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Interim report dated 26.10.2023

Delight

Design and Evaluation of Lightweight Composite PV Modules for Integration in Buildings and Infrastructure

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Zusammenfassung

Um die ehrgeizigen Ziele der Dekarbonisierung der europäischen Wirtschaft zu erreichen, sind enorme Anstrengungen erforderlich. Die Integration von PV in die bestehende Infrastruktur ist einer der Hauptpfeiler, um die Ziele für erneuerbaren Strom zu erreichen, insbesondere in Ländern, in denen nicht genügend freies Land für den Bau großer PV-Anlagen vorhanden ist: sei es, weil sie dicht besiedelt sind (Niederlande, Belgien) oder gebirgig sind (Österreich, Schweiz). Um dies erfolgreich zu erreichen, ist eine gleichzeitige Optimierung des Energieertrags und der Kosten, aber auch des Modulgewichts, der Ästhetik, der Zirkularität, der Zuverlässigkeit und der Sicherheit erforderlich. Das DELIGHT-Projekt bündelt Fachwissen in all diesen Bereichen und wird äußerst attraktive und einzigartige Lösungen für die Integration von PV entwickeln, um energiepositive Gebäude zu ermöglichen. Ziel des DELIGHT-Konsortiums ist es, nachhaltige, leichte Verbund-PV-Module für eine einfachere Integration in die bestehende Infrastruktur zu entwerfen, herzustellen und zu bewerten, mit besonderem Schwerpunkt auf erhöhter Sicherheit, optimierter Ästhetik und konstruktiver Integration. Die Hauptziele sind: (1) Reduzierung des Modulgewichts der PV-Module und des Bausystems, Erreichen eines Gewichtsziels für Module von ≤6 kg/m² (glasfrei) und ≤7 kg/m² (Ausführung mit Frontglas) für rahmenlose Fullsize-Leichtbaumodule. (2) Erfüllung der Anforderungen an ästhetische Integration durch den Einsatz neuartiger, farbiger Komponenten und Beschichtungen, alternative zuverlässige PV-Module, die sich leicht in Gebäude und Infrastrukturen integrieren lassen. (3) Optimierung des elektrischen Moduldesigns im Hinblick auf verschattungstolerante Modultopologien, Verbesserung der Leistung, Sicherheit und Zuverlässigkeit bei teilweiser Verschattung (Modulabschaltung; Abschaltung beschädigter Teilstränge; Reduzierung oder Beseitigung von Hotspots). Ein weiteres Querschnittsziel ist die Steigerung der Gesamtnachhaltigkeit der Leichtbaumodule und ihrer Komponenten. Konkrete Ziele sind der Ersatz von Fluorpolymer-Frontfolien durch Lösungen auf Basis beschichteter Polyesterfolien oder der Einsatz von recyceltem PET für die Wabenstrukturen. DELIGHT wird diese neuen Konzepte und Lösungen (z. B. Farbgebung, Verbund-Rückseite, Montagelösungen, Polymer-Frontplatte usw.) auf einen ausreichend hohen TRL (6-7) bringen und so das Ökodesign verbessern, während Leistung, Qualität und Zuverlässigkeit erhalten bleiben. Ziel des Projekts ist die Realisierung eines nachhaltigen und wettbewerbsfähigen PV-Produkts, das vollständig in der EU entwickelt, hergestellt und optimiert wird, um mit hoher Qualität und Vertrauen zum europäischen Markt beizutragen.

Résumé

Atteindre les objectifs ambitieux de décarbonisation de l’économie européenne nécessite un effort considérable. L'intégration du photovoltaïque dans les infrastructures existantes est l'un des principaux piliers pour atteindre les objectifs en matière d'électricité renouvelable, en particulier dans les pays où il n'y a pas suffisamment de terrains libres pour construire des centrales photovoltaïques à grande échelle: soit parce qu'ils sont densément peuplés (Pays-Bas, Belgique), soit parce qu'ils sont montagneux (Autriche, Suisse). Pour y parvenir, il faut optimiser simultanément le rendement énergétique et le coût, mais également le poids, l’esthétique, la circularité, la fiabilité et la sécurité des modules. Le projet DELIGHT rassemble des expertises dans tous ces domaines et développera des solutions très attractives et uniques pour l'intégration du photovoltaïque, afin de permettre des bâtiments à énergie positive. Le consortium DELIGHT vise à concevoir, fabriquer et évaluer des modules photovoltaïques composites légers et durables pour une intégration plus facile dans l'infrastructure existante, avec un accent particulier sur une sécurité accrue, une esthétique optimisée et une intégration constructive. Les principaux objectifs sont: (1) Réduire le poids des modules photovoltaïques et du système de construction, en atteignant un objectif de poids pour les modules de ≤6 kg/m² (sans verre) et ≤7 kg/m² (conception avec verre frontal) pour les modules légers pleine grandeur sans cadre. (2) Répondre aux exigences d'intégration esthétique grâce à l'utilisation de composants et de revêtements nouveaux et colorés, des modules PV alternatifs fiables et faciles à intégrer dans les bâtiments et les infrastructures. (3) Optimisation de la conception du module électrique en ce qui concerne les topologies de modules tolérantes à l'ombre, amélioration des performances, de la sécurité et de la fiabilité sous ombrage partiel (arrêt du module; déconnexion des sous-chaînes endommagées; réduction ou élimination des

points chauds). Un objectif transversal supplémentaire est d'augmenter la durabilité globale des modules légers et de leurs composants. Les objectifs spécifiques sont le remplacement des feuilles frontales en polymères fluorés, par des solutions à base de films polyester enduits ou l'utilisation de PET recyclé pour les structures en nid d'abeilles. DELIGHT amènera ces nouveaux concepts et solutions (par exemple, coloration, feuille arrière composite, solutions de montage, feuille avant en polymère, etc.) à un TRL suffisamment élevé (6-7), améliorant l'écoconception, tout en conservant les performances, la qualité et la fiabilité. Le projet vise la réalisation d'un produit photovoltaïque durable et compétitif, entièrement conçu, fabriqué et optimisé dans l'UE, pour contribuer au marché européen avec une qualité et une confiance élevée.

Summary

Achieving the ambitious targets of decarbonizing the European economy requires a huge effort. Integration of PV into existing infrastructure is one of the main pillars to reach the targets for renewable electricity, especially for countries where there is not enough free land to build largescale PV plants: either because they are densely populated (Netherlands, Belgium) or mountainous (Austria, Switzerland). Doing this successfully requires simultaneous optimization of energy yield and cost, but also module weight, aesthetics, circularity, reliability, and safety. DELIGHT project brings together expertise in all these areas and will develop highly attractive, and unique solutions for the integration of PV, to enable energy-positive buildings. The DELIGHT consortium aims to design, manufacture, and evaluate sustainable lightweight composite PV modules for easier integration into existing infrastructure, with a special focus on increased safety, optimized aesthetic, and constructive integration. The main targets are: (1) Reducing the module weight of the PV modules and the construction system, achieving a weight target for modules of ≤6 kg/m² (glass-free) and ≤7 kg/m² (design with front glass) for frameless full-size lightweight modules. (2) Fulfilling the demands for aesthetic integration by use of novel, coloured components, and coatings, alternative reliable PV modules easily to integrate into buildings and infrastructures. (3) Optimizing the electrical module design in respect to shade tolerant module topologies, improving performance, safety, and reliability under partial shading (module shut-down; disconnection of damaged substrings; reduction or elimination of hot-spots). An additional cross-sectional objective is to increase the overall sustainability of the lightweight modules and their components. Specific targets are the replacement of fluoropolymer front sheets, with solutions based on coated polyester films or the use of recycled PET for the honeycomb structures. DELIGHT will bring these new concepts and solutions (e.g., colouring, composite back sheet, mounting solutions, polymer front sheet, etc.) to sufficiently high TRL (6-7), improving eco-design, while retaining performance, quality, and reliability. The project aims at the realization of a sustainable and competitive PV product, entirely designed, manufactured, and optimized in the EU, to contribute to the European market with high quality and trust.

