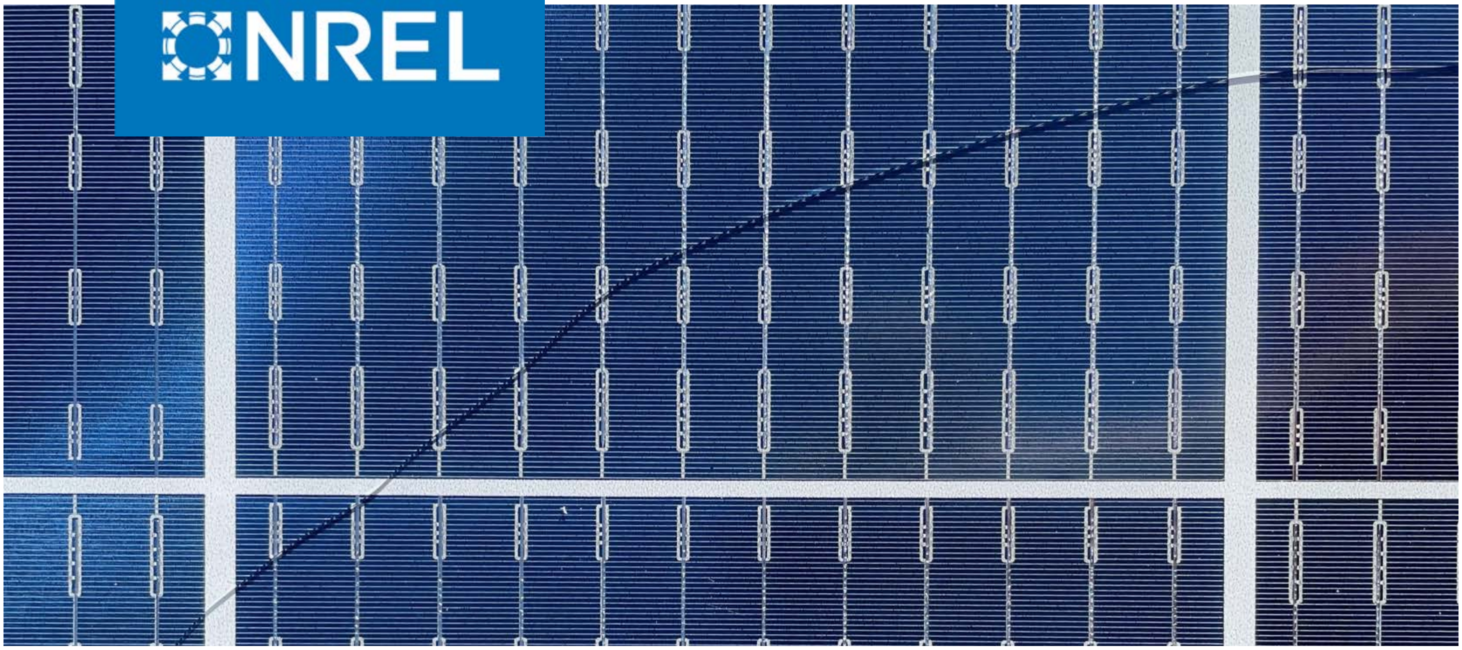

Tough Break: Many Factors Make Glass Breakage More Likely

Timothy J Silverman,[1] Elizabeth C. Palmiotti,[1]
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Technical Report
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We have seen cases of the glass in solar panels (photovoltaic [PV] modules) breaking differently, and more often, than it did 5 years ago. There have been many changes to PV module design and materials in that time. Several changes have increased the risk of glass breakage. **But there is probably no single change that is responsible for the problem.**

Here, we summarize our observations and thoughts on PV glass breakage in utility-scale power plants. We share insights from some current projects at NREL.

Glass Breakage Is Changing

Glass has been vital in PV modules on Earth since the 1960s. It protects cells and wires that are not durable on their own. It is a barrier that keeps out things like dirt and water. And it is an insulator that keeps electricity in the module. A module might keep working after its glass breaks, but not safely and not for long.

