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Federal Department of the Environment,
Transport, Energy and Communications DETEC

Swiss Federal Office of Energy
Energy Research and Cleantech

Final report from 28 November 2024

Delight

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

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Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Berne
www.energy-research.ch

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SFOE contract number: SI/502501

Summary

Achieving the ambitious targets of decarbonizing the European economy requires a huge effort. Integration of photovoltaic modules on to 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. Building integrated PV products based on glass/glass and glass/foil are normally available in the commercial market but these require a rigid structure for integration to the buildings and need a metallic frame for efficient mounting to the structure. Typically, weight of such modules alone is about **12 kg/m^2 or higher**, depending on the glass thickness. Module manufacturers also depend strongly on the global supply chain to receive glasses that are of specific size, shape and thickness. The **importance** of the DELIGHT project therefore becomes evident in developing a lightweight PV module that is less than **6 kg/m^2 (glass-free variant)** in weight, durable to environmental and mechanical stressors (especially hail-impact) as well as aesthetically pleasing and easily integrable to an existing infrastructure. **Such modules will be ideal for application to old buildings, which were deemed to be unsuitable until now, in the form of façade or rooftop applications with ease of installation.**

The main objective 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 **objectives** are:

- 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.
- Fulfilling the demands for aesthetic integration by use of novel, colored components, and coatings, alternative reliable PV modules easily to integrate into buildings and infrastructures.
- 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., coloring, 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.
- Development of lightweight PV modules **passing critical IEC61215 tests** (e.g. TC200, Hail impact) and **relevant building code requirements** (e.g. fire test).
- Shade resilience to overcome the two major issues of **partial shading**, that are a disproportionate reduction on the electrical output of PV modules and systems as a result of even very small shadows and creation of **hot-spots** that reduce PV module's reliability, lifetime and safety since too high hot-spot temperatures can permanently damage PV modules and, in extreme cases, ignite fires.
- Unexpected module **degradation modes** caused by new module components
- Reliability of **new mounting approaches** and integration concepts
- Predicting energy yield and appearance of **colored PV modules**, including environment specific degradation in yield modelling
- Improving **eco-design** while retaining performance, quality and reliability

This report presents the reliability testing results of innovative, glass-free, colored lightweight PV modules with polymeric composite backsheets, achieving a total weight of less than 6 kg/m². Four composite skins, made from

polymeric materials such as **polypropylene (PP)** or **polyethylene terephthalate (PET)**, with or without glass fibers, were tested in combination with honeycomb (HC) cores made of PET or PP. Initial tests revealed that PET-based skin-HC combinations failed to meet reliability testing requirements, including environmental testing, T-peel tests, and flammability tests. Conversely, **PP-based skin-HC combinations showed promising results** and were selected for further improvement and testing. In the second round, polyolefin elastomer (POE) replaced thermoplastic polyolefin (TPO) to enhance adhesion strength, while **colored foils from Solaxess improved aesthetics**. The two composite backsheet candidates consisted of the same PP-based honeycomb but were different in the skins. The first candidate had PPGF8, a white skin with higher fiber density **(820 g/m²),** and PPGF6, a black skin with lower fiber density **(660 g/m²).** Both sandwich structures demonstrated less than 5% degradation in relative power output after extensive climatic aging tests, including damp-heat exposure, UV exposure, thermal cycles, and humidity-freeze cycles, with damp heat causing minor delamination near module corners. Four-point bending tests revealed directional differences in flexural properties, with PPGF8 exhibiting superior stiffness due to its higher fiber density. Under a static mechanical load test, PPGF8 and PPGF6 mini-modules (40 cm X 40 cm) showed displacements of **2.25 mm** and **2.75 mm**, respectively, with **no new cell cracks** observed even at increased pressures, indicating substantial mechanical resilience. Flammability tests showed PPGF8 partly met ISO Class E flame spread criteria but was hindered by flaming droplets for full compliance, suggesting potential for improvement with fire retardants. A **demonstration site** has been established at Microcity in Neuchâtel, Switzerland, where upscaled modules are monitored in **MPP tracking mode**, with results to be reported in the future.

Overall, the study confirms that the mini-modules meet essential IEC 61215:2021 requirements, with PPGF8 offering superior mechanical and fire performance compared to PPGF6, though further refinements are needed to enhance fire safety.

Zusammenfassung

Das Erreichen der ehrgeizigen Ziele zur Dekarbonisierung der europäischen Wirtschaft erfordert enorme Anstrengungen. Die Integration von Photovoltaikmodulen in die bestehende Infrastruktur ist eine der wichtigsten Säulen, 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: entweder weil sie dicht besiedelt sind (Niederlande, Belgien) oder gebirgig sind (Österreich, Schweiz). Um dies erfolgreich zu erreichen, müssen Energieertrag und Kosten gleichzeitig optimiert werden, aber auch Modulgewicht, Ästhetik, Zirkularität, Zuverlässigkeit und Sicherheit. 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. Gebäudeintegrierte PV-Produkte auf Glas/Glas- und Glas/Folienbasis sind normalerweise auf dem kommerziellen Markt erhältlich, erfordern jedoch eine starre Struktur für die Integration in die Gebäude und einen Metallrahmen für die effiziente Befestigung an der Struktur. Typischerweise beträgt das Gewicht solcher Module allein etwa 12 kg/m^2 oder mehr, abhängig von der Glasdicke. Modulhersteller sind außerdem stark von der globalen Lieferkette abhängig, um Glas in einer bestimmten Größe, Form und Dicke zu erhalten. Die Bedeutung des DELIGHT-Projekts zeigt sich daher in der Entwicklung eines leichten PV-Moduls, das weniger als 6 kg/m^2 (glasfreie Variante) wiegt, Umwelt- und mechanischen Belastungen (insbesondere Hagelschlag) standhält, ästhetisch ansprechend ist und sich leicht in eine vorhandene Infrastruktur integrieren lässt. Solche Module eignen sich ideal für den Einsatz in alten Gebäuden, die bisher als ungeeignet galten, in Form von Fassaden- oder Dachanwendungen mit einfacher Installation.

- Das Hauptziel des DELIGHT-Konsortiums besteht in der Entwicklung, Herstellung und Evaluierung nachhaltiger, leichter Verbund-PV-Module zur einfacheren Integration in die bestehende Infrastruktur, wobei ein besonderer Schwerpunkt auf erhöhter Sicherheit, optimierter Ästhetik und konstruktiver Integration liegt. Die Hauptziele sind:
- Reduzierung des Modulgewichts der PV-Module und des Konstruktionssystems, Erreichen eines Gewichtsziels für Module von ≤6 kg/m² (glasfrei) und ≤7 kg/m² (Design mit Frontglas) für rahmenlose Leichtbaumodule in voller Größe.
- Erfüllung der Anforderungen an ästhetische Integration durch Verwendung neuartiger, farbiger Komponenten und Beschichtungen, alternativer zuverlässiger PV-Module, die sich leicht in Gebäude und Infrastrukturen integrieren lassen.

- Optimierung des elektrischen Moduldesigns im Hinblick auf schattentolerante Modultopologien, Verbesserung von Leistung, Sicherheit und Zuverlässigkeit bei teilweiser Beschattung (Modulabschaltung; Trennung beschädigter Teilstrings; 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 die Verwendung von recyceltem PET für die Wabenstrukturen. DELIGHT wird diese neuen Konzepte und Lösungen (z. B. Farbgebung, Verbundrückseitenfolie, Montagelösungen, Polymervorderseitenfolie usw.) auf einen ausreichend hohen TRL (6-7) bringen und so das Ökodesign verbessern, während Leistung, Qualität und Zuverlässigkeit erhalten bleiben. Das Projekt zielt auf die Realisierung eines nachhaltigen und wettbewerbsfähigen PV-Produkts ab, das vollständig in der EU entworfen, hergestellt und optimiert wird, um mit hoher Qualität und Vertrauen zum europäischen Markt beizutragen.
- Entwicklung von leichten PV-Modulen, die kritische IEC61215-Tests (z. B. TC200, Hagelschlag) und relevante Bauvorschriften (z. B. Brandprüfung) bestehen.
- Schattenresistenz, um die beiden Hauptprobleme der teilweisen Beschattung zu überwinden, die eine unverhältnismäßige Reduzierung der elektrischen Leistung von PV-Modulen und -Systemen aufgrund selbst sehr kleiner Schatten und der Entstehung von Hotspots darstellen, die die Zuverlässigkeit, Lebensdauer und Sicherheit von PV-Modulen verringern, da zu hohe Hotspot-Temperaturen PV-Module dauerhaft beschädigen und in extremen Fällen Brände entzünden können.
- Unerwartete Moduldegradationsmodi durch neue Modulkomponenten
- Zuverlässigkeit neuer Montageansätze und Integrationskonzepte
- Vorhersage des Energieertrags und des Erscheinungsbilds farbiger PV-Module, einschließlich umweltspezifischer Degradation bei der Ertragsmodellierung
- Verbesserung des Ökodesigns bei gleichzeitiger Beibehaltung von Leistung, Qualität und Zuverlässigkeit

Dieser Bericht präsentiert die Ergebnisse der Zuverlässigkeitstests innovativer, glasfreier, farbiger, leichter PV-Module mit polymeren Verbundrückseitenfolien, die ein Gesamtgewicht von weniger als 6 kg/m² erreichen. Vier Verbundhäute aus Polymermaterialien wie Polypropylen (PP) oder Polyethylenterephthalat (PET), mit oder ohne Glasfasern, wurden in Kombination mit Wabenkernen (HC) aus PET oder PP getestet. Erste Tests zeigten, dass PET-basierte Haut-HC-Kombinationen die Anforderungen an Zuverlässigkeitstests, darunter Umwelttests, T-Schältests und Entflammbarkeitstests, nicht erfüllten. PP-basierte Haut-HC-Kombinationen hingegen zeigten vielversprechende Ergebnisse und wurden für weitere Verbesserungen und Tests ausgewählt. In der zweiten Runde wurde thermoplastisches Polyolefin (TPO) durch Polyolefin-Elastomer (POE) ersetzt, um die Haftfestigkeit zu verbessern, während farbige Folien von Solaxess die Ästhetik verbesserten. Die beiden Kandidaten für Verbundrückseitenfolien bestanden aus derselben PP-basierten Wabe, unterschieden sich jedoch in den Häuten. Der erste Kandidat bestand aus PPGF8, einer weißen Haut mit höherer Faserdichte (820 g/m²), und PPGF6, einer schwarzen Haut mit geringerer Faserdichte (660 g/m²). Beide Sandwichstrukturen zeigten nach umfangreichen klimatischen Alterungstests, darunter Feuchtwärme- und UV-Belastung, Wärmezyklen und Feuchtigkeits-Gefrier-Zyklen, eine Abnahme der relativen Leistungsabgabe von weniger als 5 %, wobei feuchte Hitze zu geringer Delamination in der Nähe der Modulecken führte. Vierpunkt-Biegetests offenbarten Richtungsunterschiede in den Biegeeigenschaften, wobei PPGF8 aufgrund seiner höheren Faserdichte eine überlegene Steifigkeit aufwies. Bei einem statischen mechanischen Belastungstest zeigten die Minimodule PPGF8 und PPGF6 (40 cm x 40 cm) Verschiebungen von 2,25 mm bzw. 2,75 mm, ohne dass selbst bei erhöhtem Druck neue Zellrisse beobachtet wurden, was auf eine erhebliche mechanische Belastbarkeit hindeutet. Entflammbarkeitstests zeigten, dass PPGF8 die Flammenausbreitungskriterien der ISO-Klasse E teilweise erfüllte, aber durch brennende Tropfen an der vollständigen Einhaltung gehindert wurde, was auf Verbesserungspotenzial durch Flammschutzmittel hindeutet. In Microcity im schweizerischen Neuchâtel wurde ein Demonstrationsstandort eingerichtet, an dem hochskalierte Module im MPP-Tracking-Modus überwacht werden. Die Ergebnisse werden in Zukunft bekannt gegeben.

Insgesamt bestätigt die Studie, dass die Minimodule die wesentlichen Anforderungen der IEC 61215:2021 erfüllen, wobei PPGF8 im Vergleich zu PPGF6 eine bessere mechanische Leistung und ein besseres Brandverhalten bietet, allerdings sind weitere Verbesserungen erforderlich, um den Brandschutz zu verbessern.

Résumé

Atteindre les objectifs ambitieux de décarbonisation de l'économie européenne nécessite un effort considérable. L'intégration de modules photovoltaïques dans les infrastructures existantes est l'un des principaux piliers pour atteindre les objectifs en matière d'électricité renouvelable, en particulier pour les pays où il n'y a pas suffisamment de terres 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 et le coût de l'énergie, mais aussi le poids, l'esthétique, la circularité, la fiabilité et la sécurité des modules. Le projet DELIGHT rassemble l'expertise dans tous ces domaines et développera des solutions très attractives et uniques pour l'intégration du PV, afin de permettre la construction de bâtiments à énergie positive. Les produits photovoltaïques intégrés au bâtiment à base de verre/verre et de verre/feuille sont normalement disponibles sur le marché commercial, mais ils nécessitent une structure rigide pour l'intégration aux bâtiments et un cadre métallique pour un montage efficace sur la structure. En règle générale, le poids de ces modules seuls est d'environ 12 kg/m^2 ou plus, selon l'épaisseur du verre. Les fabricants de modules dépendent également fortement de la chaîne d'approvisionnement mondiale pour recevoir des verres de taille, de forme et d'épaisseur spécifiques. L'importance du projet DELIGHT devient donc évidente dans le développement d'un module PV léger de moins de 6 kg/m^2 (variante sans verre), résistant aux contraintes environnementales et mécaniques (notamment à la grêle), esthétique et facilement intégrable à une infrastructure existante. De tels modules seront idéaux pour une application sur des bâtiments anciens, jugés jusqu'à présent inadaptés, sous forme d'applications en façade ou sur toiture avec une installation facile.