Contents

1. Introduction

Solar PV is set to play a major role in achieving the EU's 2030 renewable targets and commitment to carbon neutrality by 2050. There is a need to ensure comparability in the market between module energy yield claims, long-term stability of module performance, and carbon footprint. This would help both private and public buyers. It is noteworthy that the use of PV modules and systems to improve the energy efficiency of public buildings is expected to increase significantly in the coming years. Integration of PV into existing infrastructure and buildings is one of the main pillars to achieve renewable electricity expansion goals, especially in densely populated countries such as Belgium and the Netherlands but also in mountainous countries e.g., Austria, and Switzerland there is not enough open land to build large PV power plants. There is a growing demand from the market for BIPV solutions and we already have some examples of beautiful integrated PV installations starting to take place [1], [2].

These combine the concept of a lightweight, load-bearing structure with integrated solar panels over the entire surface. Therefore, not only these countries, but also the European Commission pushes for integration of PV into buildings to enable zero emission or even energy positive buildings within the Building Renovation Wave strategy and the European Bauhaus initiative [3]. In the EU, 30 to 40 percent of existing commercial building roofs are not suitable for the installation of solar panels due to static concerns [4]. This certainly also applies to the roofs of agricultural sheds and stables, where old asbestos roofs will have to be replaced in the coming years, a total of 70 km^2 in the Netherlands alone. A similar situation applies to other EU countries. Furthermore, in many applications of infrastructure-integrated PV, e.g. industrial flat roofs and facades, the weight requirement is the bottleneck to be addressed.

However, as previously mentioned, current PV modules are too heavy (> 12 kg/m^2 and much more in the case of glass/glass designs) for many PV applications. With our DELIGHT project, we are aiming for lightweight PV modules with a weight of $\leq$6 kg/m^2. This is a huge 50% weight reduction, making it possible to install solar panels with much more flexibility, even in previously excluded locations. This means that there is a largely untapped market potential available in the EU market, which can only be addressed by innovative and lightweight BIPV solutions. It is expected that by the time the lightweight PV market becomes more competitive (3 to 5 years from now), this consortium will already be leading the PV market, and DELIGHT will be able to expand further, in a market where the demand for this type of product is increasing.

The main result of the project will be optimized approaches for sustainable lightweight composite PV modules and solutions for easier integration into existing infrastructure and buildings. Two approaches will be pursued:

1) a glass-free module design with a weight target of $\leq$ 6 kg/m^2
2) a frameless module design with front glass with a weight target of $\leq$ 7 kg/m^2.

The project will also introduce novel integration approaches for PV in Buildings, proposing alternative mounting solutions (e.g., sustainable adhesives, Velcro) to the conventional ones currently available in the market. These solutions are enabled by the lightweight PV module design and allow for more architectural freedom. Lightweight modules and innovative mounting structures also allow for easier integration of PV into existing infrastructure with reduced load capacity.

The module design also includes an increased shading tolerance compared to currently available solutions. Optimized shadow-tolerant solutions (topology and embedded electronics) are identified with respect to (1) the highest shading tolerability among the different considered solutions and (2) major safety improvements. Fire protection is of particular importance, as lightweight modules have a much higher polymer content compared to standard modules and lack the fire-retarding effect of the front glass. A redesigned PV module topology in terms of number of substrings, their length (number of PV cells per substring), and their position/interconnection, will avoid reverse breakdown (reduction or elimination of hot-spots, therefore improving reliability, lifetime, and safety) and increase PV module granularity for higher energy yield under partial shading. As a side result, also an enhanced modeling framework will be set up, which is capable of modeling colored PV modules in complex geometries, to give a digital prototype of appearance and lifetime energy yield.

Within the project, the consortium will demonstrate the longevity of lightweight modules containing the new components, to highlight their excellent properties for building and infrastructure integration. Special attention will be given to the investigation of the degradation behavior and possible material interactions and/or (in)compatibilities of the newly introduced components and their influence not only on module efficiency and reliability, but also on visual impression and aesthetic integration. A demonstration site (~10 m^2) with the developed lightweight PV modules and the novel systems of integration, which are advanced within the project, will be realized by EPFL and Kalyon. DELIGHT PV modules with innovative integrated materials and some lightweight PVs produced by Solarge and Kalyon, will be the focus of the demonstrators. Different option of colored encapsulants will be considered and shown in the demonstrator. Conventional modules will be installed side-by-side, which will be used as a benchmark technology.

The demo site will allow constant monitoring of the integrated PV products, tracking their performance and collecting data (electrical parameters, temperature, irradiance) useful to to follow the performances of the DELIGHT PV structures over time and further understand any possible (if any) degradation mechanism. Flexible automated manufacturing at Solarge and Kalyon‘s facilities will improve the quality, compared to often handcrafted BIPV products, and allow to scale towards mass customization at competitive costs. Colouring of the modules (e.g., coloured encapsulants or printing at the front side of the modules) will allow more freedom of design for an aesthetical integration of the PV modules adapted to its surrounding, finding a balance between aesthetical integration and energy yield.

Furthermore, the project will also provide suitable performance indicators for integrated PV modules based on the guidelines defined by IEA-PVPS Task 15 that allow for a better comparison of different types of integrated PV-systems. This includes energy-relevant, economic, environmental, and visual performance indicators.

- Economic and environmental benefits and contribution to SET-plan objectives:

  The project aims at significant carbon footprint reduction (> 50%) for the developed lightweight module designs. The reduction will be achieved mainly by (1) using Kalyon PV PERC cells, manufactured in Turkey using a fully integrated production site (wafer, ingot, cell, etc.), enabling much lower carbon footprints than imported PERC cells from China, and (2) by removing the aluminium frame. An additional benefit will come from replacing the front glass in the case of composite modules. Additional measures will be the integration of recyclable, or even recycled materials into the PV stacks, while still providing high performance and durability. This includes the use of recycled PET (95% aspirated recycling content) for the composite back sheets, the use of non-fluorinated polymer front sheets based on coated PET and of thermoplastic encapsulants.

- Commercialization

  For the business partners involved, the successful project outcome, namely delivering reliable lightweight PV modules for easy integration, will certainly help to further push the market penetration of infrastructure integrated PV. Currently, the need for lightweight solutions for PV applications is high. The consortium is convinced that this is the right time and, within the SOLAR Era network, the right place, to push the research studies and give the DELIGHT PV modules a chance for industrialization. We see the possibility to improve our work from a sustainable, productive, and reliable point of view thanks to this strong and strategic network we have built within DELIGHT proposal.

  For all scientific institutions, the main objective of the DELIGHT proposal is to build know-how through active collaboration among the scientific institutions of this interdisciplinary consortium. In addition, the developed knowledge will lead to high-quality publications increasing general awareness about the problems encountered and the solutions developed. Fruitful discussions and joint R&D actions of scientific and industrial partners will drastically increase the comprehension of the R&D institutions for the requirements and needs of the industrial partners and facilitate target-oriented research. Furthermore, new research topics will be identified in this way, which can form the basis for future-oriented research.

- Objectives

There are several challenges in the BIPV market today. Next to economic aspects and benefits, which are often not easy to monetize, functional integration of solar power systems is key for large-scale application in the built environment. In such a system, primary building envelope functionalities, (e.g., stiffness, wind and water tightness, roof and facade cladding) need to be combined with the generation of solar electricity. Moreover, there is a strong demand for aesthetically pleasing solutions. Meeting all these requirements at the same time is challenging, but when these challenges can be met, there are huge opportunities in the BIPV market.

