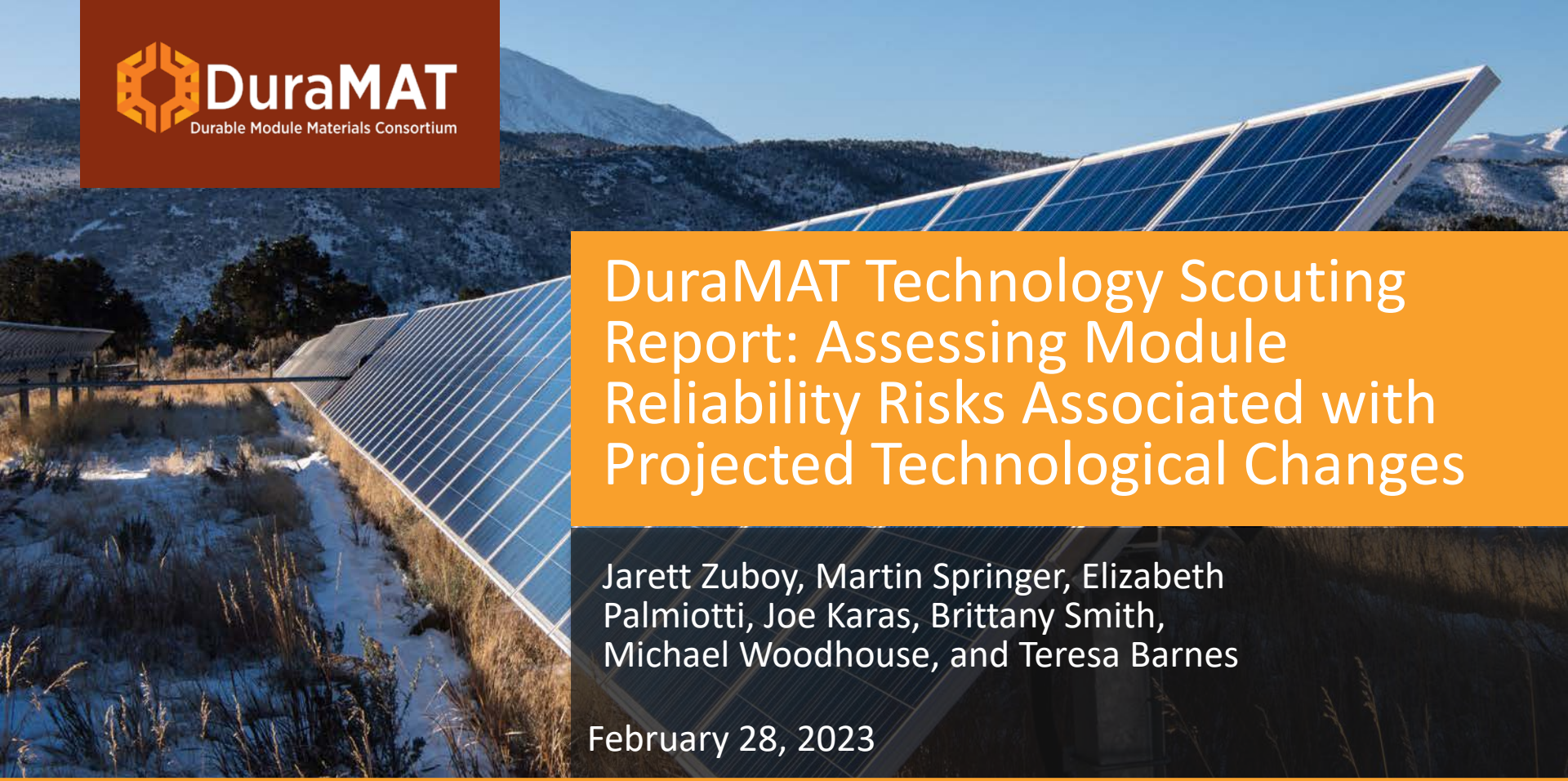

DuraMAT
Durable Module Materials Consortium

DuraMAT Technology Scouting Report: Assessing Module Reliability Risks Associated with Projected Technological Changes

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

February 28, 2023

U.S. DEPARTMENT OF ENERGY
DuraMAT
NREL
Sandia National Laboratories
BERKELEY LAB

Thank you

- Nick Bosco (NREL)
- Peter Hacke (NREL)
- Mike Kempe (NREL)
- David Miller (NREL)
- Ingrid Repins (NREL)
- DuraMAT Industry Advisory Board
- The DuraMAT community
- David Feldman (NREL)
- April Jeffries (STS)
- Dirk Jordan (NREL)
- Heather Mirletz (NREL, CSM)
- Silvana Ovaitt (NREL)
- Michael Owen-Bellini (NREL)
- Laura Schelhas (NREL)
- Tim Silverman (NREL)
- VDMA
- Al Hicks (NREL)
- Harrison Dreves (NREL)

Thank you

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy under Contract No. DE-AC36-08GO28308. Funding was provided as part of the Durable Module Materials Consortium 2 (DuraMAT 2) funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office, agreement number 38259.

And thank YOU!

- What are the biggest challenges to module reliability over the next several years?
- **Please answer via slido.com**

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What are the biggest challenges to module reliability over the next several years?

