

Development and testing of light-weight PV modules based on glass-fibre reinforcement

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Abstract. In this paper we report on our approach on integrating c-Si PV into lightweight structures, in particular towards vehicle integration. To this end we want to get rid of the (bulk weight of the) glass but seek a suitable replacement in terms of mechanical stability. First we elaborate on the most basic standards and norms that VIPV products should relate to in terms of (thermo-)mechanical testing. Then, for the experimental part, 2 concepts are investigated. In a first approach, we reinforced the encapsulant with glass fibre material, while in a second one we applied a dedicated glass-fibre-reinforced sheet as a replacement of the backsheets. In both cases we stay as close as possible to using commercially available material. For each approach we elaborate the testing that has been carried out: thermal cycling, vibrations, mechanical shock and hail impact. On a final note, we point out some initial damp heat testing results, that are a particular challenge for light-weight modules without glass.

Keywords: VIPV / light-weight materials / fibre reinforcement

1 (Thermo-)mechanical testing

In the field of vehicle-integrated photovoltaics (VIPV), we identified 4 relevant norms that describe testing related to mechanical and thermomechanical failure modes.

- IEC 61215 for PV modules: **thermal cycling** (10.11), (static) mechanical load (10.16), **hail test** (10.17).
- IEC TS 62782 for PV modules: Cyclic (dynamic) mechanical load.
- ECE R43 for laminated glass: fragmentation, ball impact 227g (A13/5 and A7/4), headform (A13/4, A7/3 and A11/3), resistance to abrasion (A13/6.1, A6/5.1 inner and A9/2 outer), resistance to temperature change (A3/8), flexibility (A3/12).
- ISO 16750-3 for environmental testing of electronics for vehicles: **vibration**, **mechanical shock** (door slamming), free fall, surface strength/scratch and abrasion resistance, gravel bombardment.

In first instance we focused on a number of them, indicated above in **bold italic**, as a first evaluation in the different types of mechanical tests.

2 Experimental module fabrication

In order to benefit from the continuously advancing PV cell and module technology, we follow as close as possible the developments in this area. Such an approach allows the highest potential of addressing performance and cost requirements in an initial stage. To this end, we consider conventional tabbing and stringing of commercial homo-junction cells, based on standard SnPb soldering, both for the older 3BB BSF cells and the more recent 9BB PERC and TOPCON half-cells and multi-wire interconnection [1–4], as well as shingling of heterojunction cells [5,6]. These last concepts of multi-wire and shingling are, apart from providing an increased performance, both also very much interesting from an aesthetics point-of-view, as they provide a more homogeneous aspect to the active area of PV modules. This is not the focus of this paper but is expected to become increasingly important for PV integration in our everyday environment.

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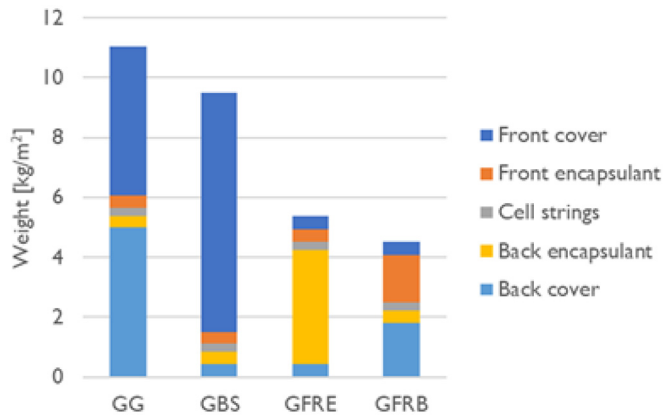


Fig. 1. Impact of the different options on overall weight of the module; the different buildups for GFRE and GFRB are explained in the following respective sections.

While for the encapsulation we also aim to stay as close as possible to the existing and proven materials and technologies, the buildup must be adapted to address weight requirements. As the glass front- and/or backside is the main showstopper for these requirements (although very thin glass may still be an option, but at a significant increase in cost), we look into alternatives, based on glass fibre reinforcement, either within the encapsulant (GFRE) or within the cover material (in first instance at the back, GFRB). **Figure 1** indicates the weight implications for these different buildup options compared to standard glass-glass (GG) and glass-backsheet (GBS) references, with resp. (2×) 2 mm and (1×) 3.2 mm thick glass.