Fig. 1: Example of lightweight BIPV solution for agricultural, commercial, industrial roofs where standard PV solutions are not adapted due to weight limitations. Source: Solarge

Therefore, the main objective of DELIGHT is to design, manufacture, and evaluate sustainable lightweight composite PV modules for easier integration into existing infrastructure (buildings, transport infrastructure, see Figure 1) with a special focus on increased safety and optimized aesthetic and constructive integration. The three main pillars of the project are:

- Reducing the module weight of the PV-modules and the construction system by development and optimization of innovative lightweight module designs using polymeric frontsheet materials, replacing glass (e.g., composite backsheets using honeycomb structures), with no frames and the use of innovative adhesive or Velcro fastener connection approaches
- Fulfilling the demands for aesthetic integration by introducing colors and specific surface appearance in the PV module stacks (surface coatings, colored encapsulants) while preserving their mechanical, electrical performances and reliability.

- Optimizing the electrical module design in respect to shade-tolerant module topologies with two main goals: (i) improved performance under non-uniform operating conditions – such as partial shading – and in case of non-uniform module degradation, and (ii) improved safety and reliability (module shut-down; disconnection of damaged substrings; reduction or elimination of hot-spots).

An additional cross-sectional objective is to increase the overall sustainability of the lightweight modules and its components. Specific targets are the replacement of fluoropolymer frontsheets with solutions based on coated polyester films or the use of recycled PET for the honeycomb structures.

1.1. Timeline

The consortium is working towards achieving results defined under various work packages. For this three-year project, about one-third of the time has elapsed so far. As can be seen in the table 1 below, the main deliverables of the project are due in the advanced stage of the project, i.e., in the second and the third year of the project. EPFL is the leader for the WP-3 wherein the deliverables are to come-up with a test design (T 3.1) and perform the reliability testing (T 3.2). EPFL is also involved in other work-packages for activities such as T 2.2 (Module components), T 2.4 (validation and demonstration), T 4.3 (Demonstrators at system level), T 5.3 (Energy yield measurement). Results from various work-packages (WP) are described in the section 3 of the report.

Table 1: Status of the Deliverables & Milestones

			Year 1				Year 2				Year 3			
			Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	1	**Project Coordination**												
	1.1	Project Management												
	1.2	Dissemination & Exploitation												
	2	**Innovative module design & manufacturing**												
	2.1	Cell Optimization												
EPFL	2.2	Module components												
	~~2.3~~	~~Shade resilient module design~~												
EPFL	2.4	Validation & Demonstration (Cell & Module level)												
EPFL	3	**Identification of reliability and safety requirements**												
EPFL	3.1	Test design												
EPFL	3.2	Reliability testing												
	4	**Design of advanced integrated PV systems**												
	4.1	Technical integration and fire safety												
	4.2	Optical integration and visual performance												
EPFL	4.3	Demonstrators (System Level)												
	5	**Energy & Economic performance evaluation**												
	5.1	Performance Indicators												
	~~5.2~~	~~Energy yield modelling~~												
EPFL	5.3	Energy yield measurement												

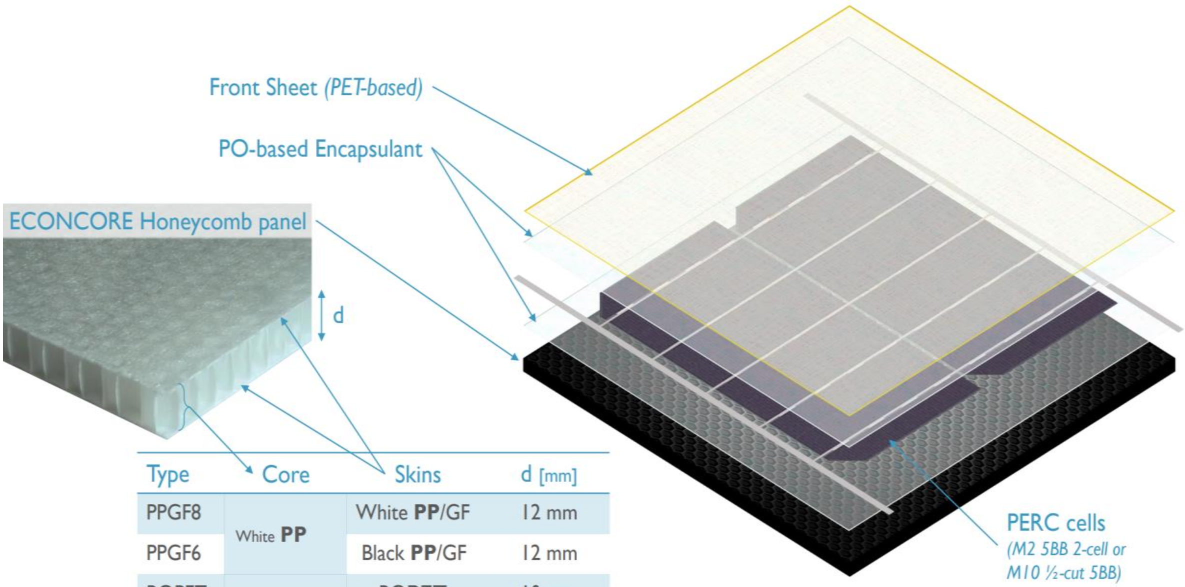
The Dutch part of the project was evaluated by the Dutch funding agency TKI (PPS toeslag). Although the evaluation was positive, the ranking was not sufficient to receive funding. Because of the exit, task 2.3 on optimization of shade resilient design and task 5.2 on energy yield modelling will be eliminated. All other tasks and work packages will be unaffected or compensated for by the remaining partners.

2. Major updates for different work packages

The results from the work-packages 2-5 are presented in this section. EPFL is involved in T 2.2, 2.4, 3.1, 3.2, 4.3 and 5.3. Out these tasks, the deliverables for T 3.2 are due in the Month 12 of the project.

2.1. Results from WP 2 (Innovative module design & manufacturing):

Kalyon and IMEC have worked together to implement standard 5BB M2 size (156.75 mm) PERC cells and larger 10 BB M10 size (182 mm) PERC cells to improve the aesthetics and reduce costs. These cells are manufactured in the integrated factory of Kalyon PV in Türkiye.



Type	Core	Skins	d [mm]
PPGF8	White PP	White PP/GF	12 mm
PPGF6		Black PP/GF	12 mm
BOPET	Black PET	BOPET	10 mm
PETGF		PET/GF	11 mm

Fig. 2: Schematic representation of the honeycomb-skin sandwich and the lay-up of different layers for modules

The sandwich structures to be used in the lightweight modules are prepared by thermoplastically adhering the two skins to the honeycomb core. For this approach, as can be seen in Fig. 2, two core materials, PP and PET are chosen. The white colored PP core is attached with either white PP skins reinforced with the glass-fibers (hereafter called as PPGF8 structure) or black PP skins reinforced with the glass fibers (hereafter called as PPGF6 structure). On the other hand, the black colored PET core is attached either to the bidirectionally oriented PET (hereafter called as BOPET structure) or to the glass-fiber reinforced PET skins (hereafter called as PET/GF structure). These sandwich structures are then stacked with the layers of thermoplastic encapsulant, solar cells, thermoplastic encapsulants, and skins, as shown in Fig. 2. The vacuum lamination was done on the modules at 135°C temperature and 300 mbar membrane pressure. The fabricated modules are depicted in Fig. 3, below.