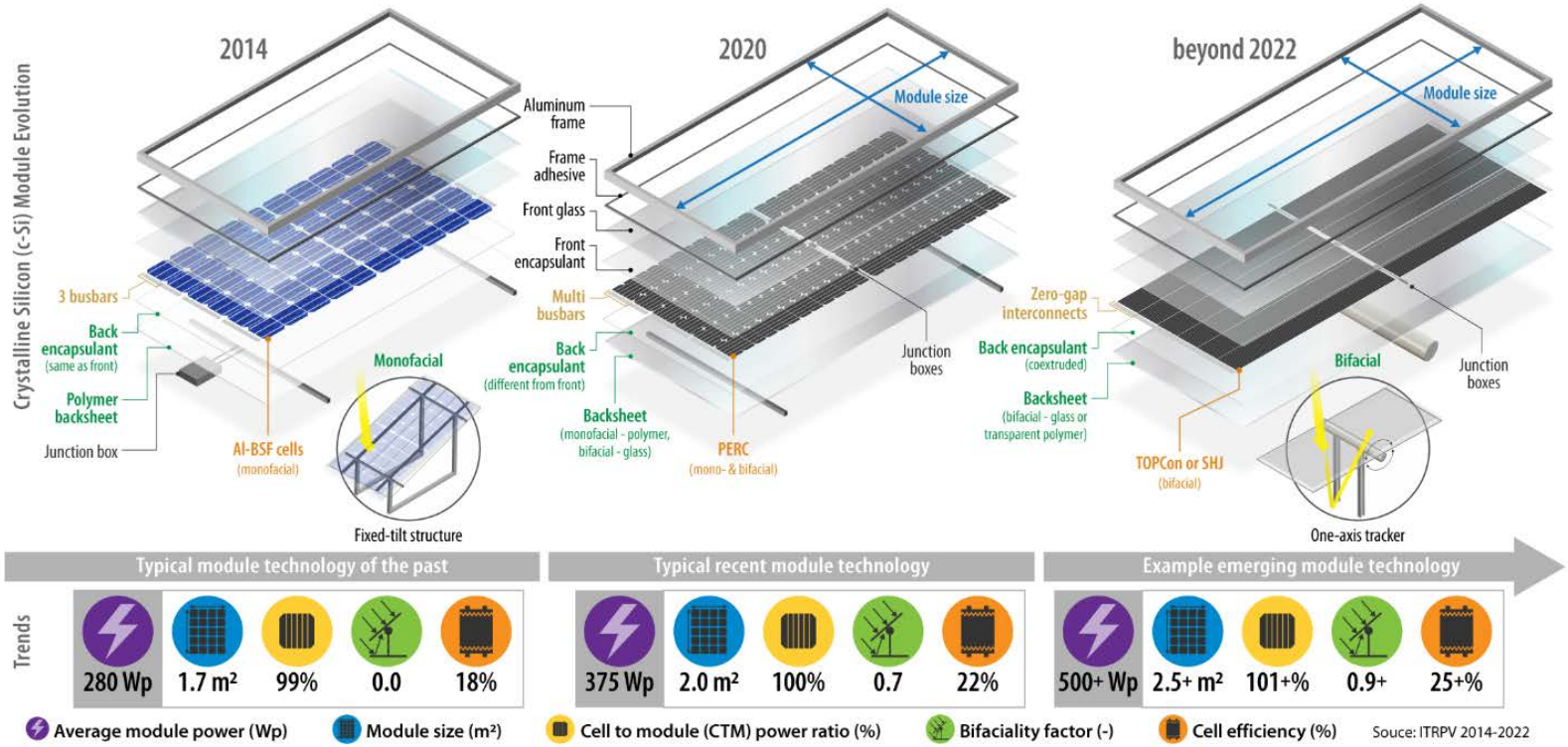
ⓘ Start presenting to display the poll results on this slide.

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

Crystalline-silicon PV module technology changes



Impacts of the Inflation Reduction Act

- Which module technologies may proliferate in the U.S. as domestic manufacturing increases under the IRA?
- **Please answer via slido.com**

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Which module technologies may proliferate in the U.S. as domestic manufacturing increases under the IRA?

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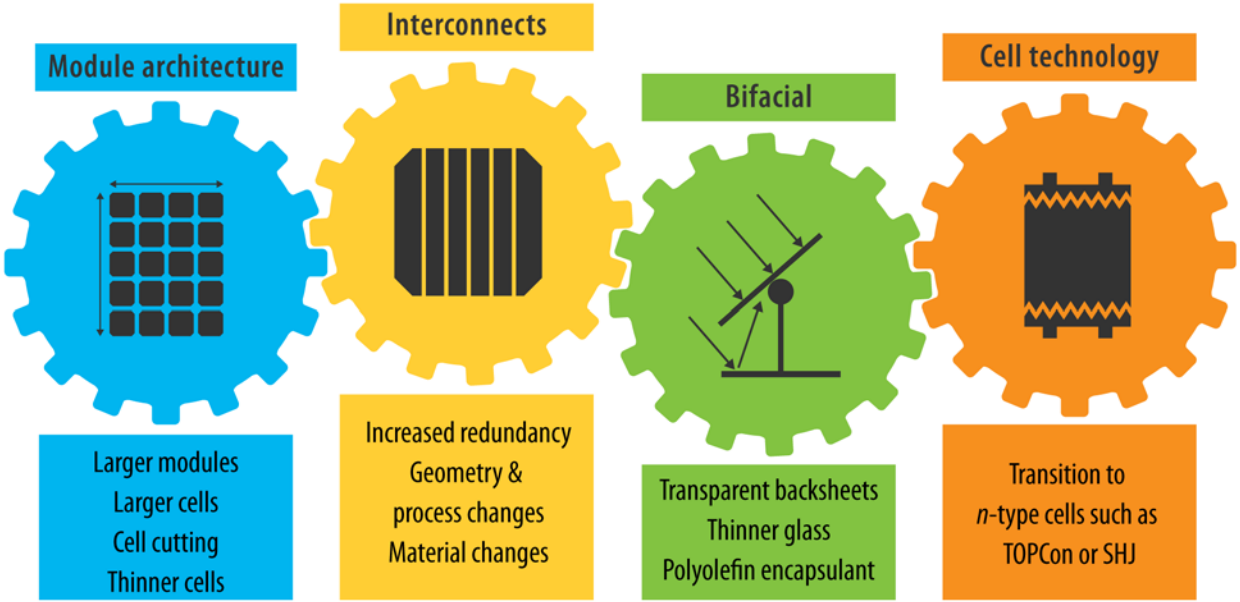
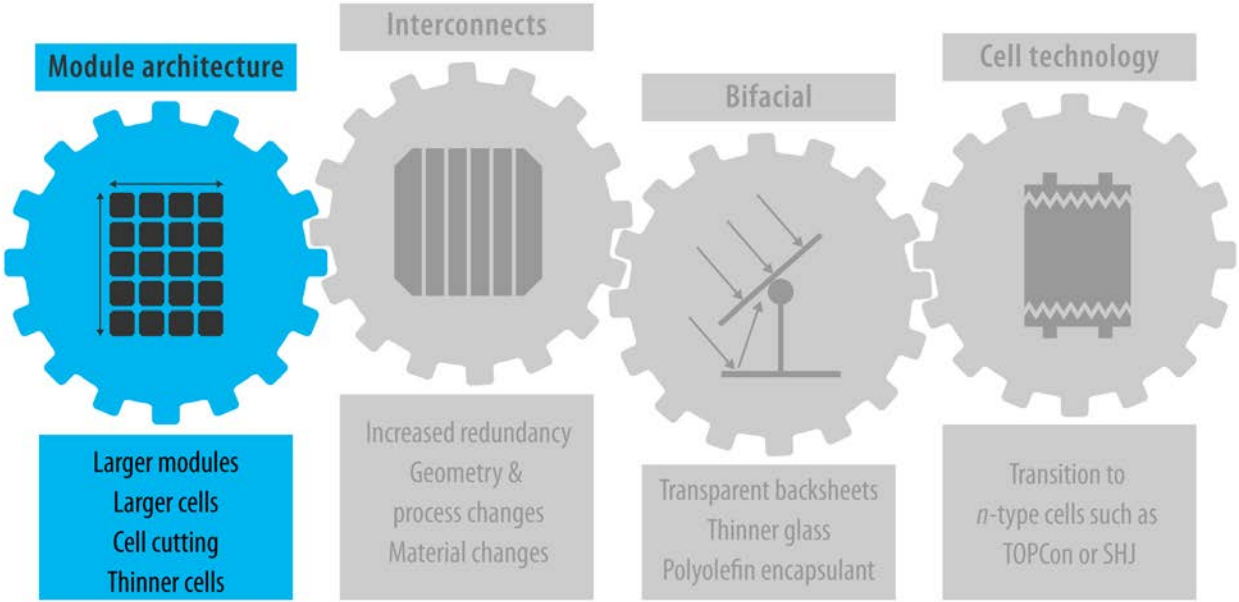
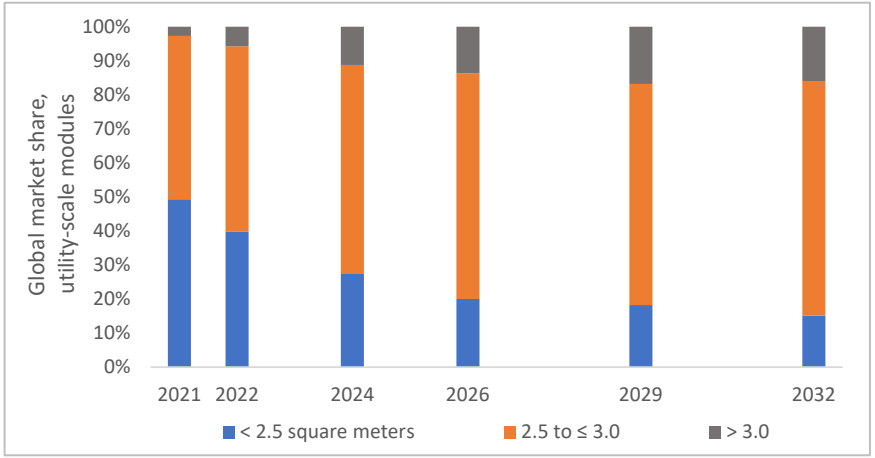
Categories of technology change



