DuraMAT
Durable Module Materials Consortium

Growing Panes: Investigating the PV Technology Trends Behind Frequent Early Failures in Modern Glass-Glass Modules

Elizabeth C. Palmiotti[1], Martin Springer[1], Jarett Zuboy[1], Timothy J. Silverman[1], Jennifer L. Braid[2], Dirk C. Jordan[1], Salil Rabade[1], Andy Walker[1], Teresa M. Barnes[1]

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DuraMAT Webinar January 13, 2025

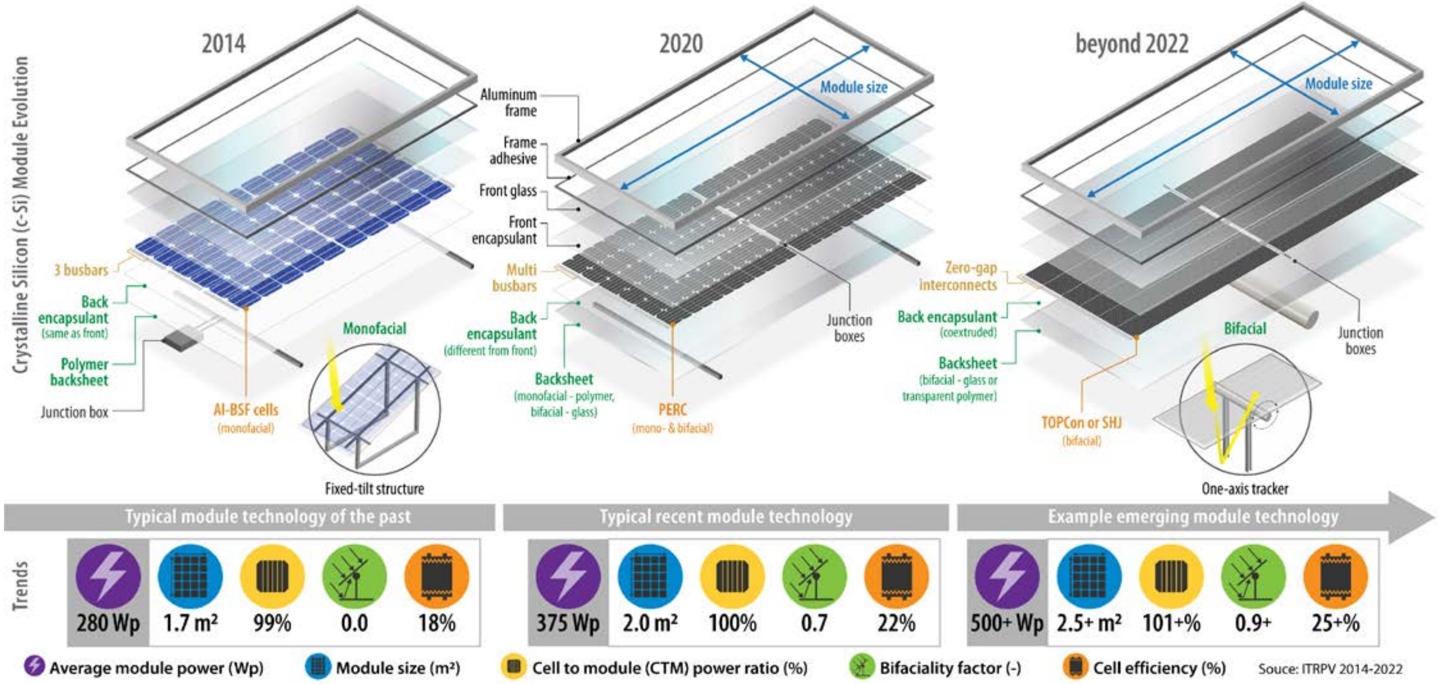
U.S. DEPARTMENT OF ENERGY | NREL | Sandia National Laboratories | BERKELEY LAB

Watching Out for Future Reliability

Technology Scouting Goals

- 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

Tech Scouting 1.0: Mapping the Terrain



Module architecture
- Larger modules
- Larger cells
- Cell cutting
- Thinner cells

Interconnects
- Increased redundancy
- Geometry & process changes
- Material changes

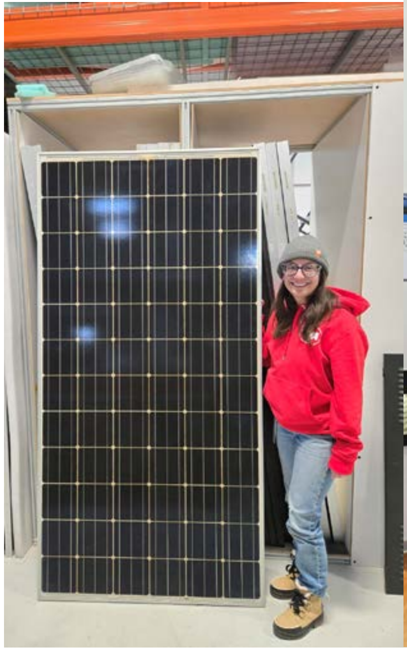
Bifacial modules
- Transparent backsheets
- Thinner glass
- POE encapsulant

Cell technology
- Transition to n-type cells

Interrelated Trends

J. Zuboy, M. Springer, E.C. Palmiotti, J. Karas, B.L. Smith, M. Woodhouse, and T.M. Barnes, "Getting Ahead of the Curve: Assessment of New Photovoltaic Module Reliability Risks Associated with Projected Technological Changes," *IEEE Journal of Photovoltaics*, Jan 2024, DOI: https://doi.org/10.1109/JPHOTOV.2023.3334477

Tech Scouting 1.0: The Big Floppy Module Phenomenon



Crystalline silicon
ca. 2014

Thin film
ca. 2024

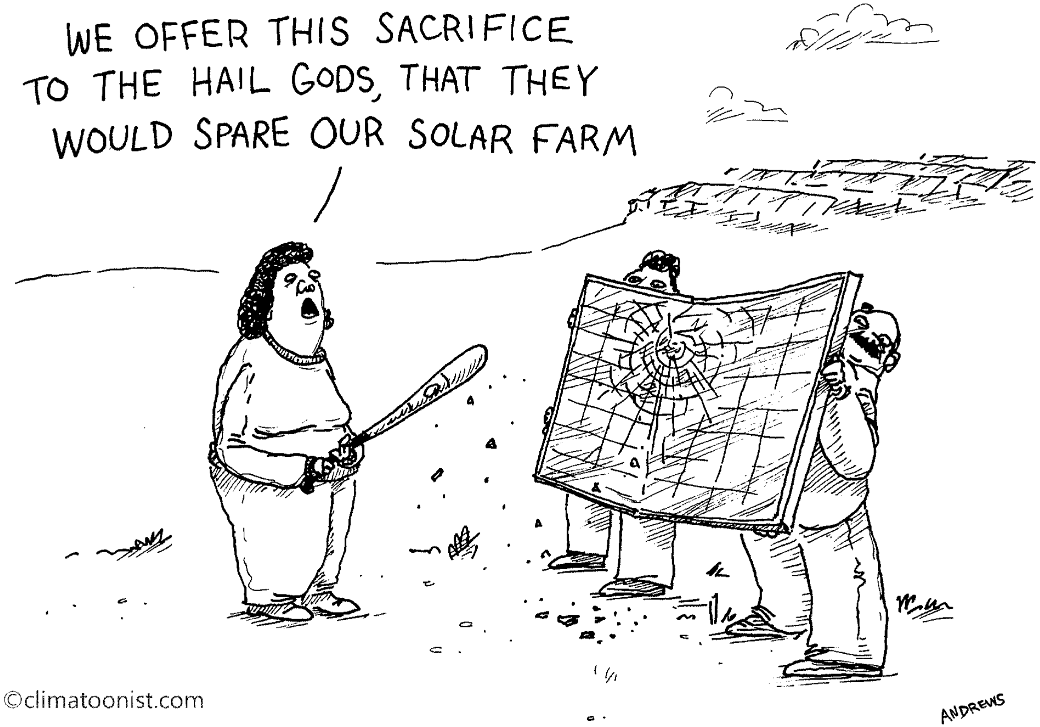
Crystalline silicon
ca. 2024

Photos by Dennice Roberts, NREL

Multiple changes increases the damage risk more than any of the changes alone.

- Larger module area
- Thinner cells
- Thinner glass
- Less-supportive framing
- Less-supportive mounting

Tech Scouting 1.0: The Big Floppy Module Phenomenon



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Cartoon from Wes Andrews, Climatoonist, with permission

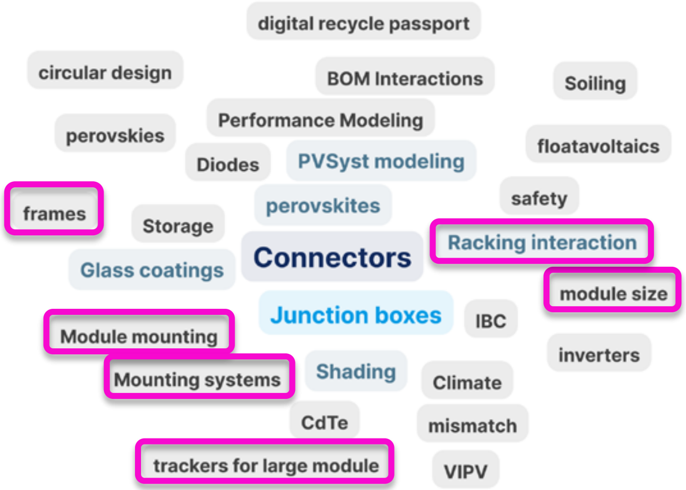
Industry Feedback: Big-Floppiness Matters