Glass breakage has always been a concern, but until recently, the cause has been obvious. Some glass always breaks into small pieces, in a pattern that shows a clear starting point. That starting point might be the impact site from a rock, a huge hailstone, a bullet, or a module being torn loose from its structure and hitting something else. It might be from a very hot fault inside the module, like a series arc or a shunt in a reverse-biased cell. Or it might be a defect introduced during manufacturing or installation.

Broken glass seems to be more common than before. In the past few years, our team has found power plants around the world where PV module glass has broken with no obvious cause. We call this type of breakage spontaneous. The fracture patterns in these cases can look completely different: Instead of hundreds of cracks dividing the glass into tiny fragments, a few large cracks can form. The cracks often don't show a clear origin, and there is often no link to severe weather or an impact event.

Most PV modules in power plants now use two pieces of glass. When modules were small, or when they had a single sheet of glass, 3.2-mm glass was common. But now, both thin-film and crystalline silicon double-glass modules almost always use glass thinner than 3.2 mm—usually just 2 mm—to reduce weight and material use (Zuboy et al. 2024). This change of thickness affects multiple risk factors for breakage, as we describe below.

In our experience, the power plants with spontaneous glass breakage problems use modules with two pieces of glass that are thinner than 3 mm. We think it's possible to make modules with 2-mm glass that are not vulnerable to spontaneous breakage, so we have been investigating other recent changes to design, materials, and assembly. So far, we haven't found a single factor that is enough to explain the recent cases of glass breakage. Interactions among these factors probably explain observed failures.

The Basics of Glass Breakage and Strengthening

Glass breaks when stress near a flaw exceeds a certain level. Heat treatment adds compression at the glass surface, keeping small flaws from growing by squeezing those flaws together. Several standards give the requirements for heat treatment (ASTM 2018; National Standard of the People's Republic of China 2017; European Committee for Standardization 2015), but qualitatively: *Heat-strengthened* glass has moderate compression. *Fully tempered* glass has high compression. *Fully tempered safety glass* is fully tempered glass with high enough compression that it *always* breaks with highly branched cracks that divide the glass into small pieces. The surface compression needed to achieve the safety glass effect is higher in thinner glass (Stewart and Prakash 2023).

When glass breaks with a highly branched crack pattern, it has a *high-energy fracture pattern*. Fully tempered safety glass has enough built-in strain energy that it always has a high-energy fracture pattern. In the other types of strengthened glass, a high-energy fracture pattern can appear if enough energy is supplied by an external load. For example, when glass is strong enough to bear a heavy static load before breaking, it can show a high-energy fracture pattern even if it is not fully tempered safety glass. In our experience, 3.2-mm PV glass that is fully tempered is also safety glass. It always breaks into small fragments.

When glass breaks with cracks that have few or no branches, it has a *low-energy fracture pattern*. This can happen in annealed or heat-strengthened glass that breaks before the external load has added enough energy for branching. Low-energy fracture patterns can also appear in fully tempered glass, even when the built-in strain energy matches that of a thicker piece of safety glass (Lee et al. 2012; Stewart and Prakash 2023). Because the fracture pattern is a function of surface compression, thickness, and the damage cause, it is impossible to assess the degree of heat strengthening by examining just a low-energy fracture pattern.

In heat-treated glass, the compression at the surfaces is balanced by tension in the center. If a flaw is deeper than the compression zone and large enough to exceed the failure criterion in the tension zone, the flaw spreads immediately, even with no external load. The depth of the compression zone is about 20% of the glass thickness. In thin glass, the region of compressive stress is thinner, so a smaller flaw can cause unloaded breakage.