Module architecture



Larger modules



Historical (2021) and projected (2022–2032) ITRPV data on utility-scale module size

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

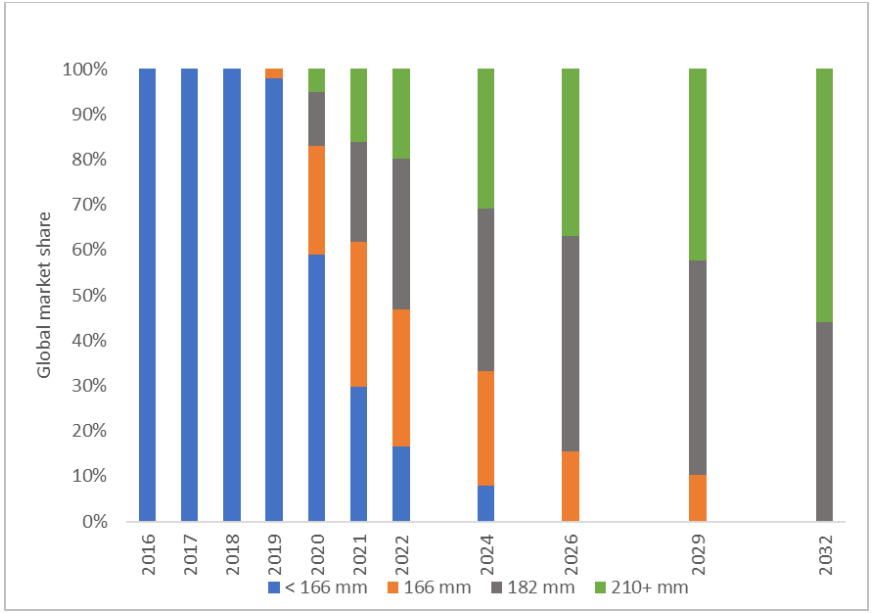
potentially more frequent cell breakage due to
- weather (wind & hail), or shipping, handling, and installation

increased weight
- Occupational Safety and Health Administration (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 BOS (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

Larger cells



Historical (2016–2021) and projected (2022–2032) ITRPV data on Czochralski monocrystalline wafer size in mass production

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

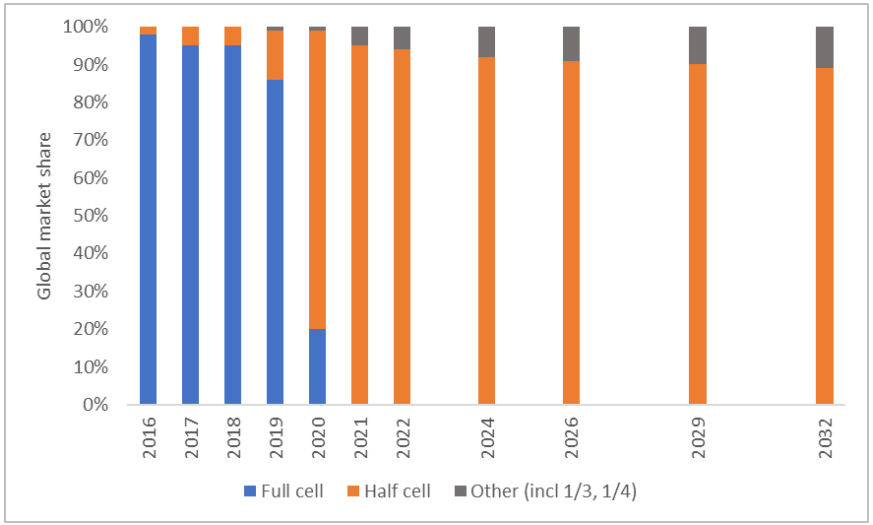
Potential Risks

introduction of additional process steps
- cell cutting (see next slide) can increase reliability risks

handling of larger wafers and cells is more complex
- increased fracture risk

Cell cutting

N. Bosco. "Turn Your Half-Cut Cells for a Stronger Module," *IEEE Journal of Photovoltaics* (2022)



Historical (2016–2021) and projected (2022–2032) ITRPV data on cell aspect ratios. The values for 2021–2032 are for wafer sizes of at least 182 mm × 182 mm. In earlier years, the assumed wafer sizes are smaller or unspecified.

Drivers & Benefits

reduces resistive losses
- by lowering electric current

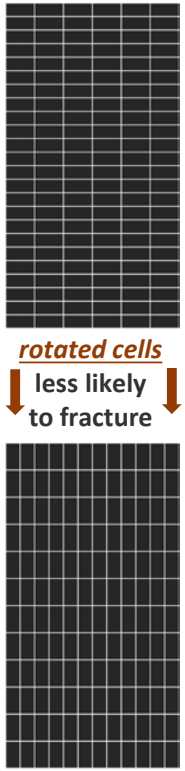
potentially higher shade tolerance
- through changed junction box position & wiring pattern