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

Wordcloud Poll 165 responses 90 participants

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

Wordcloud Poll 115 responses 74 participants

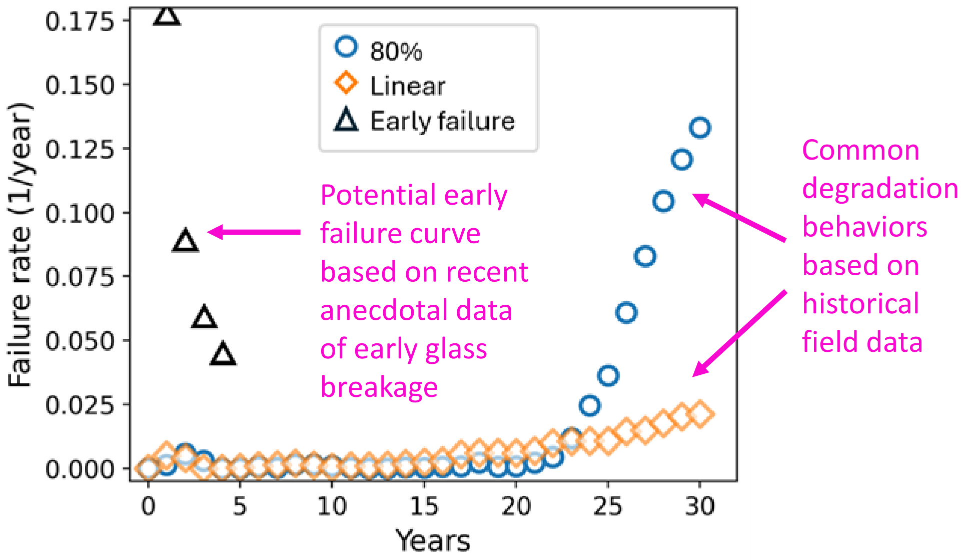


Source: Audience feedback from the NREL PV Reliability Workshop, February 2023. Pink boxes denote responses directly related to big floppy modules. Green boxes denote weather and handling responses that can relate to big floppy modules as well.

Early Glass Breakage on the Rise

Broken module from DuraMAT project “Forecasting glass resilience of large-format PV modules,” PI M. Springer

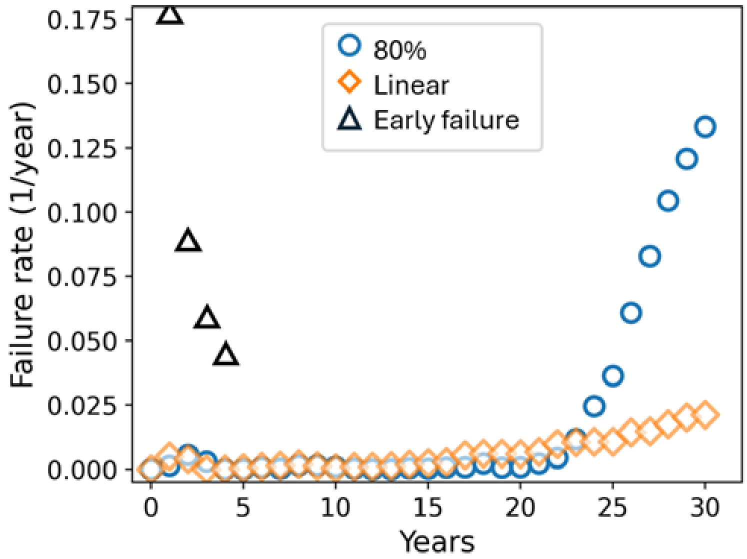
Potential module failure “bathtub curve”



Failure rates as defined by a decrease in power below 80% of the original output (blue circles) and linear degradation greater than 0.8%/year (orange diamonds) compared with increased failure rates during early-life (black triangles). Sources: Springer et al., “Future-proofing photovoltaics module reliability through a unifying predictive modeling framework,” *Prog. Photovolt. Res. Appl.*, 2023, https://doi.org/10.1002/pip.3645; Weber et al., “Glass Breakage: A Growing Phenomenon in Large-scale PV,” PV magazine webinar, Nov. 20, 2023,. www.pv-magazine.com/wp-content/uploads/2023/10/All-presentations-5.pdf.

Potential Cost of Early Breakage: Illustrative Case

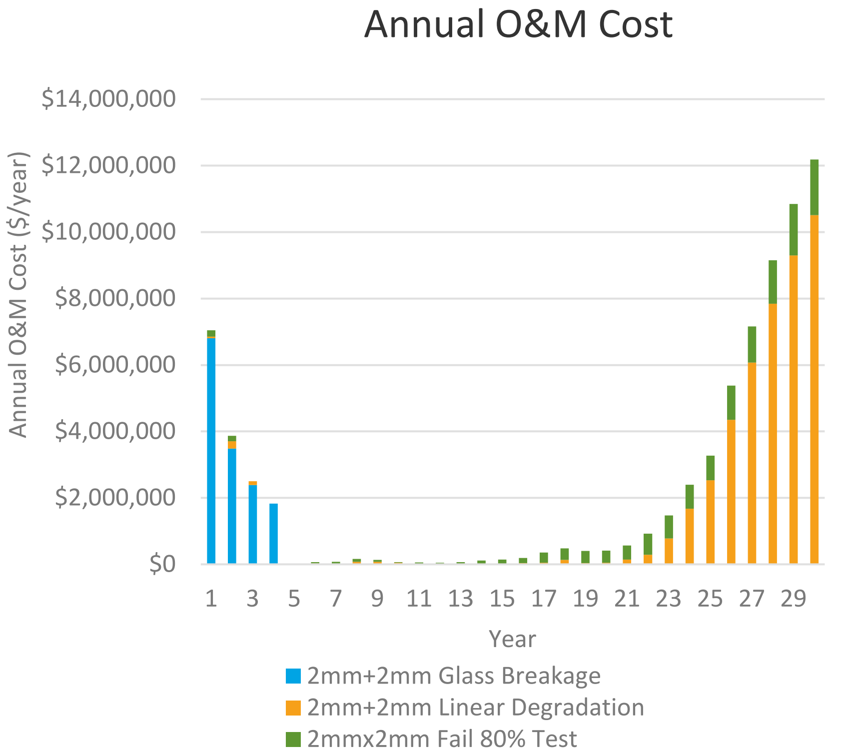
Potential module failure “bathtub curve”

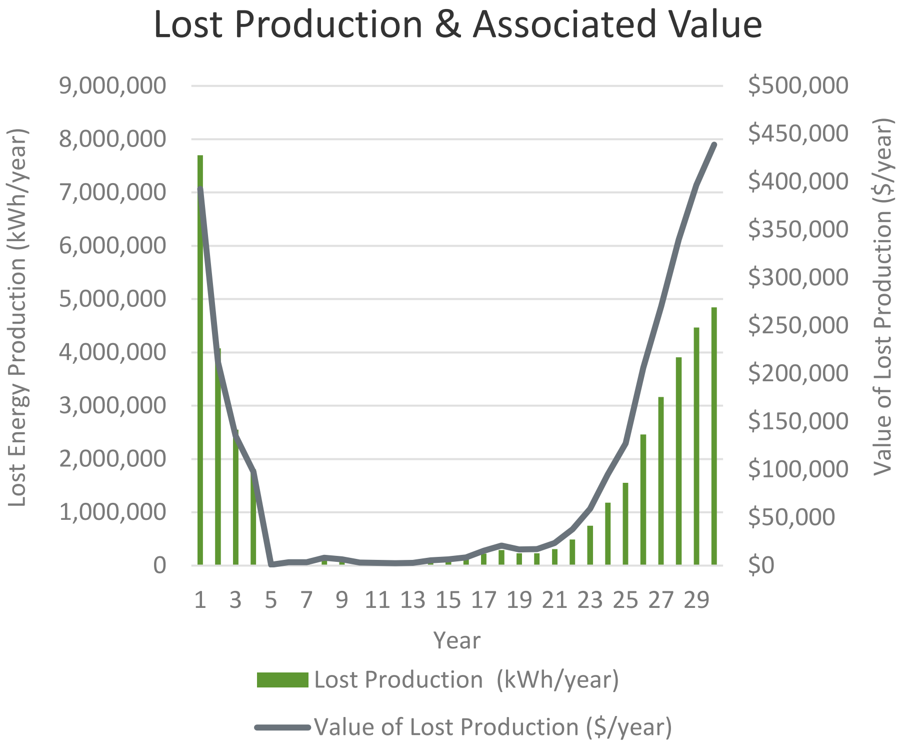


Key Assumptions	
System size	100 MW_{dc}
Analysis period (project life)	30 years
Crystalline-silicon module cost*	$152 each
Labor hours per module replacement	0.1 hour
Labor rate (journeyman electrician)	$24.12/hour
Module downtime during replacement	162 hours
Power affected by each module downtime	5.74 kW_{dc}
Discount rate	6.53%
Inflation rate	2.50%
Value of lost production ($/kWh)	$0.05/kWh
Escalation rate value of lost production	2%/year

Sources: Sandia National Laboratories, PV O&M: Common Failure Modes, Cost Impacts, and Data Analysis, accessed 2024; Walker et al., Model of Operation-and-Maintenance Costs for Photovoltaic Systems, NREL, 2020. Component downtime estimated as difference between trouble ticket open and close dates in the PV Reliability, Operations & Management database. Costs inflated to year of occurrence and discounted to present value. Module warranties are not considered, so the total potential cost of early module breakage is represented.

Potential Cost of Early Breakage: Illustrative Case





Monetary results are in present dollar values.