L'objectif principal du consortium DELIGHT est de concevoir, fabriquer et évaluer des modules photovoltaïques composites légers et durables pour une intégration plus facile dans les infrastructures existantes, en mettant l'accent sur une sécurité accrue, une esthétique optimisée et une intégration constructive. Les principaux objectifs sont les suivants :

- réduction du poids des modules PV et du système de construction, en atteignant un objectif de poids pour les modules ≤ 6 kg/m^2 (sans verre) et ≤ 7 kg/m^2 (conception avec verre frontal) pour les modules légers pleine grandeur sans cadre.
- Répondre aux exigences d'intégration esthétique en utilisant de nouveaux composants et revêtements colorés, des modules PV alternatifs fiables et faciles à intégrer dans les bâtiments et les infrastructures.
- Optimisation de la conception des modules électriques par rapport aux 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 fluoropolymère par des solutions à base de films polyester enduits ou l'utilisation de PET recyclé pour les structures en nid d'abeille. DELIGHT amènera ces nouveaux concepts et solutions (par exemple, coloration, feuille arrière composite, solutions de montage, feuille avant en polymère, etc.) à une TRL suffisamment élevée (6-7), améliorant l'éco-conception, tout en conservant les performances, la qualité et la fiabilité. Le projet vise à la réalisation d'un produit PV durable et compétitif, entièrement conçu, fabriqué et optimisé dans l'UE, pour contribuer au marché européen avec une qualité et une confiance élevée.
- Développement de modules PV légers passant les tests critiques IEC61215 (par exemple TC200, impact de grêle) et les exigences pertinentes du code du bâtiment (par exemple, test au feu).
- Résilience à l'ombre pour surmonter les deux problèmes majeurs de l'ombrage partiel, qui sont une réduction disproportionnée de la production électrique des modules et systèmes PV en raison d'ombres même très petites et la création de points chauds qui réduisent la fiabilité, la durée de vie et la sécurité des modules PV, car des températures de points chauds trop élevées peuvent endommager définitivement les modules PV et, dans les cas extrêmes, déclencher des incendies.
- Modes de dégradation inattendus des modules causés par de nouveaux composants de modules
- Fiabilité des nouvelles approches de montage et des concepts d'intégration

- Prévision du rendement énergétique et de l'apparence des modules PV colorés, y compris la dégradation spécifique à l'environnement dans la modélisation du rendement
- Amélioration de l'éco-conception tout en conservant les performances, la qualité et la fiabilité

Ce rapport présente les résultats des tests de fiabilité de modules photovoltaïques légers, colorés, sans verre et innovants, dotés de feuilles arrière composites polymères, atteignant un poids total inférieur à 6 kg/m². Quatre peaux composites, fabriquées à partir de matériaux polymères tels que le polypropylène (PP) ou le polyéthylène téréphtalate (PET), avec ou sans fibres de verre, ont été testées en combinaison avec des noyaux en nid d'abeille (HC) en PET ou PP. Les premiers tests ont révélé que les combinaisons peau-HC à base de PET ne répondaient pas aux exigences des tests de fiabilité, notamment les tests environnementaux, les tests de pelage en T et les tests d'inflammabilité. À l'inverse, les combinaisons peau-HC à base de PP ont montré des résultats prometteurs et ont été sélectionnées pour des améliorations et des tests supplémentaires. Au deuxième tour, l'élastomère de polyoléfine (POE) a remplacé la polyoléfine thermoplastique (TPO) pour améliorer la force d'adhérence, tandis que les feuilles colorées de Solaxess ont amélioré l'esthétique. Les deux candidats à la feuille arrière composite étaient constitués du même nid d'abeille à base de PP mais étaient différents au niveau des peaux. Le premier candidat était composé de PPGF8, une peau blanche avec une densité de fibres plus élevée (820 g/m²), et de PPGF6, une peau noire avec une densité de fibres plus faible (660 g/m²). Les deux structures sandwich ont démontré une dégradation inférieure à 5 % de la puissance de sortie relative après des tests de vieillissement climatique approfondis, y compris une exposition à la chaleur humide, une exposition aux UV, des cycles thermiques et des cycles humidité-gel, la chaleur humide provoquant un léger délaminage près des coins du module. Des tests de flexion à quatre points ont révélé des différences directionnelles dans les propriétés de flexion, le PPGF8 présentant une rigidité supérieure en raison de sa densité de fibres plus élevée. Lors d'un test de charge mécanique statique, les mini-modules PPGF8 et PPGF6 (40 cm X 40 cm) ont montré des déplacements de 2,25 mm et 2,75 mm, respectivement, sans aucune nouvelle fissure cellulaire observée même à des pressions accrues, ce qui indique une résilience mécanique substantielle. Les tests d'inflammabilité ont montré que le PPGF8 répondait partiellement aux critères de propagation de la flamme de classe E de l'ISO, mais qu'il était gêné par des gouttelettes enflammées pour une conformité totale, ce qui suggère un potentiel d'amélioration avec des retardateurs de flamme. Un site de démonstration a été établi à Microcity à Neuchâtel, en Suisse, où les modules mis à l'échelle sont surveillés en mode de suivi MPP, les résultats devant être communiqués ultérieurement.

Dans l'ensemble, l'étude confirme que les mini-modules répondent aux exigences essentielles de la norme IEC 61215:2021, le PPGF8 offrant des performances mécaniques et au feu supérieures à celles du PPGF6, bien que des améliorations supplémentaires soient nécessaires pour améliorer la sécurité incendie.

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SFOE	Swiss Federal Office of Energy
PP	Polypropylene
TPO	Thermoplastic polyolefin
PET	Polyethylene terephthalate
IEC	International Electrotechnical Commission
MPP	Maximum power point
BPDs	Bypass diodes
POE	Polyolefin elastomer
HC	Honeycomb
EL	Electroluminescence
Fs	Flame spread
PIB	Polyisobutylene

1 Introduction

1.1. Context and motivation

The European Union (EU) has established ambitious climate and energy targets to achieve by 2030 and a commitment to reach carbon neutrality by 2050. Solar photovoltaic (PV) technology is positioned as a critical driver in meeting these goals, due to its capacity for decentralized, clean energy generation. To support these objectives, PV technology must address three major market requirements: (1) comparable energy yield metrics across various module types, (2) consistent, long-term performance, and (3) a reduced carbon footprint. Ensuring these qualities in PV modules would benefit both private and public sector buyers by enabling informed decisions based on standardized performance and environmental criteria.

A key strategy in this transition involves the integration of PV systems directly into existing infrastructure, including both new and renovated buildings. Building-integrated photovoltaics (BIPV) provides an ideal solution for generating renewable energy in space-constrained urban and industrial areas where installing traditional, land-intensive PV farms is impractical. Densely populated countries like Belgium and the Netherlands, as well as mountainous regions such as Austria and Switzerland, face significant spatial limitations for ground-mounted PV installations. As a result, the integration of PV modules into buildings and infrastructure has become essential to meet renewable energy goals in these regions. For instance, incorporating PV into public buildings and infrastructure can significantly improve energy efficiency and support national energy targets.

However, the current PV market faces a notable barrier: traditional PV modules are often too heavy for widespread adoption in building and infrastructure applications. Many commercial, industrial, and agricultural buildings, comprising up to 40% of building stock in the EU, have structural limitations that prevent the installation of conventional PV panels, which typically weigh over 12 kg/m², or even more with glass/glass designs. This is particularly critical for aging infrastructure, such as older agricultural buildings with asbestos roofs that need replacement, representing approximately 70 km² in the Netherlands alone.

The DELIGHT project was initiated to address this critical need for lightweight, adaptable PV solutions. Aiming to develop and deploy innovative PV modules that weigh 50% less than traditional modules, DELIGHT seeks to unlock new market potential and make solar power viable for previously unsuitable sites. With a target weight of ≤6 kg/m² for glass-free designs, DELIGHT's solutions open up possibilities for greater integration flexibility across diverse applications, even in areas with limited load-bearing capacity. By pioneering lightweight BIPV technology, the project not only supports EU climate goals but also aligns with ongoing initiatives such as the Building Renovation Wave and the New European Bauhaus, both of which emphasize sustainable, aesthetically integrated, and energy-efficient buildings.

The rise in demand for BIPV aligns with broader environmental and economic incentives within the EU. Lightweight BIPV technology supports the EU's circular economy by promoting PV solutions with lower embodied carbon, modular integration options, and greater recyclability. With these advancements, DELIGHT's innovations are expected to foster market confidence, encouraging broader PV adoption in both public and private sectors. This approach not only propels Europe toward carbon neutrality but also paves the way for zero-emission, energy-positive buildings and infrastructure that balance functionality, safety, and visual appeal.

1.2. Project 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 Fig. 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 light weight 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.

1.3. State-of-the-art

The DELIGHT project focuses on development of rigid, glass-free & aesthetically pleasing PV modules utilizing crystalline silicon solar cell technology for the building integration application. Some of the existing commercially available solutions for lightweight PV module developments are as below:

- **Solarge**[1] has developed a composite solar panel that replaces traditional glass with a lightweight honeycomb material. This design achieves weight savings of up to 65%, resulting in panels that weigh approximately **14.5 kg for a 2.66 m²** module, compared to over 28 kg for conventional glass modules. The honeycomb structure not only reduces weight but also enhances rigidity and impact resistance, making the panels suitable for various applications, including rooftops with weight constraints[2]. Their approach also yields weight reduction **below 6 kg/m²** and gives modules that are mechanically rigid. Solarge modules are designed primarily for rooftop applications, especially where traditional solar panels may be unsuitable due to weight constraints. Their flagship product line, **SOLO**[3], utilizes polymer materials instead of conventional glass and aluminum, resulting in panels that are significantly lighter and easier to handle. **However, such modules are currently only available in white colored backsheets and don't incorporate colored foils, making their technology slightly on backfoot. Furthermore, the DELIGHT project aims to check the feasibility of four different candidate backsheets—one of which weighing as low as 3.3 kg/m², in combination with colored foils—making the modules aesthetically pleasing and at the forefront of the competition for building integration.**
- **DAS Energy** has reduced the weight of their photovoltaic modules by substituting the conventional glass pane with a highly transparent composite material, achieving a weight of just **3.3 kg/m².** This is significantly lower than traditional glass modules, which weigh on average over 20 kg/m². Their patented technology of the modules consists primarily of a proprietary fiberglass-reinforced plastic core (pre-preg), responsible for both flexibility and stability[4]. This design makes modules **semi-flexible,** which not only minimizes weight but also allows the modules to conform to curved surfaces. **However, such a process (pre-preg) may not be suitable for high throughput production since the resin of such a composite material is partially cured, making it tacky requiring extra protecting foils to be applied during storage. The backplane of DELIGHT modules does not require such special attention and can be cut into a required size and shape right before the lamination.**
- **MET-solar**[5] uses an approach of making flexible modules that uses a highly transparent polymeric foil at front to replace the glass and a polymeric backsheet at back, yielding a PV module that weighs **3 kg/m²**. Such a module is suitable for application such as

[1] https://solarge.com/en/
[2] EconCore, Solarge launch lightweight, sustainable solar panel, 14/4/2023, link:https://www.compositesworld.com/news/econcore-solarge-launch-lightweight-sustainable-solo-panel?
[3] https://solarge.com/en/products/solo/
[4] https://das-energy.com/en/technology
[5] https://metsolar.eu/products/met-flexible/

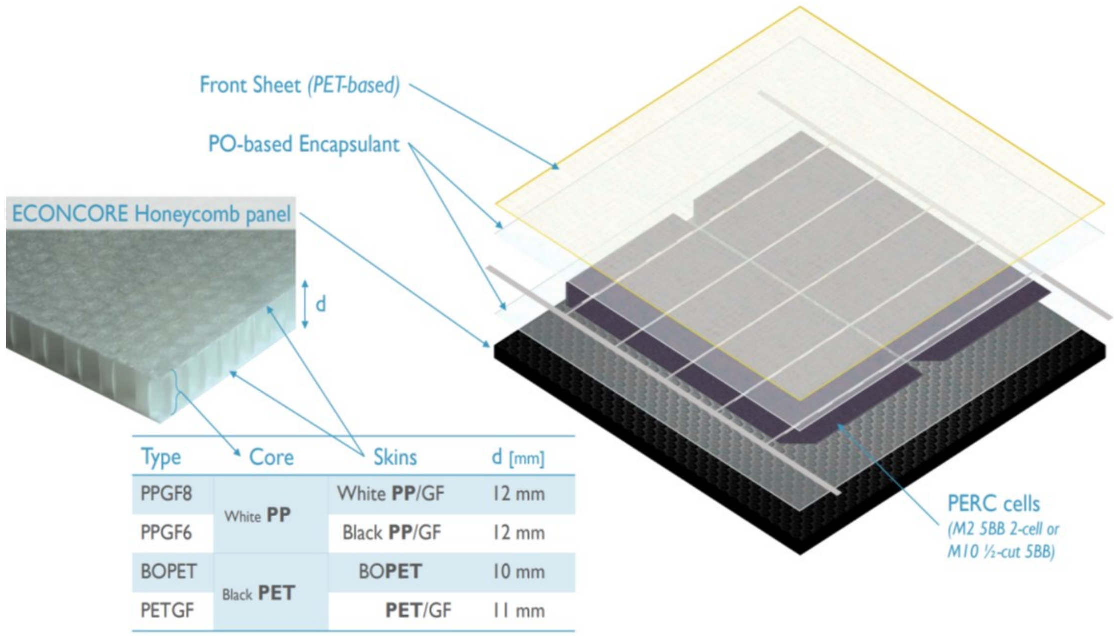
mobility, marine or custom lighting applications. **However, the mechanical resilience of these modules is under question and thus limits its use to only application areas other than building integration.**

Various other options in market are also available but are mostly based on glass/glass or glass/backbacksheet-based design making them bulky; hence, excluded from discussion here.