Potential Risks

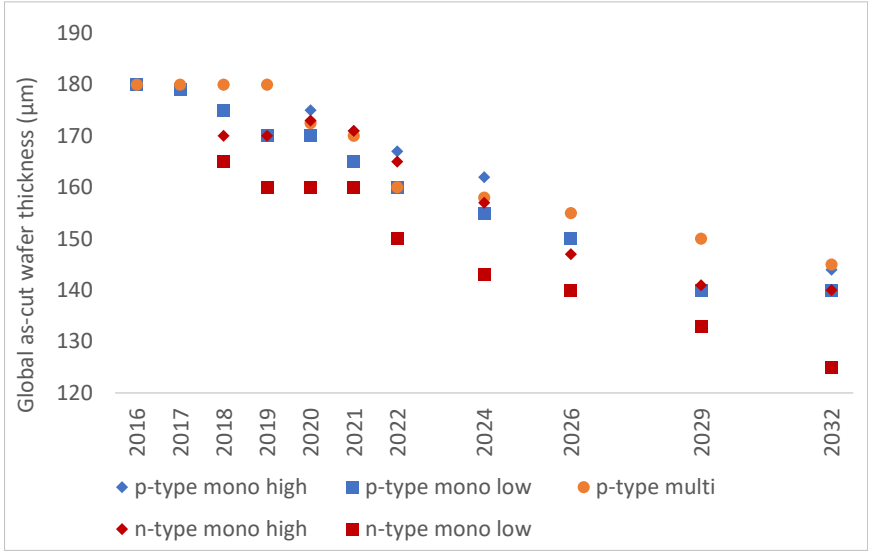
potentially increased cell fracture risk through edge-defects
- dependent on cell cutting technologies and process control

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



Historical (2016–2021) and projected (2022–2032) ITRPV data on global as-cut wafer thickness

Drivers & Benefits

reduced material input
- cost savings

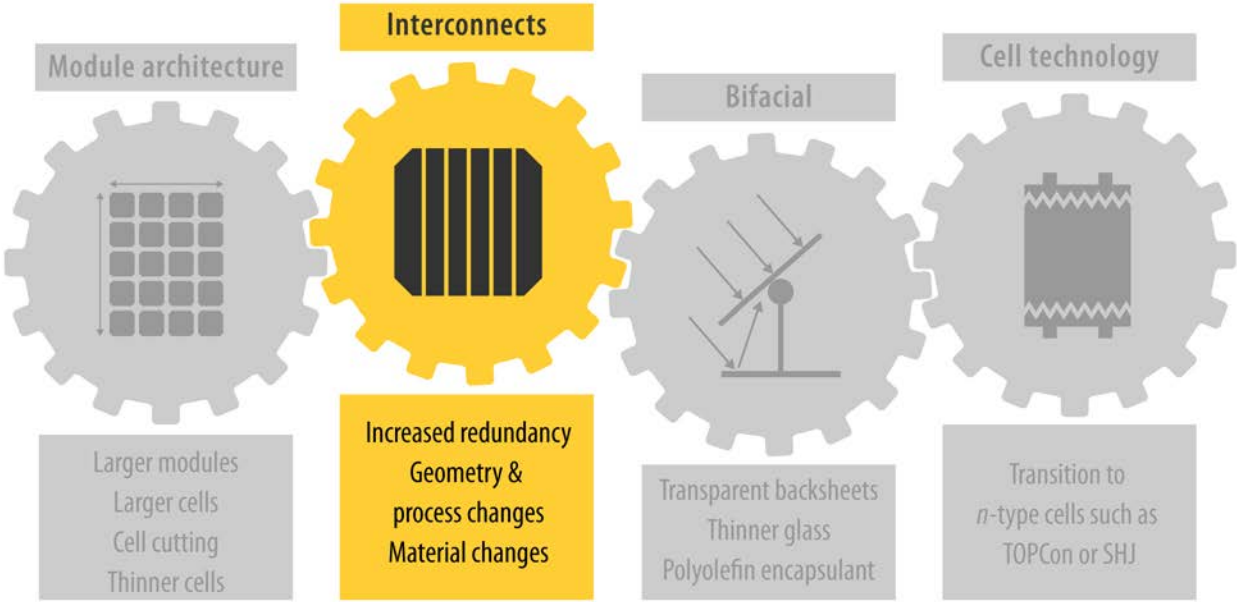
new advanced cell technologies
- thinner wafers have higher efficiency potential when paired with n-type technologies such as SHJ and TOPCon

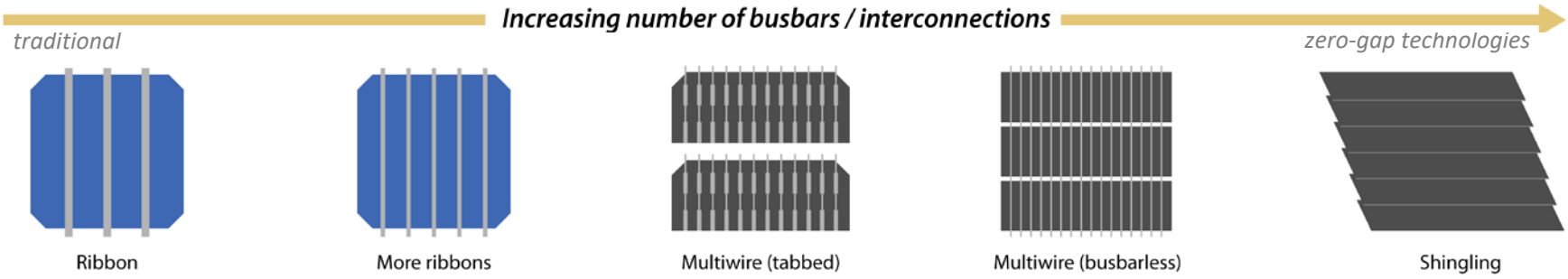
Potential Risks

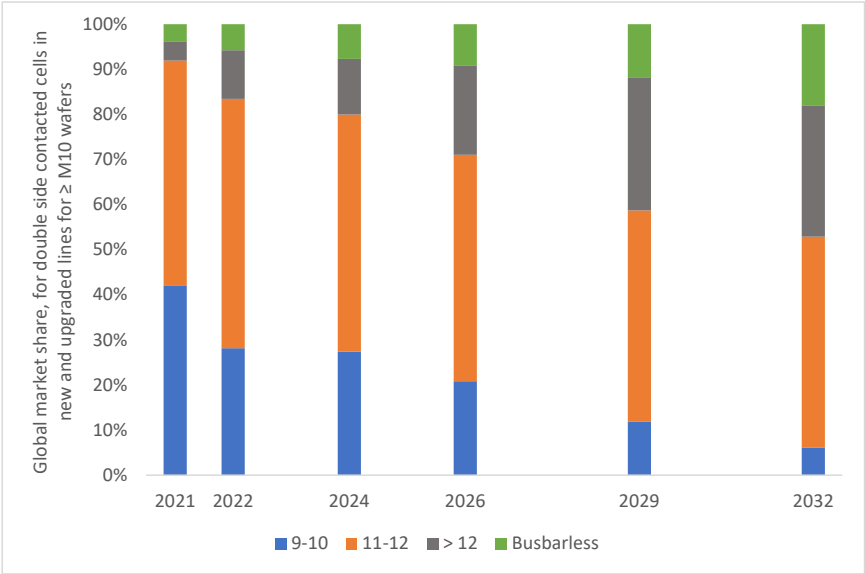
potentially reduced cell yield on production line
- handling of thin cells is complex and can break before lamination
- new manufacturing processes need to be adopted

cell cracking risk after lamination may not be 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

Interconnects







Historical (2021) and projected (2022–2032) ITRPV data on market shares by number of busbars, for double side contacted cells in new and upgraded lines, and for wafers of M10 size (182 mm × 182 mm) and larger

