

Material screening for the development of a photovoltaic module using biodegradable materials from renewable raw materials

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Abstract. The development of photovoltaic (PV) modules made of bio-degradable materials from renewable resources offers numerous advantages. It reduces the ecological footprint of the photovoltaic industry and promotes its sustainability. The use of these materials reduces the use of non-renewable resources and minimizes the environmental impact during the full life cycle of the PV module. One limitation of PV modules made from renewable raw materials is their typical limited durability compared to conventional PV modules. Due to their natural properties, biodegradable materials may not offer the same longevity and resistance to environmental influences as conventional materials. This can lead to a shortened lifespan of the modules and affect their long-term performance. The aim of this work is to present a screening of possible material candidates that may be suitable for achieving at least partially substitution of components of standard crystalline PV module with recycled, bio-based or bio-degradable materials. The focus lies on encapsulation, backsheets and module frame as replacement for aluminum. It is shown how these materials behave under the standard requirements of the PV industry, which materials are generally suitable and which mechanisms could prove to be showstoppers. The selected wood-based material as substitute for aluminum showed resistance in aging tests, but the dependence of the properties on the moisture content must be considered. In the design process differences to aluminum regarding fracture behavior must be considered with appropriate design safety factors. From 6 initial variants for mini-module manufacturing only two were identified for further investigation. Material weaknesses were identified in long-term IEC 61215-2 Damp Heat (DH) tests and the sequential test Sequence B of IEC 61730-2. The variant of EVA with bio-degradable additive and bio-based backsheets and polyamid based backsheets were identified as suitable for further testing. The tested bio-degradable materials were identified as not suitable because the temperature and humidity involved in the standard tests lead, even after short testing intervals, to severe material degradation. As result, the materials could no longer fulfill its protective function for the cells.

Keywords: Bio-degradable material / bio-based material / PV module reliability / module degradation / accelerated aging tests

1 Introduction

Sustainability and resource conservation are the major topics for the 21st century. The EU has set itself the binding target of achieving climate neutrality by 2050 – emissions are to be reduced by at least 55% by 2030 [1]. As sustainable energy resource PV modules are not generating greenhouse gas emissions during operation. However, finite resources such as silver and copper are required for production and the polymer materials are based on non-renewable resources [2]. The recycling of old PV modules will pose a challenge for waste treatment in the future [3].

Globally, it is important to align development, economic, financial, energy and transport policies with climate protection goals.

First, we need to differentiate between recyclable, bio-based and bio-degradable. The term “recyclable” refers to the ability of a material to be returned to a new production cycle after use. It means that the material can be collected, sorted and recycled to make new products. Recycling reduces the amount of waste and the need for new raw materials. The term “bio-based” refers to materials that are made from biological (plant or animal) raw materials. These raw materials can be renewable and come from agricultural products or biomass, for example plant oils, sugar, and starches. Bio-based materials can be an alternative to non-renewable or fossil-based materials

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and contribute to reducing dependence on finite resources. The term “bio-degradable” refers to the ability of a material to degrade under certain conditions through biological processes in the environment. Bio-degradable materials can be decomposed by microorganisms, such as bacteria or fungi, and converted into natural substances. This process can contribute to a reduction in the amount of waste and a reduction in environmental impact if the material is disposed of properly [4].

It is important to note that recyclable, bio-based and bio-degradable materials each have different properties and applications. Not all recyclable materials are bio-based or biodegradable, and not all bio-based materials are biodegradable. Work on the E-Quadrat project (Renewable energies from renewable raw materials: Development of photovoltaic modules using biodegradable materials from renewable raw materials) began at the beginning of 2021 to implement these benefits.

In the PV industry, the main components glass, aluminum and copper are mainly recycled using destructive methods that completely dismantle the module structure [3,5,6]. The EU’s new eco-design regulations focus on the entire CO₂ footprint and module designs with reduced footprint are being developed [7]. The recycling of the encapsulation and backsheets of PV modules at the end of their service life is usually carried out by mechanical shredding, thermal recycling or chemical processes, whereby the polymer materials are often used as fuel or incinerated [2]. However, these methods are energy-intensive and lead to emissions, which is why the use of bio-based and/or bio-degradable materials is desired. In recent years, the replacement of fluorine-containing materials with fluorine-free materials such as polyester and polyamides has been driven forward [8–10]. Ethylene vinyl acetate (EVA) is still the primary encapsulation material for commercial PV-modules [11]. EVA is a comparatively inexpensive and easy-to-handle material with good optical transparency that has been used in the construction of PV-modules for many years [12–14]. However, under long-term exposure discoloration and the release of small amounts of acetic acid may occur [15–17]. The latter can cause module damage, particularly through corrosion of metal grid and busbars, and prematurely reduce the performance of the modules [16,17]. The main alternatives are polyolefin types, including thermoplastic polyolefins (TPO) and polyolefin elastomers (POE) [16]. Fully circular recycling of these encapsulants is problematic unless efficient chemical recycling can be implemented on a large scale [2]. A bio-based EVA therefore seems to be the easiest to introduce to reduce carbon footprint.

