HAIL RESISTANCE OF COMPOSITE-BASED GLASS-FREE LIGHTWEIGHT MODULES FOR BUILDING INTEGRATED PHOTOVOLTAICS APPLICATIONS

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ABSTRACT: In this work, we manufacture lightweight (~5 kg/m^2) photovoltaic (PV) mini-modules for building integration replacing conventional glass sheets by a composite sandwich backsheet and a polymeric frontsheet. Our test devices are subjected to hail tests according to IEC 61215 and characterized electrically (to extract IV parameters) and by means of electroluminescence (EL) to visualize the hail-induced damages. The influence of both backsheet stiffness and frontsheet design on the hail test results are presented and discussed. Based on the results, two module design contributions to hail resistance are highlighted: i) a global energy dissipation, mostly related to the backsheet properties, is promoted by the deformation of the entire PV module structure and ii) a local energy dissipation occurs in the frontsheet under the hail impacts. These results clearly show that a balance between frontsheet design and backsheet stiffness has to be found in order to maximize hail resistance while minimizing the module's weight. By combining the ideal backsheet structure with the proper frontsheet layer, we show that a rigid glass-free medium-area module can easily pass relevant hail test with less than 5% power losses.

Keywords: BIPV, lightweight, composite sandwich structures, hail tests, qualification testing

1 INTRODUCTION

Photovoltaic (PV) technology has seen an increase of 50% over 2015, bringing the cumulative installed capacity worldwide to 303 GW in 2016 [1]. Of the global world's electricity demand, ~40% of the consumption is linked to buildings. Further, in several densely-populated countries, only little free-land is available for field PV installation [2]. Development of building integrated PV (BIPV) solutions is thus crucial to the growth of the total installed PV capacity as it enables electricity production with a minimal impact on free land. At European level, the main driver to massively promote the integration of PV into buildings is the Energy Performance in Buildings Directive (EPBD), which foresees that all new buildings in Europe need to comply at least with Nearly Zero-Energy-consumption Building (NZEB) standards by December 31st, 2020 [3]. The EPBD will favor the direct integration of decentralized energy sources in buildings, amongst which PV appears to be the most promising one, unlocking potentially a considerable market in Europe. To make an example, in countries like Switzerland already > 98% of solar installations take place in the built environment, and studies indicate that the use of solar energy in facades could provide up to 15 – 20% of the electricity production needed in urban areas [4]. However, current BIPV solutions suffer some limitations amongst which their relative high weight (>20 kg/m^2) due to the presence of glass as protective front and back layers [5, 6]. In many cases, especially old buildings, the weight loading capacity is limited. For some, rooftops in industrial parks, the limit is less than 10 kg/m^2, thus much lower than a typical PV module weight [7]. Moreover, most industrial buildings built before the 1997 Uniform Building Code (UBC) change are not suitable for conventional rooftop solar installation without costly structural improvements [6]. If lightweight PV modules were available, not only would this market segment be covered, but also other potentially interesting markets, such as that of temporary buildings and/or buildings in developing countries, where the load-bearing capacity of the building is limited, could benefit from this innovation.

Amongst the various types of PV modules, crystalline-silicon (c-Si) PV modules held close to 90% of the PV module market in 2016 [8]. Standard PV modules of c-Si solar cells are typically glass/backsheet modules having a weight of 12-16 kg/m^2, or glass/glass modules weighting 14-17 kg/m^2. For BIPV applications, glass/glass modules are generally preferred for the higher structural stability and for safety reasons. Lightweight PV modules based on glass-glass technology exist. For example, few companies propose a reduction of glass thickness from the standard 3.2 mm up to 0.8mm, achieving weight of 6.5kg/m^2. However, the cost of ultra-thin glass contributes to a considerable increase on PV module cost.

The commercially available lightweight PV modules on the market are predominantly flexible or semi-rigid solutions. The standard glass sheets are substituted by polymeric material as frontsheet and a glass fiber reinforced polymer as backsheet [9, 10] . These lightweight solutions have weights of 2.7-7 kg/m^2. From our laboratory experience, the drawback of these lightweight solutions is related to the long-term performance (reliability), even when the manufacturer claims compliance to IEC/UL certifications.