Many Factors Contribute to Glass Breakage

Glass Strengthening

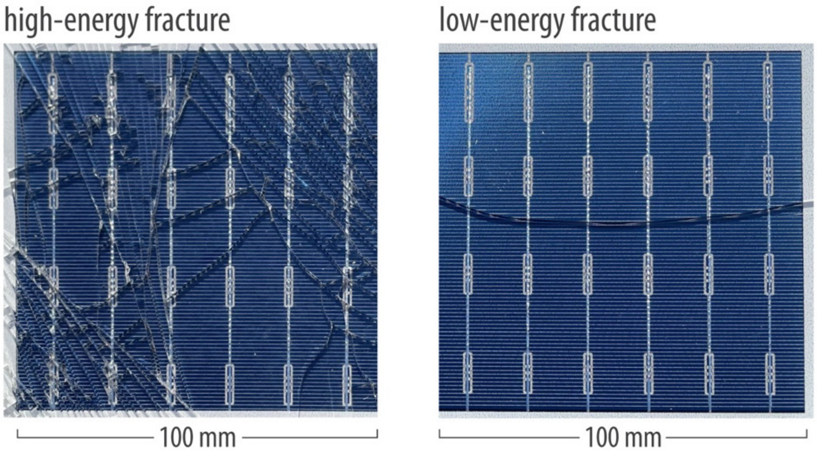

Figure 1. The same piece of 2-mm fully tempered glass can break with a high-energy fracture pattern (left) or a low-energy fracture pattern (right). These photos are from the same module type broken in two different ways. Fully tempered safety glass can only break with the high-energy fracture pattern. ***Photos by Timothy J Silverman and Illustration by Al Hicks, NREL.***

The trend toward thinner glass in PV modules has raised questions about heat treatment. PV module data sheets are not usually specific about the heat treatment of glass. They almost never cite a standard. One of the available standards for heat-treated glass is ASTM C1048 (ASTM 2018). A common misconception is that 2-mm glass cannot be tempered, but **with the right equipment, 2-mm glass can be heat-treated to make fully tempered glass or fully tempered safety glass.**

In our experience, 2-mm glass in PV modules is almost always fully tempered according to the threshold in this standard, at least 69 MPa of surface compression. We have not yet seen 2-mm fully tempered *safety glass* in a PV module, but remember that the surface compression required to be safety glass is higher in thinner glass. **Depending on the conditions, the same piece of 2-mm fully tempered glass may break with either a low-energy or a high-energy fracture pattern.** That's because thin, fully tempered glass is sometimes strong enough to bear heavy loads before it breaks. If low-energy cracks happen in the field, accelerated tests that cause high-energy cracks probably aren't driving the same chain of mechanisms. Even though we've found that 2-mm glass in PV modules is usually fully tempered per ASTM C1048, it tends to have a lower surface compression than the 3.2-mm glass used in PV modules. Even so, **changes to heat treatment alone are not enough to explain recent breakage problems.**

Flaws at Edges and Surfaces

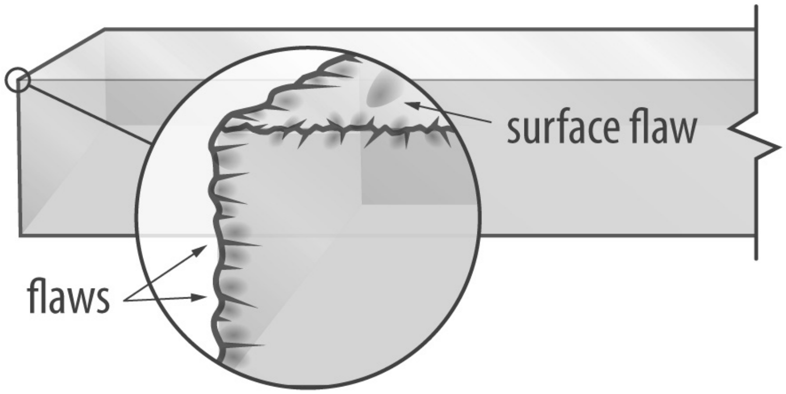

Figure 2. Cracks in glass always begin at a flaw, often microscopic and often at the edge. Larger flaws can make glass easier to break. ***Illustration by Al Hicks, NREL.***

The strength of a brittle object like a piece of glass is set by preexisting flaws, usually microscopic ones. **Even if glass is properly supported and properly strengthened, it will be easy to break if it has a major flaw on a surface or edge.** In an example module type with fully tempered 2-mm glass, we have seen both the high-energy fracture pattern and the low-energy fracture pattern, depending on the following conditions. If we introduce a large flaw in the glass edge, the glass breaks when the load is close to zero, and we get the low-energy fracture pattern. If we apply uniform pressure to a pristine module, the glass breaks when the load is large, and we get the high-energy fracture pattern.