This study presents the first part of the EQuadrat project on material selection and qualification. Following a comprehensive market analysis, various candidates were identified for the encapsulation, backsheets and alternative frame materials. For the frame, mainly mechanical material tests were performed both initially and after selected accelerated aging tests. Mini-modules with the candidate materials were produced. Thermo-mechanical analyses and lamination experiments were first carried out to determine the suitability of the materials. The

mini-modules were then subjected to accelerated aging tests for PV modules in accordance with IEC 61215 [18] and IEC 61730 standards [19].

2 Materials and methods

2.1 Overview of material candidates

A market research was conducted to find commercially available materials or granulates that fulfill at least one of the requirements bio-based, bio-degradable or at least recyclable were procured. Tables 1 and 2 give an overview of encapsulant and backsheets material candidates. Some of the materials were processed in the Fraunhofer IMWS pilot plant center for Polymer Synthesis and Processing PAZ. For the extrusion of encapsulants, a PolyLab PTW16 Thermofisher lab extruder was employed (see Fig. 1 for the schematic work flow). The encapsulants without a biodegradation-promoting additive were extruded in a one-step extrusion process, whereas the encapsulants containing it in a two-step process. The two-step extrusion involved a preliminary masterbatch preparation with 10 wt % of the additive, which was then diluted using a masterbatch with common stabilizing and crosslinking additives as well as pure EVA to precisely reach 1 wt%. In the master batch, typical additives for the EVA stabilization were used such as UV absorber, hindered amine light stabilizer, adhesion promoter on the silane basis, crosslinking peroxide and accelerator. Similar additives with an exception of the UV absorber and adhesion promoter types were present in the commercial EVA used for reference, which was characterized by Py-GC-MS. We are aware of possible interactions of additives in the encapsulant and the backsheets [20,21] as well as dependence of performance on material composition [22]. A specific analysis is not part of this paper.

Initially, the adhesion and optical properties of the materials and their processability were evaluated for the found encapsulants. The data for the optical properties were taken from the corresponding datasheets. The adhesion was tested by lamination on a glass substrate. Due to the scarcity of potentially suitable candidates, encapsulants not showing spontaneous delamination within the first week after the lamination qualified the selection procedure. For the backsheets, a melting point above the typical lamination temperature of 150 °C was required. This was proofed by differential scanning calorimetry (DSC, see SI). PET, PLA, and PA11 met this requirement, whereas PBS did not. Some variants of encapsulants and backsheets have already been ruled out during this process and therefore not mentioned here. Results of the analytics can be found in the supplementary material section of this paper [23,24].

A weather-resistant composite material made of polyethylene and wood, which is fully cradle-to-cradle recyclable, is being investigated as alternative for the aluminum frame. In Detail, GCC (German Compact Composite) is a wood-based material that contains up to 75% natural fibers in its basic formulation – a uniquely high proportion worldwide. Additionally, the GCC meet the extremely high demands of the Cradle to Cradle® principle. With Cradle to Cradle Certified® at the Gold

Table 1. Sustainable encapsulant material candidates for PV module construction.

#	Material description	Sustainable feature	Pros and Cons
1	Blend of vinylacetat/vinyl laurat copolymer, polyvinyl acetate and polylactic acid (PLA#1)*	Bio-based, Bio-degradable	Pros: suitable optical properties, good adhesion to glass Cons: too rigid, bad adhesion to backsheets
2	Bio-based EVA*	Bio-based	Pros: nearly same properties as oil-based EVA Cons: higher cost, somewhat lower transmittance, additives necessary Material procurement difficult, not part of this study
3	EVA with bio-degradable additive*	Bio-degradable	Pros: nearly same properties as oil-based EVA Cons: somewhat lower transmittance, additive performance not guaranteed Combination with standard EVA Masterbatch (Ref2)
4	PLA#0	Bio-degradable	Poor adhesion to glass and therefore not taken into account
5	Polybutylene adipate terephthalate (PBAT)	Bio-based, bio-degradable	Pros: suitable mechanical properties Cons: low transmittance

* Self-extruded at Fraunhofer IMWS.