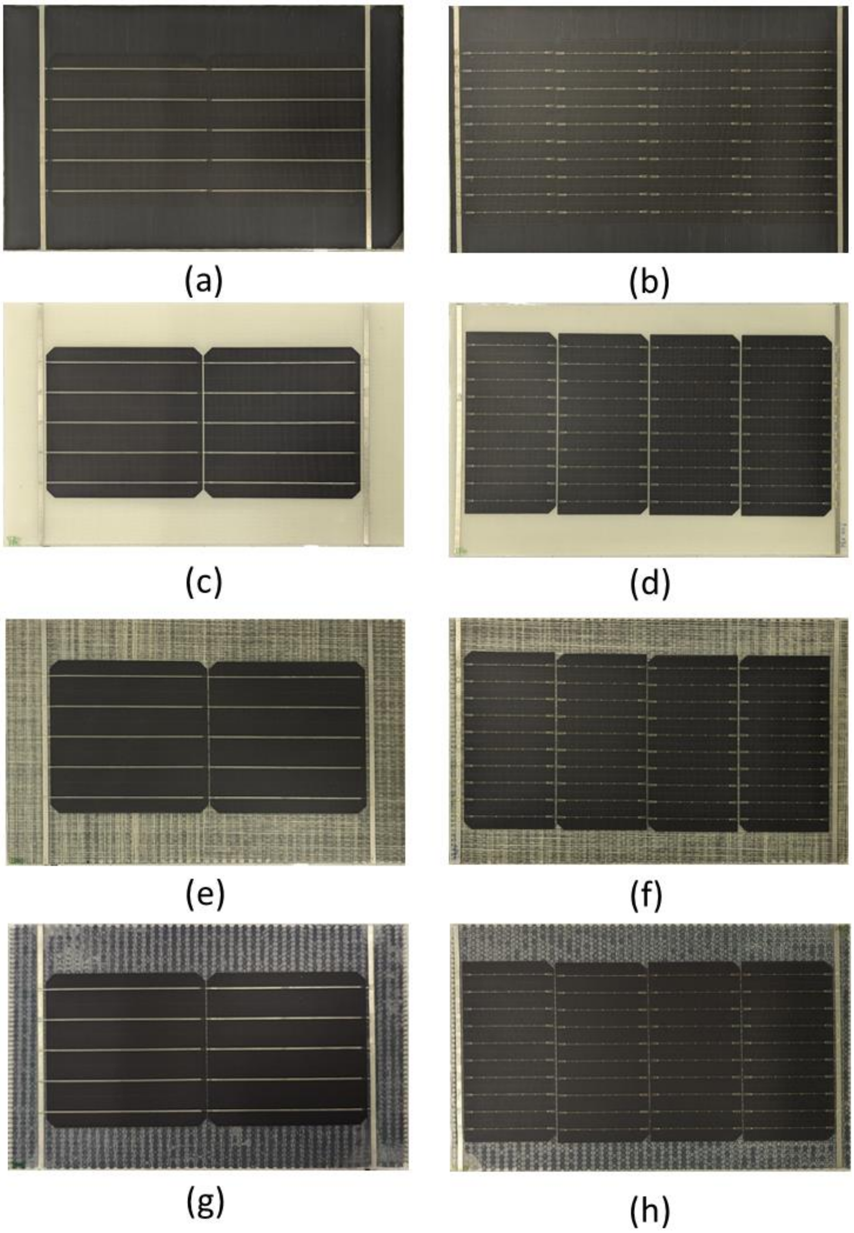


Fig 3: Front view of the modules: PPGF6 structures with (a) M2 size 5BB cells & (b) M10 size 10BB cells; PPGF8 structures with (c) M2 size 5BB cells & (d) M10 size 10BB cells; PETGF structures with (e) M2 size 5BB cells & (f) M10 size 10BB cells; BOPET structures with (g) M2 size 5BB cells & (h) M10 size 10BB cells

The current-voltage characteristics and weight of the modules are provided in table 2 and table 3, respectively.

Table 2: Current-voltage characteristics of the modules described in fig. 3.

Specimen	I_{sc} [A]	V_{oc} [V]	FF [%]	P_{mpp} [W]
5BB_PPGF6	9.56 ± 0.11	1.34 ± 0.00	78.5 ± 0.2	10.05 ±0.12
10BB_PPGF6	6.51 ± 0.08	2.78 ± 0.01	81.3 ± 0.2	14.70 ± 0.20
5BB_PPGF8	9.91 ± 0.17	1.34 ± 0.01	78.3 ± 0.1	10.41 ± 0.20
10BB_PPGF8	6.74 ± 0.07	2.78 ± 0.01	81.1 ± 0.3	15.22 ± 0.16
5BB_PETGF	9.74 ± 0.12	1.34 ± 0.01	78.0 ± 0.1	10.20 ± 0.19
10BB_PETGF	6.60 ± 0.08	2.78 ± 0.00	81.3 ± 0.4	14.92 ± 0.16
5BB_BOPET	9.66 ± 0.13	1.35 ± 0.00	78.3 ± 0.2	10.18 ± 0.13
10BB_BOPET	6.52 ± 0.08	2.78 ± 0.01	81.7 ± 0.3	14.80 ± 0.16
5BB_GLASS	9.92 ± 0.31	1.34 ± 0.01	78.0 ± 0.4	10.39 ± 0.29

Table 3: Weight of the modules described in fig. 3

Specimen	Weight [g]	Weight [kg/m^2]
5BB_PPGF6	450	4.5
10BB_PPGF6	456	4.6
5BB_PPGF8	483	4.8
10BB_PPGF8	487	4.9
5BB_PETGF	421	4.2
10BB_PETGF	426	4.3
5BB_BOPET	334	3.3
10BB_BOPET	339	3.4

2.2. Results from WP 3 (Identification of reliability and safety requirements):

The modules developed under work-package 2 are analyzed for reliability in work-package 3. The modules were therefore subjected to accelerated ageing against environmental stressors such as damp-heat ageing, thermal cycling and humidity-freeze. The reliability of the modules was also tested against hail-stones and the adhesion at encapsulant-skin interface was also assessed before and after the damp-heat ageing.

2.2.1. Test design

At the start of the project, it was decided to understand the effect of individual environmental stressors such as thermal cycling, damp-heat ageing and humidity freeze on the performance of the newly developed LW PV modules. The effect of the individual stressors has been discussed in the next sections of the report.

The consortium has decided to adapt two testing sequences that combine several factors from the IEC 61215-2. Fire safety, wet leakage and effect of hail-impact is considered as critical stressors, in addition to the environmental stressors such as UV radiation, moisture and thermal cycling. The testing sequences, C and E, adapted from the IEC 61215-1 are presented below:

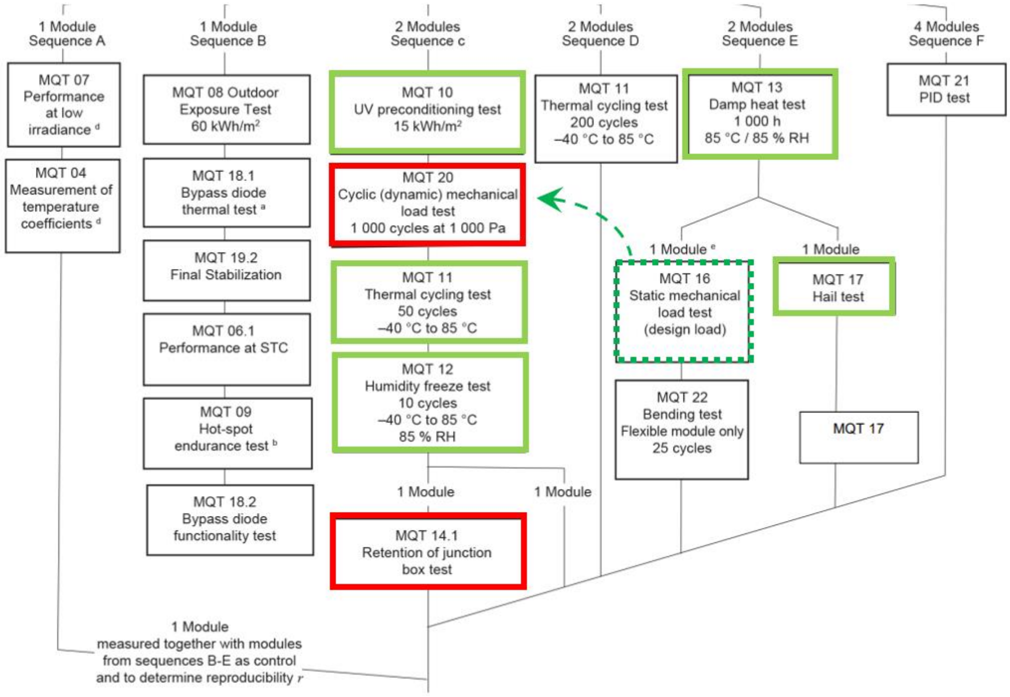


Fig. 4: Selection of testing sequences from IEC 61215-2 standard

2.2.2. Effect of thermal cycling

Figure 5 indicates the performance degradation during TC in terms of FF. The performance at maximum power point (Pmpp) could also be shown but due to the limited degradation so far (in the range of percentages) this would distort the graphs due to variations in Isc related to the calibration accuracy of the solar simulator (as these are also in the lower %-range). Very limited degradation is observed for all 10BB samples, except for the BOPET samples (an additional one, 10BB_BOPET_5, was made as verification after the first one failed early). This sample showed a significant drop in FF and consequently Pmpp beyond 150 thermal cycles. EL imaging in Figure 5 indicates that this is due to an interconnect failure. Though it could be that 1 or more wire got fully detached from the cell metallization, it is more likely that 1 or more wires was broken, a failure mode that has been reported earlier (albeit with ribbons instead of wires) [5].