The addition of glass fibres in front of the cells may have a slight impact in the (optical) performance. However, this can be minimized by tuning the optical properties (absorption) of the used glass fibres, and by minimizing the thickness of the material in front of the cells. This last is anyway preferable, as also the optical absorption in the encapsulant increases with its thickness. The scattering due to the interfaces with the encapsulant material can be minimized by matching the refractive index, but a minimal scattering is likely unavoidable. This should not have a significant on the overall performance of the module, but it may cause some increased haze resulting in an impact on aesthetics, that could be important depending on the application.

For the lamination process, we apply typical lamination profiles with an industrial-type laminator, albeit at slightly elevated temperatures, to reduce the risk of cracking cells during the pressure step. Profiles range from 12 min at 145 °C up to 20 min at 165 °C with pressures typically around 700 mbar.

3 Reinforced encapsulant (GFRE)

Here, we replace the front glass with a polymer frontsheet, and provide additional strength by thickening and incorporating glass fibres (GF) into the encapsulant during the lamination of the laminate. This results in a total thickness slightly below 5 mm.

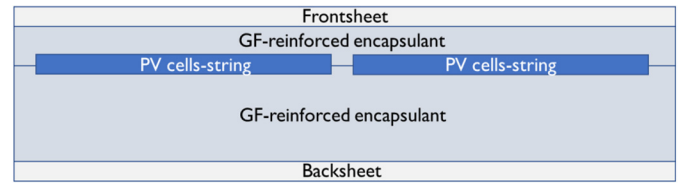


Fig. 2. Schematic buildup of a lightweight module with reinforced encapsulant.

In first instance, we made 2 × 2-cell laminates based on tabbing and stringing of 3BB cells where each string could be measured separately, and we varied in buildup between a commercial EVA and thermoplastic PO encapsulant (from respectively Hangzhou First and Arkema), including glass fibre or not and frontsheet or not. If a frontsheet is included, it is also applied as the backsheet. If there is no frontsheet, there is also no backsheet. Each sample is IV-measured and EL-inspected throughout the thermal cycling they are subjected to.

The mismatch in coefficient of thermal expansion (CTE), in combination with the absence of the front glass, causes significant stresses on the interconnect ribbons during the cooldown after lamination, and results in fatigue failure during thermal cycling between 85 and −40 °C. In all cases the failure mode is interconnect ribbon breakage as has been reported also previously [7,8]. However, incorporating chopped glass fibres in the encapsulant clearly ameliorates this impact, as shown in **Figure 3**. This may be attributed to a reduced “effective” CTE of the glass-fibre loaded encapsulant.

By including GF into the encapsulant, it will thus be possible to avoid this ribbon breakage and meet thermal cycling demands. Checking its potential with shingling as upcoming interconnection technology, with 1/6th silicon heterojunction cells [6], it is also possible to meet thermal cycling demands in the IEC standards and beyond. For this, we prepared laminates with a similar buildup, using shingled strings of 2-cell equivalent length (12 shingles), as well as 1 m long strings. **Figure 4** shows that both lengths can sustain >400 cycles with limited degradation. Interesting to note (in the EL image) is that even the significant initial cracks in 3 shingles, in one of the strings, do not result in major Pmpp degradation during this cycling.

Additionally, we also looked at testing the resilience of such a buildup under dynamical mechanical stress. Sample modules were submitted to random vibrations as experienced by spring mounted vehicle body parts in accordance with the standard for vehicle electronic components ISO FDIS 16750-3 [9]. The vibrations range from 10 Hz to 1000 Hz with a rms acceleration value of 27.8 m/s² and are applied in a direction perpendicular to the module surface during 8 h. Although notable deflections of the sample middle point out of module plane have been observed during the vibration sequences, both the buildup with reinforced PO and the glass-glass references did not show significant damage, as illustrated in **Figure 5**.