Table 2. Sustainable backsheets material candidates for PV module construction.

#	Material description	Sustainable feature	Remark
1	Bio-based polyethylene terephthalate (bio-PET)**	Bio-based, recyclable	Pros: nearly the same properties as oil-based PET backsheets Cons: still to be found out 30% organic content (ethylene glycol)
2	Polylactic Acid (PLA#2)***	Bio-based, bio-degradable	Pros: rigidity, good adhesion to EVA Cons: high WVTR, low weatherability Only small plates initially available
3	PLA#3	Bio-based, bio-degradable	Thin film with a special primer for the enhanced adhesion with EVA encapsulants Pros: intrinsically improved sustainability Cons: poor barrier properties and hydrolysis stability
4	PLA#4 and bio-PET#2 with coating**	Bio-based, bio-degradable	Only small plates initially available, that were treated with experimental coatings for better adhesion
5	PA11***	Bio-based, recyclable	Pros: rigidity, high melting point Cons: expected low UV-stability Only small plates initially available
6	Polybutylene succinate (PBS)***	Bio-based, bio-degradable	Pros: sufficient rigidity Cons: melting point too low

** Specially prepared and provided by our industrial partners.

*** Semi-finished products.

level, GCC is one of only about 20 building materials worldwide that can be classified at this level. GCC goes even further and can achieve the highest level in material health, the Platinum standard. This is only awarded when all ingredients are listed in detail – with a precision of 100 parts per million – and the human and ecotoxicological safety can be proven [25].

2.2 Mini-module test specimen

Due to the size of the available materials (PA11 and PLA sheets only 14 cm × 20 cm), samples are produced using commercial half cells. Three mini-modules were planned per each mini-module composition. An overview of the mini-module test series setups is given in Table 3 and an

Table 3. Sample matrix of the first mini-module test series.

Layer Variant	Var 1	Var 2	Var 3	Var 4	Var 5	Var 6	Ref	Ref 2
Front side (thickness)	Glass (3 mm)	Glass (3 mm)	Glass (3 mm)	Glass (3 mm)	Glass (3 mm)	Glass (3 mm)	Glass (3 mm)	Glass (3 mm)
Encapsulant (thickness, UV absorption type)	EVA #2 biodegradable additive (450 μm , UV-block)	PLA #1 bio-based, biodegradable (450 μm , UV-pass)	EVA #2 biodegradable additive (450 μm , UV-block)	EVA #2 biodegradable additive (450 μm , UV-block)	EVA #2 biodegradable additive (450 μm , UV-block)	EVA #2 biodegradable additive (450 μm , UV-block)	EVA #1 Standard ² (450 μm UV-pass)	EVA #2 Standard ³ (380 μm UV-block)
Cell technology	PERC	PERC	PERC	PERC	PERC	PERC	PERC	PERC
Encapsulant (thickness, UV absorption type)	EVA #2 biodegradable additive (450 μm UV-block)	PLA #1 bio-based, biodegradable (450 μm UV-block)	EVA #2 biodegradable additive (450 μm UV-block)	EVA #2 biodegradable additive (450 μm UV-block)	EVA #2 biodegradable additive (450 μm UV-block)	EVA #2 biodegradable additive (450 μm UV-block)	EVA #1 Standard ² (450 μm UV-block)	EVA #2 Standard ³ (380 μm UV-block)
Back sheet (thickness)	PET #1 bio-based 180 μm	PET #1 Standard ² 175 μm	PA11 bio-based, recyclable 3 mm	PLA #2 bio-based, bio-degradable 3.5 mm	PLA #3 bio-based, bio-degradable 209 μm	2xPLA #4 + 2xPET #2 bio-based coating 400 μm	PET #1 Standard ² 175 μm	PET #1 Standard ² 175 μm
Sample amount	15	15	15	15	3 ¹	4 ¹	15	15

¹ Limited amount of material.² Standard-commercial-material Fraunhofer CSP.³ Master batch material.



Fig. 1. Schematic overview of the customized in-house extrusion of EVA encapsulants at the Fraunhofer IMWS.