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)

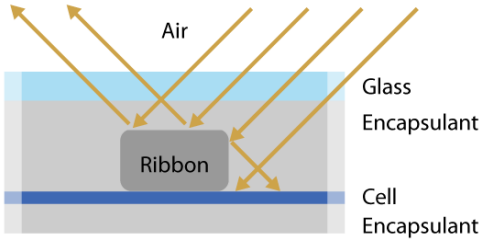
improved redundancy and reliability
- higher likelihood of fractured cell fragments staying electrically connected
- minimizes localized mechanical stresses around busbars

Potential Risks

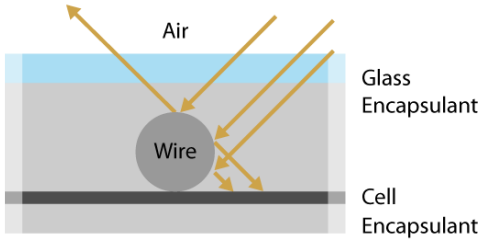
introduction of new manufacturing processes and materials
- geometry change from rectangular ribbons to wires
- material change from metallurgical connections to mechanical contact

Geometry and process changes

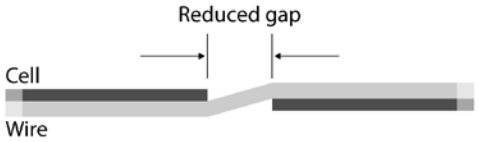
traditional → zero-gap technologies

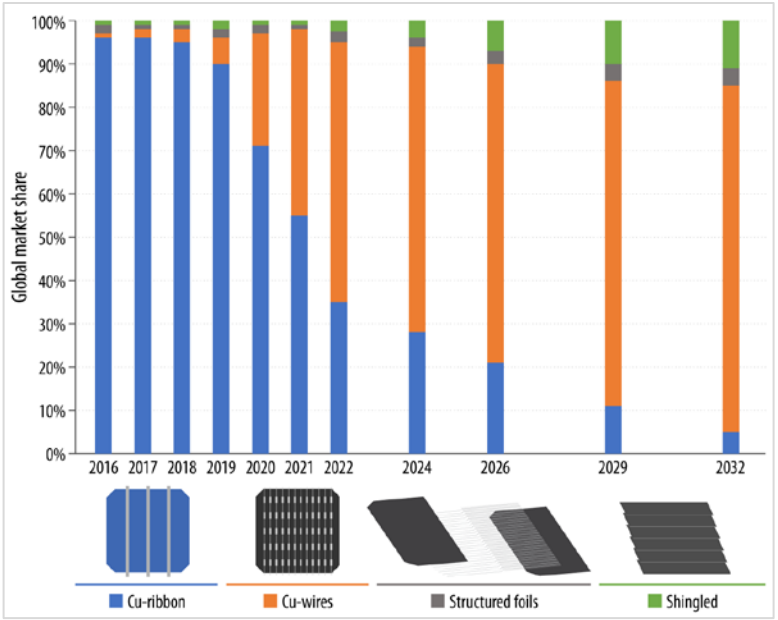


Flat ribbon



Round wire





Historical (2016–2021) and projected (2022–2032) ITRPV data on shares of interconnect technologies

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 such as SHJ

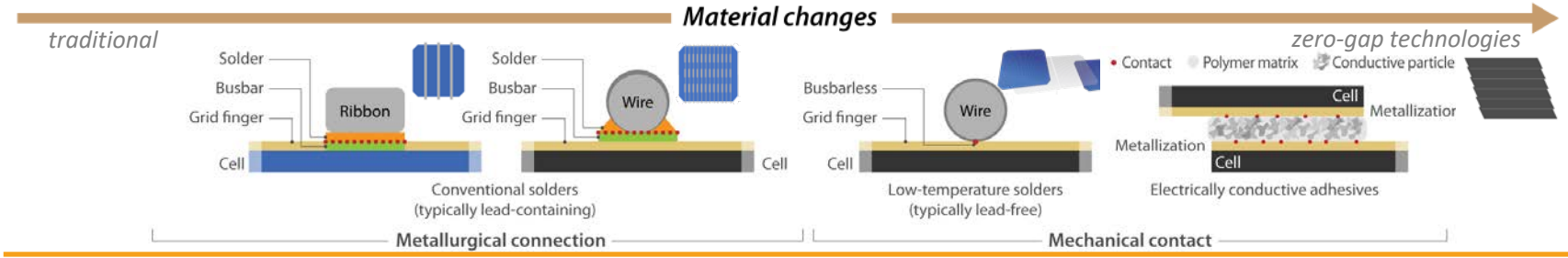
increased efficiency
- increase active cell area and light reflection on wire
- reduced gap between cells or overlapping cells

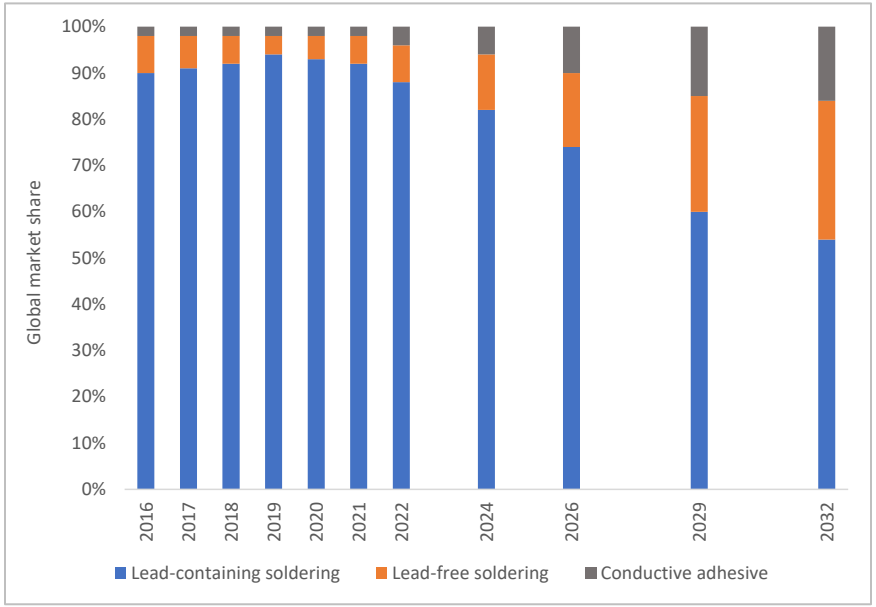
Potential Risks

geometry changes
- multiwire might need thicker encapsulant

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

shingled/overlapping cells
- changes in packaging and structure while introducing new materials





Historical (2016–2021) and projected (2022–2032) ITRPV data on shares of interconnect materials