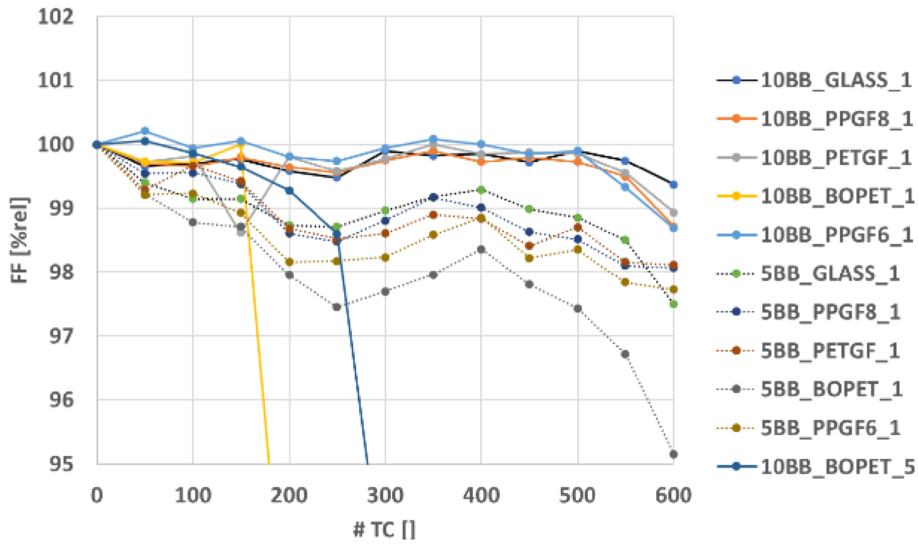
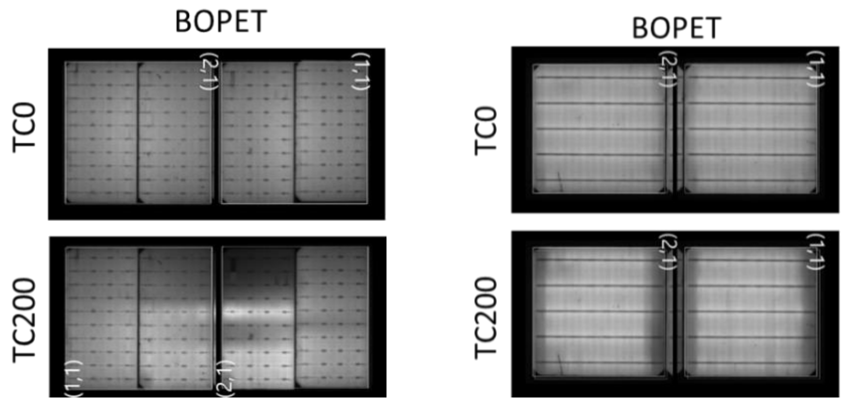


Fig. 5: Degradation in fill factor for different modules during thermal cycling

Figure 5 also indicates a slight but consistent degradation of all 5BB samples compared to the 10BB ones. This might be attributed to a pressure contact at the edges of the cells, which is formed during lamination but is released in subsequent TC. Figure 6 shows the EL footprint of this mechanism for the BOPET sample as a reduced intensity at the edges of the cells, which is also observed for all other 5BB samples. Similarly, as for the 10BB laminates, the BOPET version of the 5BB laminates is the first to fail.



(a) (b)

Fig. 6: (a) EL of 10BB_BOPET sample before (top) and after (bottom) 200 TC and (b) EL of 5BB_BOPET sample before (top) and after (bottom) 200 TC indicating degradation at the edges of the cells.

2.2.3. Effect of damp-heat ageing

During DH testing, for which the results are shown in Figure 7, no significant degradation is observed except for the 10BB_PETGF sample.

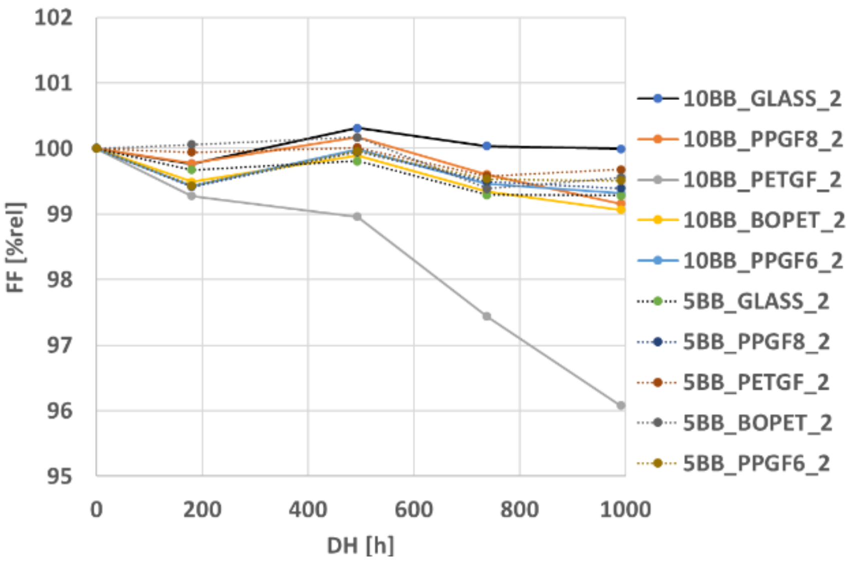


Fig. 7: Degradation in fill factor for different modules during damp-heat ageing

Looking into the EL images before and after DH as shown in Figure 8, some degradation is observed throughout the different cells in the module. It is clear that the degradation is not specifically coming from the edges, and not all cells are affected equally. Unlike with glass-glass encapsulation, where moisture can only gradually get to the cells from the sides, the light-weight (glass fibre reinforced) polymer encapsulation will be less of a barrier due to the higher WVTRs of the polymers. The edges of the honeycomb are also not fully sealed.

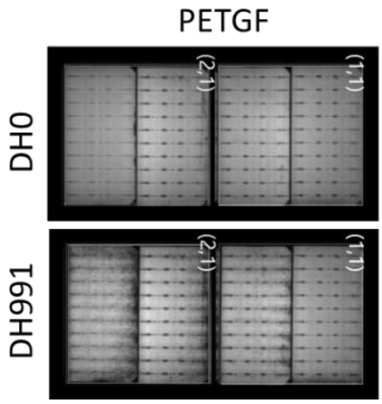


Fig. 8: EL images for PETGF based modules before and after DH ageing

2.2.4. Effect of humidity freeze

HF testing results are given in Figure 9. With the basic test comprising 10 HF cycles, no significant degradation was observed. However, with extended testing to 20 HF cycles, some degradation appears for the 10BB_PETGF sample and to a lesser extent for the 10BB_BOPET sample.