Potential Cost of Early Breakage: Illustrative Case

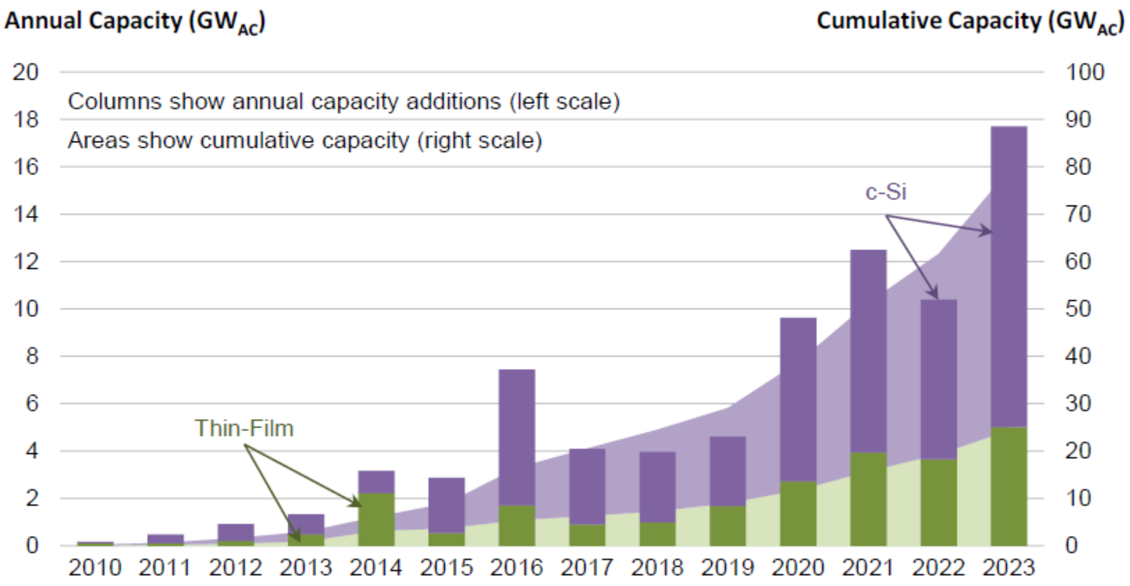
- Adding the high early glass breakage rate increases LCOE by $0.01 (1 cent) per kWh.
  - Equivalent to ~20% of current U.S. average LCOE for utility-scale systems.
- Analysis is sensitive to assumed failure distribution.

Results	No Early Breakage	Early Breakage
Annualized O&M costs ($/year)	$1.60 million	$2.55 million
Annualized unit O&M costs ($/kW/year)	$16.00	$25.48
NPV O&M costs ($)	$27.90 million	$44.42 million
NPV ($) per Wp	$0.279	$0.444
NPV annual O&M cost per kWh	$0.0145	$0.0233
NPV lost production ($)	$0	$1.90 million
NPV lost production per kWh	$0	$0.001

Thin Film: The Other Glass-Glass Module

U.S. shares of silicon and thin-film modules in utility-scale systems

PV project population: 1,494 projects totaling 79.3 GW_{AC}



System with glass-glass thin film modules

Source: LBNL, Utility-Scale Solar, 2024 Edition.

Putting it All Together: Tech Scouting 2.0

Identify concurrent module changes that may be contributing to increased early failure due to glass breakage, explain the trends, and discuss their reliability implications.

Coming soon to IEEE Journal of Photovoltaics

Growing Panes: Investigating the PV Technology Trends Behind Frequent Early Failures in Modern Glass-Glass Modules

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Abstract— **Photovoltaic (PV) module materials and technologies continue to evolve as module manufacturers and buyers try to minimize costs, maximize performance, and speed deployment. Both silicon and thin film modules are converging towards similar ~3 m² glass-glass designs with thinner glass sheets to increase power output while reducing module weight, and both types are increasingly mounted on single-axis trackers. At the same time, an increasing number of PV sites have been reporting spontaneous glass breakage in early-life systems deployed with these "big, floppy modules." In this article, we identify the concurrent module changes that may be contributing to increased early failure, explain the trends, and discuss their reliability implications. We suggest that larger, thinner glass sheets along with variations in heat treatment and quality may be contributing to glass vulnerability. We note that trends toward weaker or back-mounted frames may also be contributing to module failures, especially for "extra-extra-large" modules mounted on trackers. Combinations of these trends may have pushed modules to a threshold at which increasing early failures are causing the front edge of the "bathtub curve" to reemerge. Current qualification testing appears to be ineffective for catching these early failures in new module designs, and module buyers do not have enough reliability information—or cannot prioritize such information—during module procurement. Additional research is needed to identify the field conditions leading to glass breakage and if there is one or multiple limiting flaws in new module designs causing glass breakage. Early failures may be mitigated by returning to more robust designs or ensuring better module testing and quality assurance.**

Index Terms— **degradation, fracture, glass, photovoltaic, racking, reliability, silicon, thin film**

I. Introduction

THE path to decarbonization almost certainly will require widespread deployment of photovoltaic (PV) systems [1]. Deploying reliable PV modules helps ensure long power plant service life, energy resilience, and greater lifetime energy production [2], [3]. Although accelerated testing may be used to deduce—albeit with large uncertainties—module degradation rates in different environments, it is important to confirm test results are still representative for new technologies. There is a high installation rate of PV modules occurring in conjunction with rapidly changing technologies and supply chain disruptions. This means that most modules do not have a long enough field history to validate these accelerated tests and show that current standards may not be sufficient [4].

In recent years, crystalline-silicon (c-Si) PV modules have seen dramatic increases in module area and increased use of bifacial architectures [5]. Indeed, the module description "large format" has become ambiguous. To clarify, we refer to module areas of ~2 m² as large (1.75 m² ≤ L < 2.25 m²), ~2.5 m² as extra-large (2.25 m² ≤ XL < 2.75 m²), and ~3 m² as extra-extra-large (2.75 m² ≤ XXL < 3.25 m²). Glass-glass modules expose the rear surface to light but add weight compared with designs that use a polymer backsheet. Use of thinner glass and frames helps reduce module weight, resulting in what some industry observers have dubbed "big, floppy modules," whose structural weaknesses may be exacerbated by mounting on trackers.

As module sizes for glass-glass c-Si modules have increased from XL to XXL, spontaneous glass breakage in recently deployed systems has increasingly been reported [6], [7], [8], [9], [10], [11], [12]. One site reported that more than 15% of their large, glass-glass c-Si modules had glass breakage due to moderate wind in the first few years after installation [7]. Glass breakage is a serious failure mode that requires immediate module replacement owing to electrical safety hazards.

The dramatic impact of early failures on the module failure rate curve is illustrated in Fig. 1. In previous work, some of the authors used a Monte Carlo simulation of common PV module degradation behaviors to construct a module-specific failure rate curve [4], [13]. Because different definitions of "module failure" have been used historically, the concept is shown using two different definitions. First, failure can be defined as the power output of a module decreasing below 80% of its original rating (blue circles). Second, failure may also be defined to occur when the linear degradation exceeds 0.8%/year, which aligns with typical linear warranty rates [4] (orange diamonds). In the field of reliability, the failure rate curve is often envisioned as a "bathtub curve" because of its increased rates in the early- and late-life stages [14]. The two definitions of failure lead to different onsets of increased failure rates in the curve's wear-out phase after 15-25 years, but the early-life phase has much lower failure rates than the wear-out phase under both definitions—in alignment with failure rates obtained

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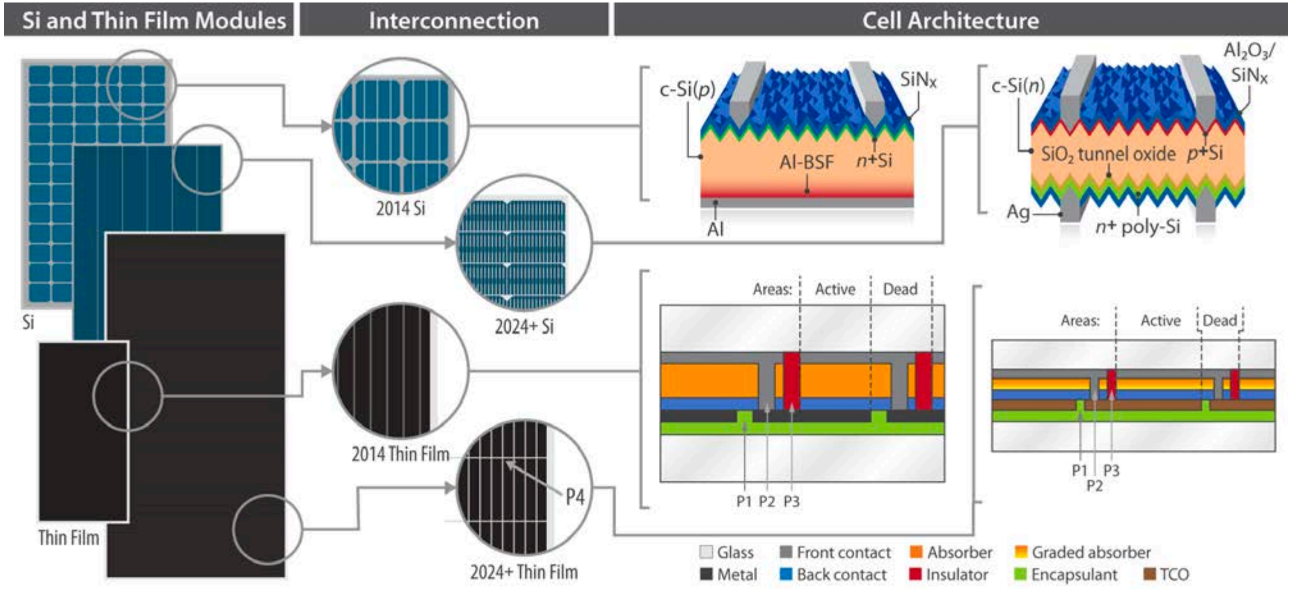
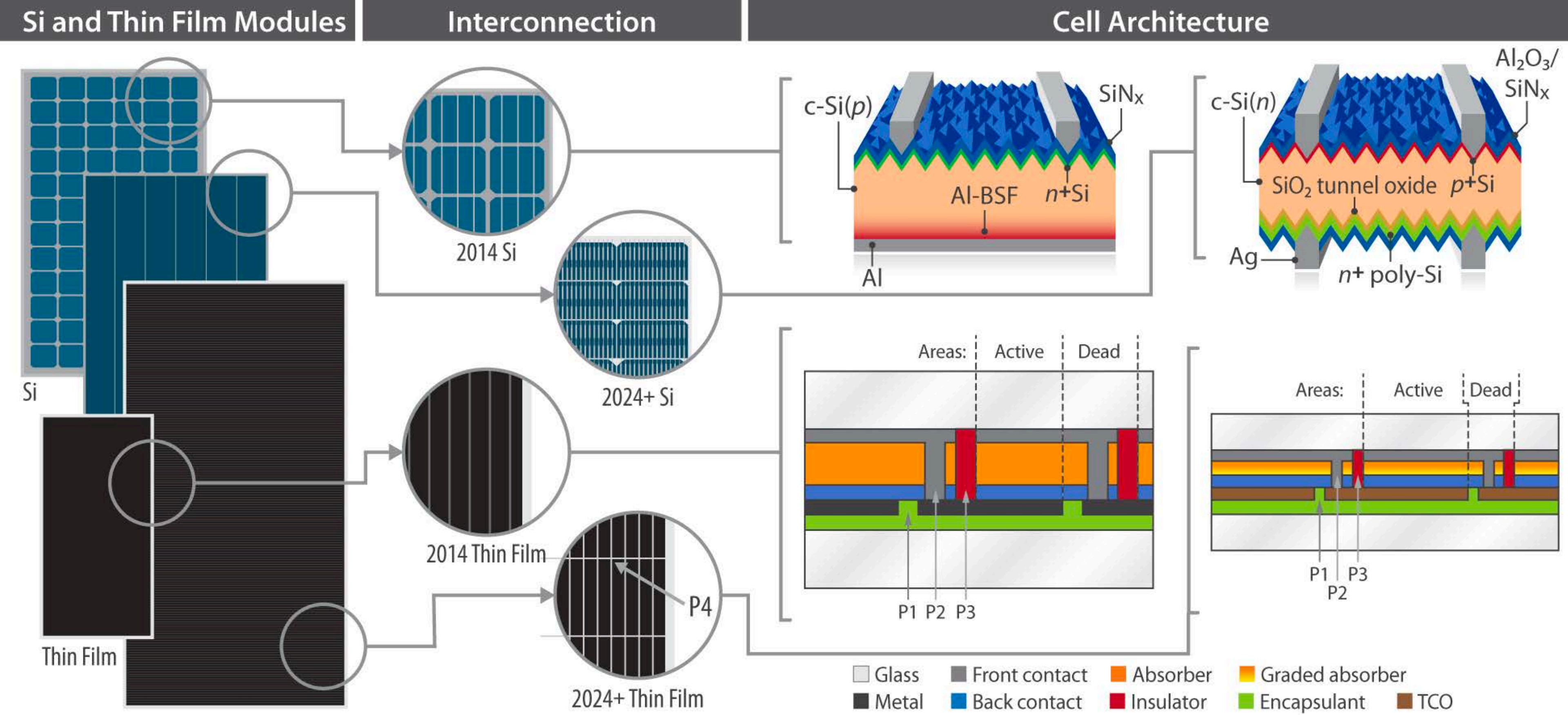
Module level