Drivers & Benefits

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

cost savings potential
- reduction of silver content

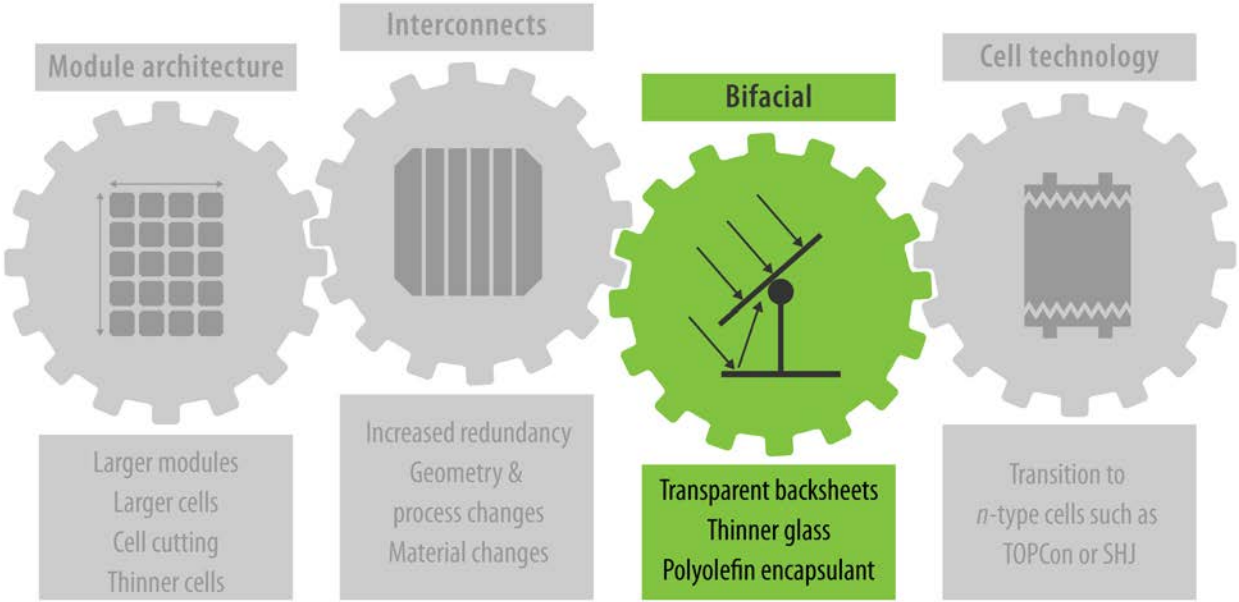
reduce processing temperatures and material input
- required for new cell technologies such as SHJ
- reduce thermal stresses
- elimination of processing steps such as soldering at high temperature

Potential Risks

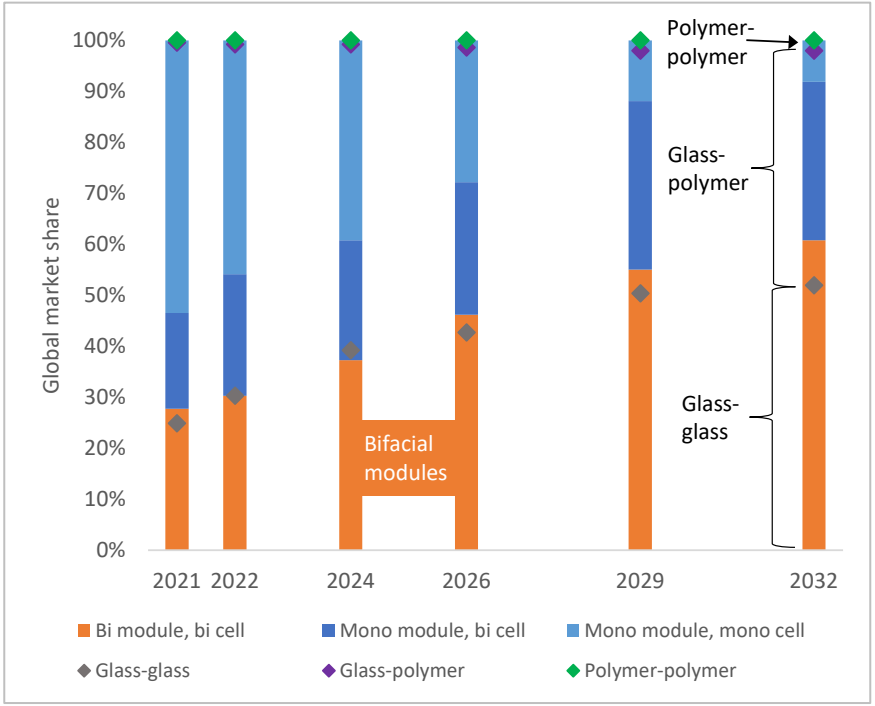
change in solder materials (high vs. low temp & lead-containing vs. lead-free)
- potential degradation from poorer mechanical characteristics
- change from metallurgical connection to mechanical contact will require new accelerated tests and development of standards

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

Bifacial modules



Bifacial modules



Historical (2021) and projected (2022–2032) ITRPV data on bifacial and monofacial module, cell, and frontsheet-backsheet market shares

Drivers & Benefits

enabled by new(er) cell technologies

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

Potential Risks

corrosion

- acetic acid formation from ethylene-vinyl acetate (EVA) encapsulant

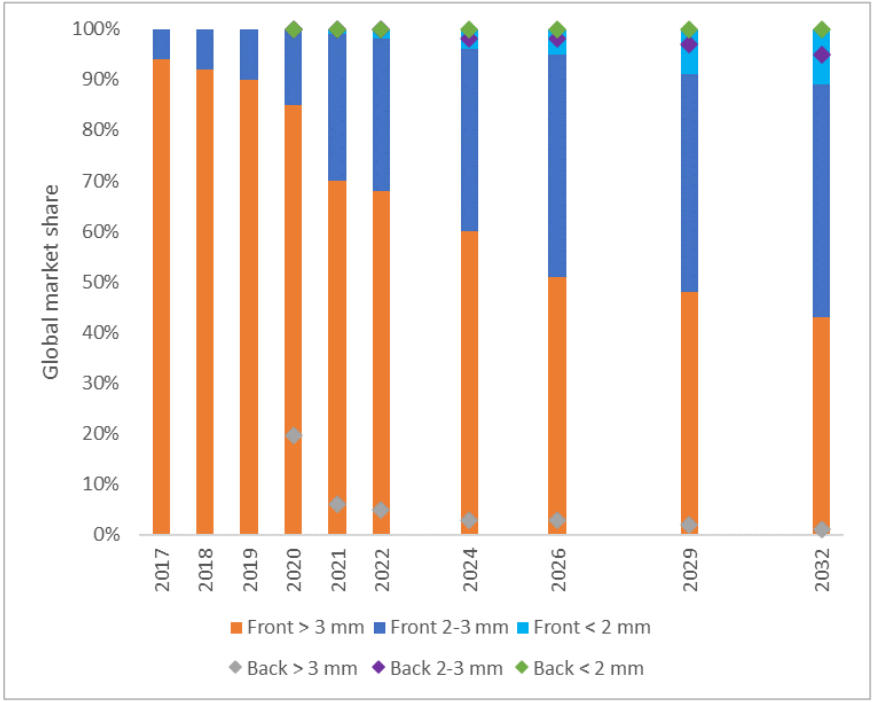
cell fracture risk

- 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 silicon below the passivating layers