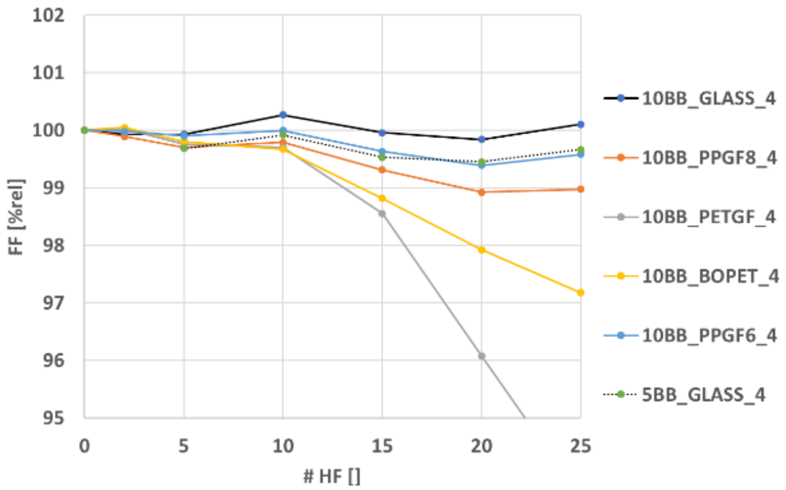


Fig. 9: Degradation in fill factor for different modules during humidity freeze cycling

At first glance, EL imaging after HF (Figure 10) indicates a similar degradation footprint as for DH (Figure 8).

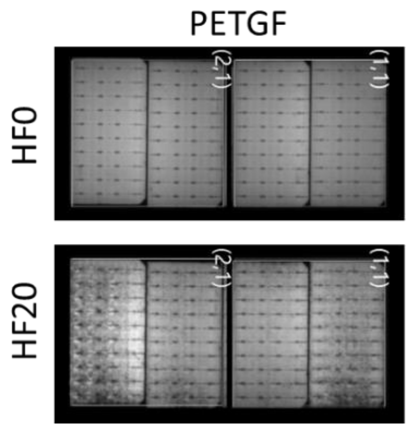


Fig. 10: EL images for PETGF based modules before and after HF cycling

2.2.5. Effect of hail stones

Hail stones of the mass ranging between 6.5-8 g were shot at five different spots on the modules in the range of speed between 21-25 m/s, as per the IEC 61215 standard. The modules are then inspected visually (Fig. 11), under the EL images (Fig. 12) and for the IV characteristics (Table 4).

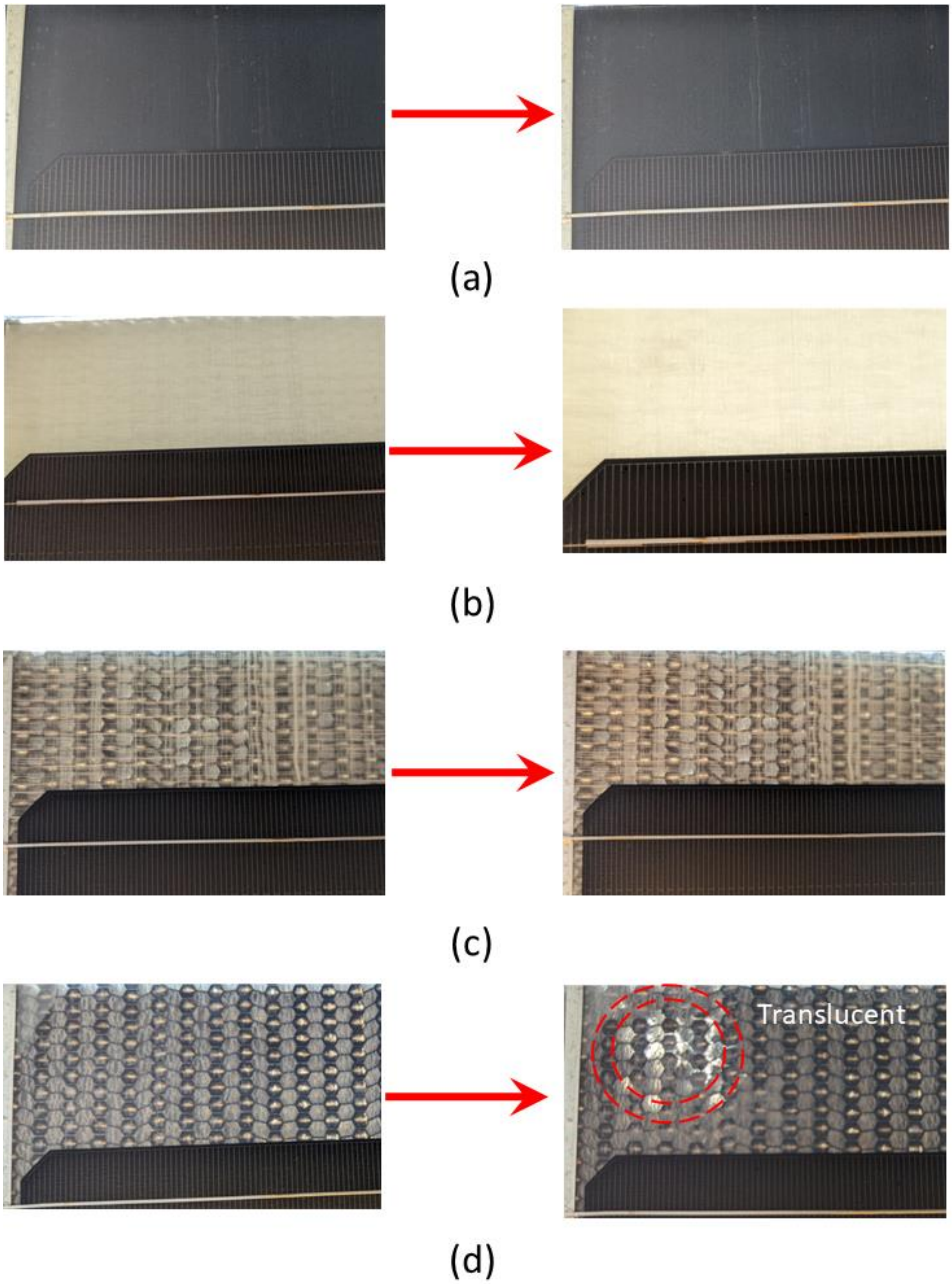


Fig. 11: Visual cues of damage on the modules due to hail-stones: (a) PPGF6, (b) PPGF8, (c) PETGF and (d) BOPET.