Cell and Interconnection Trends



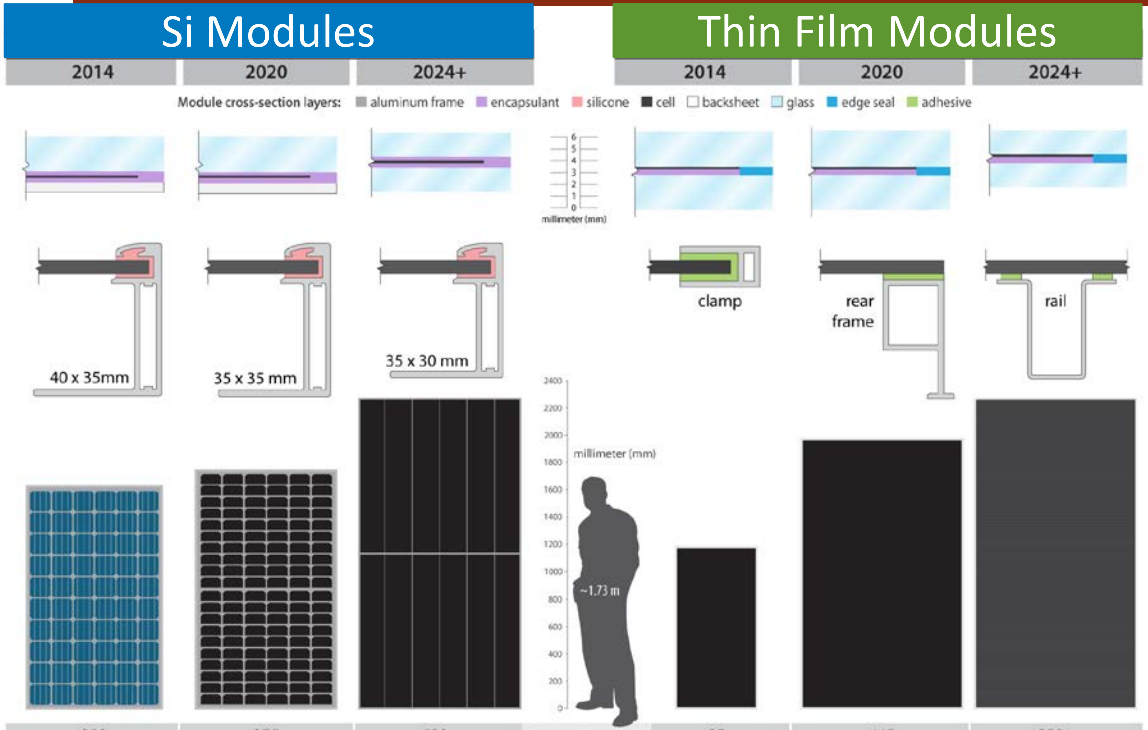
Module packaging trends may be converging…

…but reliability implications of cells and interconnections differ



Si and Thin Film Modules
Interconnection
Cell Architecture
Si
Thin Film
2014 Si
2024+ Si
2014 Thin Film
2024+ Thin Film
P4
c-Si(p)
SiNx
Al-BSF
n+Si
Al
c-Si(n)
Al2O3/
SiNx
SiO2 tunnel oxide
p+Si
Ag
n+ poly-Si
Areas:
Active
Dead
P1
P2
P3
Glass
Metal
Front contact
Back contact
Absorber
Insulator
Graded absorber
Encapsulant
TCO

Packaging trends are converging for c-Si and thin film modules



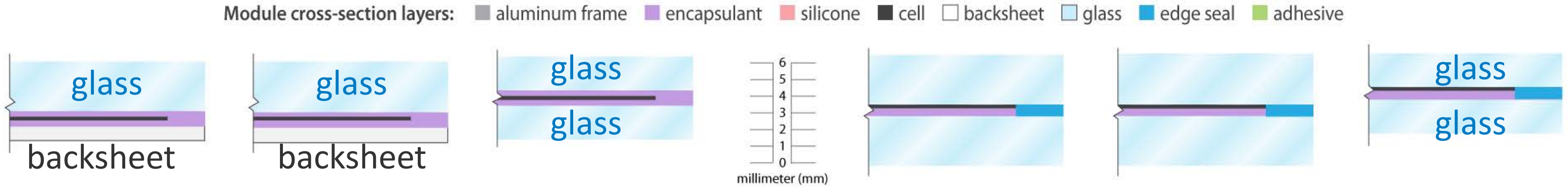
2014	2020	2024+		2014	2020	2024+
280	375	600+	Average Power (W)	95	445	550+
1.7	2.1	2.8	Area (m²)	0.72	2.5	2.8
19.0	21.1	37.8	Weight (kg)	12	34.5	39.7

- Glass-glass architecture
- Glass is getting thinner
- Modules are getting bigger!
  - ❖ $1.75\ m^2 \leq L < 2.25\ m^2$
  - ❖ $2.25\ m^2 \leq XL < 2.75\ m^2$
  - ❖ $2.75\ m^2 \leq XXL < 3.25\ m^2$

  ...and heavier

Glass trends for c-Si and thin film modules

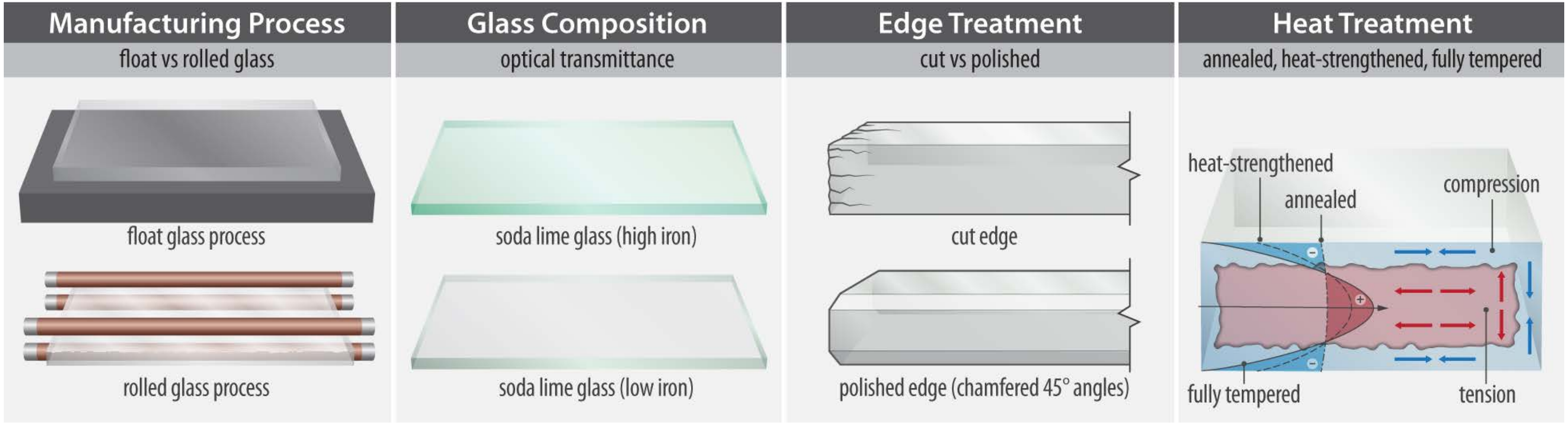
Si Modules			Thin Film Modules		
2014	2020	2024+	2014	2020	2024+



- Trend to glass-glass from glass-backsheet to enable benefits of bifacial cell technologies
- Trend toward thinner glass
- Heat treatment trend unclear based on data sheets

- Typically heat strengthened glass in thin film modules
    - Limited by deposition temperature
    - Sometimes one sheet is tempered
- Trend toward thinner glass

