensions are unspecified for earlier data.

## Drivers & Benefits

**reduces resistive losses**

- by lowering electric current

**potentially higher shade tolerance**

- through changed junction box position & wiring pattern

## Potential Risks

**potentially increased cell fracture risk through edge-defects**

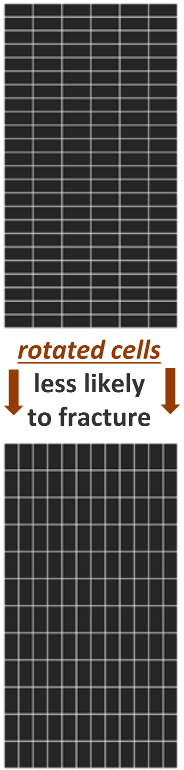
- dependent on cell cutting technologies and process control

**changed mechanical stress and strain field**

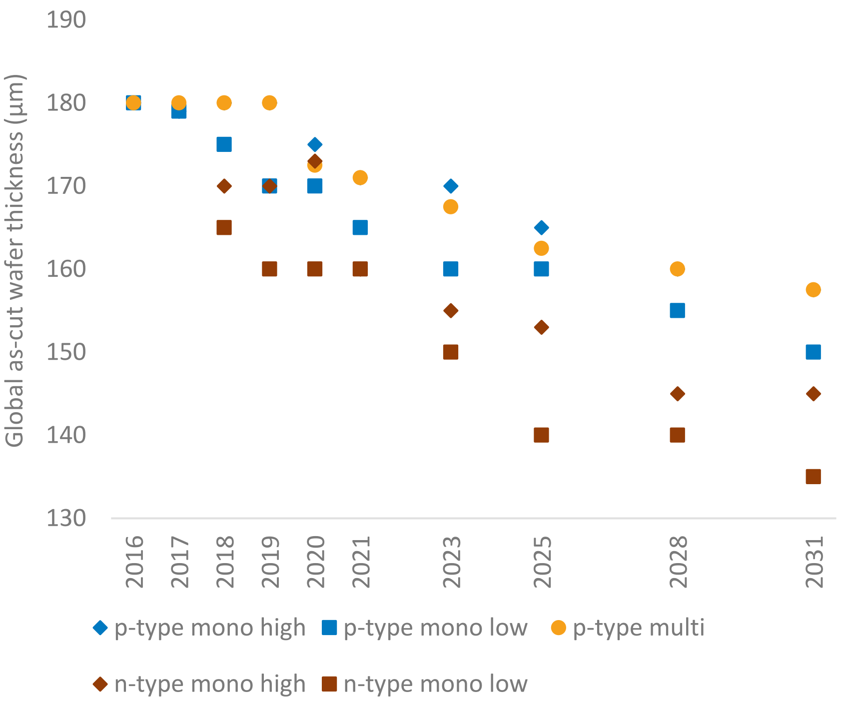
- potential for reduced cell deformation and decreased cell fracture risk

**orientation of half cut cells can decrease fracture risk**

- fracture risk of current industry standard is similar to the risk for full-size cells
- rotation of 90 degrees can reduce the probability of fracture under static loading conditions



# Thinner cells




Author synthesis of data from ITRPV (2017–2021)

## Drivers & Benefits

**reduced material input**

- cost savings

**new advanced cell technologies**

- thinner wafers have higher efficiency potential when paired with n-type technologies such as SHJ and TOPCon

## Potential Risks

**potentially reduced cell yield on production line**

- handling of thin cells is complex and can break before lamination
- new manufacturing processes need to be adopted

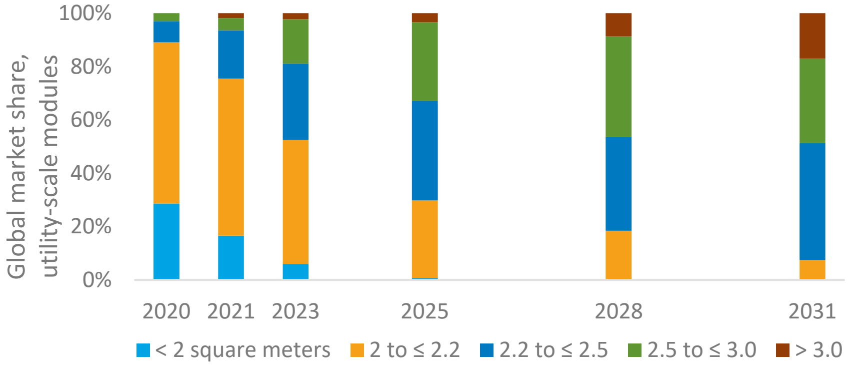
**cell cracking risk after lamination not inherently higher than for thick cells, depends on**