2 Approach, method, results and discussion

2.1. Initial prototypes

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 by consortium partner Econcore. For this approach, as can be seen in Fig. 2, PP and PET are chosen as the honeycomb core materials. 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). Additionally, the black colored PET core is attached either to the bidirectionally oriented PET skins (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. The current-voltage characteristics and weight of the modules are provided in Table 1 and Table 2, respectively.

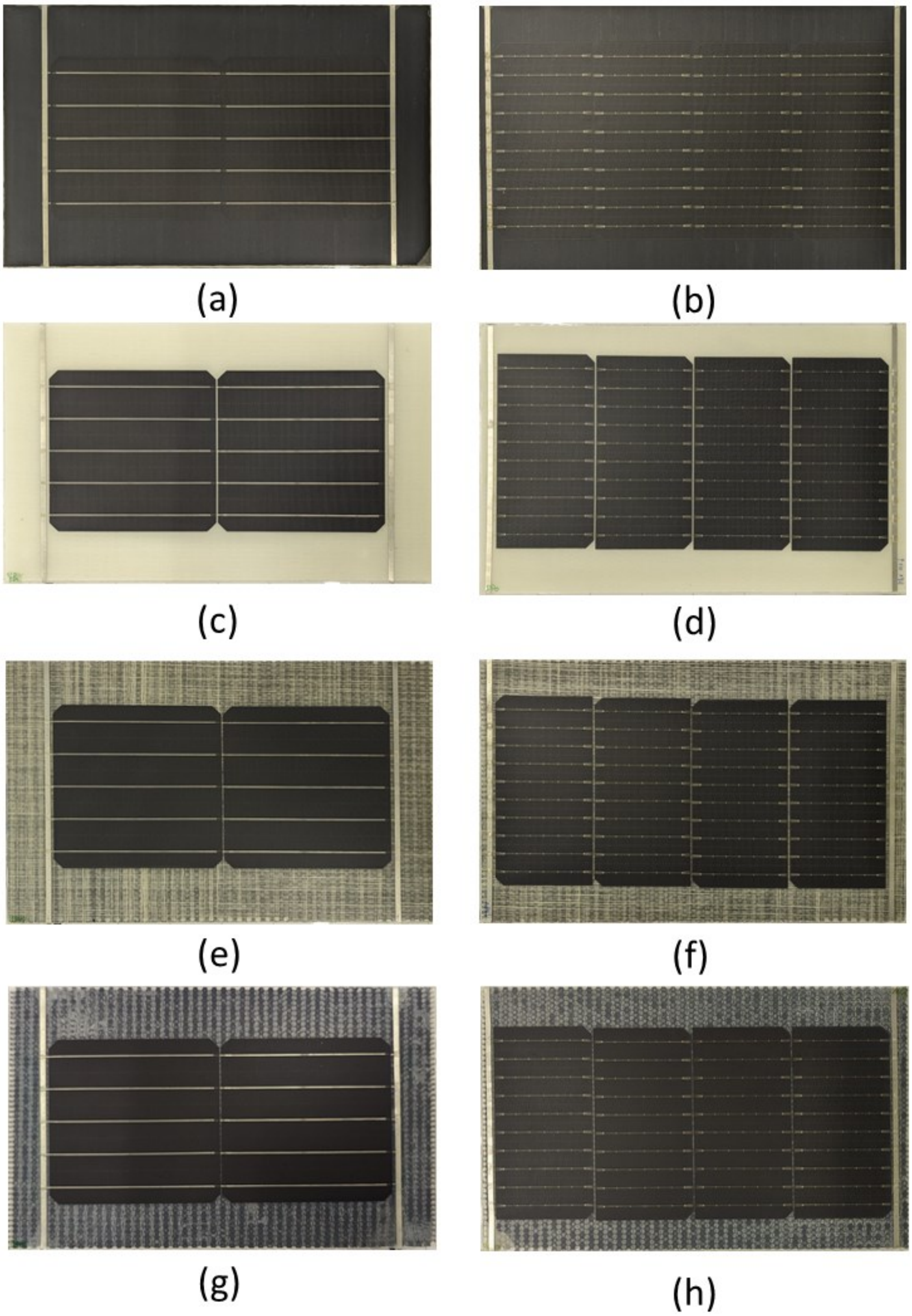


Fig. 3 Front view of the modules: PPGF6 structures with (a) M2 size 5BB cells & (b) M10 size 10BB cells; PPGF8 structures with (c) M2 size 5BB cells & (d) M10 size 10BB cells; PETGF structures with (e) M2 size 5BB cells & (f) M10 size 10BB cells; BOPET structure

Table 1 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 2 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

The developed modules are analyzed for further for reliability testing by subjecting them 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. Furthermore, it was decided to understand first the effect of individual environmental stressors only. At the advanced stages, 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):

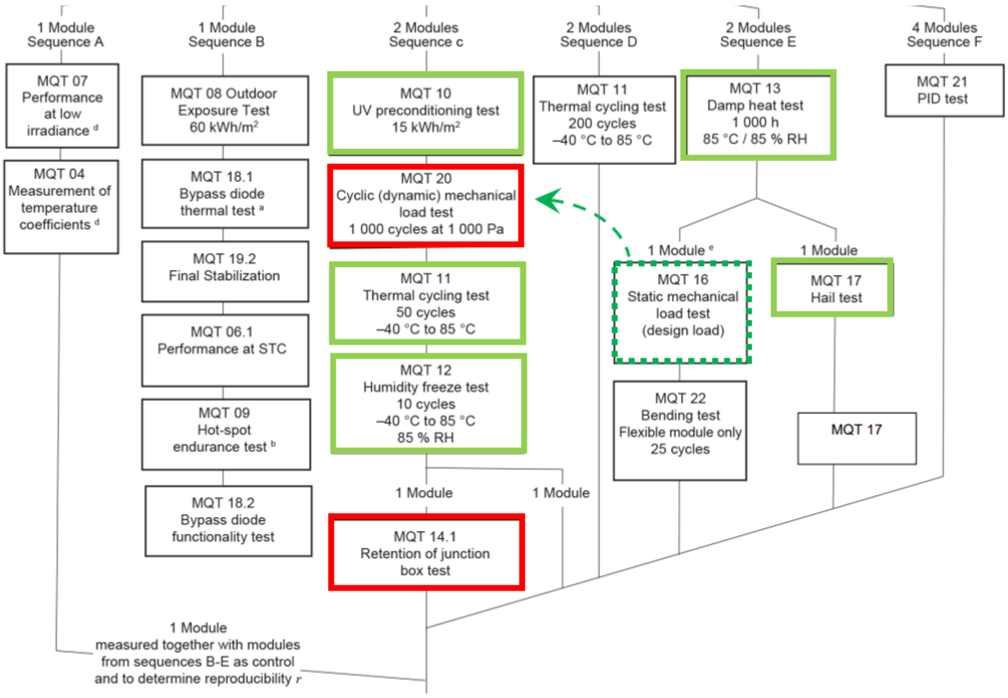


Fig. 4: Selection of testing sequences from IEC 61215-2 standard

2.1.1 Effect of thermal cycling

Fig. 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 Fig. 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) [1].

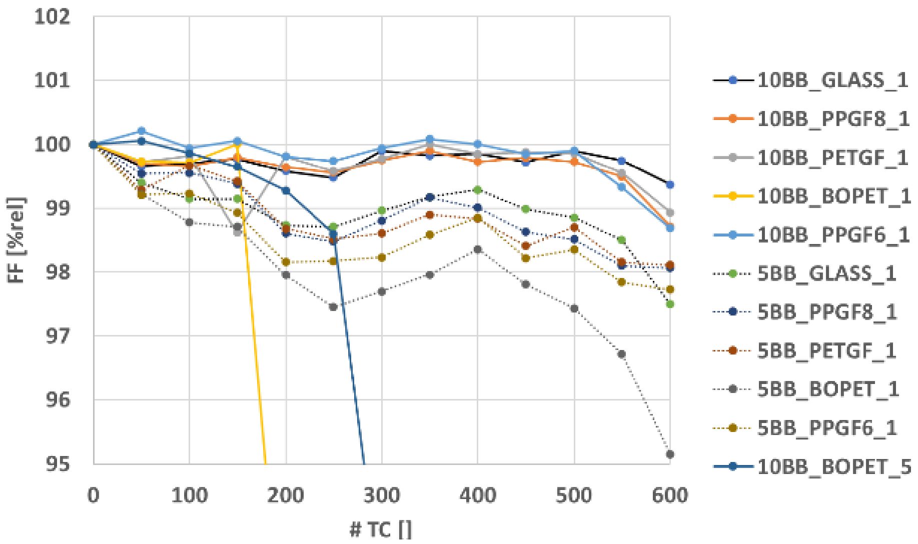
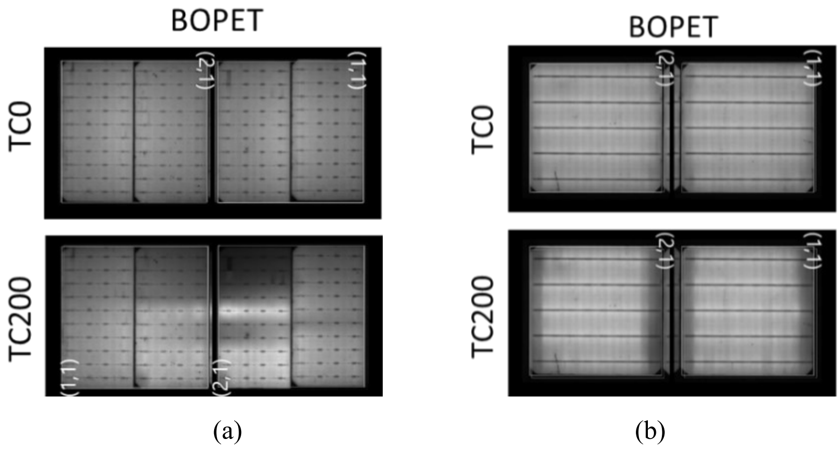


Fig. 5: Degradation in fill factor for different modules during thermal cycling

Fig. 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. Fig. 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.

2.1.2. Effect of damp-heat ageing

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

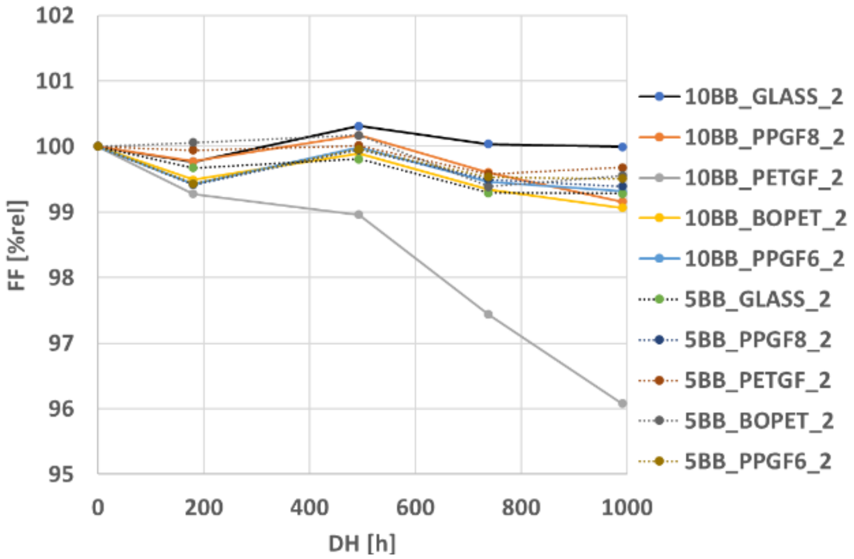


Fig. 7: Degradation in fill factor for different modules during damp-heat ageing

Looking into the EL images before and after DH is shown in Fig. 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 lightweight (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.

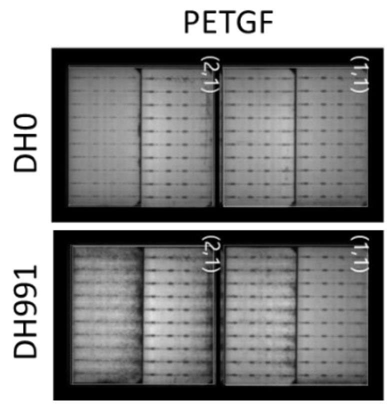


Fig. 8: EL images for PETGF based modules before and after DH ageing

2.1.3. Effect of humidity freeze

HF testing results are given in Fig. 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.