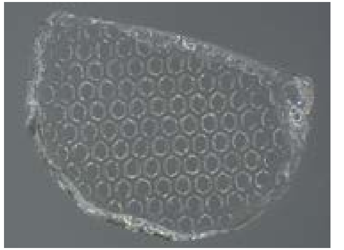
Characteristics and Implications of PV Glass

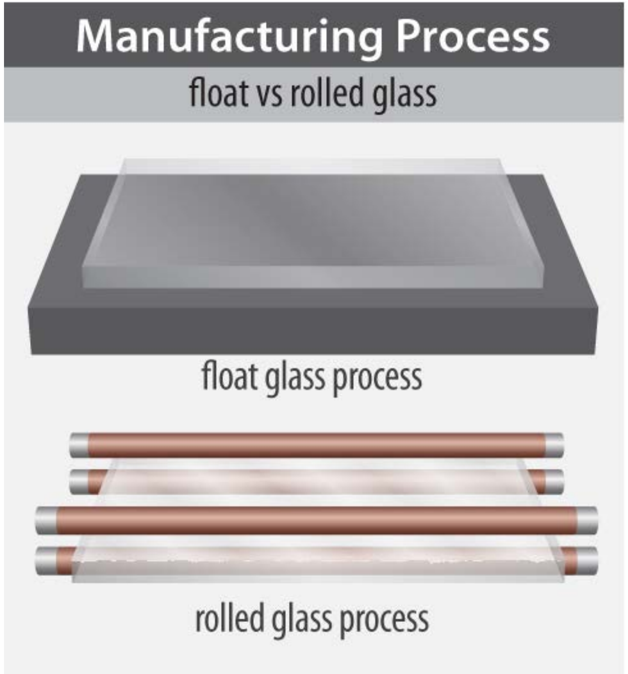


- Glass strength is determined by factors including composition, surface condition, the presence of flaws, and the environment
- Its strength is influenced by the distribution of microscopic flaws
- The dimensions of a piece of glass also influence the propensity for damage
  - Increasing the area of the glass sheet increases the likelihood of the glass containing strength-limiting flaws
  - Larger sheets are generally considered more likely than smaller sheets to break when subjected to the same conditions

Manufacturing Process

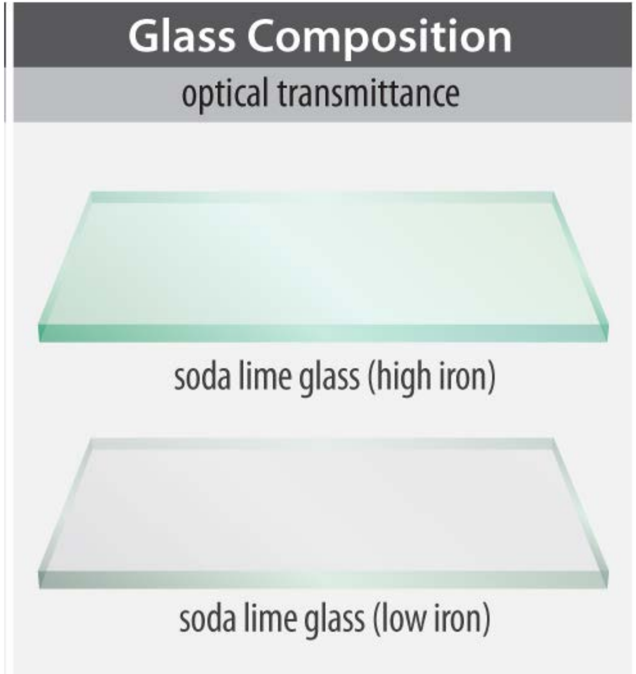
Dimpled glass





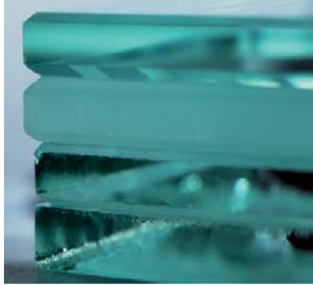
- Most c-Si modules use rolled glass on the front and back
  - Results in dimpled pattern which has no documented benefit
  - Refractive index match between encapsulant and glass eliminates the dimples’ optical effect
- Most thin film modules and a small fraction of c-Si modules use float glass
  - Better thickness control and planarity of surface for depositing thin films
  - High substrate temperatures available in the float line, which saves on energy costs

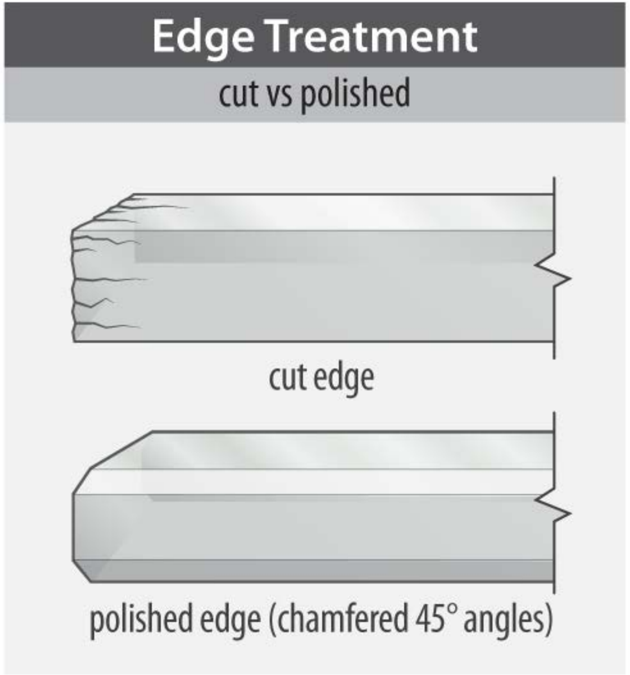
Glass Composition



- Glass for PV is low-iron soda lime glass designed to minimizing light absorption and reflection
  - Optical transmittance of 91%
  - Anti-reflective coatings bring this to 94%
- Contamination (ex: nickel sulfide) could manifest as foreign particles which could act as stress concentrators or initial flaws
  - Rare
  - Not documented in PV glass

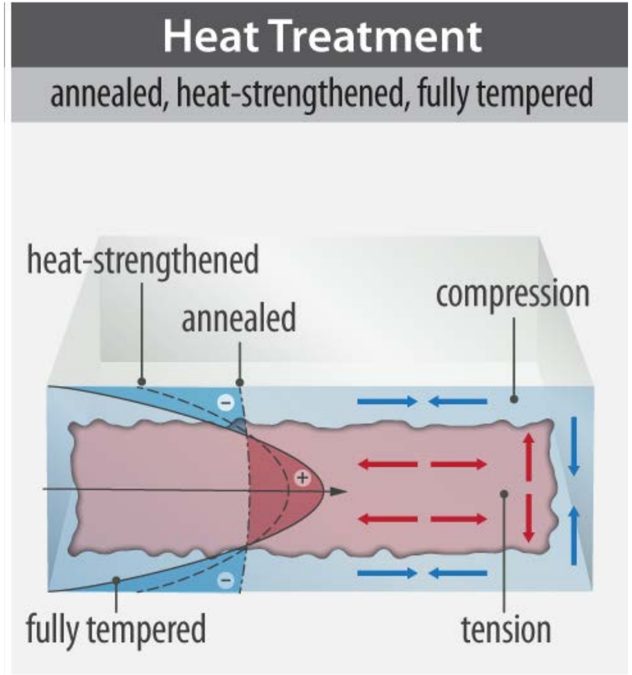
Edge Treatment





- Cutting module glass from larger sheets results in a cut edge with mechanical damage that can serve as the origin for breakage
  - Drilling or cutting holes for junction boxes in the rear glass sheet also creates mechanical flaws
- Edges can be ground and polished to change the size and number of flaws, improving the strength of the glass sheet
  - Prevalence in PV is unknown

Heat Treatment



- Heat treatment introduces built-in stress (compressive region) that prevents flaws from opening
  - Compressive region balanced by tensile region
  - Flaw overcoming compressive region causes fracture
  - Different heat treatments have different compressive stresses

There are no PV-specific glass standards

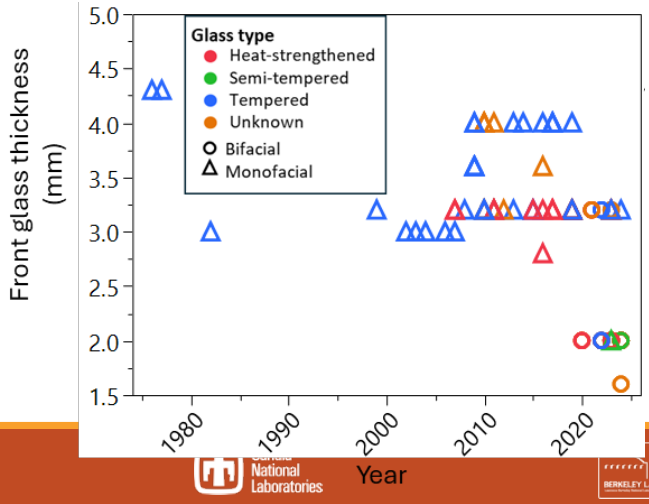
ASTM C1048 - 18

heat-treatment	surface compression
annealed	< 1.52 MPa
heat-strengthened	24 – 52 MPa
fully tempered	> 69 MPa

GB/T 34328-2017

heat-treatment	surface compression
annealed	N/A
thermally strengthened type B	≥ 60 MPa (≤ 20 MPa)
thermally strengthened type A	≥ 95 MPa (≤ 20 MPa)

Led to increased variability in datasheets



However, same surface compression does not mean same fracture pattern!

low energy fracture pattern

this single crack was formed through a big flaw on an unloaded module

(big flaw, low load)

high energy fracture pattern

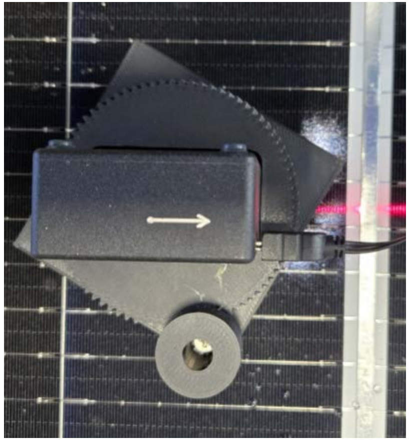
this fracture pattern was formed through static mechanical testing.