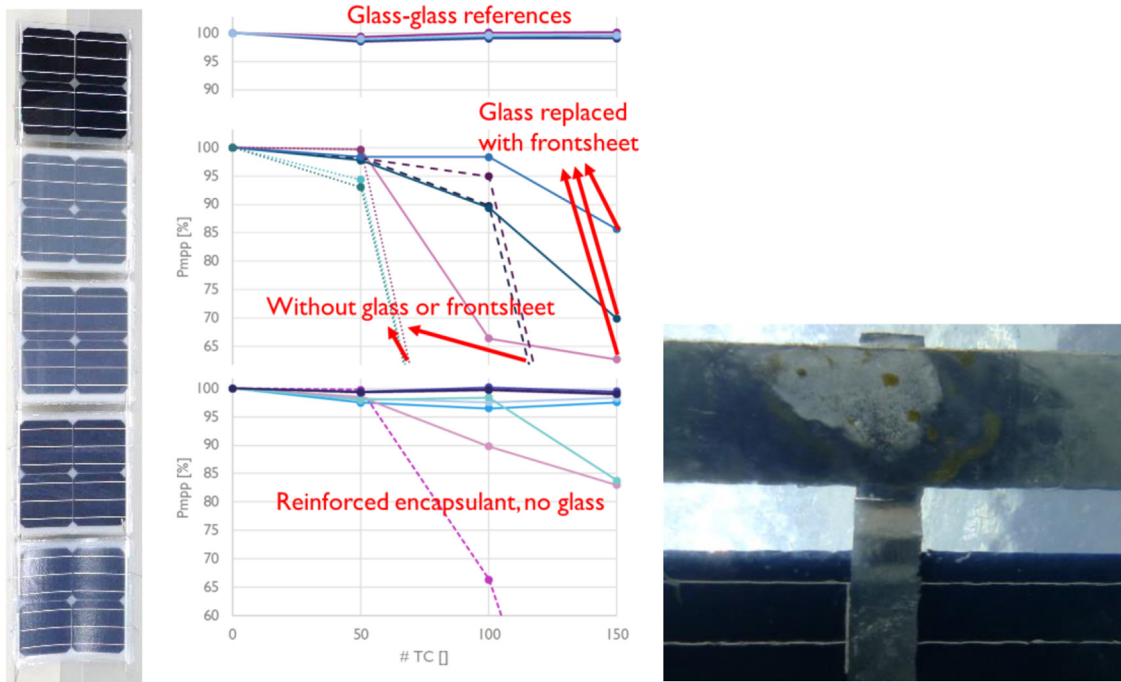


Fig. 3. Thermal cycling (TC) of 2×2 laminates: comparison graphs (center) between degradation in glass-glass laminates (top), versus glassless laminates (center, dotted lines represent samples with only encapsulant, so no cover material as glass or front- or backsheets) and GF-reinforced encapsulants (bottom, with and without cover material); picture of partial ribbon breakage as failure mechanism (right).

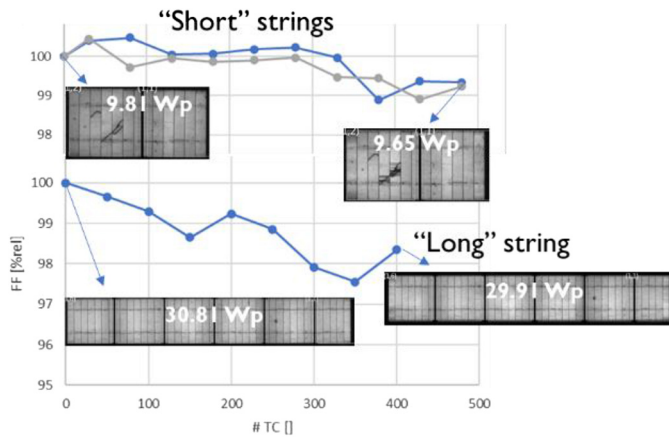


Fig. 4. Evolution of relative FF throughout thermal cycling for 2 short strings and 1 long string based on shingling.

Next to vibrations, another mechanical test assesses the impact of shocks. Using the same setup, such shocks were induced as specified as in ISO FDIS 16750-3, each time 10 shocks of 6 ms, gradually increasing the acceleration of from 50 to 500 m/s^2 . The deflection of the middle point of the sample surface is closely monitored with a laser sensor. This measurement, shown in Figure 6, indicates deflection amplitudes increases linearly with acceleration, with up to 20 mm for the highest acceleration of 500 m/s^2 . Despite this significant deflection compared to the glass-glass reference samples, no significant damage was observed in EL.