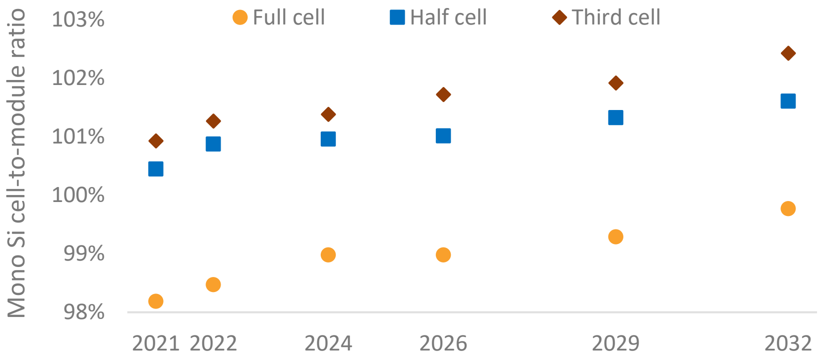
- stress localizations around interconnect technologies
- stress state and effective area of cell under tension
- packaging technology (glass-glass vs. glass-backsheet)
- edge-damage caused by the cutting process
- residual stresses caused by firing of the metallization

**adaptation of thinner cells has been slower than predicted**

- caused by complications in packaging process (likely ongoing)

# Larger modules




Author synthesis of data from ITRPV (2017–2022)

## Drivers & Benefits

**wafer/cell size**

- larger cells allow for larger module sizes

**increased power output**

- larger active area
- improved cell-to-module (CTM) power ratio: $\mathrm{CTM} = \frac{P_{\mathrm{module}}}{P_{\mathrm{cell}} \cdot n_{\mathrm{cell}}}$

## Potential Risks

**potentially more frequent cell breakage due to**

- weather (wind & hail), or shipping, handling, and installation

**increased weight**

- OSHA handling issues with very large modules; 100-lb modules may be the practical limit
- implications for mounting structure design and cost

**increase in electrical current**

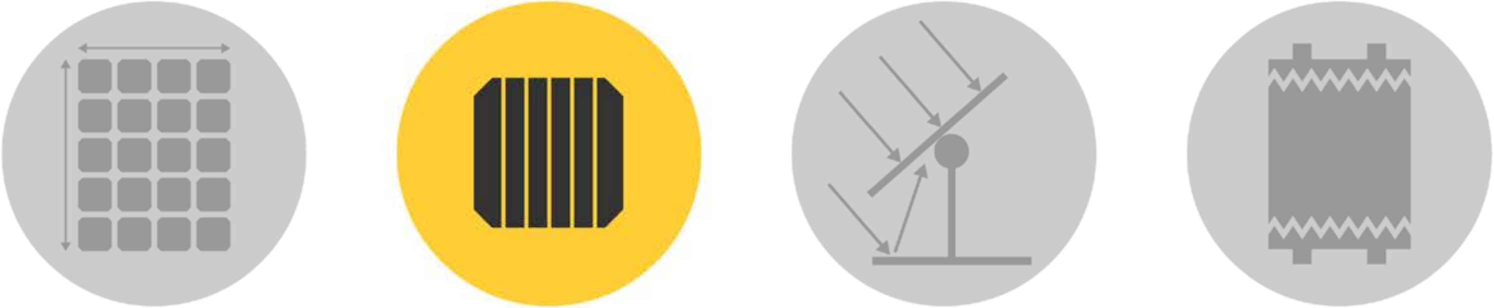
- electrical balance of sys. (wire size, fusing, bypass diode) must be adapted

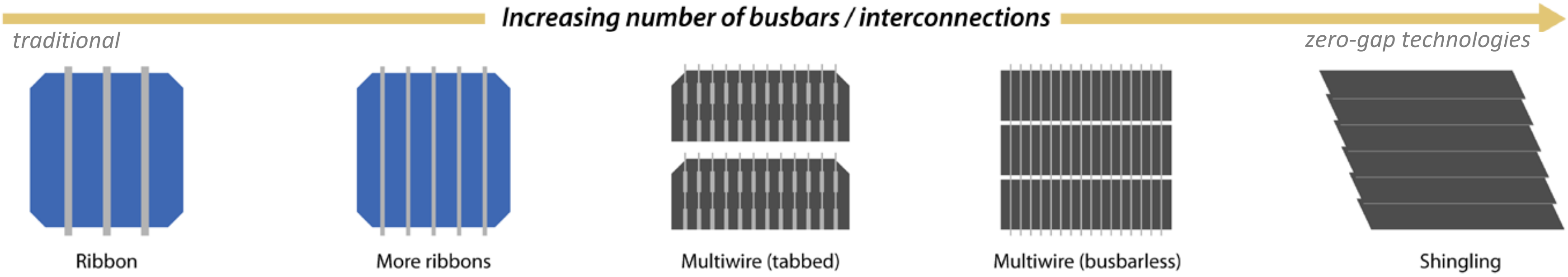
**new testing equipment necessary to accommodate large modules**