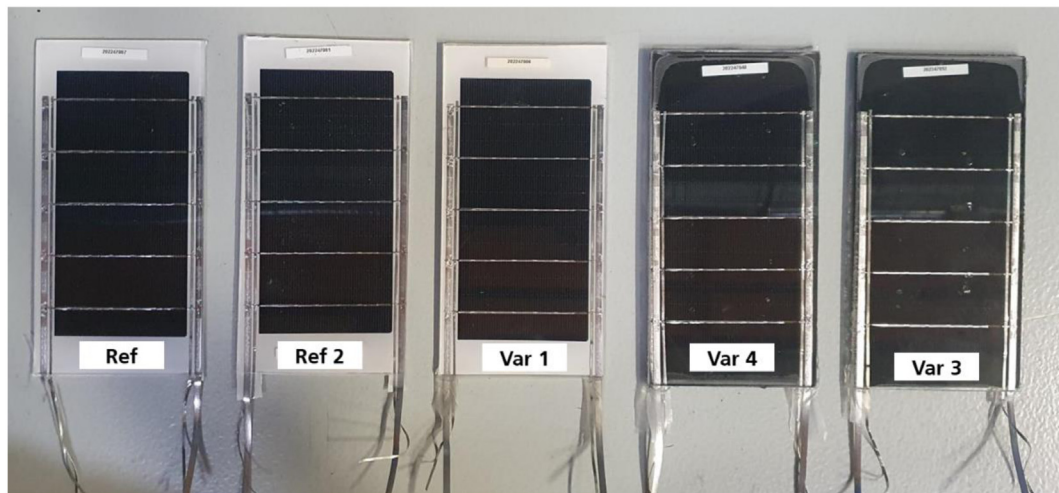


Fig. 2. Exemplary photograph of five of the 97 manufactured mini modules (one for the five main groups).

exemplary photo of the produced samples is given in [Figure 2](#). In the lamination run the variant “Var 2” has already turned out to be non-processable. The other samples were subjected to the specified accelerated aging tests. “Var 4” was expected to experience higher degradation due to the biodegradable PLA and serves here as a potential negative example. There were also two reference setups produced as benchmark in the test sequence and to allow assessment of the effect of the biodegradable additive. One consists of a commercially available EVA material (EVA#1) and another is the EVA Master batch (EVA#2) provided by a project partner that is planned for usage with the biodegradable EVA. The samples were produced without additional edge sealing to be most comparable with standard PV modules with same cell technology. Due to the small cell to edge spacings, this represents a worst-case scenario regarding the diffusion of moisture. However, this can also lead to degradation products, such as acetic acid able to autocatalyze the EVA degradation, diffusing out more quickly.

2.3 Mini-module characterization

Module characterization was done using a Berger Licht-technik class AAA Solar simulator. The repeatability of the

system is usually better than 0.3% for maximum power determination. Contacting of the samples was more difficult, which led to increased uncertainty (estimated 0.8%) in the measurement by different operators. Flash measurements were done at STC conditions and 200 W/m^2 . Electroluminescence images were taken in a commercial EL system (greateyes Lumisolar Professional) with a cooled CCD camera. The injection current was set close to I_{SC} (5 A) and at 10% I_{SC} (500 mA). Since there were no issues related to shunting that are more pronounced under low irradiance and low current injection, we limit the presented results to the STC characterization.

2.4 Frame material characterization

The alternative bio-based frame material was evaluated by means of bending tests on test bars measuring $40 \times 40 \times 700 \text{ mm}$. A 3-point bending test setup is used in a universal testing machine (see also supplementary material). The bearing distance was 480 mm. The test was carried out until breakage at a test speed of 10 mm/min. The elastic parameters were evaluated: flexural modulus $E_{Modulus}$, elongation at break ε_B and breaking stress σ_B .

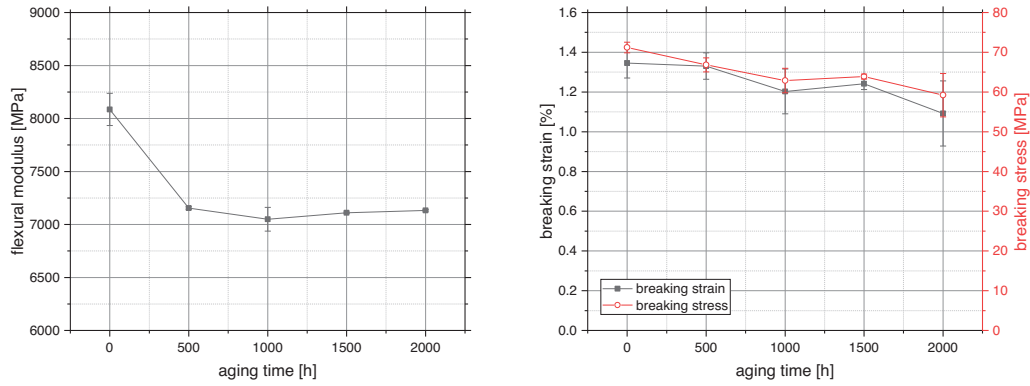


Fig. 3. Frame material, DH-aging, left) flexural modulus, right) breaking strain and breaking stress.