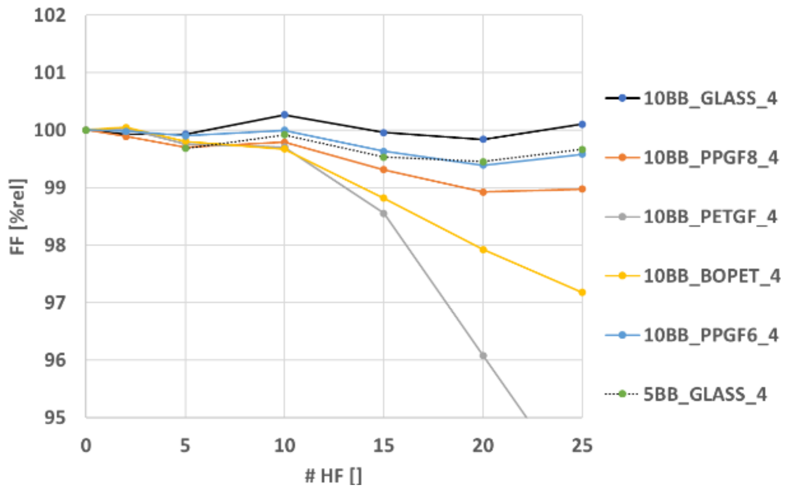


Fig. 9: Degradation in fill factor for different modules during humidity freeze cycling

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

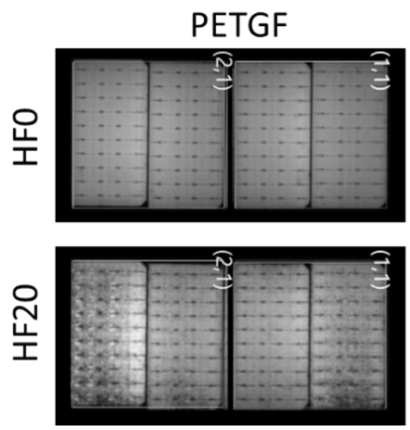


Fig. 10: EL images for PETGF based modules before and after HF cycling

2.1.4. 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 21-25m/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 3).

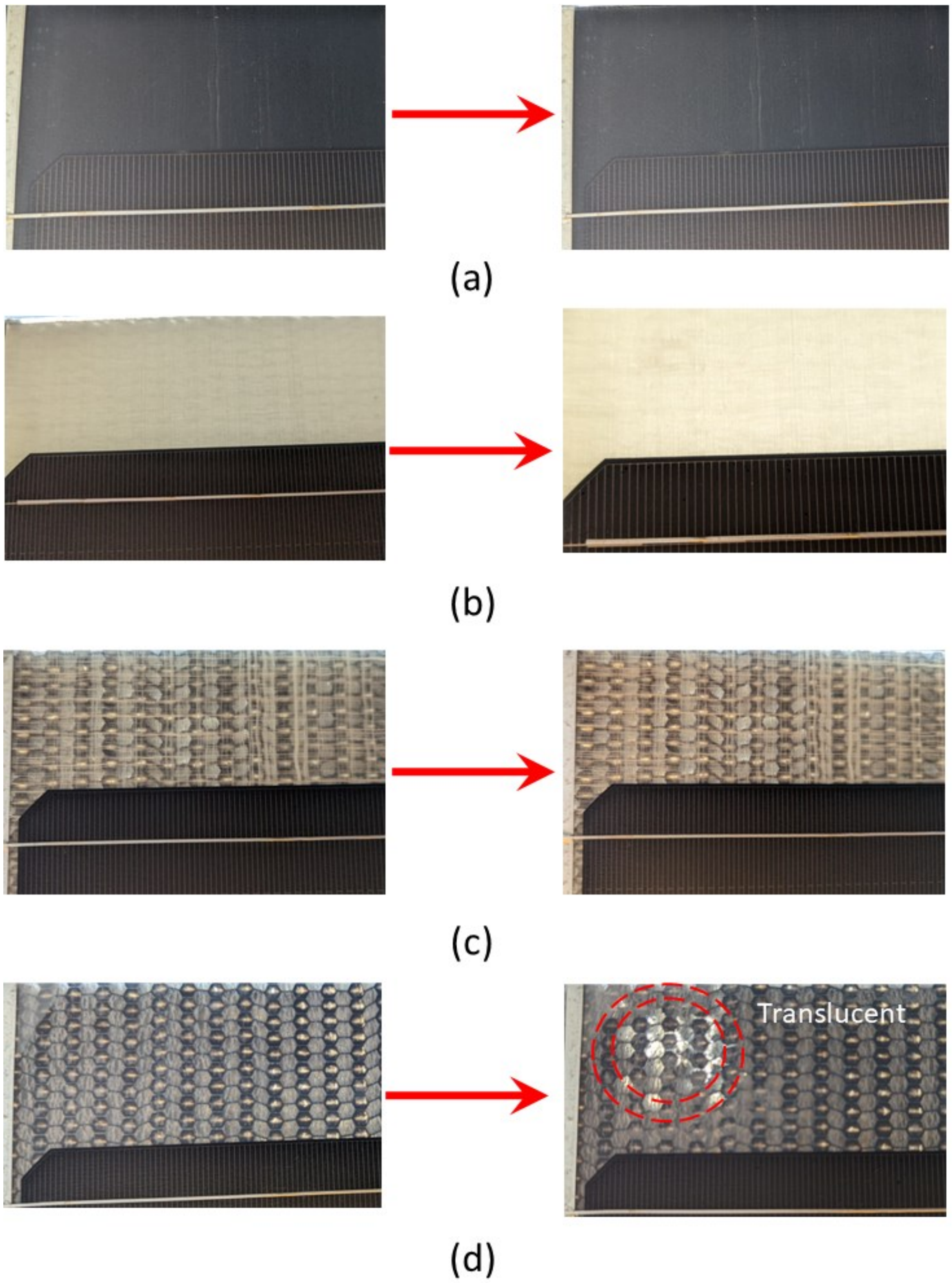


Fig. 11: Visual cues of damage on the modules due to hail-stones: (a) PPGF6, (b) PPGF8, (c) PETGF and (d) BOPET.

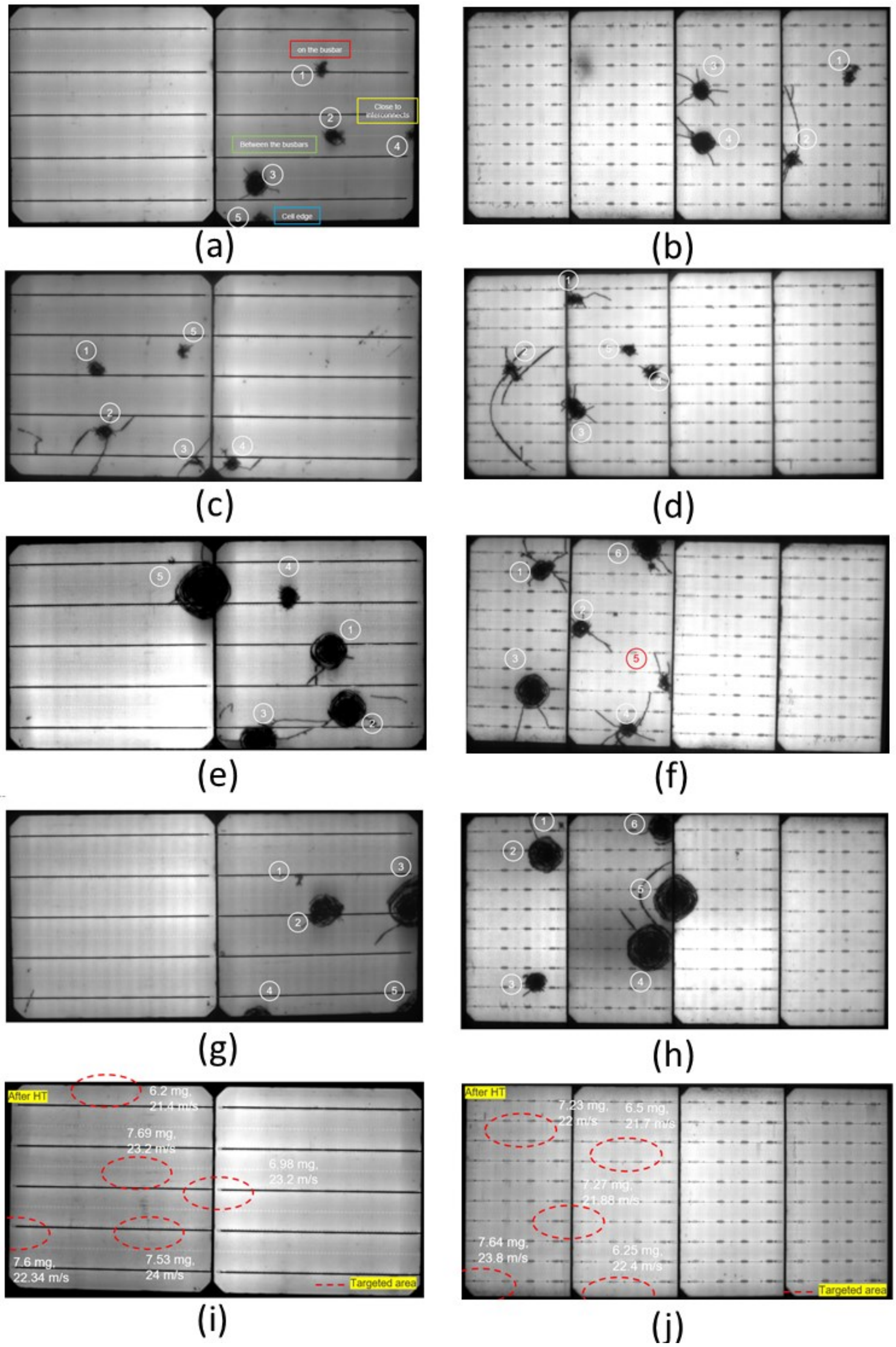


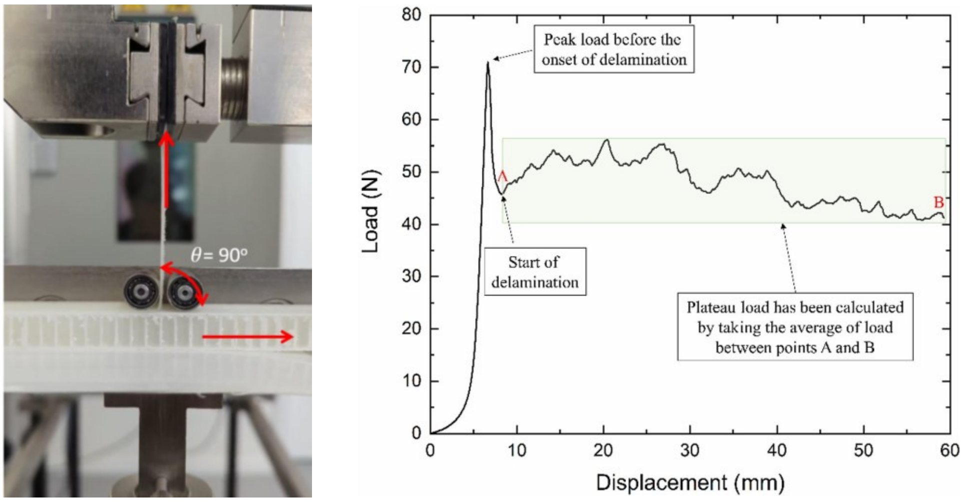
Fig. 12: EL images of the modules after the hail test: PPGF6 structures with (a) M2 size 5BB cells & (b) M10 size 10BB cells; PPGF8 structures with (c) M2 size 5BB cells & (d) M10 size 10BB cells; PETGF structures with (e) M2 size 5BB cells & (f) M10 size 10BB

Table 3 IV characteristics before and after the impact of hail stones

Specimen	Condition	Isc (mA)	Voc (V)	FF (%)	P_{max} (W)	% change in P_{max}
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

2.1.5. Adhesion testing

The adhesion at the encapsulant-skin interface is assessed using the 90° peel tests, as shown in the Fig. 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).

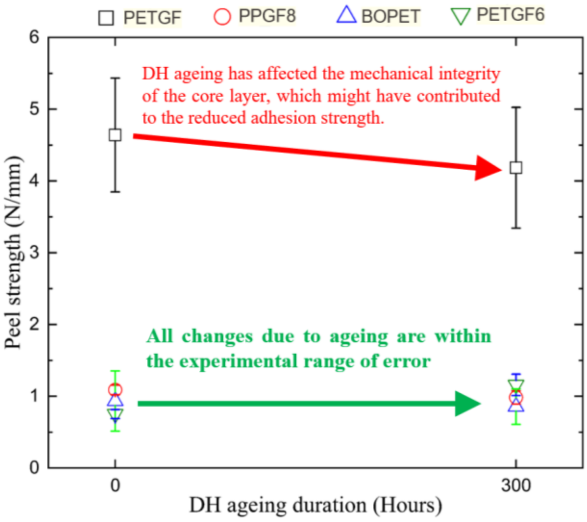


Fig. 14: Effect of 300 hours of DH ageing on the adhesion strength of encapsulant with various skins

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 (Table 4):

Table 4 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).