Despite the promising results shown above, an important challenge is the mechanical stability at higher temperatures, when the encapsulant becomes too soft and can no longer sufficiently fixate the reinforcement fibres. This deformation is illustrated in the picture in Figure 7, after long-term exposure to damp heat conditions.

4 Reinforced “backsheets” (GFRB)

To ensure stability of the laminate also at higher temperatures, the buildup can be modified. Instead of using the encapsulant as polymer matrix (EVA or PO) for the chopped glass fibres, we implement so-called unidirectional (UD) tapes to provide long (unidirectional) glass fibre reinforcement into a polymer matrix with a higher melting temperature at the backside. Of course, to provide stability not only in one direction, tapes are integrated in perpendicular orientations. The resulting total thickness lies around 3 mm.

In this way, we can similarly reduce the weight, as indicated in Figure 1.

In first instance, we assembled 1-cell laminates using tabbing and stringing of 3 BB cells and subjected them to thermal cycling. The results are shown in Figure 9, with very low, ~linear degradation beyond 600 cycles.

Secondly, we prepared also laminates using multi-wire interconnection of 2×2 busbarless cells, as well as shingled SHJ strings (12 shingles as 2-cell equivalent, similar to the ones in the previous paragraph). For the test, we also

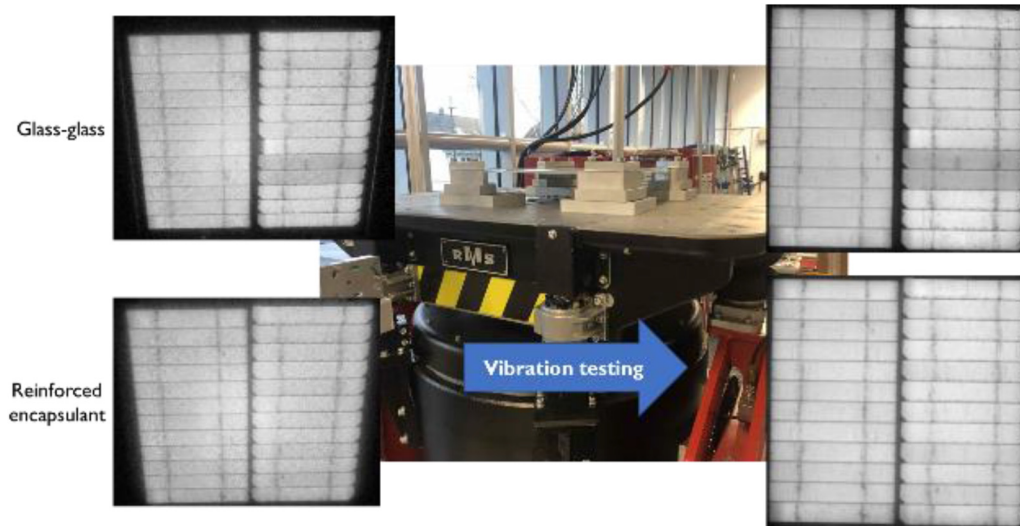


Fig. 5. EL images of a sample buildup with reinforced PO and a glass-glass reference before (left) and after (right) the random vibration testing carried out with a shaker (central image).