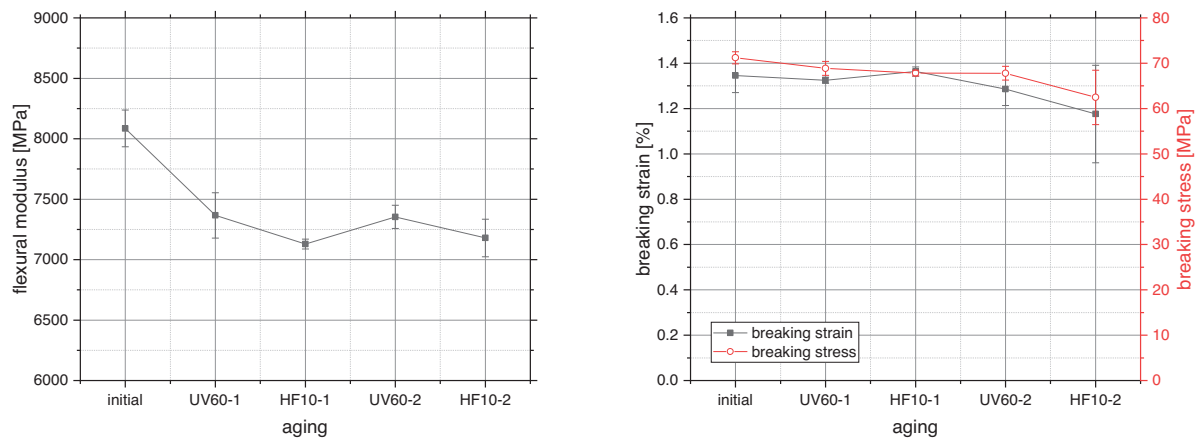


Fig. 4. Frame material, IEC 61730 Seq B, left) flexural modulus, right) breaking strain and breaking stress.

2.5 Accelerated aging test

The following accelerated aging tests from IEC 61215 and IEC 61370 were selected to assess the suitability of the materials for module construction:

- IEC 61370 Seq B: DH200-UV60-HF10-UV60-HF10.
- IEC 61215 Seq C: UV15 – TC50 – HF10.
- IEC 61215 Seq D: DH1000, DH2000.
- IEC 61215 Seq E: TC200, TC400, TC600.

After the initial characterization (STC performance measurement, EL), the samples were distributed to the individual test sequences and measured regularly after a partial test or a specific test duration. The aim of the selected tests is described briefly below. The frame material was only subjected to the Seq B and Seq D test, because there are no issues related to thermal cycling (TC) expected and UV and humidity freeze (HF) from Seq C is also covered by Seq B.

2.5.1 IEC 61730 sequence B

This test sequence is one of the most challenging tests in the current IEC certification. That is why this test was chosen for screening of the variants where only few samples were

available. It is important to note that IEC 61730 is the safety standard, so strictly speaking there is no performance criterion. The aim is to identify problems with polymer components that are particularly susceptible to UV radiation in combination with moisture [19]. The first step is preconditioning with moisture for 200 h in a damp heat (85 °C/85%rh, DH200), followed by 60 kWh/m² UV irradiation (UV60) and a humidity freeze test (20 h at 85 °C/85%rh and 30 min at –40 °C) with 10 cycles (HF10). The back side is then also irradiated with 60 kWh/m² UV (UV60b) and another HF10 is carried out. For technical reasons and availability, the UV irradiation was harsher (85 °C, 60%rh) than required by the standard (60 °C and no humidity control).

2.5.2 IEC 61215 Sequence C: UV15–TC50–HF10

This Sequence starts with a 15 kWh/m² UV preconditioning (UV15) followed by a thermal cycle test with 50 cycles of temperature changes between –40 and 85 °C (TC50) and 10 cycles humidity freeze (HF10). With this sequence material compatibility shall be addressed in a way that adhesive bonds are weakened by the UV radiation and the temperature changes and humidity freeze may propagate delamination and problems with internal contacts.