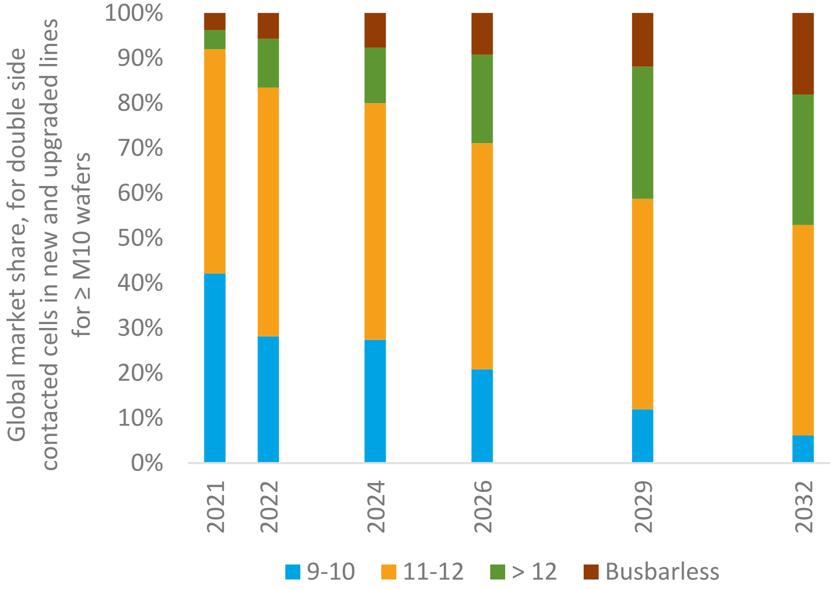
- such as dynamic mechanical loading (DML) to assess hail damage and inform insurance coverage

# Interconnects

Large modules | Interconnects | Bifacial | Cell technology






ITRPV (2022)

## Drivers & Benefits

**increasing cell sizes require a larger number of interconnects**

- improved manufacturing capabilities of wafers (cost reduction)

**reduction in finger width**

- less silver metallization (cost reduction)
- increase active cell area (efficiency gain)

**improved redundancy and reliability**

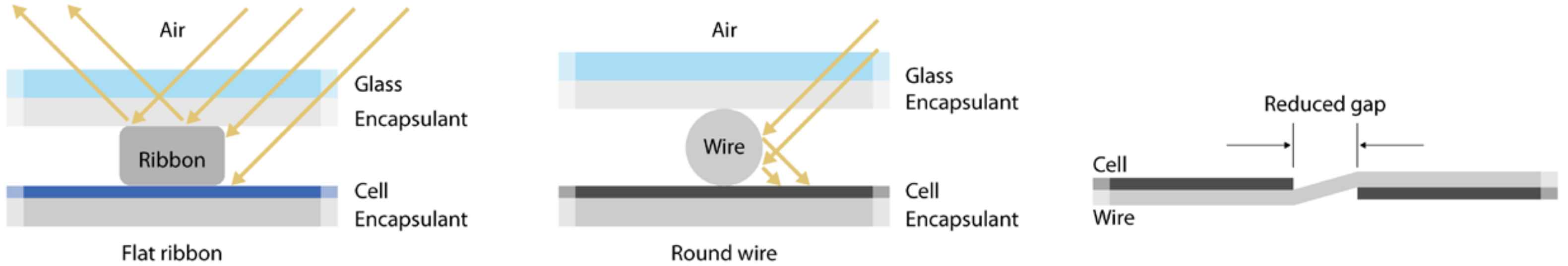
- higher likelihood of fractured cell fragments staying electrically connected
- minimizes localized mechanical stresses around busbars