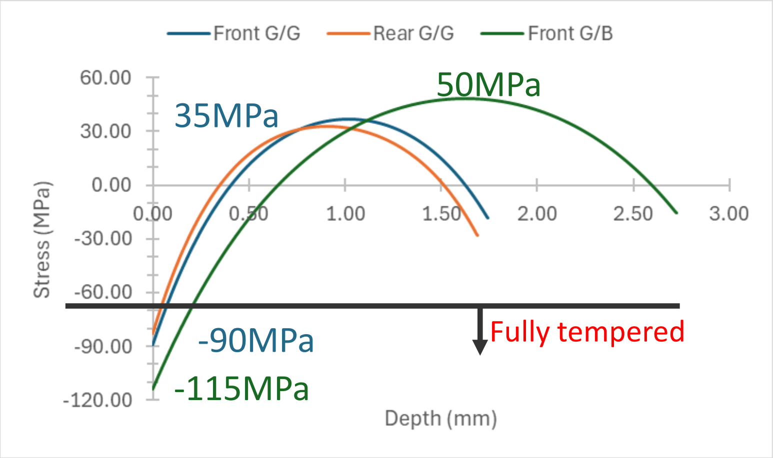
(small flaw, high load)

Both images show the same module type!

What to believe?

Scattered light polariscope



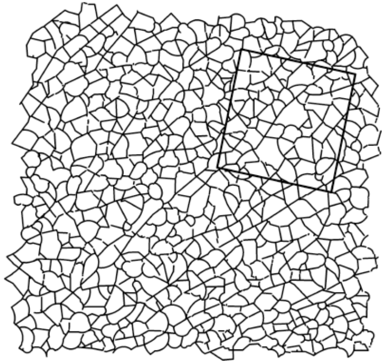


XXL Glass/Glass Module
144 HALF CUT MONO PERC CELL 525-555 W
with 2.0mm Glass
Front: -82.7 MPa
Rear: -89.2 MPa

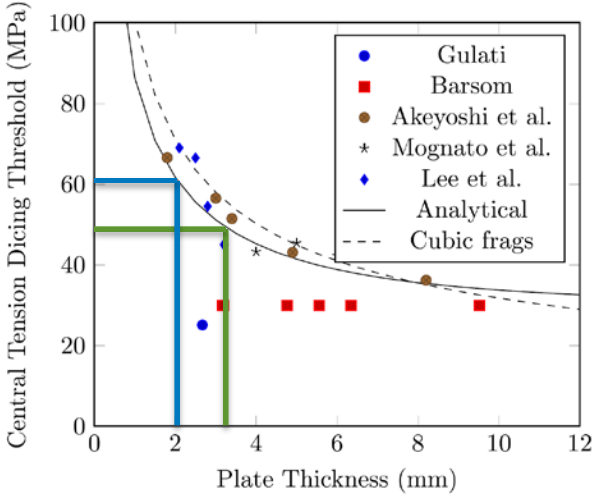
L Glass/Backsheet Module
with 3.2mm Glass
Front: -114.1 MPa

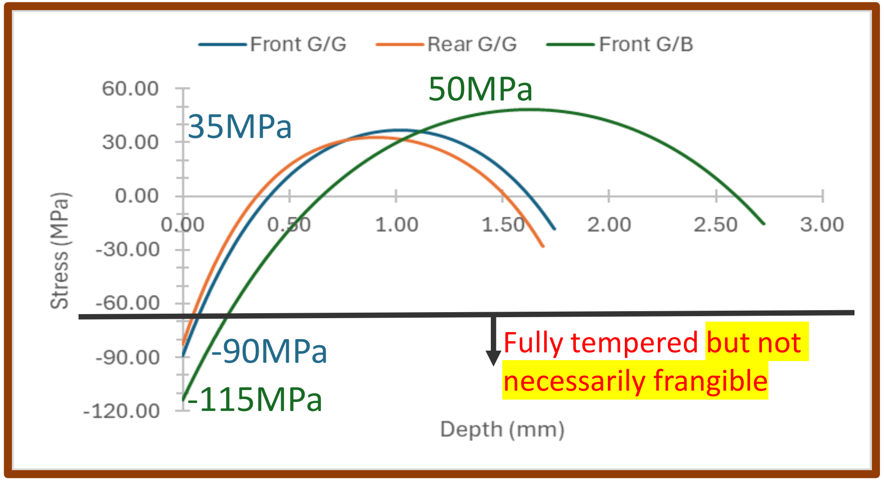
2.0 mm glass can be fully tempered!

Frangibility of Glass



"The core of tempered glass may have sufficient tension to drive the crack automatically with no need of external loads. There could be enough tension in the core to drive the crack up to high enough speeds to cause the crack to branch repeatedly. This attribute is referred to as frangible and results in a fragmented glass sheet."

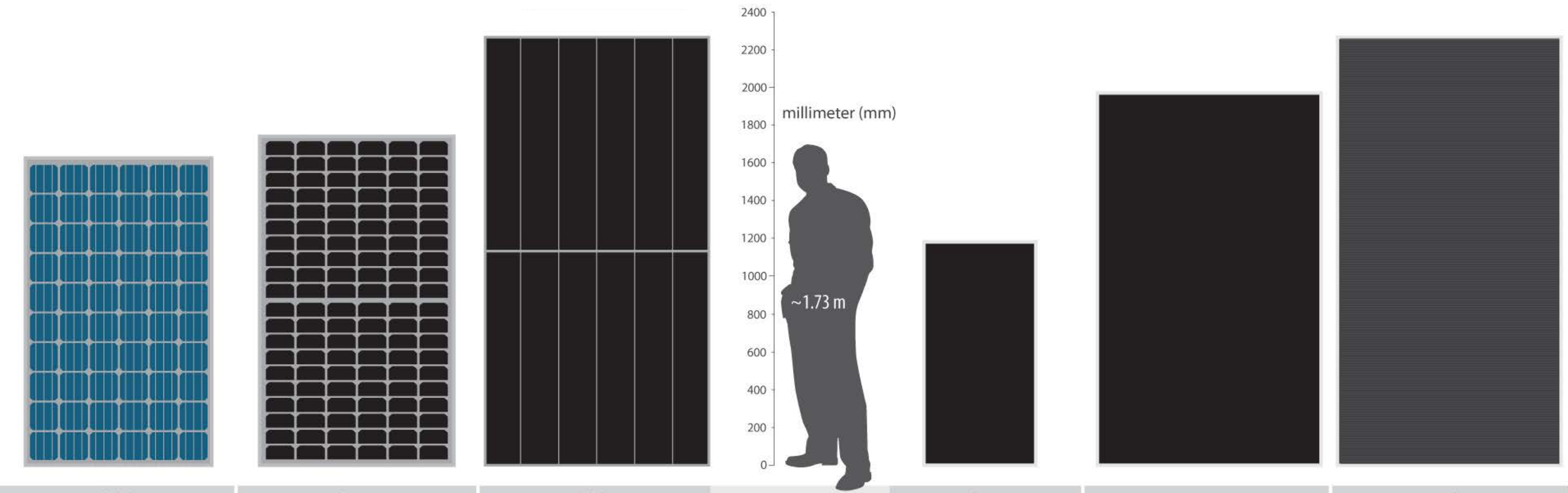




[Ross J. Stewart, Naveen Prakash, Modeling dynamic fragmentation of tempered glass, Engineering Fracture Mechanics, 2023 https://doi.org/10.1016/j.engfracmech.2023.109422]

System level

Modules got bigger
(which can help reduce BOS costs)



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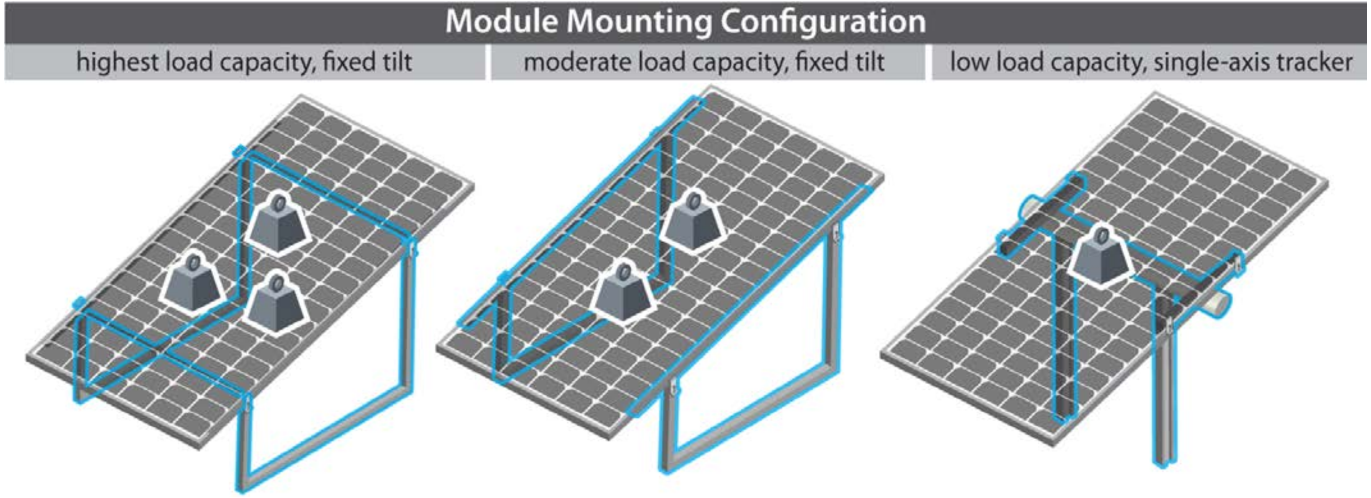
Modules became load bearing components
PV Framing and Racking Strategies