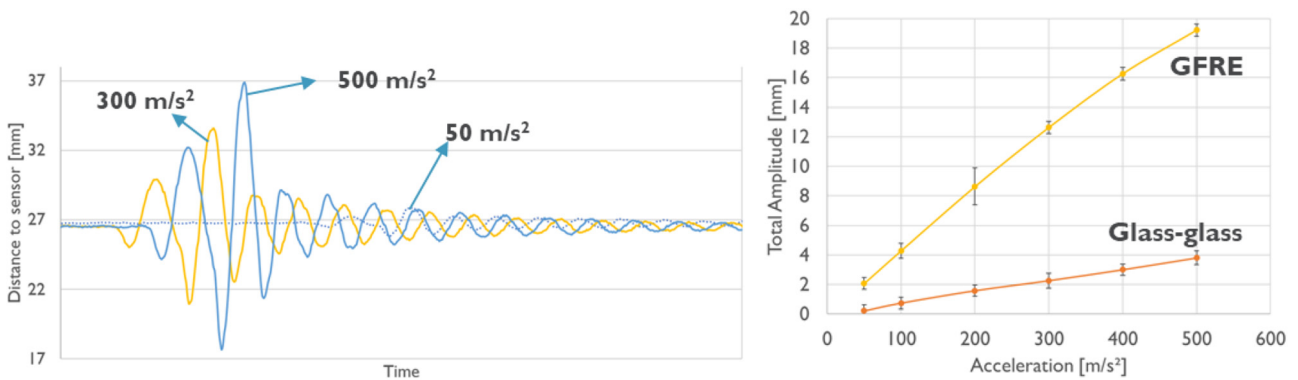


Fig. 6. Measurement of the deflection of the centre of the laminate during shock impact testing for accelerations of 50, 300 and 500 m/s² (left) and (mostly linear) increase of amplitude with increasing acceleration for GFRE vs glass-glass reference laminates.

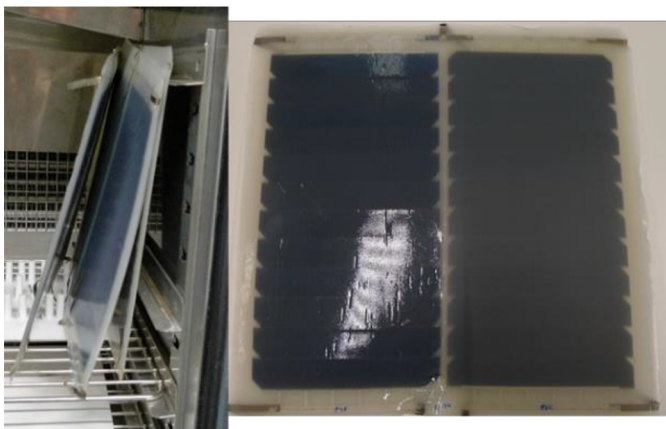


Fig. 7. Deformation of an “encapsulant-reinforced” laminate, due to vertical loading in damp heat conditions.

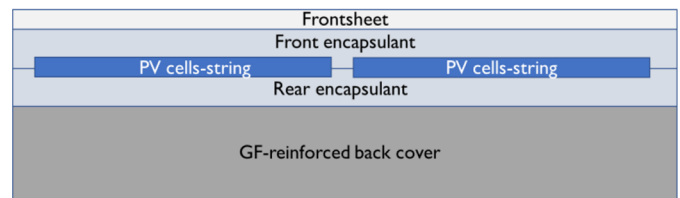


Fig. 8. Schematic buildup of a lightweight module with reinforced encapsulant.

fabricated a reference multi-wire glass-glass laminate. In thermal cycling degradation remains below 2% up to 700 cycles, as illustrated in Figure 10.

Thirdly, random vibrations on these samples did result in minor or no damage observed in EL monitoring, similarly as for the GFRE samples in the previous

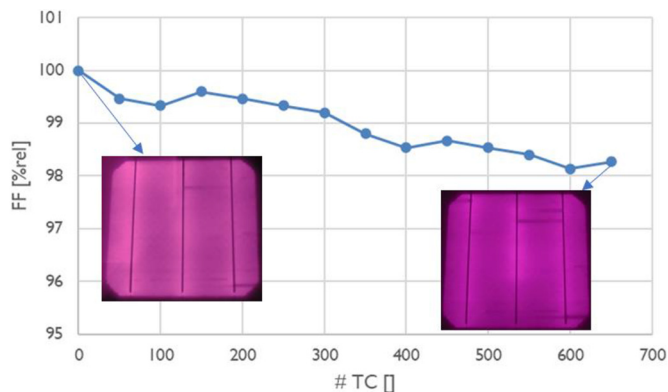


Fig. 9. Relative fill-factor degradation of a 1-cell GFRB laminate throughout thermal cycling.