With pressure to reduce cost, the processes for finishing the glass edges and assembling the modules may be done less carefully. Processes that are harsher on glass edges create more and bigger flaws. **Glass with bigger flaws, especially at surfaces and edges, can break more easily and into a lower-energy pattern.** Even if manufacturing steps make the same flaws as they did with thick glass, thin glass is more sensitive to these flaws.

Edge Pinch

The margin of a crystalline silicon PV module has no solar cells or ribbons, and encapsulant can flow a little bit during lamination. In a single-glass module, the flexible backsheet bends and the margin comes out thinner. In a double-glass module, the glass can pinch together at the edges during lamination. **Edge pinch bends the glass, sometimes putting it at the brink of failure as soon as the module is made** (Cording 2008)**.**

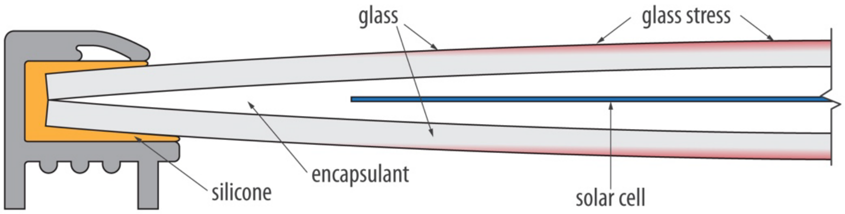

Figure 3. When a double-glass laminate has edge pinch, the curved shape can put the glass in tension, making it easier to break. Areas where edge pinch has put the glass in tension are highlighted in red. *Illustration by Al Hicks, NREL.*

Some manufacturers use a spacer in the laminator to keep the laminate a uniform thickness or a style of laminator that ensures uniform thickness, eliminating edge pinch. This has been done in the thin-film PV industry for decades. But we have measured substantial edge pinch in crystalline silicon modules from several manufacturers. **In some cases, we've seen enough edge pinch to cancel out the extra strength gained from thermal strengthening.** But sometimes we see edge pinch in module types that have not had widespread field breakage. **Edge pinch alone is not enough to explain recent breakage problems.**

Module Size, Glass Thickness, and Mounting

PV modules have gotten bigger, growing from what we call size L (around 2 m^2) to size XXL (around 3 m^2) in just a few years. If you stand an L module up, it is taller than most people. If you stand an XXL module up, most people cannot reach the top. Spare a thought for the people who handle XXL modules, and for the users of test equipment that is suddenly too small.

When loaded by wind or snow, a bigger module has more total load on it. When the glass is only supported near its edges, these edges bear more load in bigger modules. When the frame is only supported at four mounting points, these mounting points bear more load in bigger modules. Mounting clamps designed for low cost or fast assembly may put more stress on glass. When the size of the frame extrusion is kept the same or reduced, as module area increases, the frame is under greater stress and deflects more. This is why some have started calling them "big floppy modules."

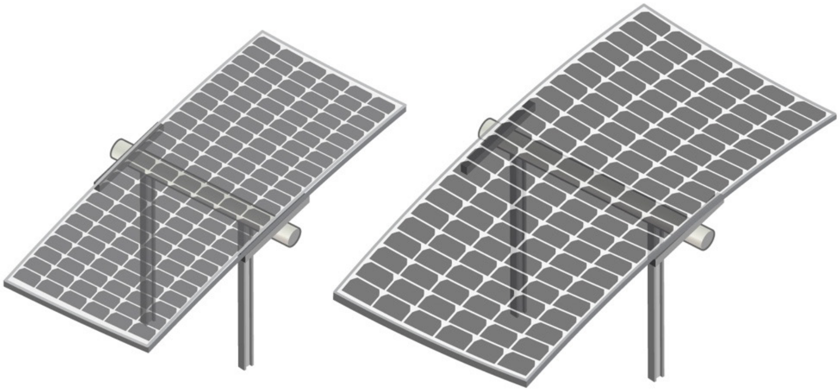

Figure 4. Larger modules bear larger total wind and snow load, which can cause more deflection if the frame and mounting structure stay the same. ***Illustration by Al Hicks, NREL.***