The aim of this work is to propose a BIPV module design that is contemporarily lightweight, rigid and resistant to hail, solving the problems of installation, supporting structure and reliability at the same time.

2 STRUCTURE OF THE LIGHWEIGHT SOLAR MODULES

The lightweight solar module is achieved by replacing the standard glass frontsheet by a thin transparent polymeric layer and by engineering the backsheet to replace the standard thin polymeric co-laminated PV backsheet by a composite sandwich structure. The presented lightweight module has a final weight of

5 kg/m^2. Figure 1 shows our lightweight design developed for BIPV applications. As one of the critical tests for glass-free solutions is the hail test, we show how the polymeric frontsheet design and composite backsheet stiffness influence the capability of the module to resist hail impacts. The composite sandwich element (based on glass fibers reinforced polymer and a honeycomb core) is intended to provide to the module its entire mechanical stability and is placed at the back of the module stack. Additionally, this lightweight solution is manufactured in a single lamination process, which we use to manufacture the composite backsheet and the full module in a single run. The main concern linked to this new module architecture, where the layer providing the mechanical stability is placed behind the cells and not in front, as in the case of glass/backsheet modules, is linked to its capability to still provide a sufficient protection against environmental degradations and especially against hail impacts. We show here how the composite backsheet and the polymeric frontsheet of our product must be engineered in terms of stiffness and thickness to provide optimal hail resistance.

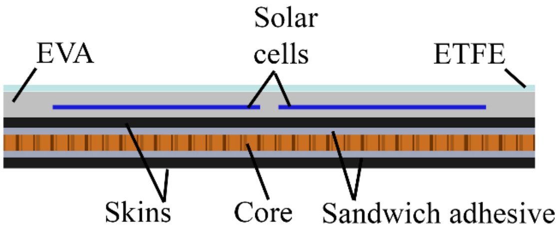

Figure 1: Sketch of lightweight PV module design for BIPV applications.

3 EXPERIMENTAL WORK

3.1 Mini-modules production

Two-cells (156 x 156 mm^2 Al-BSF c-Si solar cells with 3 busbars) mini-modules are produced according to Figure 1.

3.1.1 Influence of composite sandwich structure

To study the influence of the backsheet on the resistance to hail impact we prepare mini-modules using a constant frontsheet made of 100µm fluorine-based polymer (ETFE) and 900µm ethylene-vinyl acetate (EVA) and changing the composite backsheet materials or processing to tune its stiffness. The composite sandwich backsheet is made of glass fiber reinforced polymer (GFRP) skins (~0.7 mm thick) glued to a light honeycomb core (6 mm thick). The materials and process used to glue the skins to the core are varied to tune the final sandwich bending stiffness. The mini-modules composed of BS_1, BS_2 and BS_3 are processed in a vacuum-bag laminator in a single run by using conventional PV encapsulants. The mini-module composed of BS_4 is produced in a two-steps process. In a first step the solar cells are laminated to a single skin (see Figure 1) by using a simple lamination process. This proto-module composed of ETFE / EVA / solar cells / EVA / skin is then, in a second step, introduced in a vacuum bag to bond to the core and the other skin by using a liquid thermoset material (epoxy). This vacuum bag process takes 24h for a full adhesive crosslinking. Table I shows the bending stiffness of the composite sandwich structures selected for this study and measured by four-points bending test [11]. For each backsheet configuration, three mini-modules are prepared and subjected to a hail test.

Table I: Composite sandwich bending stiffness measured in four-points bending tests.

	Bending Stiffness, D [N.m^2]
BS_1	4.8
BS_2	6.6
BS_3	8.4
BS_4	11.6

3.2.2 Influence of frontsheet thickness

In order to study the effect of the frontsheet on the hail resistance we evaluate four different frontsheet designs based on ETFE / EVA combinations. For one set of samples (FS_3), an additional glass scrim (GS) layer (17 g/m^2) is introduced. Table II summarizes all test conditions. For this study, the backsheet is kept constant (composite backsheet with bending stiffness of 6.6 N.m^2). For each condition, three identical samples are produced and tested using the same protocol as for the former study.