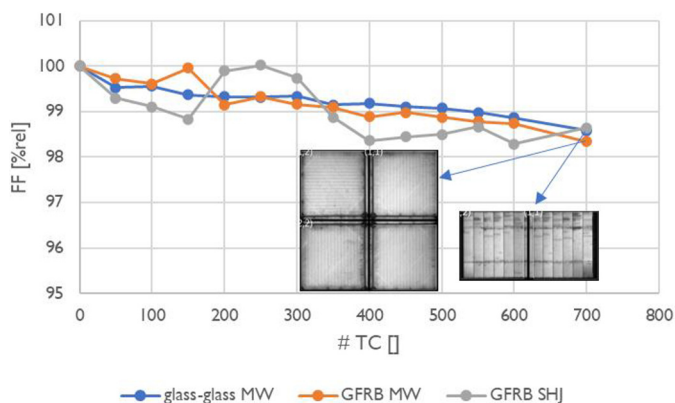


Fig. 10. Relative fill-factor degradation of GFRB laminates up until 700 cycles of GFRB laminates with multi-wire or shingled interconnection, compared to a glass-glass reference multi-wire laminate.

paragraph, as illustrated in Figure 11. Shock testing is currently still in progress.

Fourthly and finally, a screening was also conducted to check on hail impact testing [10]. In this case, ice balls of 25 mm diameter were fired at the laminates at 23 m/s. For this, again 2 × 2-cell laminates were fabricated, based on both multi-wire as well as shingling interconnection, including also reference glass-glass laminates. The main results are illustrated in Figure 12. While the glass-glass laminates did not sustain any significant damage that could be observed with EL, the standard GFRB buildup did not pass the test, with significant losses in power. Increasing the front side encapsulant improves it slightly though. However, if we keep the frontside, and use glass (only) at the backside, the ice balls do not have any significant impact. Based on this, we tried to reinforce the backside encapsulant with glass fibre, yielding some

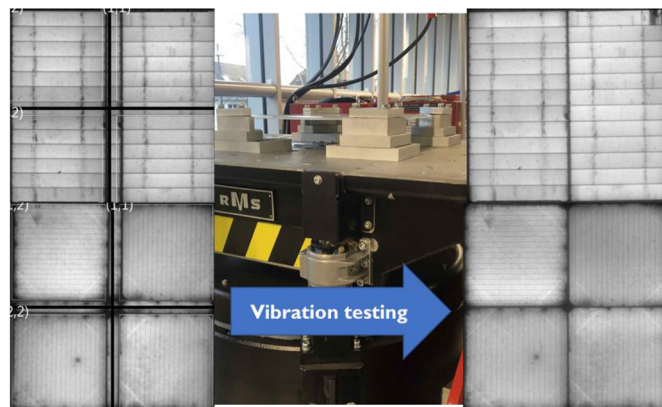


Fig. 11. EL images of GFRB samples with shingling or multi-wire interconnection before (left) and after (right) the random vibration testing carried out with a shaker (central image).

improvement, while a major improvement (no damage observed in EL) could be obtained by doubling the GFRB thickness.

The hypothesis based on our current understanding is that a soft front encapsulant may help to absorb some mechanical impact, while the back cover with the back encapsulant should be stiff enough, and placed close to the cells, to provide the required support during the impact.

Apart from the mechanical impact, also other considerations are important and need to be assessed. In particular for an all-polymer buildup, e.g. damp heat testing, UV exposure and optical characterization will be relevant. To this end we exposed to 1-cell modules to UV in a climate chamber at 60 °C. Figure 13 indicates the limited degradation after 1600 h.

Damp heat testing on the other hand proves more challenging. In all cases, illustrated in Figure 14, we observe significant degradation compared to a glass-glass reference, though not all to the same extent. The severity of this degradation depends on the one hand on the possibility of moisture being able to reach the cells. Using glass on both sides, any moisture is effectively blocked by this layer, and thus moisture needs to get in from the edges. On the other hand, the effect also depends on the sensitivity of the cells to exposure to moisture. From Figure 14 it is clear that the used (bifacial) Al BSF cell (labeled “3BB”) is less sensitive than the Topcon and SHJ cells.

To further illustrate this and indicate potential routes to improve the damp heat resilience, Figure 15 shows how it is possible to limit the degradation in our current GFRB encapsulation stack by integrating a different type of cells (labeled “PERC”), or by changing the encapsulation materials. For the latter case, the “UBSF” label represents samples where the frontsheet has a >1000× lower water vapour transmission rate than the “FSC” samples (<5E−4 g/m²/d; frontsheets are implemented on both sides).