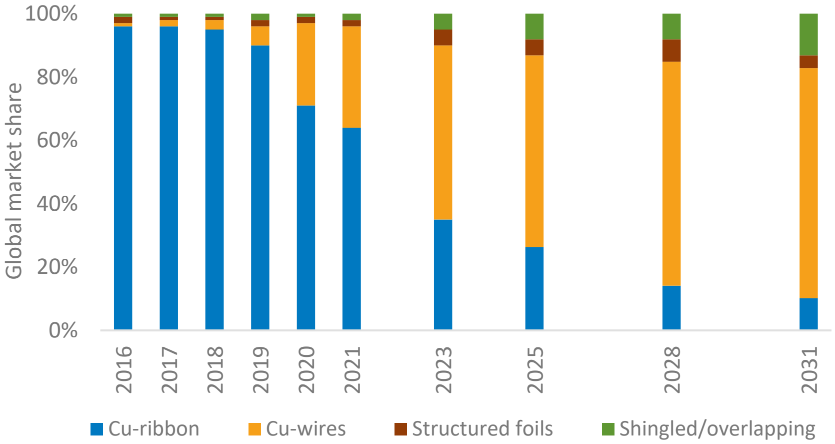
## Potential Risks

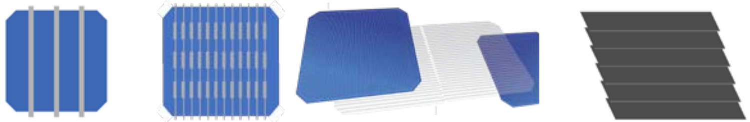
**introduction of new manufacturing processes and materials**

- geometry change from rectangular ribbons to wires
- material change from metallurgical connections to mechanical contact

## *Geometry and process changes*



Author synthesis of data from ITRPV (2017–2021)
SolarTech Universal (2022)

### Drivers & Benefits

**increasing number of busbars**
- allows for reduction of cross-sectional ribbon area

**allow for low-temperature approaches**
- future-proofing for new cell technologies as SHJ

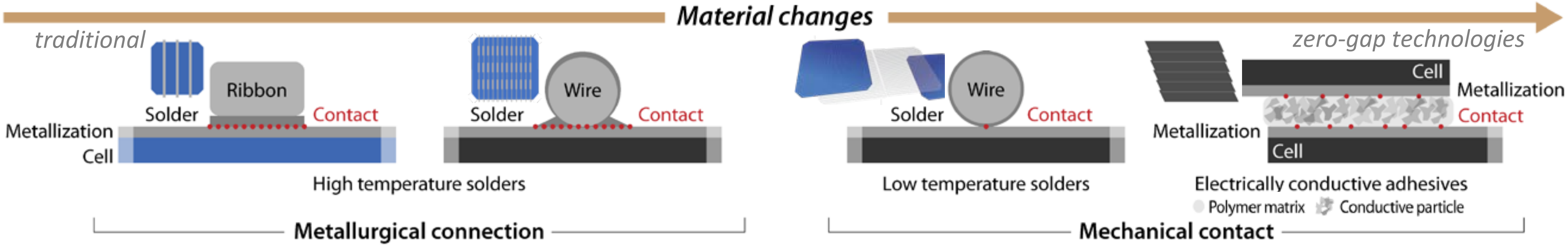
**increased efficiency**
- increase active cell area and light reflection on wire
- reduced gap between cells or overlapping cells

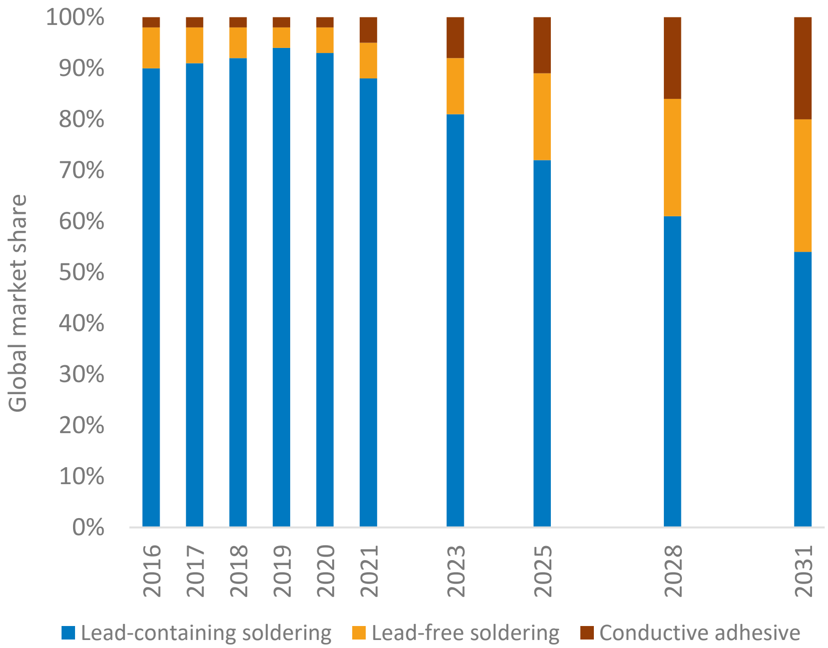
### Potential Risks

**geometry changes**
- multiwire might need thicker encapsulant

**process changes**
- new components, such as structured foils, may require new reliability tests

**shingled/overlapping cells**
- potentially higher stresses at overlapping cell edge, increasing fracture risk




Author synthesis of data from ITRPV (2017–2021)