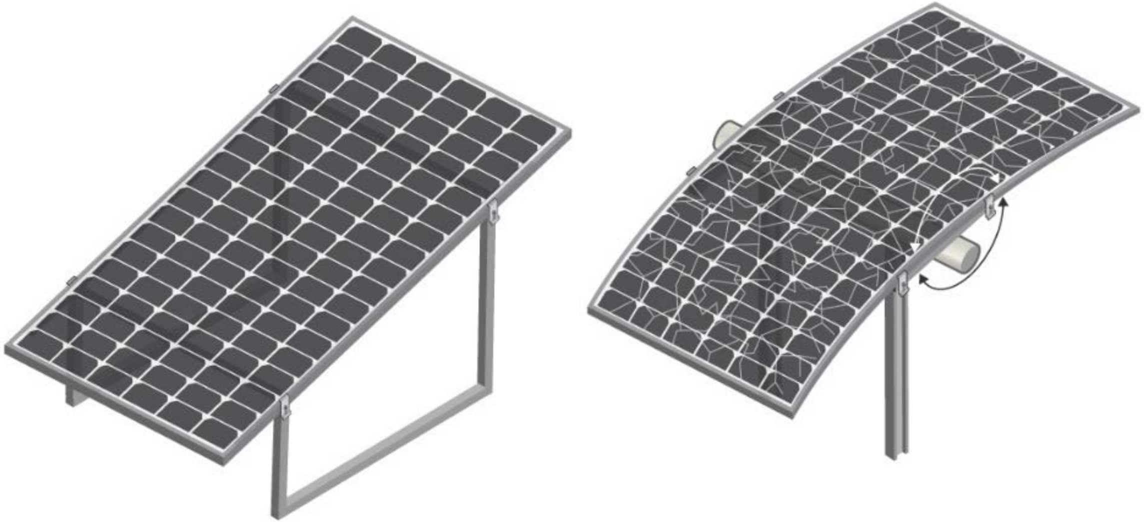
- Module is fully supported
- Steel substructure is the main load-bearing component
- Stiff mounting points through cross braces

- Module is partially supported
- Steel substructure is still the main load-bearing component
- Mounting points are more compliant.

- Module frame is used to transfer loads to short mounting brackets

Qualification testing

Test load = 1.5 (safety factor) x design load



IEC 61215-1:2021

The minimum required design load per this document is 1600 Pa, resulting in a **minimum test load of 2400 Pa.**

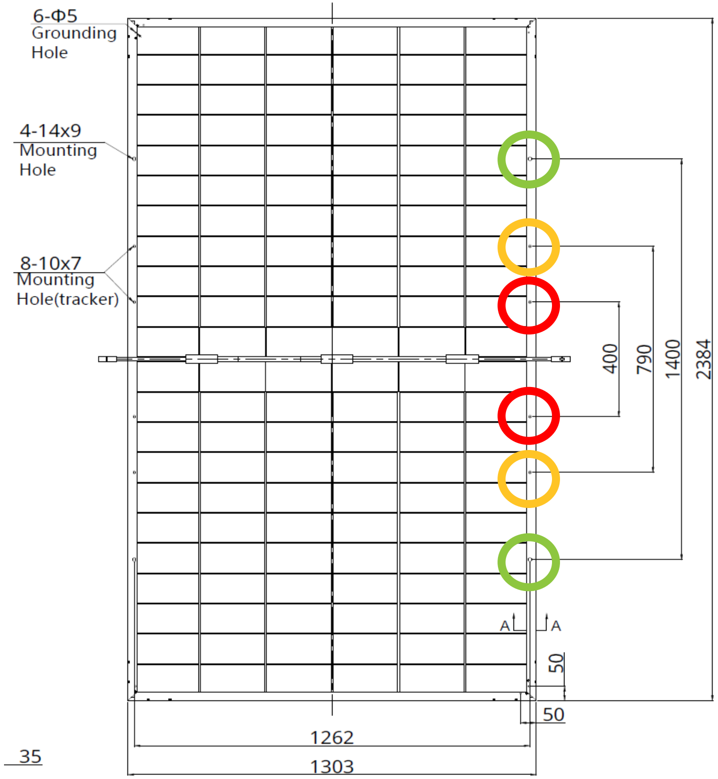
IEC 61215-1:2005

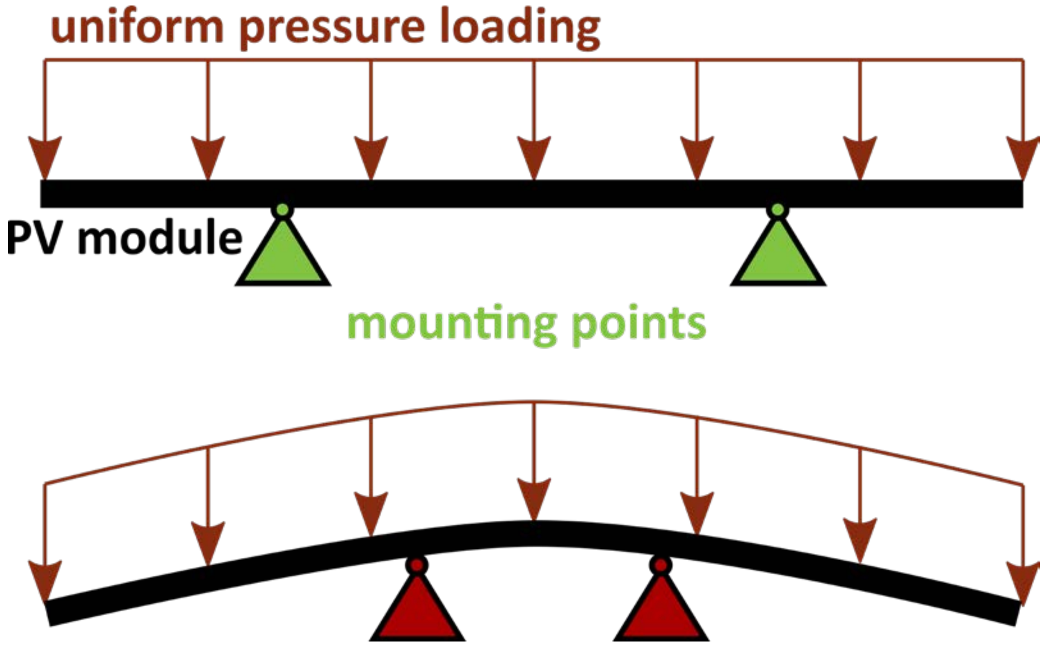
IEC 62938:2020 (inhomogeneous snow loads)

if the module is to be qualified to withstand heavy accumulations of snow and ice, the test load is ***increased to 5400Pa***

+5400 Pa / -2400 Pa	**Test load**	**+1500 Pa / -1500 Pa**
+3600 Pa / -1600 Pa	**Design load**	**+1000 Pa / -1000 Pa**

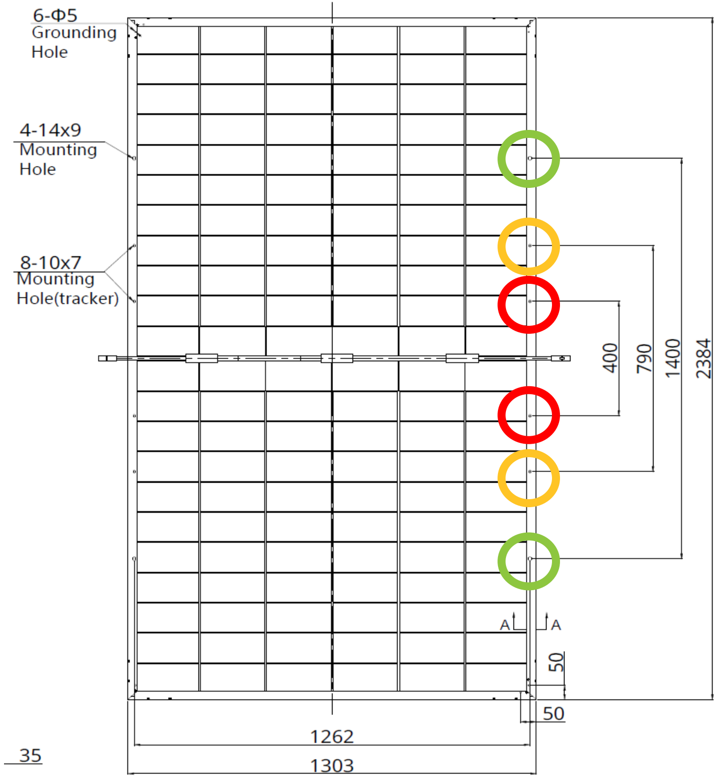
Installation and mounting instructions

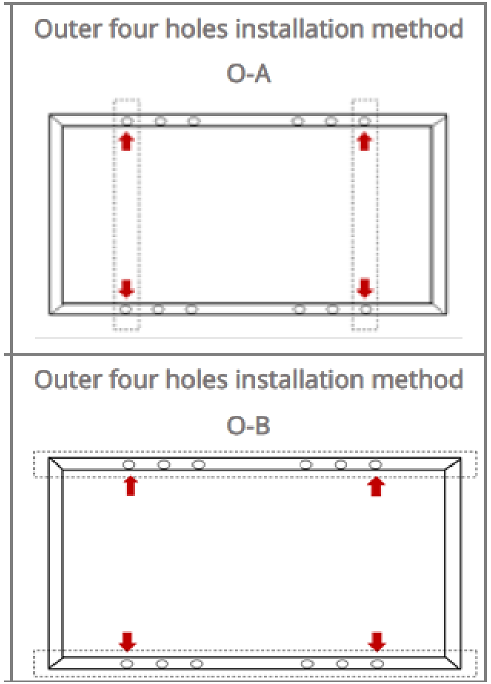




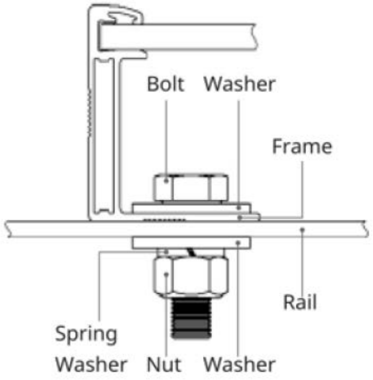
Installation and mounting instructions

fixed tilted installation





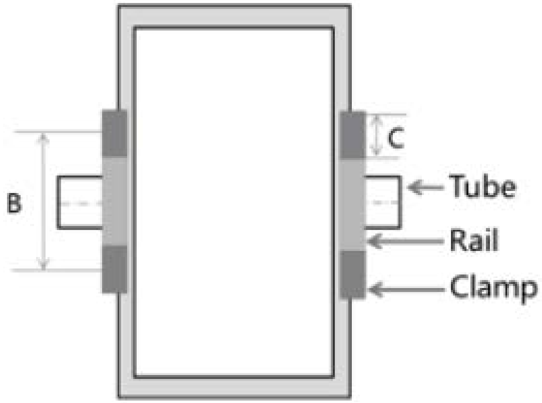
through-bolt



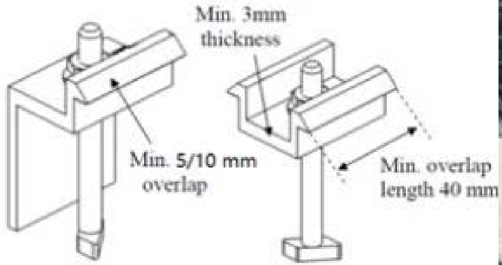
O-A	O-B
+5400Pa/ -2400Pa	+3600Pa/ -2400Pa