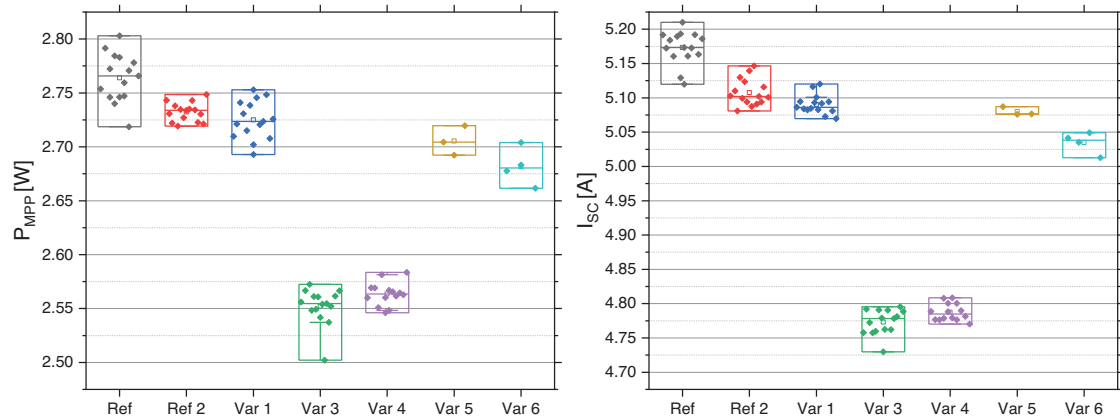


Fig. 5. Left) Initial STC power measurement result of the mini-module samples, right) initial STC short circuit current result of the mini-module samples.

2.5.3 IEC 61215 Sequence D: Damp heat

The Damp heat test with a constant exposure of the module to 85 °C/85% rel. humidity is one of the most established tests in the PV industry. It is designed to determine the ability of the module to withstand the effects of long-term penetration of humidity [18]. This test normally reveals susceptibility to delamination, metal grid discoloration and corrosion of cell contacts. The minimum test duration of 1000 hours is usually extended in the industry in order to demonstrate a longer service life. In this investigation also up to 2000 hours are tested. Intermediate measurements every 500 h were specified.

2.5.4 IEC 61215 Sequence E: Thermal cycling test

The other single factor test of IEC 61215 is a temperature change between −40 and 85 °C for a minimum of 200 cycles. The purpose of this test is to determine the ability of the module to withstand thermal mismatch, fatigue and other stresses caused by repeated changes of temperature [18]. In this case, too, the number of cycles was increased to up to 600 cycles to ensure and demonstrate a longer service life and find weaknesses.

3 Results

3.1 Aging of frame material

DH aging initially shows a significant drop in the flexural modulus after 500 h. The value then remains largely constant and ends up at around 88% of the original level (see Fig. 3). Elongation at break and breaking stress also decrease due to aging. The elongation at break drops to 81% and the breaking stress drops to 83% of the original level after 2000 h.

The aging in sequence B shows a decrease of flexural modulus after the first DH200 and 60 kWh/m² irradiation (UV60) and the first humidity freeze test (HF10-1),

followed by a slight increase after second 60 kWh/m² irradiation (UV60-2) and decrease after the second humidity freeze test (HF10-2) (Fig. 4). The value drops to ~88% of the original level at HF10-1 and HF10-2 similar to that of DH. Breaking stress and elongation at break only change more significantly in the final aging stage. The values fall to 87% of the original level.

After accelerated aging, no significant deterioration in properties was observed, so the material appears to be fundamentally suitable for use as a frame. The modulus of elasticity changes mainly due to moisture. Therefore, preconditioning is useful before characterization. A reduction in elongation at break and breaking stress must be taken into account in the design. Furthermore, the elastic characteristics and load limits are inferior to aluminum. An improvement through fiber or other additives is possible. An observed discoloration of the material is mainly caused by UV-induced aging and is generally not unusual for wood.

3.2 Initial characterization of mini-modules

The same cell type of one performance class was installed in all samples therefore comparable power of the samples can be expected. The results of the initial power measurement show that differences in performance are due to optical differences (Fig. 5). Most of the power difference can be attributed almost entirely to differences in the short-circuit current. Var 3 and Var 4 are at a disadvantage due to the black PLA or PA11, which have a lower reflectivity. Additionally, the master-batch EVA has 1.4% less transmission comparing the median I_{SC} of Ref and Ref2 samples. The bio-degradable additive reduces transmission by additional 0.3%. Apart from a few outliers, the fluctuations are small. In the EL images, small cracks were found in some samples and larger cracks in a few samples. These errors occurred randomly during production and were outliers.