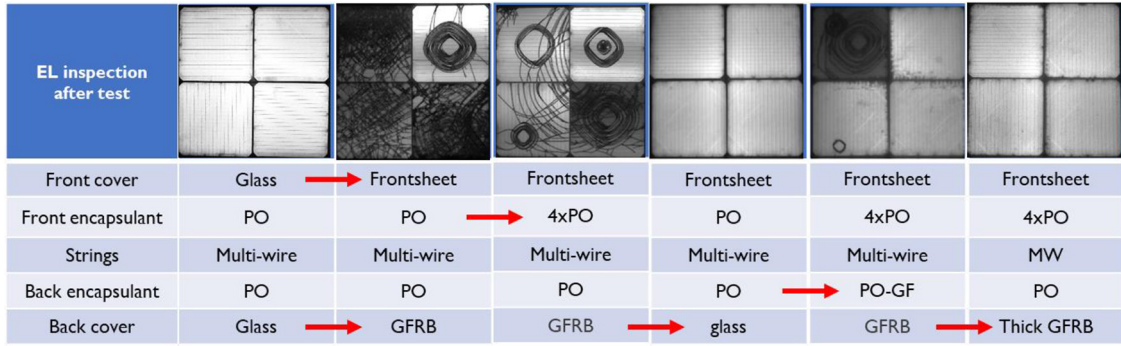


Fig. 12. EL images of the shingled laminates after hail testing. Variations in BOM between the laminate structures are highlighted with red arrows.

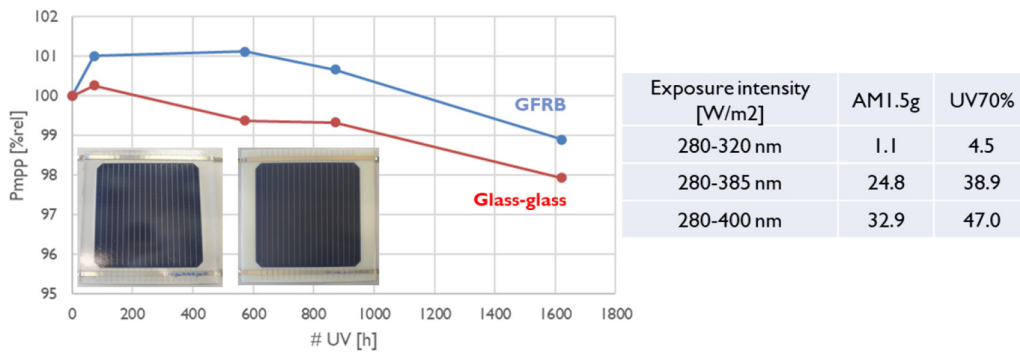


Fig. 13. Pmpp of 1-cell laminates under UV exposure up to 1600 h.

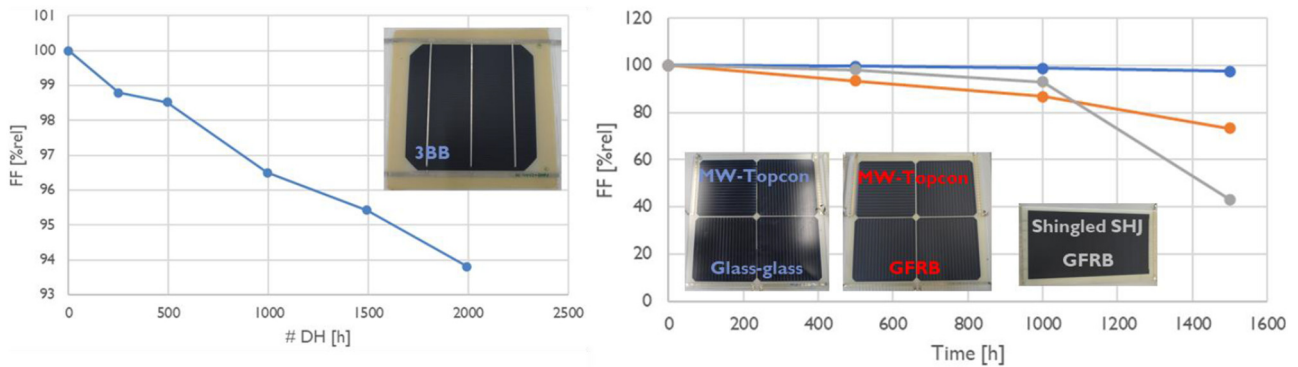


Fig. 14. Damp heat degradation of GFRB laminates compared to a glass-glass reference: a “3BB” Al BSF cell (left), and Topcon and SHJ laminates (right).