## Drivers & Benefits

**potential regulatory requirements**

- materials containing lead are restricted under EU Directive (RoHS 2)

**cost savings potential**

- reduction of silver content

**reduce processing temperatures and material input**

- required for new cell technologies such as SHJ
- reduce thermal stresses
- elimination of processing steps such as soldering at high temperature

## Potential Risks

**change in solder materials (high vs. low temp & lead-containing vs. lead-free)**

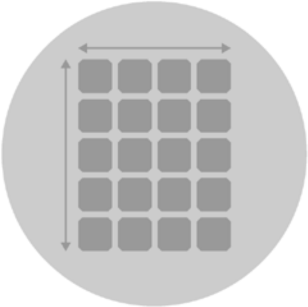
- potential degradation from poorer mechanical characteristics
- change from metallurgical connection to mechanical contact will require new accelerated tests and development of standards

**Electrically conductive adhesives**

- introduction of possible new degradation mechanisms such as debonding or corrosion of non-silver conductive particles

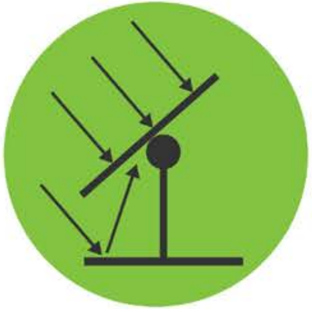
# Bifacial modules

**Large modules**



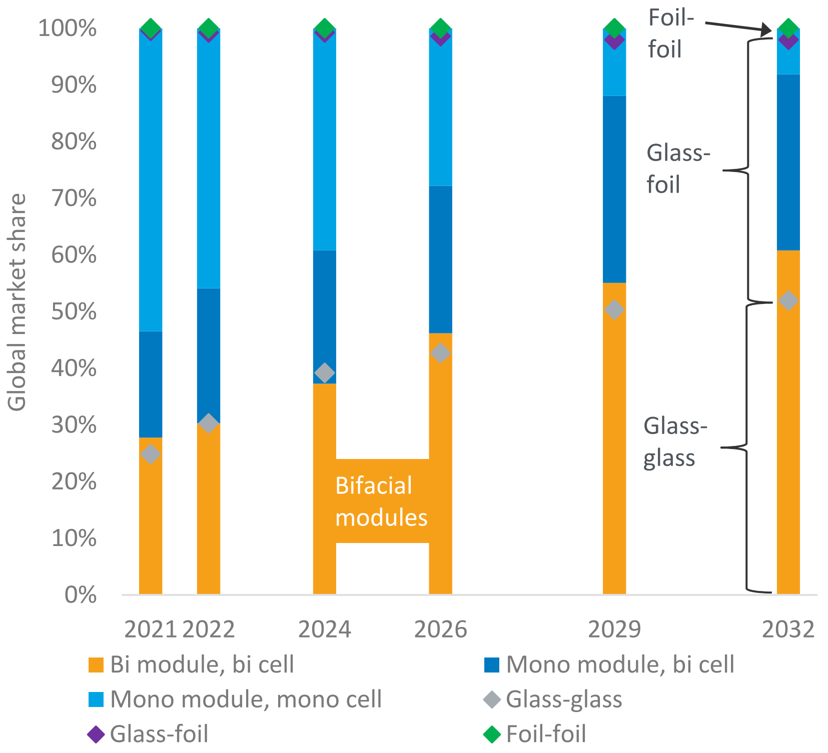
**Interconnects**

**Bifacial**



**Cell technology**

# Bifacial modules




Author synthesis of ITRPV (2022)

## Drivers & Benefits

**enabled by new(er) cell technologies**

- increased power output
- cost gap between mono- and bifacial module keeps decreasing

## Potential Risks

**increased weight**

- glass-glass construction with large format module leads to higher risk of damage during shipping, handling, and installation

**corrosion**

- acetic acid formation from EVA encapsulant

**cell fracture risk**

- benefits of putting cells into neutral axis, might be offset by residual stresses introduced during lamination
- thinner glass front sheets make cells more prone to crack during hail events