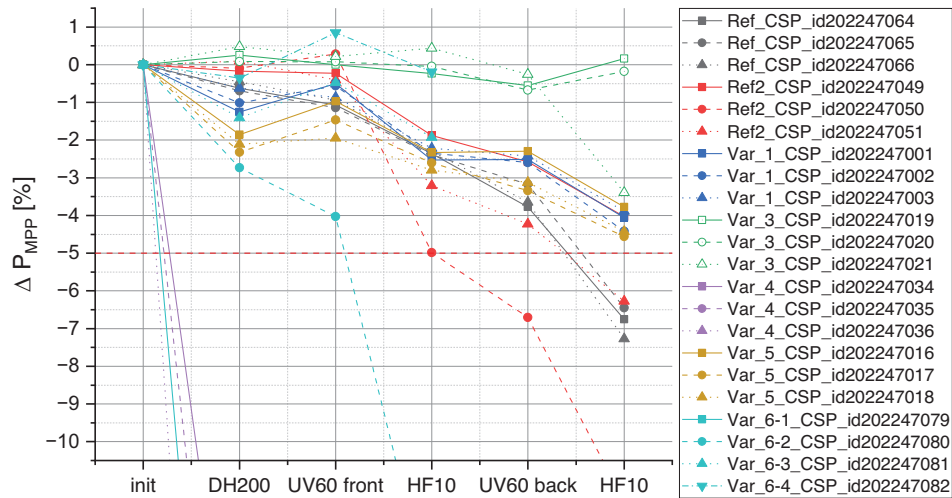


Fig. 6. STC power change of the Mini-module samples during sequence B.



Fig. 7. Photos of specific samples after DH200: left) Var 4 (PLA), right) Var 6 samples with coating.

3.3 Accelerated aging of mini-modules

3.3.1 Results Sequence B (DH200–UV60–HF10–UV60 (b)–HF10)

The harsher temperature and humidity conditions during the UV irradiation may have favored degradation in the follow-up tests. The performance changes of the variants are shown in Figure 6. Var 4 already completely fails after 200 h of DH (DH200) as the PLA cracked and delaminates (Fig. 7). Var 5 was not in the second UV60 as here too the outer coating of the films has already peeled off after DH200. This can be explained by poor barrier properties and hydrolysis stability of PLA (see permeation measurements data in the supplementary material). Var 6-1-4 (coating) also peels off after DH200. These are therefore unsuitable for the requirements. Var 1 and Var 3 are better or comparable to the reference. Some of the references also show significant performance degradation (4–11%) in the course of the test. The increase of power after the first

UV60 for some samples cannot be attributed to a specific reason. Moisture ingress and UV irradiation have a much higher effect due to the sample structure.

The EL images can be used to analyze the causes of degradation. Figure 8 shows an example of the results for Var 1 and Ref2. It can be seen, especially after the two HF10, that penetrating moisture from the edge leads to a degradation of the cell metallization. Due to the inhomogeneity of the UV irradiation in the climate chamber, it is possible that Ref2 was exposed to up to 20% more irradiation and therefore formation of acetic acid and subsequent corrosion is more pronounced. In the case of Var 3, it can be assumed that the thickness of the PA11 reduces moisture penetration during the test time compared to the other variants which also reduces humidity related degradation. The particular sample shown in Figure 8 shows a problem with the cross connection (joint between the ribbons on the cell and cross connector) after the final HF10 which explains the offset to the other two Var 3 samples.



Fig. 8. Selected EL images to analyze the degradation during sequence B.

3.3.2 Results Sequence C (UV15–TC50–HF10)

In this test sequence, the changes in performance were comparable for all groups except Var 4 (PLA) (see Fig. 9). The change in performance between 1 and 2% is moderate. The reason for the power increase after UV for some samples cannot be explained afterwards. For the two very high Var 4 samples the I_{SC} increased and additionally a higher V_{OC} was measured for most samples. This might be attributed to an offset in the temperature measurement for this measurement point. Only Var 4 (PLA) fails completely after HF10, as the PLA has no resistance to moisture, as discussed in the previous sequence.

3.3.3 Results Sequence D (DH2000)

Figure 10 shows the STC performance changes. As expected from the tests presented so far, Var 4 (PLA) is already severely degraded after the first intermediate measurement after 500 h (see Fig. 11 left). Var 1 shows a reduction in performance of $\sim 5\%$ and compared to the remaining variants a significant yellowing after just 1000 h (Fig. 11 right). The degradation is additionally accelerated by the sample build-up and is already over 10% at 1500 h. Ref, Ref2 and Var 3 remain close to each other up to 1500 h. During the additional intermediate measurement after 1750 h, the degradation increases considerably in some cases, especially for Var 3.