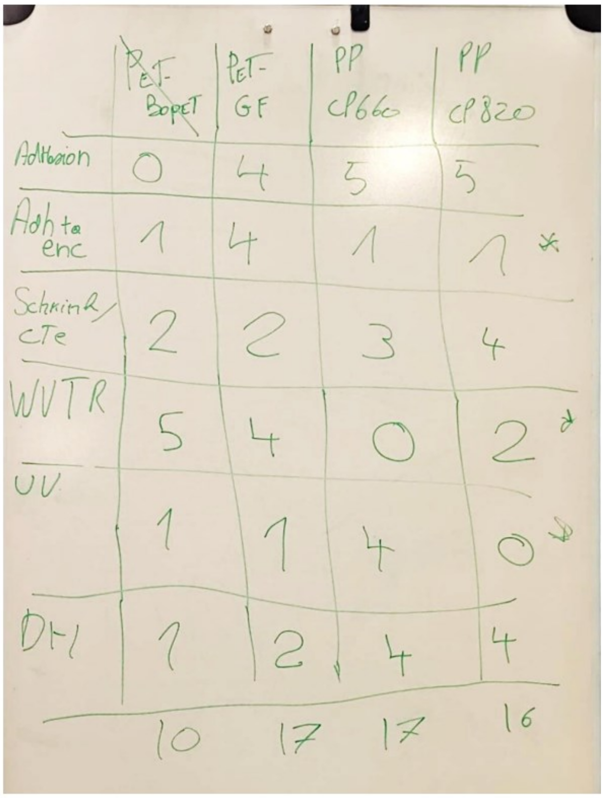


Fig. 15: The ranking matrix for various skins being considered.

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 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 5).

Table 5 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

2.2. Reliability testing on improved bill of materials

Based on the reliability testing performed in the previous round of experiments on the initial candidate materials, it was decided to only focus on developing and testing the modules based on polypropylene based skin/honeycomb sandwich structures. Another key decision taken was regarding selection of encapsulant, where the consortium has decided to use polyolefin elastomer (POE) instead of thermoplastic polyolefin (TPO) due to very low adhesion of TPO with the novel skins.

Therefore, this document will further only focus on modules based on PP, with improved bill of materials. Furthermore, the rest of the document is also focused on improving the aesthetics of the lightweight modules, assessment of mechanical robustness of the modules through four-point bending tests on sandwich structures & static mechanical load tests on mini-modules, reliability testing to assess the effect of climatic stressors (including ultraviolet radiation, humidity freeze cycling, temperature cycling and damp-heat ageing) on colored modules. Furthermore, ways of improving the fire resistance of the modules were explored. Finally, fabrication of large modules and set-up of monitoring site with the module prototypes was done on the rooftop of Microcity building at Neuchatel to assess the effects of outdoor exposure in the central European climate.

2.2.1. Selection of bill-of-materials for further testing

For performance and aesthetics, the existing bill of materials were reviewed and improved; wherein, PET-based transparent polymeric foils were chosen as front-sheet, polyolefin elastomer was chosen as encapsulant, a coloured foil was incorporated to improve the aesthetics, M2-size passivated emitter rear contacted cells having five busbars were selected, along with the polypropylene based skin/honeycomb/skin candidates. For the skins, two candidates of different fibre density were selected: 660 g/m^2 (black in appearance, hereafter referred to as PPGF6) and 820 g/m^2 (white in appearance, hereafter referred to as PPGF8). The architecture of such modules is presented in Fig. 16, below.

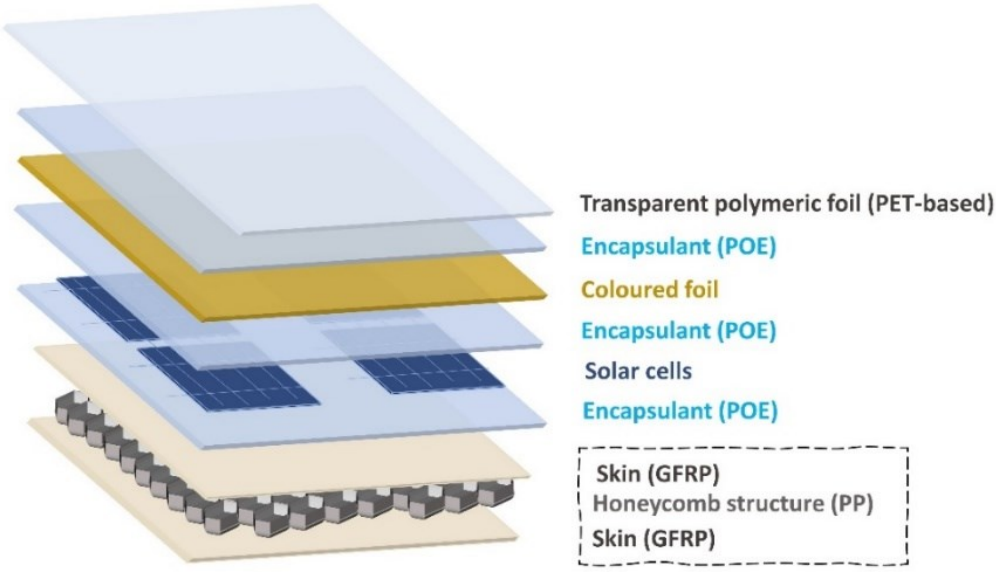


Fig. 16 Structure of the lightweight PV module based on polymeric honeycomb

The prototypes developed as per the bill of materials described above are presented below, in Fig. 17. As can be seen in Fig. 17, the difference in the two skin types changes the overall perception of the coloured foils in the minimodules. The darker background of the PPGF6 skin effectively hides the profiles of the cells, which improves the aesthetics of these mini modules. However, it is evident that the strip used to interconnect the strips is still clearly noticeable, but this can be addressed by the use of a black coloured ribbon. Therefore, it was decided to focus on assessing the reliability of these mini-modules against accelerated climatic ageing, like, damp-heat ageing, thermal cycling, humidity freeze cycling and exposure to ultraviolet ageing. In addition to this, a sample of PPGF8 without any colour was also investigated for its stability against the environmental stressors.

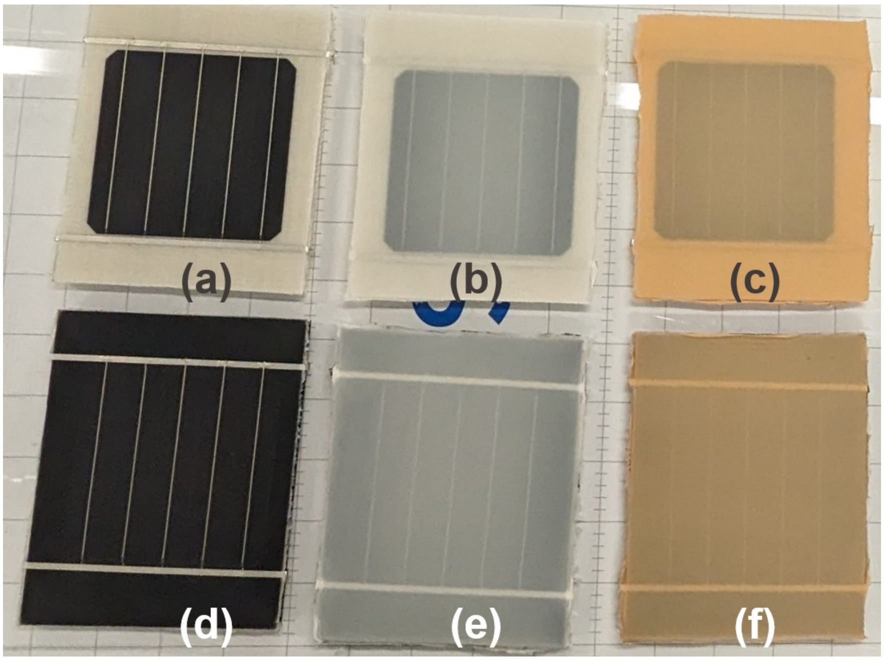
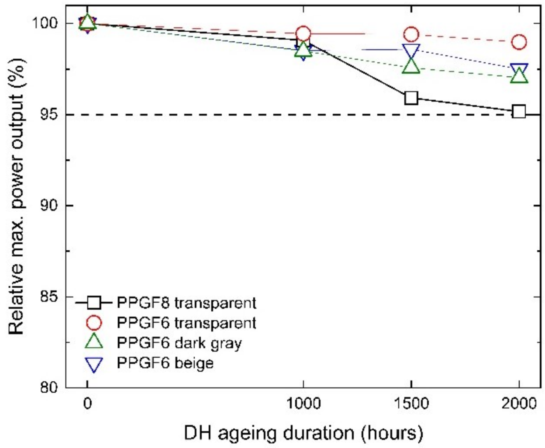


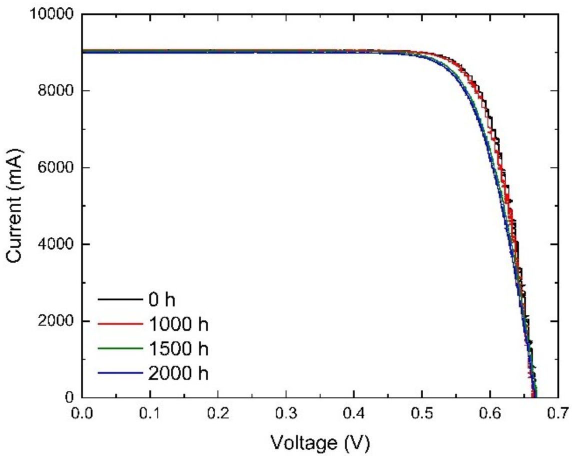
Fig. 17 Mini-modules based on PPGF8 skins with (a) no coloured, (b) dark grey coloured, and (c) beige coloured foils; as well as based on PPGF6 skins with (d) no coloured, (e) dark grey coloured, and (f) beige coloured foils

2.2.2 Reliability testing of mini-modules against climatic stressors

To examine how climatic stressors, such as moisture ingress, UV irradiation, and temperature changes in the real-world scenario, impact the performance of lightweight PV modules, one-cell mini-modules were fabricated and exposed to accelerated artificial tests, as per IEC 61215:2021 standard. These included damp-heat aging at 85°C/85%RH for upto 2000 hours, UV aging at 340nm wavelength with irradiation of 0.8 W/m^2 @ 60°C up to 60 kWh/m^2, 40 humidity-freeze cycles between -40°C and 85°C, and 400 thermal cycles as per IEC 61215 standard, i.e., applied between 85 deg C and -40 deg C, with dwell times and rates of heating and cooling as per the IEC standard. Humidity is maintained at 85 % RH during the time 85 deg C is maintained, otherwise not controlled. In Fig. 18a, the relative maximum power output is plotted against hours of damp-heat aging for these mini-modules. Findings indicate that all modules, except the white-transparent one, showed degradation levels below 5%. In the white-transparent module, a rapid drop in power output occurred due to a busbar breakage, which hindered the use of four-probe contact measurements for IV characterization. This breakage increased the series resistance, resulting in lower power output, which can be regarded as negligible in this context. For the other modules, a slight decrease in power output is mainly attributed to the decline in short-circuit current due to damp-heat aging. Fig. 18b and c present the IV characteristics for the white-transparent and black-transparent samples, respectively. Fig. 18c further shows that the increase in series resistance observed in the white-transparent sample is absent in the black-transparent sample, suggesting it is not associated with cell degradation.