5 Conclusion and outlook

In this work we elaborate on the potential of glass reinforcement for PV modules, replacing the glass to reduce their weight. In 2 encapsulation approaches, either reinforcing the encapsulant or reinforcing the back cover, we perform thermo-mechanical tests to determine challenges and opportunities. For its increasing relevance, we include in these tests, apart from industrial tabbing and stringing, state-of-the-art multi-wire and shingled interconnection.

With promising results so far on thermal cycling and vibration testing, and initial (experimental) understanding of the mechanism behind hail impact resilience, further testing is needed to fine-tune the layer buildup to be able to assess the trade-offs with considerations of cost, thicknesses, weight etc. Additionally, simulations could prove very useful for increased understanding and confirmation of the dominant mechanisms, while of course also the impact of boundary conditions remains to be investigated for the mechanical testing (e.g. clamping method and layout).

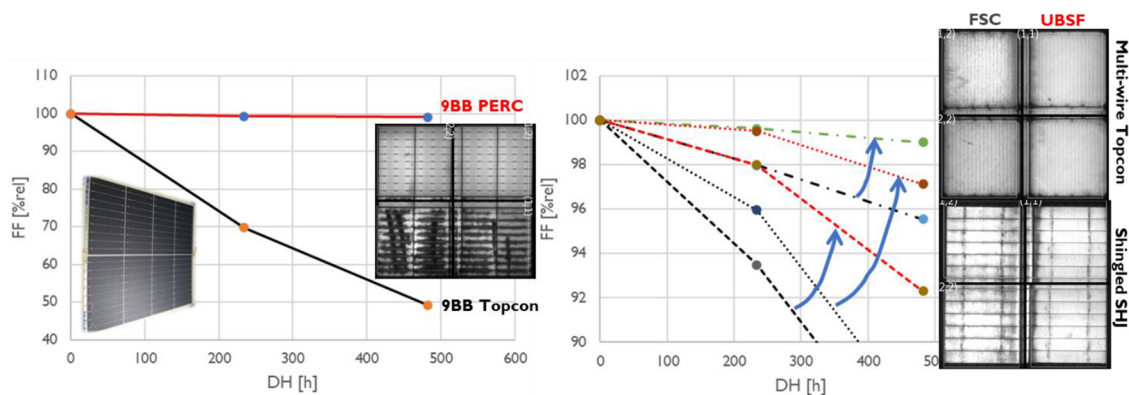


Fig. 15. Damp heat degradation of “PERC” compared to “Topcon” in an identical GFRB stack (left) and the improvement of implementing a frontsheet (“UBSF”, red lines) with a lower WVTR than the standard one (“FSC”, black lines).

Finally, we indicate that apart from the mechanical impact, in particular for an all-polymer buildup, also other environmental testing (damp heat, UV exposure, etc.) is needed and might pose additional challenges, and illustrate it with some first results. Of course the requirements also here will depend on the application with its boundary conditions of expected lifetime (and cost, thickness, weight, etc.

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Author contribution statement

Jonathan Govaerts, Bin Luo, Tom Borgers and Rik Van Dyck conceived the idea and developed it in terms of acquiring the materials. Experimental fabrication was done by the same, with additional help from Lorenzo Cerasti and Marco Galiazzo, in particular for the shingled heterojunction strings.

Environmental tests (thermal cycling, UV exposure and damp heat) and monitoring were conducted by Jonathan Govaerts, Bin Luo and Arvid van der Heide. Vibration and shock testing was set up by Arnaud Morlier, while hail impact testing was performed by Fabiana Lisco. Loic Tous and Jef Poortmans supervised the work on a higher level.

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