Table II: Conditions tested to evaluate the impact of the frontsheet design on hail resistance.

	Frontsheet layup			
	Layer 1 polymer	Layer 2 adhesive	Layer 3 polymer	Layer 4 adhesive
FS_1	100um	900um	-	-
FS_2	50um	450um	50um	450um
FS_3	100um	450um	GS-17/m^2	450um
FS_4	200um	900um	-	-

3.2 Hail test setup

Hail test is performed according to IEC 61215-2:2016 [12]. Figure 2 represents the fixation system used and the impact spots selected. Ice balls of 25 mm diameter are shot at a velocity of 23.4 ± 1.5 m/s.

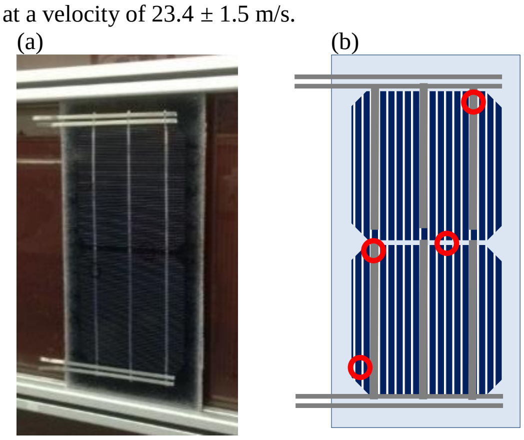

Figure 2: Hail test setup (a) example of fixation system used on two-cell mini-module during the hail test and (b) impact spots for the hail test.

The lightweight mini-modules are hit in four critical locations: (1) at the border of the solar cell, (2) at the electrical connection, (3) in between solar cells and (4) in any point vulnerable to hail impacts.

The electrical characterization of the mini-modules was performed at standard test conditions (STC: AM1.5G, 25°C, 1000W/m^2) by means of current–voltage (IV) characteristics using a LED-halogen based sun simulator.

3.3 Drop-weight test

In a drop-weight test, a weight is dropped on the specimen under test from a given height. Knowing the mass and the height at the start position, we can easily control the impact energy at contact between the two objects. During the test, a weight of 5.5 kg is dropped on a specimen placed at the bottom of the system and the velocity before and after is measured by two light gates placed just above the impact spot. From the measured velocities, the absorbed energy can be obtained as follows:

$$E_{absorbed} = E_{impact} - E_{rebound} \quad (1)$$

The four types of frontsheet presented in Table II are manufactured on the top of a rigid aluminum plate. A replica of three samples per type of frontsheet is tested.

4 RESULTS

4.1 Influence of backsheet stiffness on hail resistance

Figure 3a shows the power and fill factor losses after hail test for each backsheet configuration and Figure 3b shows the corresponding EL image.

(a)

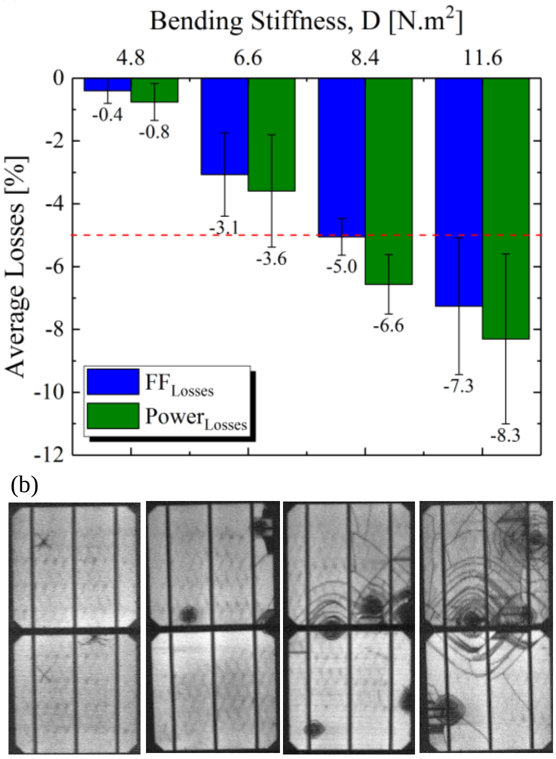

Figure 3: (a) Power and fill factor losses for our mini-modules after the hail test and (b) corresponding EL images. The test devices were manufactured using backsheets with different bending stiffness's.