(a)



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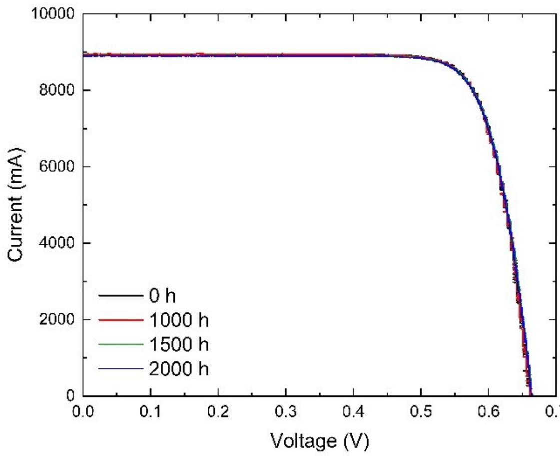
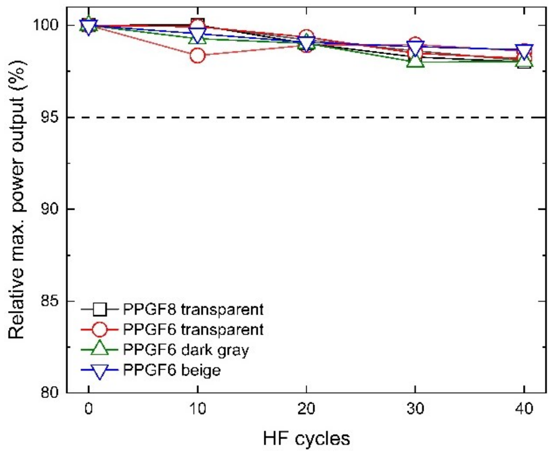


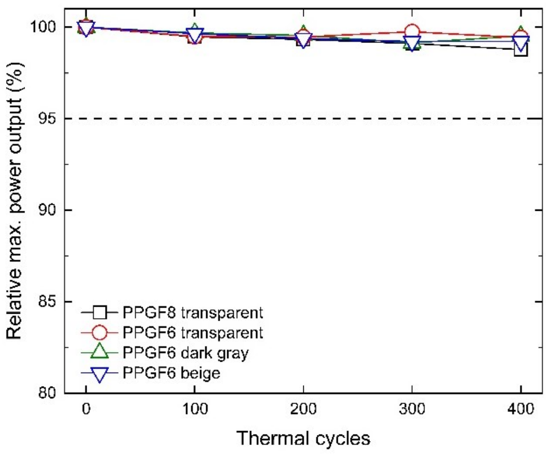
(c)

Fig. 18 (a): Change in relative max. power output with DH ageing, (b): Evolution of IV characteristics with DH ageing for White-transparent sample and (c) Evolution of IV characteristics with DH ageing for black-transparent sample

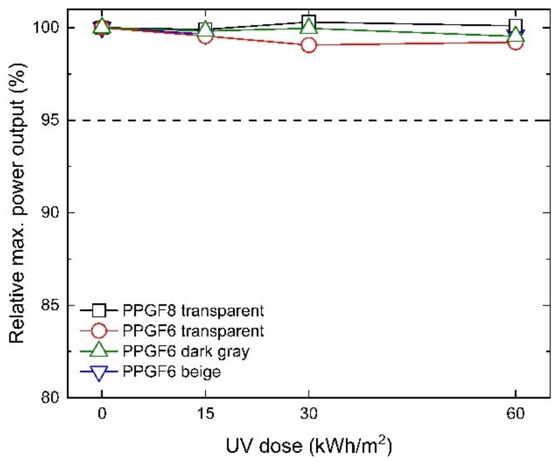
The effect of other climatic stressors, like, UV, TC, and HF on the performance of the PV modules is presented in Fig. 19, below. A gradual yet steady decline in power output was observed in the modules exposed to UV irradiation, thermal cycling, and humidity-freeze cycling. It is observed that within the test durations as described in IEC-61215:2021, i.e., 1000 hours of DH ageing, 200 thermal cycling and 20 HF cycles, the reduction in relative max. power output is not significant for these modules after the ageing. It is also required to assess the mechanical response of these modules against the applied loads.



(a)



(b)



(c)

Fig. 19 Evolution of % relative maximum power output with respect to (a) Humidity freeze cycles, (b) thermal cycles and (c) UV dose

2.2.3 Flexural tests

To determine the mechanical stiffness and load-bearing capacity of two composite backsheets, flexural testing was performed using a four-point bending setup. Samples with a width of 25 mm were tested under a loading rate of 20 µm/s, using an outer span of 190 mm and an inner span of 90 mm (Fig. 20a). The flexural properties were analyzed in two orientations for each backsheet: the longitudinal (L) direction, which aligns with the bonded walls of the honeycomb structure, and the transverse (T) direction, which is perpendicular to this alignment (illustrated in Fig. 20b).

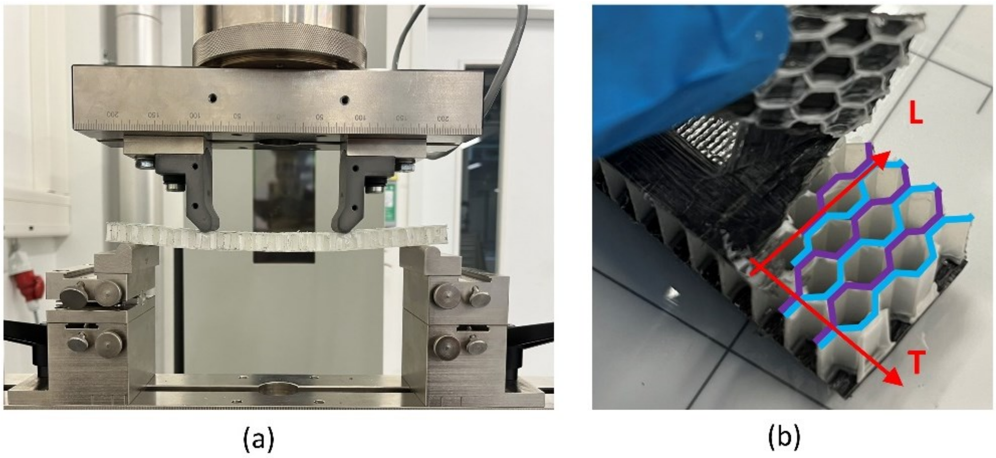


Fig. 20 (a) The set-up used for four-point bending and (b) indication of two mutually perpendicular directions, longitudinal (L) and transverse (T) of the honeycomb along which the testing is done

The results of the four-point bending tests for sandwich structures with a skin/HC/skin configuration, as shown in Fig. 21. The results indicate that the PPGF8 structure exhibits greater bending stiffness than the PPGF6 structure, attributed to the higher fibre density in the PPGF8 skins. Flexural properties were evaluated for both types of samples in the longitudinal and transverse directions of the honeycomb core. The tests revealed that both sandwich structures possess higher flexural stiffness along the longitudinal direction than the transverse direction. This finding highlights the anisotropic properties of the honeycomb core, leading to approximately a 50% reduction in the structure's maximum load-bearing capacity when bending occurs in the transverse direction compared to the longitudinal direction.

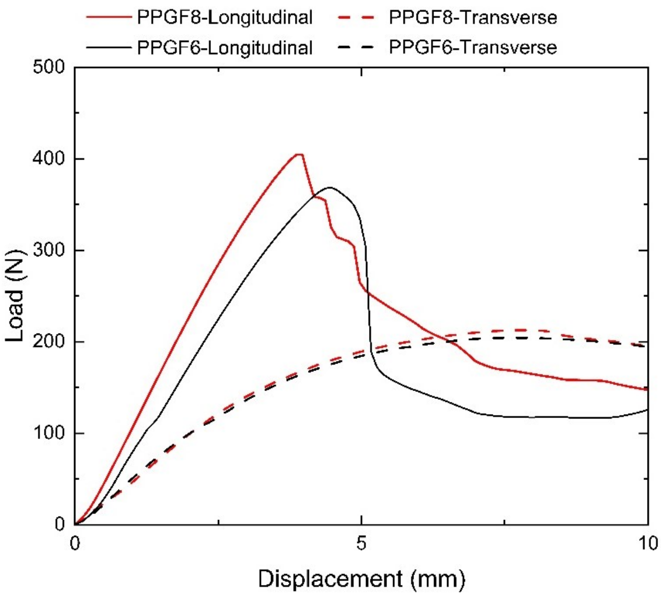


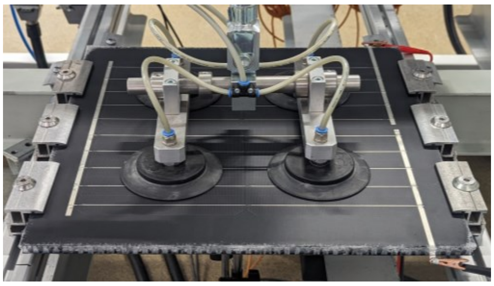
Fig. 21 Comparison of flexural bending behaviour for PPGF6 and PPGF8 samples along both longitudinal as well as transverse direction

2.2.4. Static mechanical load tests

To assess the mechanical response of modules with PPGF8 and PPGF6 backsheets, static mechanical load tests were conducted on mini-modules with dimensions of 40 cm x 40 cm, each consisting of four series-connected cells. These modules were securely clamped onto a metallic frame, as shown in Fig. 22a and Fig. 22b, and pressure was applied using vacuum cups. Two distinct loading cycles were used to analyse the modules' behaviour.

In type 1 loading, three cycles with an amplitude of 2400 Pa and a mean pressure of 0 Pa were applied, while type 2 loading involved a sequence of one cycle at 5400 Pa and another at 8000 Pa, both with a mean pressure of 0 Pa. Each loading cycle was held at maximum load for a duration of 1 hour. Type 1 loading was performed on both PPGF8 and PPGF6 samples, whereas type 2 loading was specific to PPGF8. To verify electrical continuity, a 1A current was applied and monitored throughout the tests. Displacement at the centre of the modules was measured using a spring-loaded sensor positioned at the back, as depicted in Fig. 22c. The corresponding electroluminescence (EL) images and load-displacement curves for these modules are presented in Fig. 23 and, Fig. 24, below. It appears that the loading cycles did not result in any major crack formation after the loading.


(a)


(b)

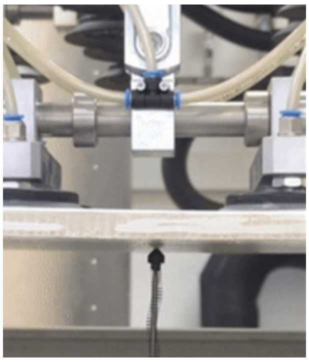

(c)

Fig. 22 LW modules based on (a) PPGF8 and (b) PPGF6, under static mechanical loading, (c) attachment of a spring-loaded displacement sensor at the back of a module's centre. To keep track of any possible circuit disconnection, the modules were subjected to 1 A current.

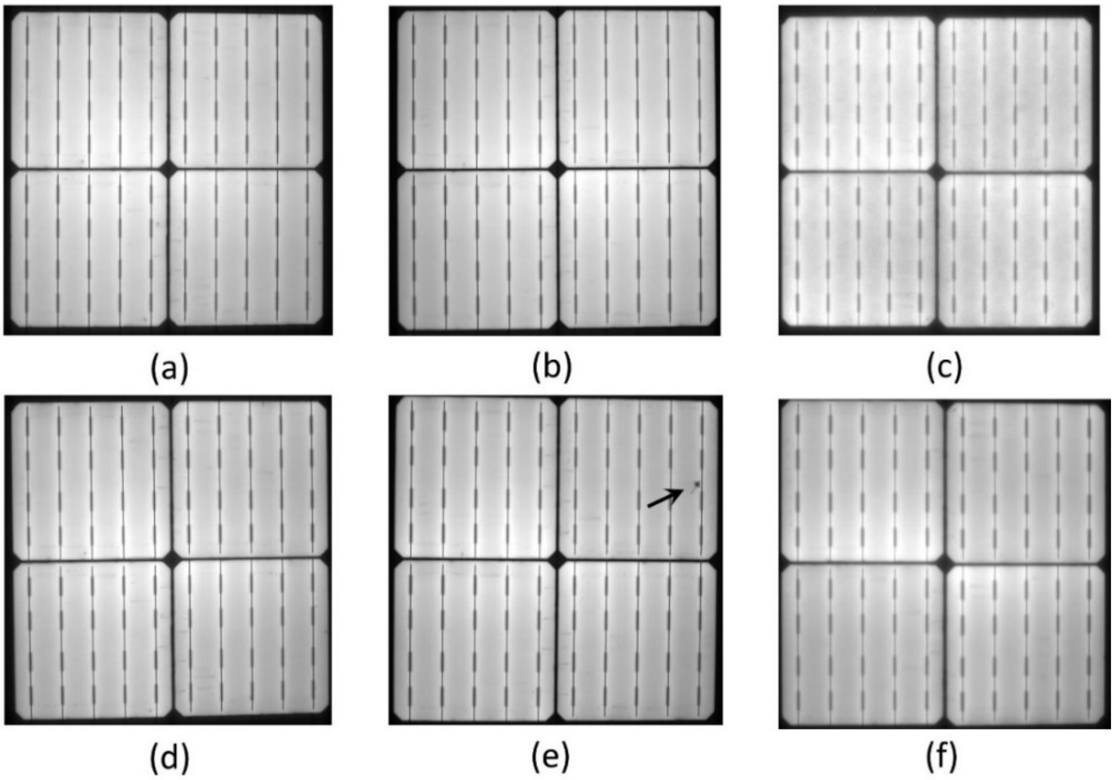


Fig. 23 EL images of mini-modules for (a) PPGF8 and (b) PPGF6 in the pristine condition & after applying type 1 loading cycles on (d) PPGF8 and (e) PPGF6. Furthermore, EL images of mini-modules consisting PPGF8 (a) before and (f) after applying type 2 loading cycles