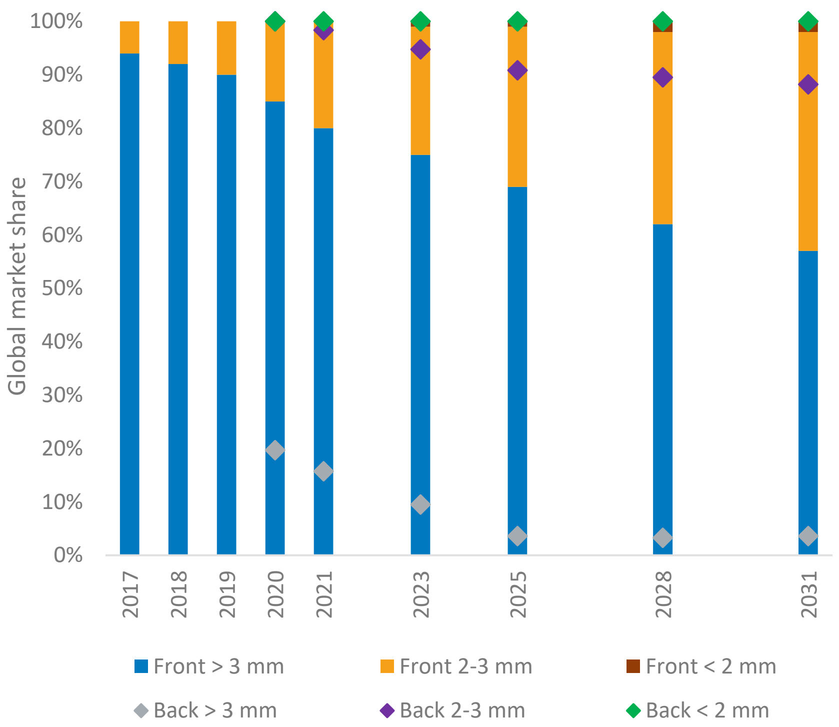
**rear-side potential induced degradation (PID)**

- degradation due to depolarization of the passivation layers (PID-p)
- corrosive PID (PID-c) due to corrosion of the Si below the passivating layers

**rear-side light-induced degradation (LID)**

- potentially very slow to no recovery

# Thinner glass




Author synthesis of ITRPV (2018–2021)

## Drivers & Benefits

**bifacial module technology**

- need for transparent backsheet

**decreasing weight - cost savings**

- lighter glass reduces shipping and installation costs, but ultrathin glass can be expensive

## Potential Risks

**change in structural integrity**

- possibly larger deflection due to mechanical loading

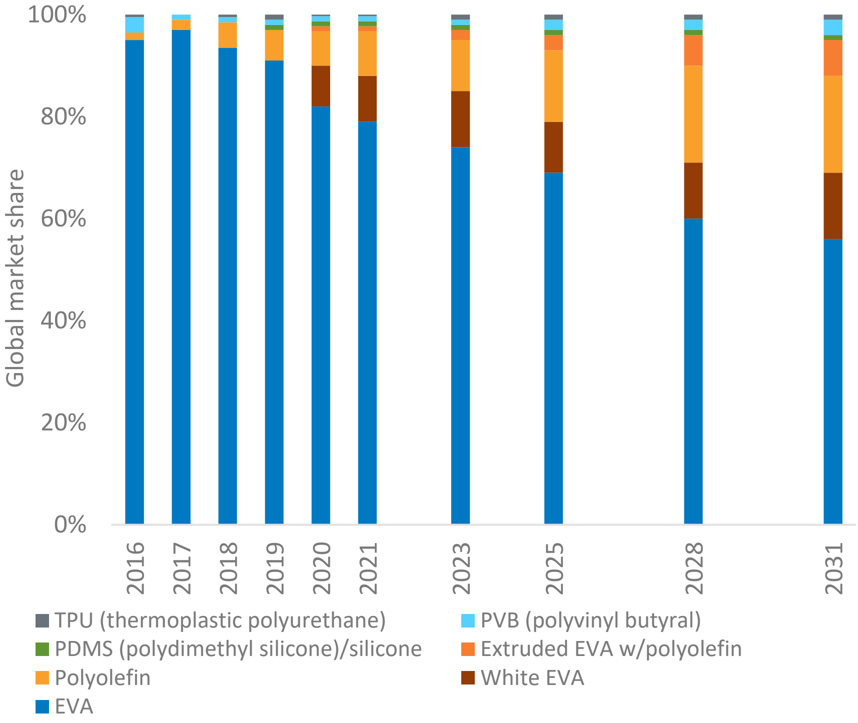
**lower resistance to environmental factors and handling**

- decreased resistance to severe weather events (hail, wind, snow), and handling during installation

**change in heat treatment**

- thinner glass can require a process change from tempering to heat-strengthening, which can increase the risk of glass breakage

# Polyolefin encapsulant




Author synthesis of ITRPV (2017–2021)

## Drivers & Benefits

**reduces acetic acid corrosion (compared to EVA)**

- but polyolefin encapsulant is ~10% more expensive than EVA and has ~0.25% lower transmission