None of the modules showed any visual damages after hail test (no crack visible to the naked eye). The results show that the power loss increases with the backsheet stiffness, with the maximum acceptable power loss of 5% being reached for a backsheet stiffness between 6.6 and 8.4 N.m^2. The EL images clearly show the change in damage patterns between the 6.6 N.m^2 backsheet for which the negative influence of the hail impact stays localized below the impact point and the 8.4 N.m^2 backsheet for which the damaged zone extends far away from the impact points.

Reducing the backsheet bending stiffness will enhance the resistance to hail of our lightweight PV module. However, it may not always be the ideal solution as it may lead to the need for a stronger support structure depending on the module size and depending on the loading (snow/wind load) it will experience during service lifetime. Therefore, it is equally important to evaluate the potential for hail damage reduction through energy dissipation in the frontsheet.

4.2 Influence of frontsheet thickness on hail resistance

The results summarized in Figure 4 show the fill factor and power loss after the hail test along with the corresponding EL images. As expected, reinforcing the frontsheet by increasing its volume (i.e. the thickness) leads to a decrease of the power loss after the hail test, as can be seen by comparing the results for FS_1 and FS_4. Using a drop-weight test we are able to quantify the energy absorbed by the different frontsheet.

(a)

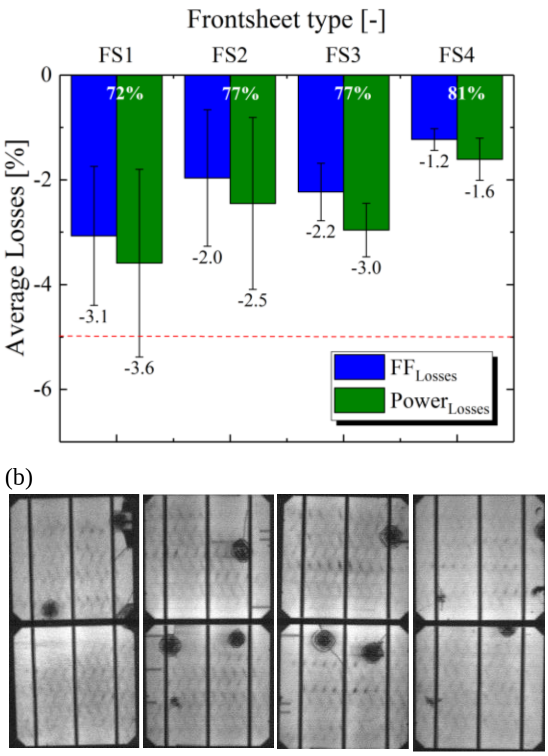

Figure 4: (a) Power and fill factor losses after the hail test for our 2-cells mini-modules with different frontsheet, and (b) the corresponding EL images after the ice-balls impact.

We observe that the frontsheet exhibiting the highest power loss (FS_1) is the one absorbing the less energy (72%). Interestingly, keeping constant the volume of absorbing material but changing the materials layup (FS_1 vs FS_2) leads to a measurable improvement of the power loss by 35%. Again, we measured an increase of absorbed energy of 5% when the frontsheet is reinforced with two interlayers instead of a single thin layer. These results suggest that the presence of double interlayers contributes to the absorption of higher amount of energy during the impact. Moreover, we also see (FS_2 vs FS_3) that the glass scrim layer of 17 g/m^2 can be used to substitute one of the 50-µm fluorine-based polymer layer resulting in a thinner frontsheet showing equivalent hail resistance but improved thermal behavior thanks to the presence of the glass fibers. The FS_4 is the frontsheet that absorbed higher energy (81%) and consequently, is the one that show lower power loss.