Thinner glass



Historical (2017–2021) and projected (2022–2032) ITRPV data on module front and back glass thickness

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

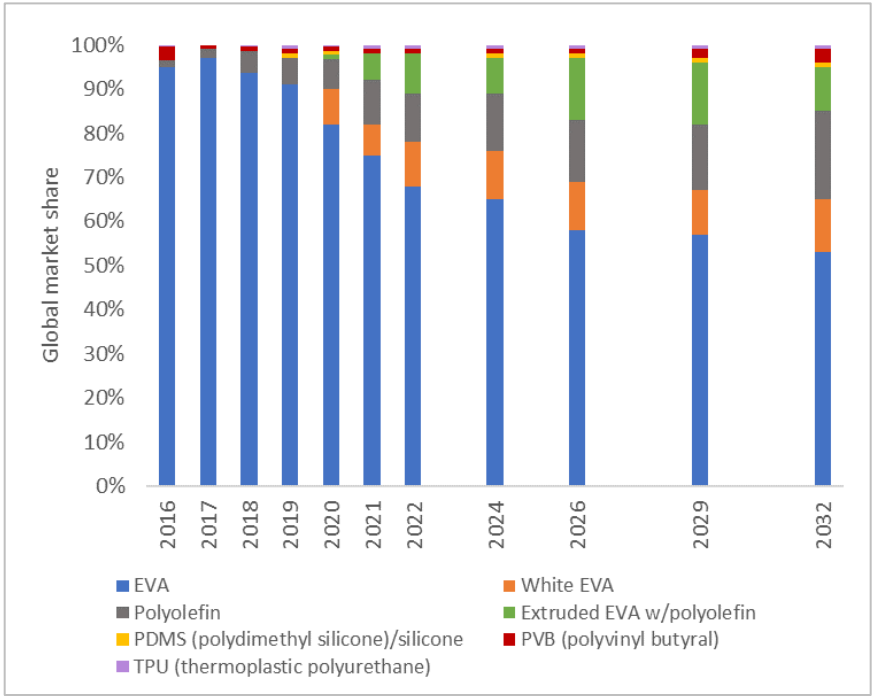
Potential Risks

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-based encapsulants



Historical (2021) and projected (2022–2032) ITRPV data on encapsulant material market shares

Drivers & Benefits

reduces acetic acid corrosion (compared to EVA)
- but polyolefin-based encapsulants has higher cost and lower light transmission compared to EVA-based encapsulants

reduces risk of rear-side PID
- especially relevant for glass-glass type constructions

Potential Risks

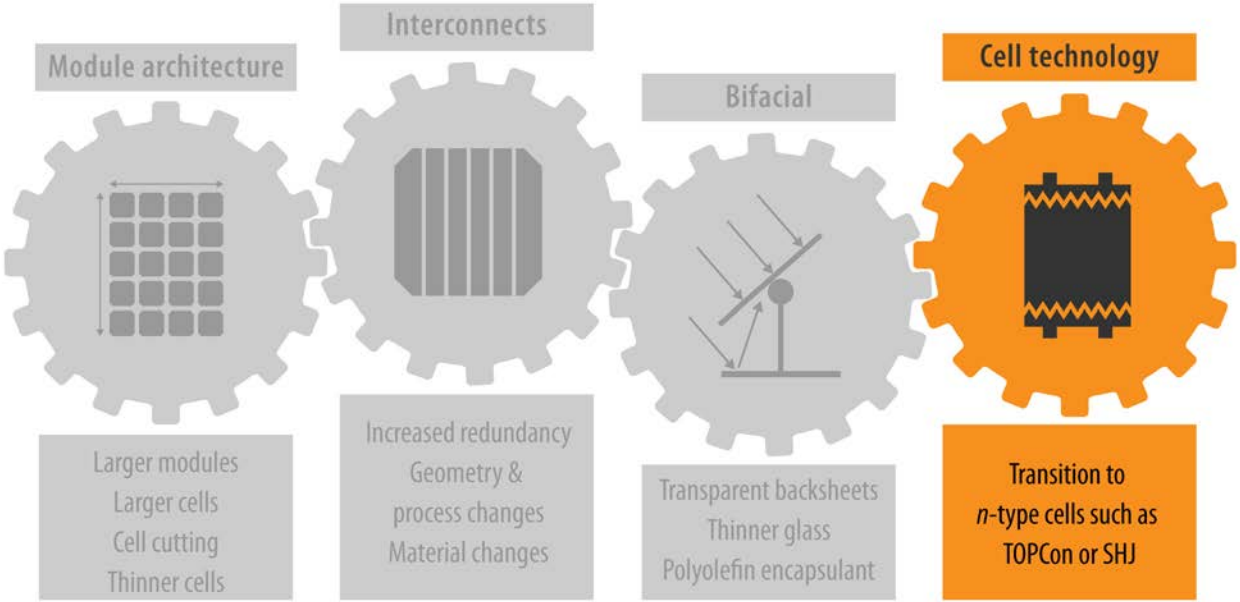
incompatibility with bills of materials optimized for EVA
- may affect adhesion of the encapsulant to other components

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 – knowledge of long-term reliability limited by lack of accelerated and field testing and lack of known products

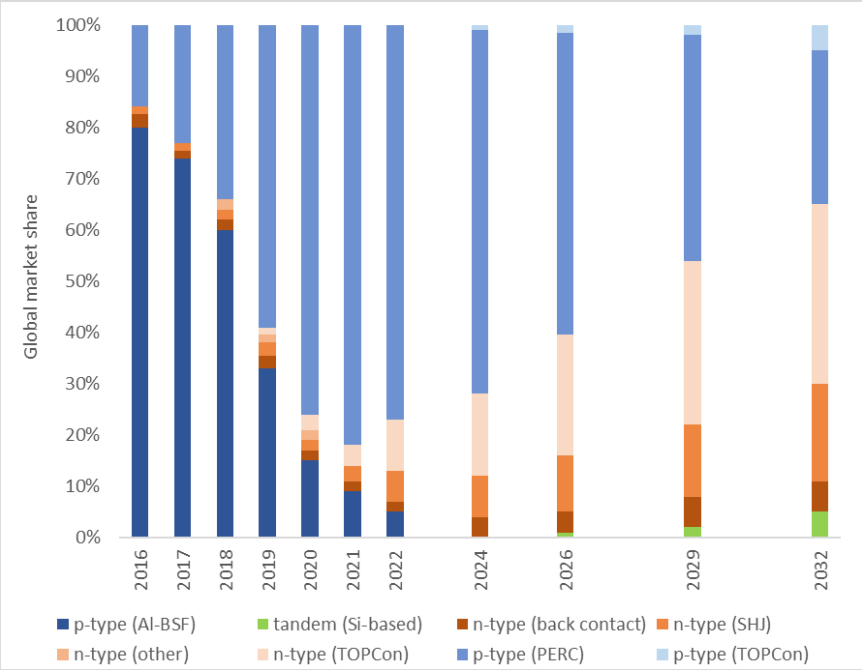
process changes necessary
- possible longer manufacturing times and narrower control windows for temperature

long-term durability unknown
- often 10-20 years of data needed to discover issues