**reduces risk of rear-side PID**

- especially relevant for glass-glass type constructions

## Potential Risks

**cost-reduction methods introduce new manufacturing processes**

- different encapsulant types at the front and back of the cell might introduce new, unknown failure modes
- co-extruded encapsulants – possible difficulties in controlling the thickness and uniformity of thin polyolefin layers

**process changes necessary**

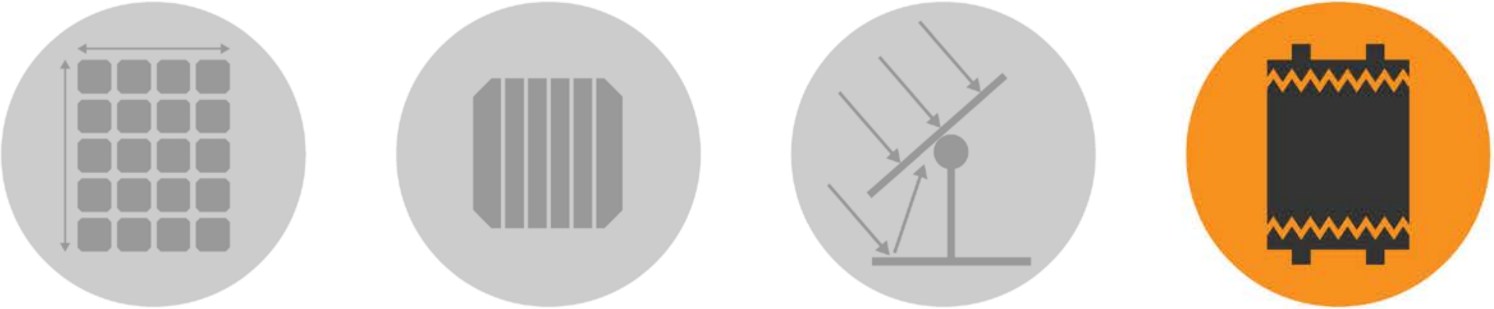
- possible longer manufacturing times and narrower control windows for temperature

**long-term durability unknown**

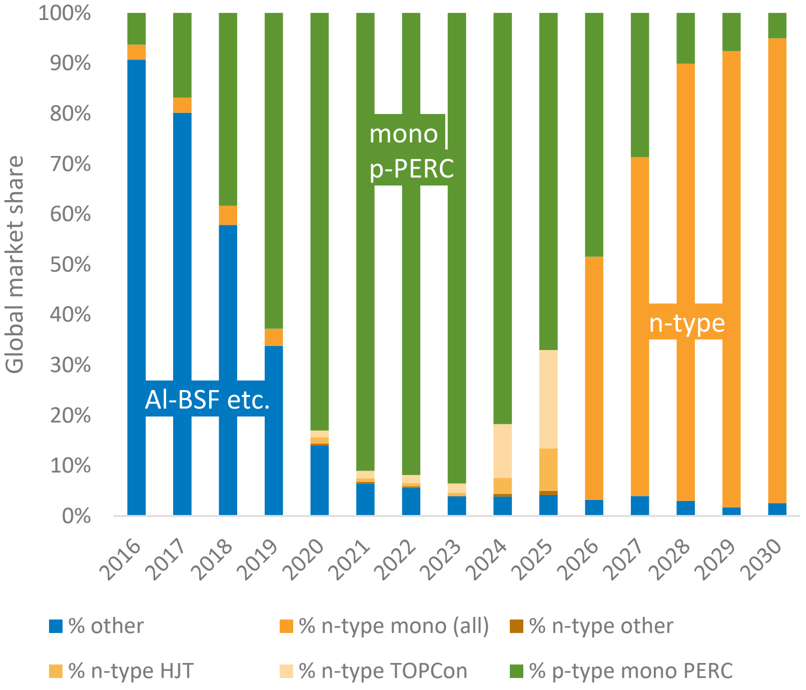
- often 10-20 years of data needed to discover issues

# Cell technology

Large modules | Interconnects | Bifacial | **Cell technology**



# Transition to n-type cells




Author synthesis of data from Stoker (2021c) and InfoLink (2022)

## Drivers & Benefits

**increased efficiency**

- higher charge carrier lifetime
- improved temperature coefficient
- less sensitive to metallic impurities of the silicon

**reduced light-induced degradation (LID)**

- boron-oxygen defect disappears when using n-type doping with phosphorous

**reduced light and elevated temperature-induced degradation (LeTID)**

- possibly due to reduced hydrogen content in n-type cells and/or other factors

## Potential Risks

**complexity & purity multiply cell sensitivities**

- vulnerabilities include diffusion of impurities into bulk wafer, UV-LID, and degradation of ultrathin layers
- may need specific stress combinations and long test cycles