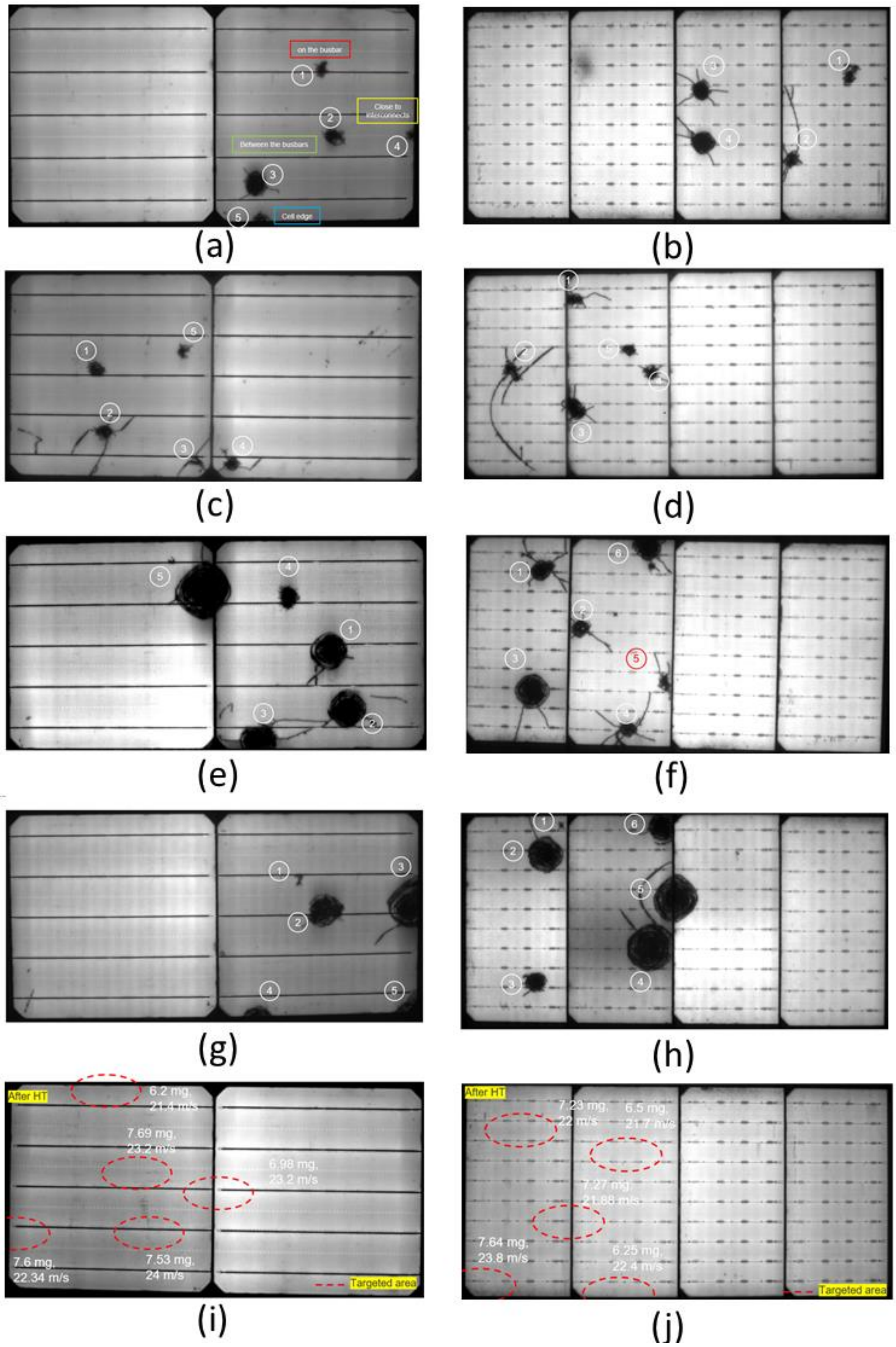


Fig. 12: EL images of the modules after the hail test: PPGF6 structures with (a) M2 size 5BB cells & (b) M10 size 10BB cells; PPGF8 structures with (c) M2 size 5BB cells & (d) M10 size 10BB cells; PETGF structures with (e) M2 size 5BB cells & (f) M10 size 10BB cells; BOPET

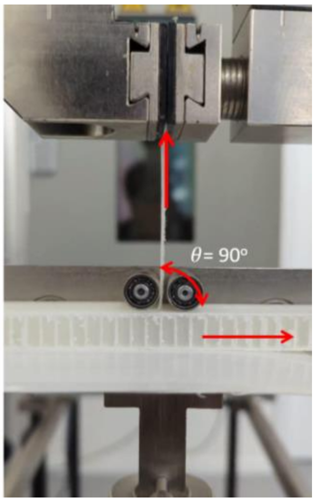
structures with (g) M2 size 5BB cells & (h) M10 size 10BB cells; Glasss/glass reference modules with (i) M2 size 5BB cells & (j) M10 size 10BB cells.

Table 4: IV characteristics before and after the impact of hail stones

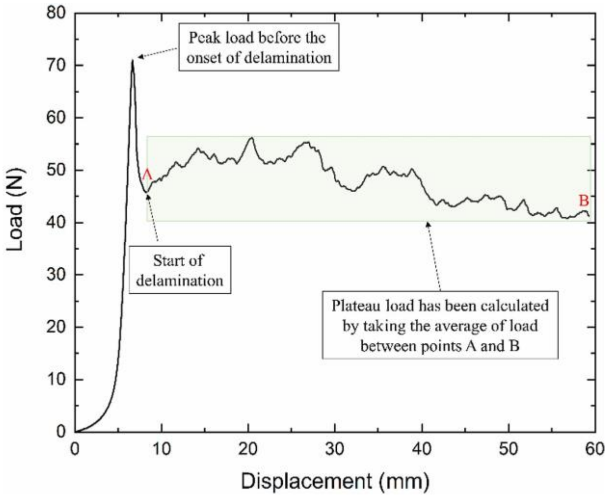
Specimen	Condition	Isc (mA)	Voc (V)	FF (%)	Pmax (W)	% change in Pmax
5BB_PPGF6	Pristine	8918.42	1.31	77.4	9.042	-
	After hail test	8901.69	1.31	74.7	8.692	-3.87
10BB_PPGF6	Pristine	6177.25	2.738	79.3	13.409	-
	After hail test	6104.93	2.724	76	12.6	-6.03
5BB_PPGF8	Pristine	9359.49	1.32	76.8	9.479	-
	After hail test	9253.91	1.315	75.3	9.165	-3.31
10BB_PPGF8	Pristine	6447.38	2.743	79.5	14.058	-
	After hail test	6411.45	2.733	74.9	13.1	-6.81
5BB_PETGF	Pristine	9108.54	1.323	76.6	9.235	-
	After hail test	8996.37	1.296	68.2	7.956	-13.84
10BB_PETGF	Pristine	6296.81	2.739	79.4	13.686	-
	After hail test	6286.83	2.735	71.2	12.244	-10.53
5BB_BOPET	Pristine	9051.15	1.311	76.7	9.104	-
	After hail test	9062.47	1.306	70.2	8.306	-8.76
10BB_BOPET	Pristine	6198.67	2.729	79.6	13.467	-
	After hail test	6234.66	2.702	63.5	10.689	-20.62
5BB_GLASS	Pristine	9024.09	1.309	78.4	9.265	-
	After hail test	9042.28	1.309	78.3	9.261	-0.04
5BB_GLASS	Pristine	6263.11	2.747	80.6	13.858	-
	After hail test	6268.56	2.747	80.1	13.809	-0.35

2.2.6. Adhesion testing

The adhesion at the encapsulant-skin interface is assessed using the 90° peel tests, as shown in the figure 13, below. During the peel test, a pleatuating load between points a and b is taken and divided by the width of the samples to get the peel strength.



(a)



(b)

Fig. 13: (a) set-up for 90° peel tests and (b) characteristic load vs displacement diagram.

For the initial screening of the adhesion strength between the encapsulant and the skins, the samples are tested for both the pristine and the 300 hours DH aged condition. It was observed that the adhesion strength of the PETGF skins was the highest with the encapsulants, while the adhesion to the other skins was unsatisfactory. The adhesion strength was found to reduce slightly after 300 hours of DH ageing; however, the adhesion strength did not reduce for the rest of the samples after the ageing.

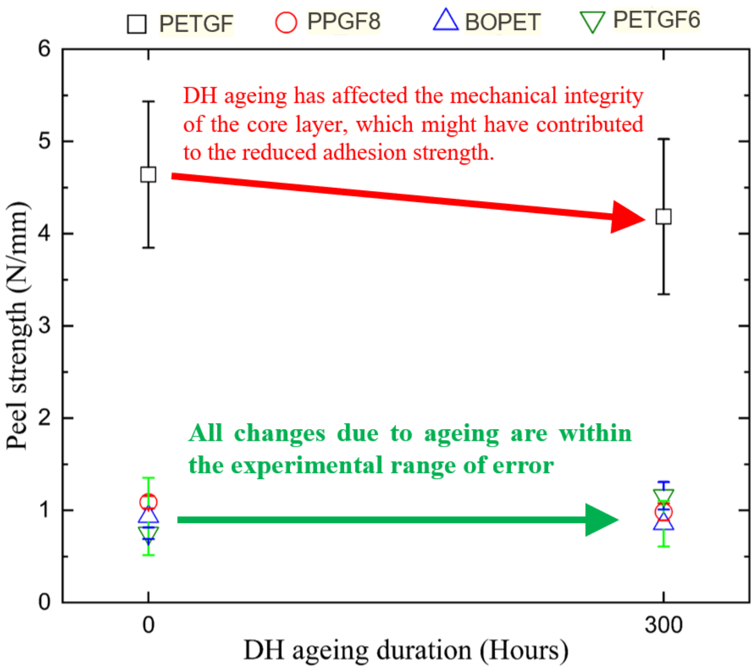


Fig. 14: Effect of 300 hours of DH ageing on the adhesion strength of encapsulant with various skins

Several other factors for the skins such as shrinkage test, water vapor transmittance rate (WVTR), UV ageing and DH ageing of the skins was evaluated by other members of the consortium, as shown below in table 5:

Table 5: Other aspects of reliability of skins being studied by other consortium members.