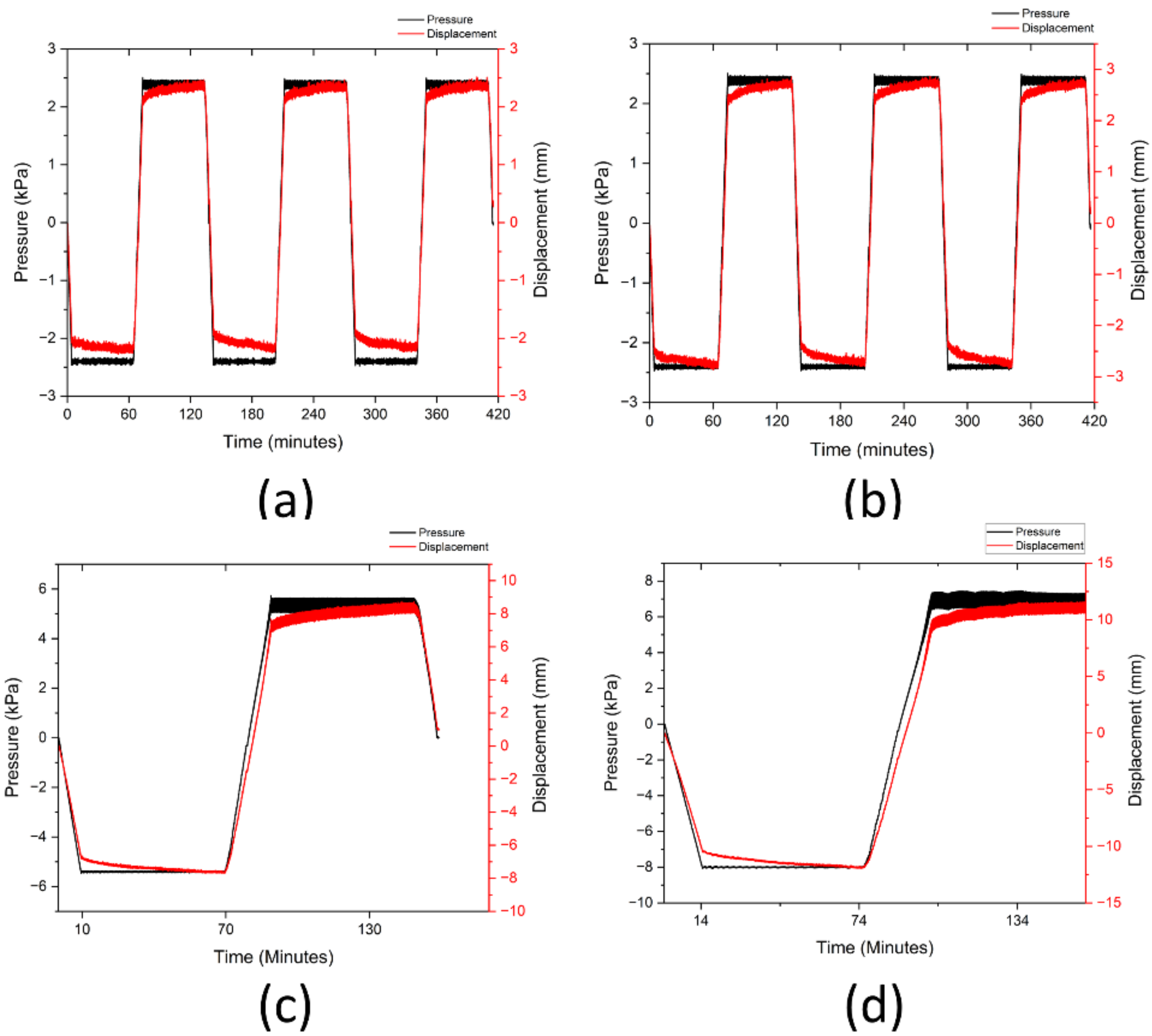


Fig. 24 Evolution of pressure and displacement profiles with time for the mini modules subjected to type 1 loading based on (a) PPGF8 type backsheet and (b) PPGF6 type backsheet; and type 2 loading on PPGF8 based backsheet for amplitude of (c) 5400 Pa and (d) 8000

2.2.5 Flammability tests

To assess fire performance, two types of sandwich structures were subjected to flame exposure to observe behaviours such as flaming droplet production, smoke generation, and flame spread from the point of contact (Fs). The objective was to determine if the samples meet the requirements of Class 'E' according to ISO 11925, which stipulates that Fs must remain below 150 mm. During testing, a flame composed of 30% propane and 70% butane was applied to each specimen for 15 seconds, then removed, followed by a 5-second wait before extinguishing.

The instances of maximum flame spread (Fs) within the 20-second test duration are presented in Fig. 25. For the PPGF8-based sandwich structure, Fs remained below 150 mm, while for the PPGF6-based structure, it reached approximately 170 mm. Both samples exhibited flaming droplets within the 20-second test period, suggesting a need for enhanced fire resistance in these composite backsheets, potentially through the addition of fire retardants or other modifications.

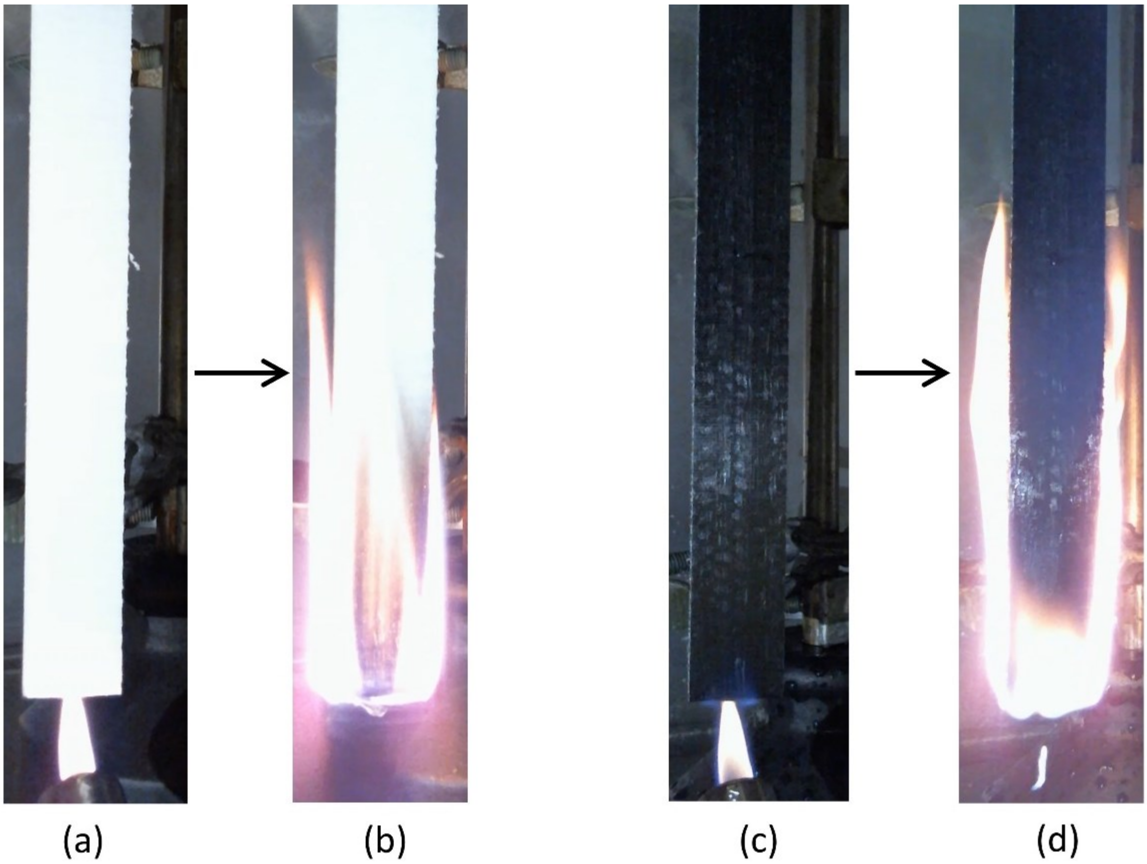


Fig. 25 Flammability tests for PPGF8 based backsheets (a) before the test and (b) at the instance when the flame propagation is the highest; and for PPGF6 based backsheets (a) before the test and (b) at the instance when the flame propagation is the highest

Mini-PV modules based on both the polypropylene based skins were also subjected to flammability tests and the results are shown in Fig. 26. It appears that the damage due to the flame is almost the same and the edge and the front of the modules sustained the greatest damage.

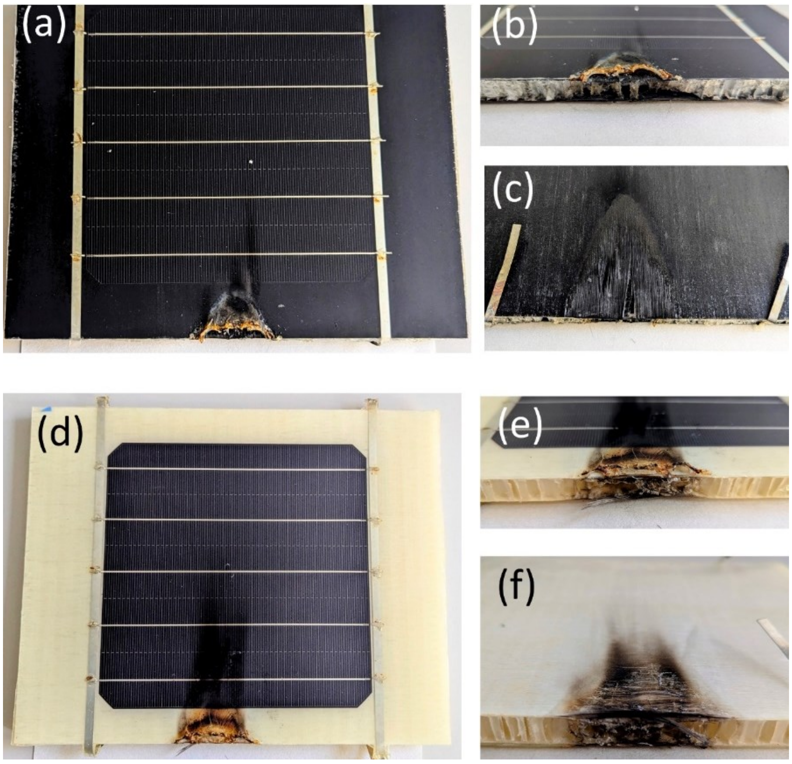


Fig. 26 Visual appearance of the mini-PV modules based on PPGF6 are shown in (a, b and c); while the same is indicated in for PPGF8 in (d, e, and f).

2.2.6 Fabrication of large modules

Accelerated environmental aging tests have shown that the packaging materials used in these lightweight PV modules effectively shield the solar cells from environmental stress, limiting the maximum power output degradation to less than 5%. Based on these promising results, larger modules were fabricated using the previously specified materials and are ready to be exposed to the Central European climate in Neuchâtel, Switzerland. The design of these modules, as shown in Fig. 27, includes 40 series-connected solar cells and four bypass diodes (BPDs), with each BPD connected in parallel to a set of 10 cells. The modules were built with either beige or dark grey colored foils, or with no color foil, as illustrated in Fig. 28. Additionally, colored moduels based on dark gray and beige foils are also fabricated for the comparison of aesthetics.

Electroluminescence (EL) images, as well as IV characteristics, are displayed in Fig. 29 and Fig. 30, respectively. Key electrical parameters, such as short-circuit current, open-circuit voltage, maximum power output, and efficiencies, are summarized in Table 6 for these modules.

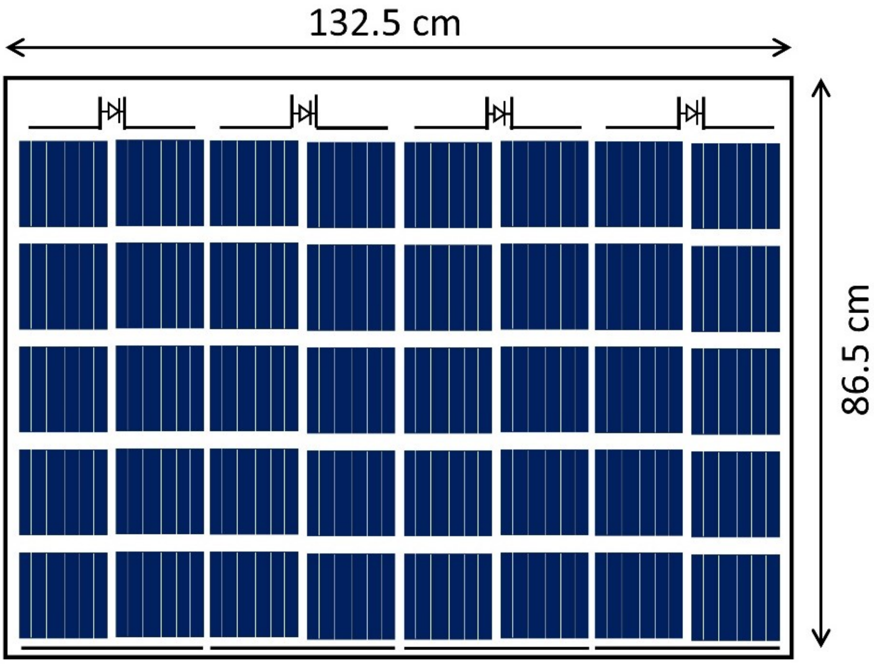


Fig. 27 Design of an upscaled module consisting of 40 series connected cells

Fig. 28 Upscaled modules based on both PPGF8 and PPGF6 skins. The modules with beige and dark grey coloured foils are based on PPGF6 skins.