Installation and mounting instructions

tracker installation

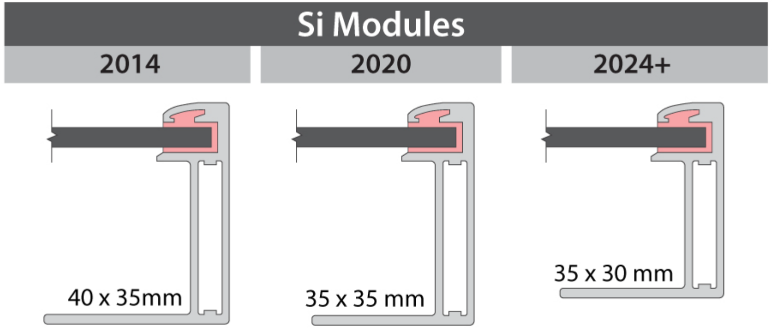


top clamp

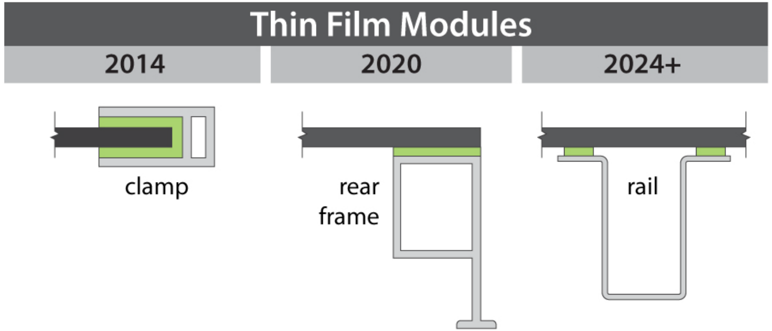


B Value (mm)	Clamp length C (mm)	Test load (Pa)
≥400	≥40	+1500/-1500

Evolution of frame design



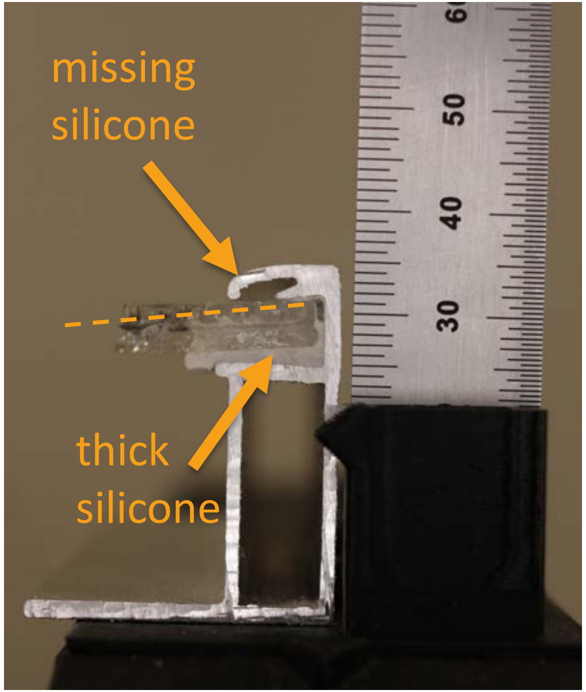
- Trend to smaller frames
- A lot of manufacturer variability



- A lot of manufacturer variability
- Trend to rear mounting (rear rails)
- Exposed glass edges

Possible silicone distribution issues

- Glass contacting frame
- Current QA checks only for silicone weight
- Does not check for equal distribution after lamination
- Downwards angled frame



PVFleet analysis – Mounting and racking

RdTools

PV Fleet Performance Data Initiative

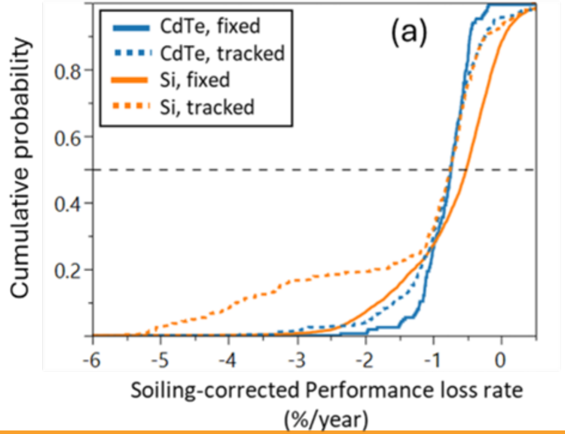
chris.deline@nrel.gov

We leveraged historical data from the PV fleets initiative to analyze the impact of fixed tilt vs. tracker mounted systems.

>2200 systems, > 24,000 Inverters, >8.5 GW capacity

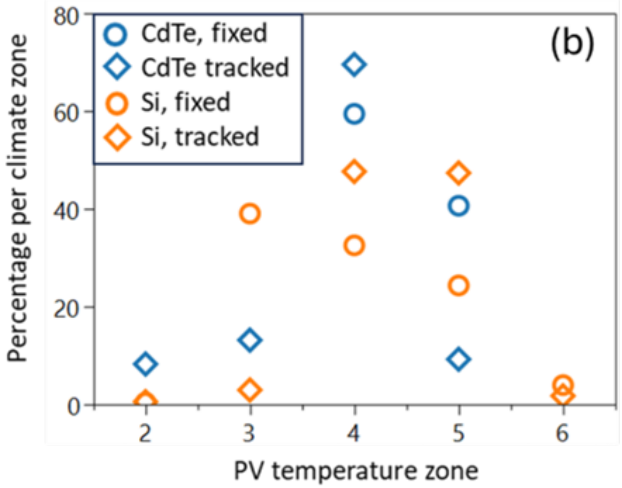
- We looked at CdTe/Si and fixed/tracked systems
- fixed-tilt c-Si exhibit a median PLR of around -0.5 %/year
- while the other categories show a median of -0.75 %/year

Is this evidence that fixed tilt systems perform better?



PVFleet analysis – PV mounting and racking

- Multiple factors may contribute to the lower degradation rate observed in these fixed-tilt systems.
- The c-Si fixed category contains a larger percentage of systems in a cooler climate which can correspond to a more modest performance loss
- In addition, the systems in the fixed c-Si category are considerably smaller than systems in the other categories.
- Because of these confounding variables, the impact of system configuration cannot be isolated.



In summary

- C-Si and thin film module design become increasingly similar
- All module types grew bigger,
- while racking support got less (especially in tracker mounted systems),
- which led to modules becoming a load bearing component of the system
- while also making the load carrying frames thinner
- and not improving quality control for frame mounts
- but lowering test loads…

Tough Break

https://bit.ly/4g6dHIk

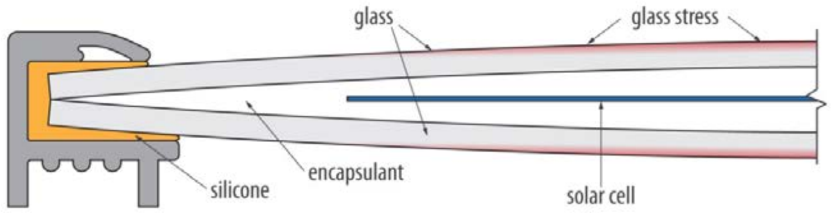
Tough Break: Many Factors Make Glass Breakage More Likely

Timothy J Silverman,[1] Elizabeth C. Palmiotti,[1] Martin Springer,[1] Nick Bosco,[1] Mike Deceglie,[1] Ingrid Repins,[1] and Ashley Gaulding[1]

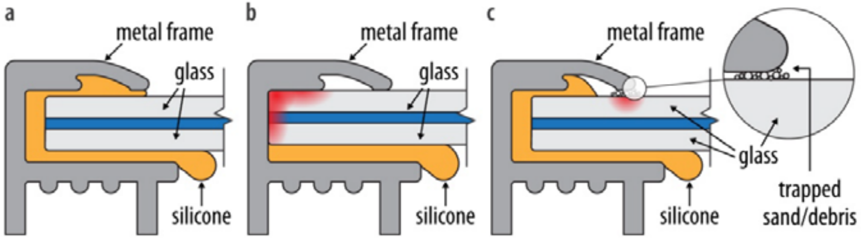
National Renewable Energy Laboratory

- Technical report summarizing observations from fielded modules experiencing spontaneous glass breakage
- Multiple factors may be contributing!

Edge pinch has been observed in many XL and XXL G/G modules.



Insufficient silicone may cause contact between frame and glass.



Watch out for new Journal article!

Growing Panes: Investigating the PV Technology Trends Behind Frequent Early Failures in Modern Glass-Glass Modules

Elizabeth C. Palmiotti[1], Martin Springer[1], Jarett Zuboy[1], Timothy J. Silverman[1], Jennifer L. Braid[2], Dirk C. Jordan[1], Salil Rabade[1], Teresa M. Barnes[1]

[1] National Renewable Energy Laboratory, Golden, CO 80401

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Thank you!

www.duramat.org

NREL/PR-5K00-92746

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