Factor	Partner investigating it
Shrinkage (CET)	PCCL & OFI
WVTR	OFI
UV ageing	EconCore
DH ageing	PCCL

Based on all the factors studied so far by various partners, a ranking was given to all the four candidate materials during the project meeting held at Genk, Belgium. The ranking matrix suggested that PET-BOPET option of the sandwich, which scored the least among all the candidate materials was decided to be discarded (Fig. 15).

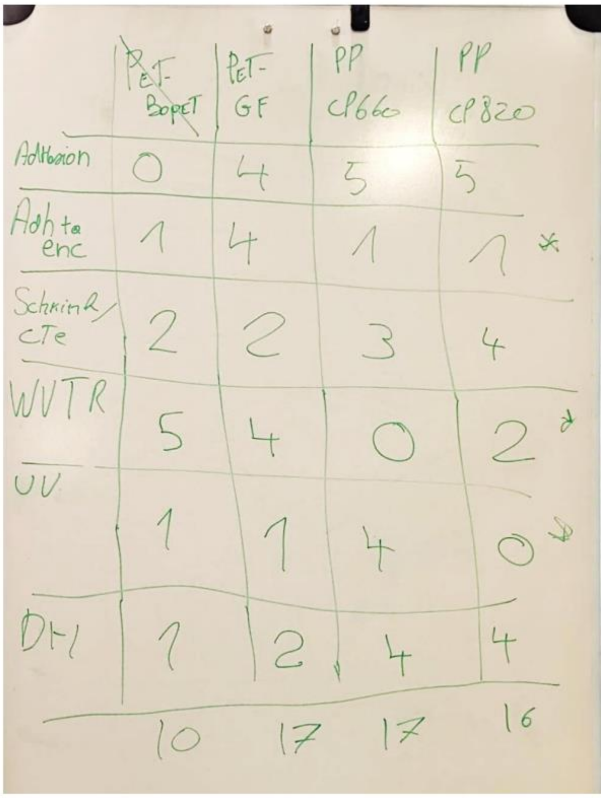


Fig. 15: The ranking matrix for various skins being considered.

Furthermore, the adhesion strength measurement was tried by varying the lamination parameters for the BPO encapsulant and the other candidate materials such as Arkema TPO and 3M POE. It was found out (table 6) that the adhesion strength for the 3M POE was the highest as compared to the rest of the encapsulants, both before and after the DH ageing of 1000 hours.

Table 6: Results of peel tests carried out for different lamination parameters and encapsulants

Skin	Encapsulant	Pressure [mbar]	Temperature [°C]	Interface	Pristine	DH1000
PPGF8	BPO	300	135	Encapsulant-skin	0.22 ± 0.05	0.09 ± 0.07
	BPO	700	135	Encapsulant-skin	0.46 ± 0.04	0.38 ± 0.02
	BPO	700	150	Encapsulant-skin	0.64 ± 0.04	0.40 ± 0.07
	3M POE	700	150	Encapsulant-skin	3.37 ± 0.46	4.95 ± 0.55
	Arkema TPO	700	150	Encapsulant-skin	0.64 ± 0.07	0.30 ± 0.03
PPGF6	BPO	300	135	Encapsulant-skin	0.44 ± 0.07	0.36 ± 0.02
	BPO	700	135	Encapsulant-skin	0.39 ± 0.00	0.31 ± 0.10
	BPO	700	150	Encapsulant-skin	2.05 ± 0.02	0.51 ± 0.05
	3M POE	700	150	Encapsulant-skin	3.33 ± 0.14	3.67 ± 0.50
	Arkema TPO	700	150	Encapsulant-skin	0.79 ± 0.05	0.62 ± 0.09

3. Next steps

In the first year of the project, consortium has successfully developed LW modules that are based on polymeric honeycomb. Going forward, the consortium will have to adapt to the exit of IMEC and EconCore. For EPFL, the major tasks will be to incorporate different colored options to improve the aesthetics, come-up with an innovative solution for the mounting of the modules, set-up a demo site for the LW modules, and assess the reliability of the modules.

3.1. Modifications to the consortium

IMEC and EconCore, both the consortium partners from Belgium have stepped out of the project at the end of the first year of the project. EconCore had a key responsibility of not only providing the consortium with the sandwich structures but also optimizing it. IMEC played a key role in fabrication of the modules and carrying out reliability testing. As a result of their exit, important activities like, the supply of materials and fabrication of modules has affected. EconCore has agreed to continue to supply their commercialized materials. However, the consortium will have to bear the additional cost of purchasing the materials.

The PV lab of EPFL has pioneered in the field of lightweight photovoltaic products that are aesthetically pleasing and apt for the need of the niche market of Switzerland. The PV lab is currently engaged in an Innosuisse project called, BeePV (https://www.aramis.admin.ch/Texte/?ProjectID=52282), which also deals with the hot topic of lightweight modules for building integration. BeePV project is aimed for increasing the technology readiness level (TRL) of the LW modules. The goal of the BeePV project is to set up in Switzerland a pilot production line for a cost competitive building-integrated lightweight photovoltaics (BIPV) element for façade application based on composite materials. Similarly, the Delight project is also aimed at developing the lightweight modules. The development of a PV product under the Delight project is also directly beneficial to its associated consortium partners from Switzerland.

To adapt to the exit of IMEC, EPFL will take-up an additional responsibility of the tasks of fabrication of PV modules and reliability testing from IMEC. EconCore has agreed to supply the consortium with their commercially available materials, but it will have to be purchased. Due to this, EPFL would like to ask for an additional funding from OFEN to make-up for the costs of material and manufacturing of PV modules.

4. Publications and dissemination

Oral presentation/invited talks:

- U. Desai, F. Lisco, A. Virtuani, A. Faes, C. Ballif, Development and testing of light weight PV modules, *SOPHIA PV Module Reliability Workshop*, Italy, 2023

- Jonathan Govaerts, Paul Dufke, Bin Luo, Matthias Bonnart, Rik Van Dyck, Tom Borgers, Jef Poortmans, Arne Derluyn, Jarne Saelens, Wouter Winant, Meric Caliskan Arslan, Umang Desai, Fabiana Lisco, Antonin Faes, Christophe Ballif, Gernot Oreski, Nikolina Pervan, Gabriele Eder, Light as heaven, strong as hell(?): Testing honeycomb-based laminates for light-weight c-si pv applications, *EU PVSEC*, Portugal, 2023

Posters:

- U. Desai et al, Overview of the project "DELIGHT" DE sign and Evaluation of LIGHT weight Composite PV Modules for Integration in Buildings and Infrastructure, *21st Swiss Solar Conference*, Bern, 2023

- N. Pervan et al., Honeycomb structures as backsheets for light weight PV modules, *EU PVSEC*, Portugal, 2023

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[5] J. Govaerts *et al.*, “Development and testing of light-weight PV modules based on glass-fibre reinforcement,” *EPJ Photovoltaics*, vol. 13, 2022, doi: 10.1051/epjpv/2022007.