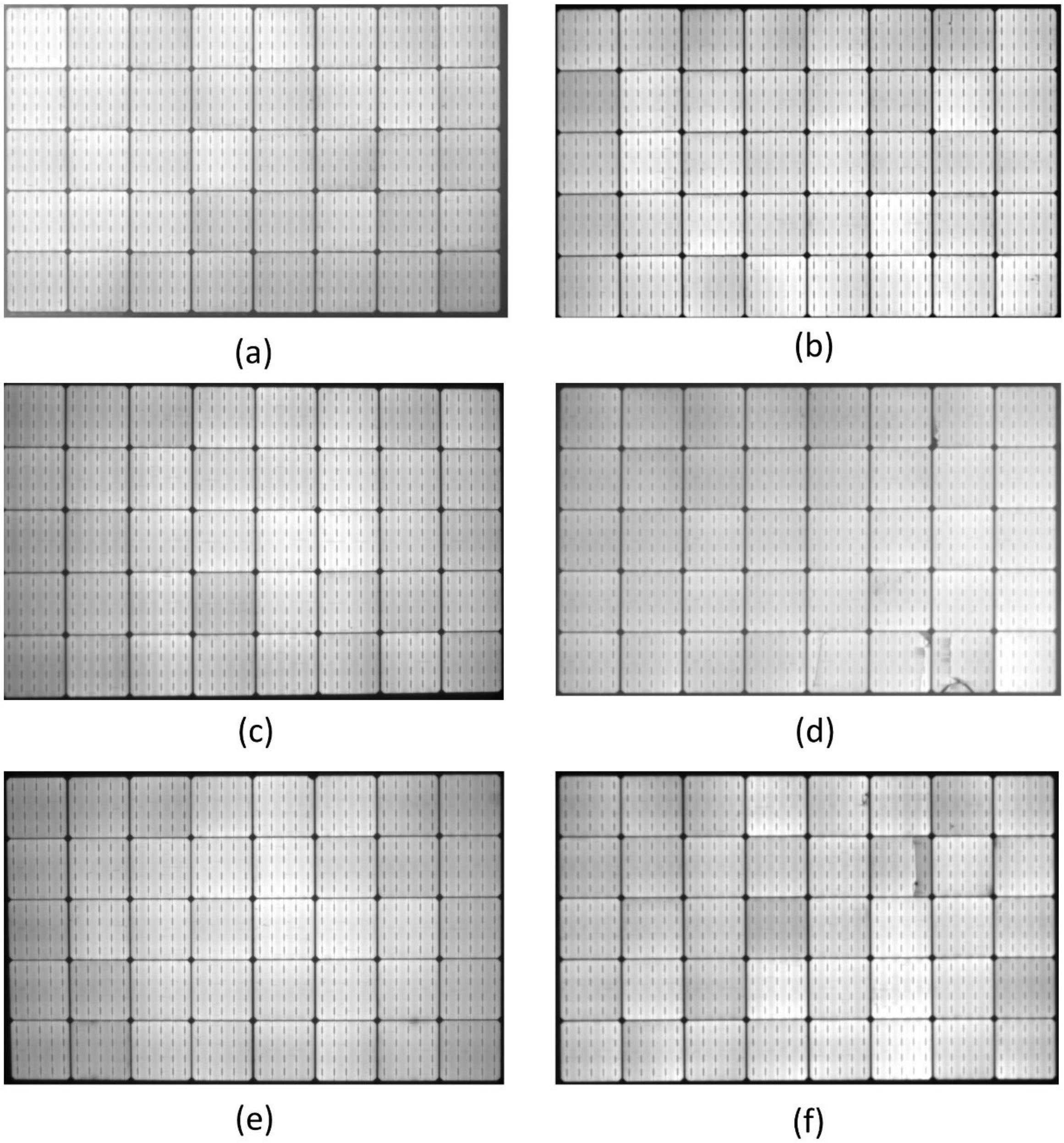


Fig. 29 EL images for modules based on (a) PPGF8 without coloured foil, (b) PPGF6 without coloured foil, (c) PPGF6 with dark grey coloured foil, and (d) PPGF6 with beige coloured foil.

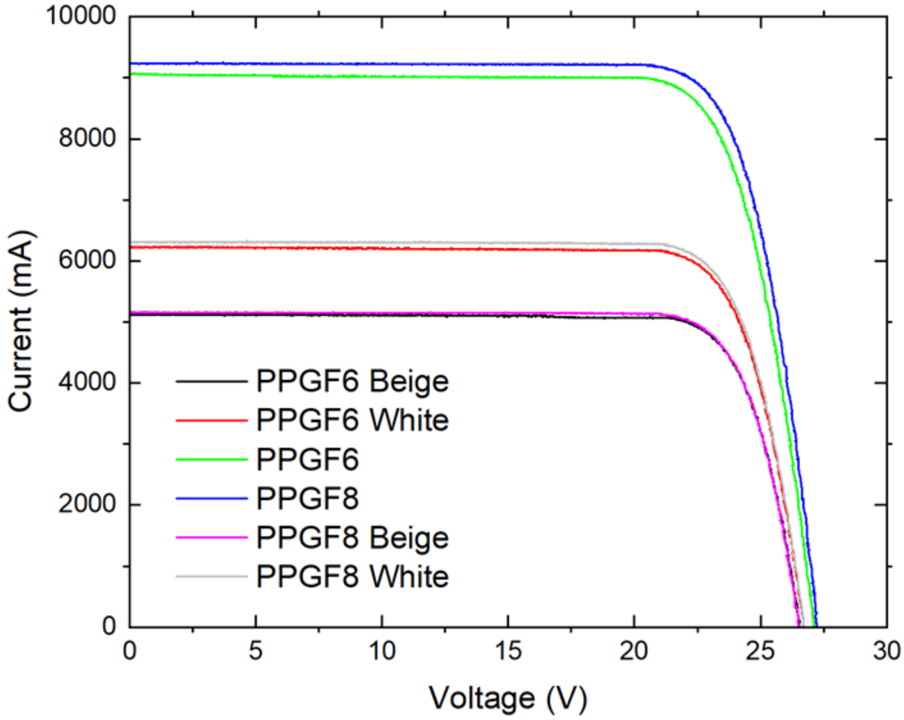


Fig. 30 IV characteristics for upscaled modules

Table 6 Electrical parameters for upscaled modules

Module	Isc (mA)	Voc (V)	Max. Power (W)	Efficiency (%)
PPGF8-Transparent	9122	27.1	195.74	19.57
PPGF6-Transparent	9065	27.1	193.61	19.36
PPGF6-Dark Gray	6215	26.7	134.08	13.4
PPGF6-Beige	5112	26.5	110.94	11.09
PPGF8-Dark Gray	6305	26.7	136.18	13.6
PPGF8-Beige	5220	26.5	112.8	11.19

2.2.7 Set-up of demo site at microcity

A demonstrator test site is being realized on the rooftop of microcity building at Neuchâtel, Switzerland as shown in Fig. 31. This demonstrator will have above-described modules mounted in the form of a façade. The modules will be oriented towards the East direction. Several important outdoor weather data such as, global horizontal irradiance, direct normal irradiance, wind speed, air temperature, etc will be recorded as well. It is planned to monitor the modules in maximum power point (MPP) tracking mode of operation and take time to time indoor characterization to understand if the modules are undergoing degradation during their outdoor operation or not.

Fig. 31 Demonstrator site on microcity rooftop at Neuchatel, Switzerland

The demo site also showcases, for a comparison purpose, two modules based on white skins with colored foils. The goal behind this is to compare aesthetical aspects on the modules of larger format in outdoor condition when installed in the form of a façade. Besides this, another goal of installing these two modules was to compare the energy generated with the modules of the same color that uses black skins.

3 Conclusions and outlook

This report presents the reliability testing results of innovative, glass-free, colored lightweight PV modules with polymeric composite backsheets, achieving a total weight of less than 6 kg/m². Four composite skins, made from polymeric materials such as polypropylene (PP) or polyethylene terephthalate (PET), with or without glass fibers, were tested in combination with honeycomb (HC) cores made of PET or PP.

Initial exhibits: The modules based on the novel composite backsheets could achieve the target of weight less than **6 kg/m²**. Among the modules, the candidate with PET based honeycomb and BOPET skin could achieve weight as low as **3.3 kg/m²**.

Initial reliability testing: Tests revealed that PET-based skin-HC combinations failed to meet reliability testing requirements, including environmental testing, T-peel tests, and flammability tests. Conversely, **PP-based skin-HC combinations showed promising results and were selected for further improvement and testing**.

Improvement in the bill-of-materials: Going forward, polyolefin elastomer (POE) replaced thermoplastic polyolefin (TPO) to enhance adhesion strength, while colored foils from Solaxess improved aesthetics. The two composite backsheet candidates (PPGF6 and PPGF8) consisted of the same PP-based honeycomb but were different in the skins. The first candidate, PPGF8, had white skin with 820 g/m² fiber density, while the second, PPGF6 is black with 660 g/m² fiber density.

Further tests on modules with improved bill-of-materials: Modules with both PPGF8 and PPGF6 sandwich structures showed less than 5% degradation in relative power output after extensive separate climatic aging conditions, including 2000 hours of damp-heat exposure, 60 kWh/m² UV exposure at 340 nm and 60°C, 400 thermal cycles, and 40 humidity-freeze cycles. Damp-heat aging had the most noticeable impact on aesthetics, leading to minor delamination near the frontsheet-encapsulant interface at the module corners.

Four-Point Bending: Both PPGF8 and PPGF6 composite backsheets displayed directional differences in flexural properties, with bending stiffness and load capacity higher in the longitudinal direction (aligned with the bonded honeycomb walls) than in the transverse direction. PPGF8 also demonstrated superior stiffness in both directions compared to PPGF6, likely due to its higher fibre density.

Static Mechanical Load Test: Mini-modules (40 cm x 40 cm) made with PPGF8 and PPGF6 structures experienced maximum displacements of 2.25 mm and 2.75 mm, respectively, at the module centre under a 2400 Pa load. No new cell cracks were observed in either module, even when the test pressure was increased to 8000 Pa, indicating substantial mechanical resilience for small-scale modules, with further tests required on a larger scale.

Flammability Tests: Flame spread from the ignition point was under 150 mm for the PPGF8 backsheet, whereas PPGF6 exceeded this limit. Thus, PPGF8 met one of the critical criteria for

ISO Class E; however, flaming droplets were observed in both cases, preventing full Class E compliance.

Demo site and outdoor exposure: A test demo site has been created on the rooftop of microcity building at Neuchâtel, Switzerland. Where all the candidate upscaled modules are attached in the form of an East-facing façade to be monitored in the MPP tracking mode. The results of this demo site will be made available in the future along with the any potential degradation mode.

Overall, this work demonstrates promising outcomes, with the mini-modules meeting the essential test requirements of the IEC 61215:2021 standard. The PPGF8 backsheet showed stronger mechanical performance than PPGF6 and exhibited slightly better fire behaviour, with lower flame spread. While flaming droplets remain an issue, adding fire retardants may further enhance the safety profile of these composite backsheets.

4 Publications and other communications

Type	Description	Year
Poster	*Nikolina Pervan, Gabriele C. Eder, Yuliya Voronko, Umang Desai, Antonin Faes, Christophe Ballif, Jarne Saelens, Wouter Winant, Bin Luo, Jonathan Govaerts, Gernot Oreski,* ***"Honeycomb structures as backsheets for light weight PV modules"***	PV in Motion Conference, 06. - 08. 03. 2024. Neuchatel (CH)
Presentation	*Umang Desai, Jonathan Govaerts, Bin Luo, Yuliya Voronko, Gabriele Eder, Jarne Saelens, Wouter Winant, Nikolina Pervan, Gernot Oreski, Antonin Faes, Christophe Ballif,* ***"Novel lightweight PV modules based on polymeric honeycomb for building integration"***	IEEE-PVSC, 9.-14.06.2024, Seattle (USA)
Poster	*Nikolina Pervan, Sonja Feldbacher, Gabriele C. Eder, Yuliya Voronko, Umang Desai, Antonin Faes, Christophe Ballif, Wouter Winant, Bin Luo, Jonathan Govaerts, Gernot Oreski,* ***"Enabling glass-free light weight PV modules via honeycomb structures"***	EUROREG Conference, 20. – 21. 06. 2024., Ljubljana (SI)
Presentation	*Umang Desai, Jonathan Govaerts, Bin Luo, Yuliya Voronko, Gabriele Eder, Jarne Saelens, Wouter Winant, Nikolina Pervan, Gernot Oreski, Antonin Faes, Christophe Ballif,* ***"Mechanically Robust and Environmentally Stable Novel Lightweight PV Modules for Building Integration Based on Polymeric Honeycomb"***	41th European Photovoltaic Solar Energy Conference and Exhibition, 23.-27.9.2024, Vienna (AUT)
Poster	*Leïla Mazirt, Umang Desai, Yuliya Voronko, Nikolina Pervan, Gernot Oreski, Gabriele Eder, Antonin Faes, Christophe Ballif,* ***"Upscaling of lightweight polymeric honeycomb based solar panels for BIPV"***	Solar and Storage conference, 17-18 09.2024, Zürich (CH)
Invited talk	*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
Presentation	*Jonathan Govaerts, Paul Dufke, Bin Luo, Matthias Bonnart, Rik Van Dyck, Tom Borgers, Jef Poortmans, Arne Derluyn, Jarne Saelens, Wouter Winant, Meric Caliskan, Arslan,*	*EU PVSEC, Portugal, 2023*

	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***	
Poster	*U. Desai et al,* ***Overview of the project "DE-LIGHT" DE sign and Evaluation of LIGHT weight Composite PV Modules for Integration in Buildings and Infrastructure***	*21st Swiss Solar Conference, Bern, 2023*
Poster	*N. Pervan et al.,* ***Honeycomb structures as backsheets for light weight PV modules***	*EU PVSEC, Portugal, 2023*