Cell technology



Transition to n-type cells



Historical (2016–2021) and projected (2022–2032) ITRPV data on cell technologies (ITRPV cell categories reclassified by authors to highlight key trends)

Drivers & Benefits

increased efficiency and power
- higher charge carrier lifetime
- higher bifaciality factors

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, ultraviolet light-induced degradation (UV-LID), and degradation of ultrathin layers
- may need specific stress combinations and long test cycles

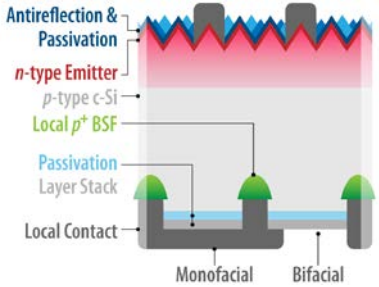
potentially different PID polarization
- cell architectures (e.g., TOPCon, PERT, PERC) show different PID trends

higher silver content in contacts increases costs
- copper (as a silver replacement) could introduce new reliability issues

Cell technologies

p-type

PERC (Passivated Emitter and Rear Cell)



Drivers & Benefits

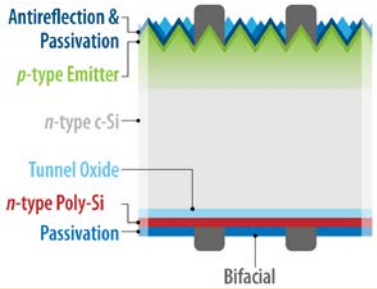
- supply chain is aligned with the technology
- industry transitioned from boron to gallium doping to mitigate BO-LID

Potential Risks & Challenges

- current production cells close to practical efficiency limits - further improvements difficult
- bifaciality is lower compared to TOPCon/SHJ

transition to n-type

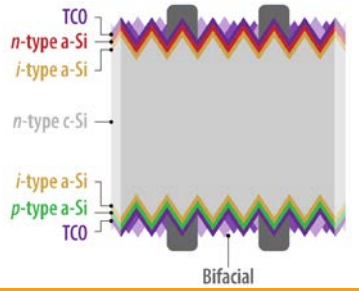
TOPCon (Tunnel Oxide Passivating Contact)



- physical separation of rear metal from bulk Si reduces surface recombination and improves carrier lifetime and cell voltage (720 mV)
- inherently bifacial

- newer technology than SHJ - less production history, but fundamentally compatible with the conventional Si solar cell process

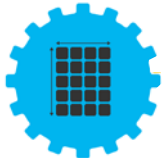
SHJ (Silicon Hetero-Junction)



- superior surface passivation quality improves carrier lifetime and increases cell voltage even further (750 mV)
- inherently bifacial and very high bifaciality

- after deposition, process temperature limited to <200°C, impacts metallization and interconnect technologies
- substantially different manufacturing process
- higher tool costs

Recommendations



Module architecture

- Characterize the reliability implications of larger and thinner cells in conjunction with variations in module design, including interconnect type and thinner glass
- Research and develop tests for assessing the effect of larger modules on cell cracking due to weather, shipping, handling, and installation
- Understand multi-step relationships between defects/cracks and long-term module degradation causing potential power loss

Interconnections

- Research potential new degradation mechanisms associated with conductive adhesives, such as debonding and corrosion of non-silver conductive particles
- Develop accelerated tests and standards to address the change from metallurgical to mechanical contacts

Recommendations

Bifacial

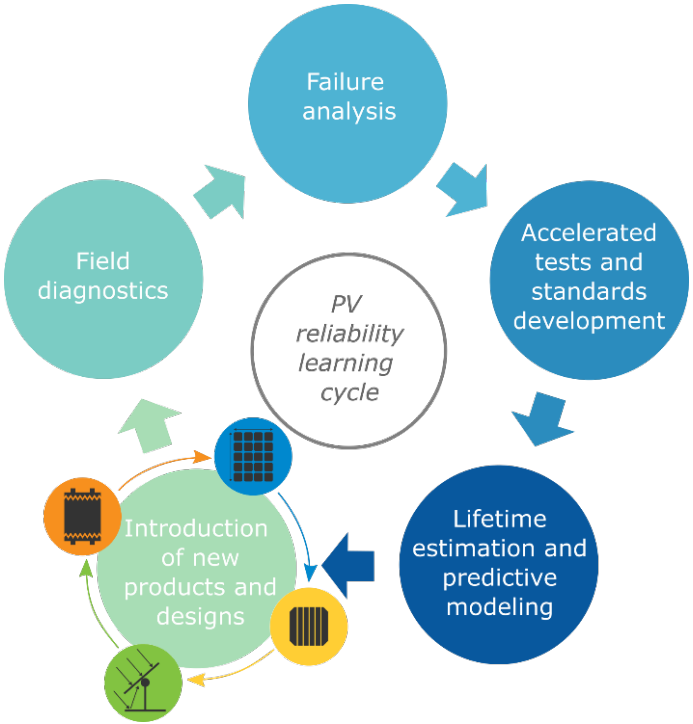
- Assess whether current PID testing optimized for monofacial modules should be modified for bifacial modules
- Develop accelerated and field testing to assess the long-term reliability of mixed and co-extruded encapsulants as well as transparent polymer backsheets
- Modify hail testing to account for thinner glass and more hail-prone PV system locations

Cell technology

- Develop specific stress combinations and sequences for testing the reliability of n-type cells and their ultrathin surface passivation layers
- Develop tests and standards to assess and screen for UV light-induced degradation and PID risk in industrial implementations of bifacial TOPCon and SHJ architectures

Recommendations

- Continue tracking module technologies and reliability implications to accelerate the PV reliability learning cycle
- Incorporate fundamental knowledge into models that can predict module reliability, reduce the time required to assess new designs, and mitigate risks associated with large-scale deployment of new products



The PV reliability learning cycle, enabling continuous improvement to ensure quality despite ongoing technological changes.

What did we miss?

- What important module technology trends and reliability implications did we miss?
- **Please answer via slido.com**

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What important module technology trends and reliability implications did we miss?

ⓘ Start presenting to display the poll results on this slide.

Preprint available … and thank you again!

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Teresa Barnes: Teresa.Barnes@nrel.gov

Sources

- All technology trend-over-time graphs are from ITRPV. *International Technology Roadmap for Photovoltaic (ITRPV), 7th – 13th Editions*. Frankfurt Am Main: VDMA; 2016 – 2022.
- Technical diagrams were created by the authors.
- For the full list of sources used to develop this presentation, see J. Zuboy, M. Springer, E. Palmiotti, J. Karas, B. Smith, M. Woodhouse, and T. Barnes. *Getting Ahead of the Curve: Assessment of New Photovoltaic Module Reliability Risks Associated with Projected Technological Changes* (November 3, 2022). Available at SSRN: https://ssrn.com/abstract=4273054 or http://dx.doi.org/10.2139/ssrn.4273054.

NREL/PR-6A20-85232

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided as part of the Durable Module Materials Consortium 2 (DuraMAT 2) funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office, agreement number 38259. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.