4 UPSACALING: FROM MINI- TO MEDIUM-AREA MODULES

Targeting the upscaling of our mini-modules, we demonstrate that we are able to manufacture medium-area modules composed of 16 cell and we subject them to the IEC hail test as well. A medium-area module composed of a sandwich bending stiffness of 10 N.m^2 and a FS_1 is produced. Based on the IEC 61215-2 the hail test is performed after the damp-heat (DH) test (*Sequence E*). For this reason, before testing the resistance to hail of the medium-area module, we decided to aged it to meet the requirements presented in [12]. After lamination, the modules are characterized electrically and solar cells cracks identified by help of electroluminescence test. As a check, the leakage current test is performed as well before and after each test as required in IEC 61215 [12]. Following the initial characterization, the modules are introduced in DH for 1000h and subsequently to the hail test. The following impact spots are selected:

1. A corner of the module
2. Edge of the module
3. Edge of circuit (individual cell)
4. Close to the mounting structure
5. Any point which may prove especially vulnerable to hail
6. A point farthest from the above-selected points.

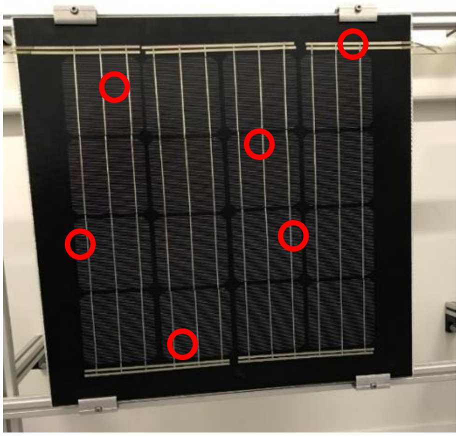

Figure 5: Medium-area module with indication of the impact spots used for the hail test.

Figure 5 shows the impacts locations considered and the fixation system. The test is performed considering the same test conditions as the ones used with the mini-modules (ice balls shot at 23.4 m/s with one-meter distance from canon). A moderate degradation is obtained after full *Sequence E*, being lower than the 5% pass/fail criterion set in the IEC standard. Moreover, the leakage current measure after both degradation tests is higher than the 40 MOhm·m^2 threshold to pass the test. Beside the good electrical performance, the EL images show small localized cracks due to the impact of the ice balls during the test (Figure 6). The presence of these small localized deformations can still be improved by using a frontsheet able to absorbed higher energy and thus reduce the amount of energy transfer to the solar cells. Moreover, the frontsheet used in the realization of the medium-area modules is the one exhibiting the weakest resistance to hail (FS_1), as can be seen in Figure 4.

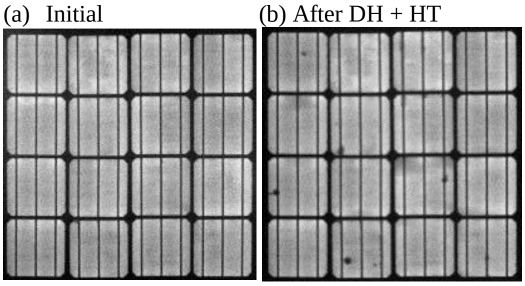

Figure 6: EL images of medium are modules composed of a stiff composite backsheet and a thin polymer frontsheet.

5 CONCLUSIONS

In this study, we show that we are able to manufacture a lightweight glass-free module with a rigid composite sandwich backsheet weighing 5 kg/m^2.

We show that the stiffness of the composite backsheet has a strong impact on the hail resistance, with a reduction of the hail induced damages for the low stiffness backsheet. This effect is attributed to a global energy dissipation of the hail impacts through the entire structure. Concerning the frontsheet, we show that not only the volume (thickness) of the polymeric frontsheet has a strong impact on resistance to hail, but that the distribution of materials in the thickness can further help mitigating hail induced damage. This effect is attributed to a local energy dissipation of the hail impact below the impact point.

Finally, we show that by using the correct trade-off between reinforcing the frontsheet and backsheet stiffness, it is possible to produce a lightweight glass-free module, with a thin polymer frontsheet and a rigid composite backsheet that passes *Sequence E* (DH+HT) of IEC 61215:2-2016.

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