Module mounting points have often stayed the same or moved closer together, even as module size increases. Cost pressure can force mounting structures to be smaller, less rigid, or both. Even a rigid module may be more likely to fail if it is mounted on a floppy structure.

When glass deflects in a PV module, it can contact the frame or other solid objects. That contact can apply local stress that makes a small flaw grow, or it can create a new flaw. Glass thickness is one of the factors that affects deflection when a module is loaded.

Larger size worsens the effects we list here, but **size alone is not enough to explain recent breakage problems.** We are also studying plants with spontaneous glass breakage with size L modules.

Frame Interactions

Forcing glass into contact with something solid can create a new flaw that weakens the piece of glass, local stress that makes a flaw more likely to turn into a crack, or both. **Wind and thermal expansion can force PV module glass into contact with a metal frame. Sand trapped in the frame could make frame contact more damaging to glass.** Larger modules worsen both of these problems.

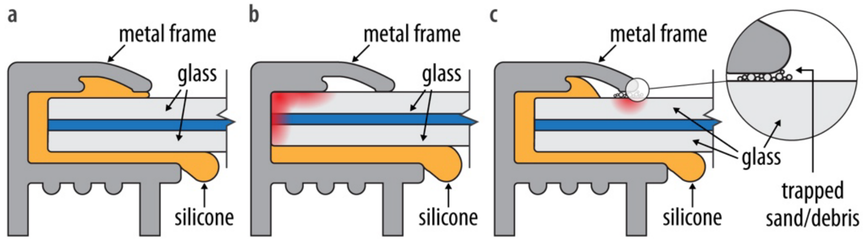

Figure 5. Cross sections of the frames in double-glass modules show (a) glass completely separated from the metal frame by rubbery silicone, (b) glass contact with the inside of the frame, and (c) sand or debris trapped between the frame and the glass. Contact between glass and other objects can make breakage more likely. Areas of contact are highlighted in red. *Illustration by Al Hicks, NREL.*

PV cover glass breakage from contact with a metal frame was found as early as the 1960s. It was addressed with a rubber gasket between the glass and the frame. A layer of rubbery silicone between the laminate and the frame is still very common today. But in many modules, we have seen a silicone layer that leaves part of the frame with little or no barrier to touching the glass. We have also seen dirt and sand trapped between the frame and the glass. Only some of these modules were vulnerable to spontaneous cracking. **Contact between glass and frame, with or without trapped sand, is not enough to explain recent breakage problems by itself.**

How To Proceed

We haven't identified a single reason for the recent glass breakage problem. It is probably a combination of the factors above, plus others we haven't found yet. And it is probably a different combination at different sites and for different products.

We're working on tests and characterization methods that can detect modules vulnerable to breakage at low loads. We're also continuing to collect modules from plants with a problem so we can keep tracking changes.

In the meantime, addressing some or all of the factors listed above may reduce the risk of spontaneous breakage. In the plants we've studied, no one factor is responsible, but none of these factors are helping, either. Even without a single cause identified, we can recommend some actions: The community can develop and use tools for measuring these factors. Suppliers and customers can communicate more about which of these factors a product has. Manufacturers can try to reduce or eliminate factors. Module buyers can choose products with fewer factors.

Reviewing the Factors

1. Reduced glass strengthening
2. Flaws at edges and surfaces
3. Edge pinch
4. Larger module area and thinner glass without reevaluating frame and mounting points
5. Contact between glass and frame, with or without sand.

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