**potentially different PID polarization**

- cell architectures (e.g., TOPCon, PERT, PERC) show different PID trends

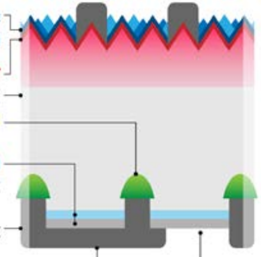
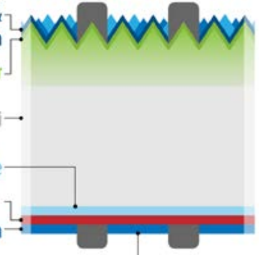
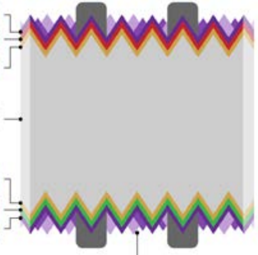
**potentially lower reliability from new n-type cell market entrants**

- extended cell reliability testing might not be in place yet
- packaging optimization still ongoing

**higher silver content in contacts increases costs**

- copper (as a silver replacement) could introduce new reliability issues

# Cell technologies

| p-type | transition to n-type | |
|---|---|---|
| **PERC** (Passivated Emitter and Rear Cell) | **TOPCon** (Tunnel Oxide Passivating Contact) | **SHJ** ( Silicon hetero-junction solar cell) |
|   |   |   |
| **Drivers & Benefits** | | |
| • supply chain is aligned with the technology<br>• industry transitioned from boron to gallium doping to mitigate boron-oxygen LID | • physical separation of rear metal from bulk Si reduces surface recombination and improves carrier lifetime and cell voltage (720 mV)<br>• inherently bifacial | • superior surface passivation quality improves carrier lifetime and increases cell voltage even further (750 mV)<br>• inherently bifacial and very high bifaciality |
| **Potential Risks & Challenges** | | |
| • current production cells close to practical efficiency limits - further improvements difficult<br>• bifaciality is lower compared to TOPCon/SHJ | • newer technology than SHJ - less production history, but fundamentally compatible with the conventional Si solar cell process | • after deposition, process temperature limited to <200°C, impacts metallization and interconnect technologies<br>• substantially different manufacturing process<br>• higher tool costs |

# Case study: recent **700 W** SHJ module announcement

PVTECH

EDITORS' BLOG, FEATURES

## Thinner cells, more busbars and gigawatt manufacturing capacity: Inside Risen's heterojunction plans

Xiao (2022)


(Photo from Risen Energy Group, with permission)

| Power output | 700 W |
|---|---|
| Module size | ≈1.3 m x 2.35 m ≈ 3.0 m$^2$ |
| Cell size | 210 mm / half-cut |
| Cell thickness | 120 µm |
| Module efficiency | 22.52% |
| Metallization | low temperature, low silver |
| Interconnect type | multiwire |
| Interconnect # | 24 |
| Cell technology | n-type SHJ<br>a-Si film replaced with microcrystalline Si |
| Cell efficiency | 25.2% |
| $V_{OC}$ | 750 mV |
| Cell | SHJ inherently high bifaciality |
| Module | bifacial |

# Next steps

- Synthesize feedback from reviewers and webinar audience
- Prioritize trends and risk areas by potential impact
- Identify key knowledge gaps and potential new research needed to fill those gaps
- Finalize the report and distribute for peer review

- Update annually, starting in 2023

# Additional trends

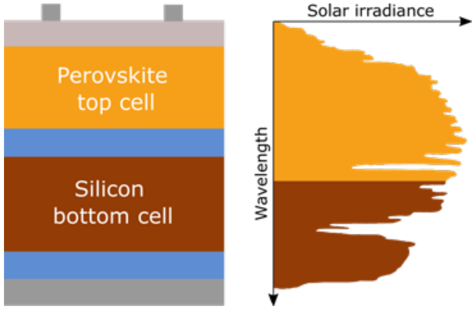
## Building-integrated PV

(Photo by Dennis Schroeder / NREL)

## Agrivoltaics

(Photo by Werner Slocum / NREL)

## Tandems




## Floatovoltaics

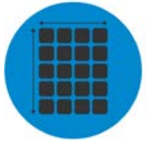
(Photo by Dennis Schroeder / NREL)

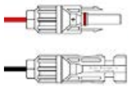
## Trackers

(Photo by Werner Slocum / NREL)

## Standardization

*module size* *cell size* *connectors*





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# Thank you!

## Contacts

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