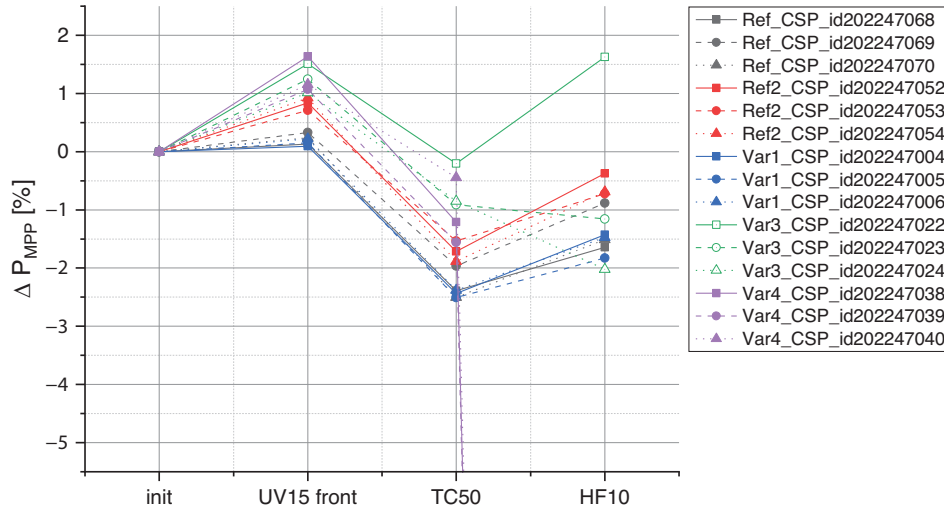


Fig. 9. STC power change of the Mini-module samples during sequence C.

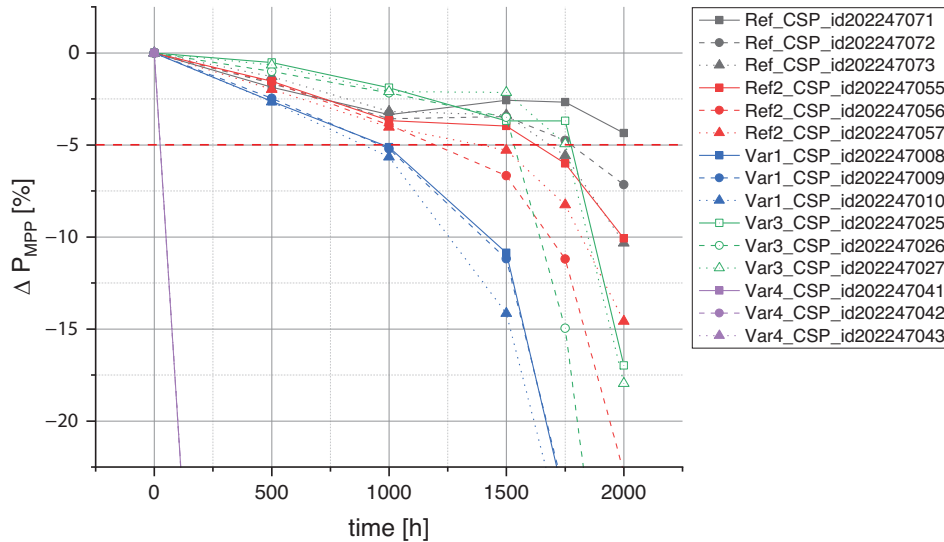


Fig. 10. STC power change of the Mini-module samples during sequence D (DH).

The EL images (Fig. 12) again show the progress of degradation caused by moisture penetration. For Var 1, the first signs of moisture penetrating from the edge can already be seen at 1000 hours. The very clear signs of degradation from 1500 h onwards on the busbars correlate with the increasing power losses. From 1750 h onwards, finger detachment can be assumed, which is associated with the high power loss. In the case of Var 3 and Ref, the degradation is shifted to a later time.

3.3.4 Results Sequence E (TC600)

Figure 13 shows the changes in performance of the samples. Var 1 and the references show similar behavior. Var 3 (PA11) shows significant power reductions in one sample after just 200 cycles. There are problems with

the cross-connection here. But it can be assumed that the high coefficient of thermal expansion of the polyamide combined with the thickness of the sheets leads to significantly increased loads due to the thermo-mechanical stresses. Var 4 performs slightly better here, as there is no moisture present in the test, but the panels show cracks and samples are somehow bended and the placement on the Flasher system was difficult which leads to the fluctuation of the power measurements. The references still show <5% change in performance after TC600, but here too, some faults were found in the cross-connection. This suggests a general weakness due to the structure of the samples with thinner cross-connectors.

The EL images (Fig. 14) show the contacting problems mentioned above. Darker areas appear at the ends of the cells, which indicates a deterioration of the solder

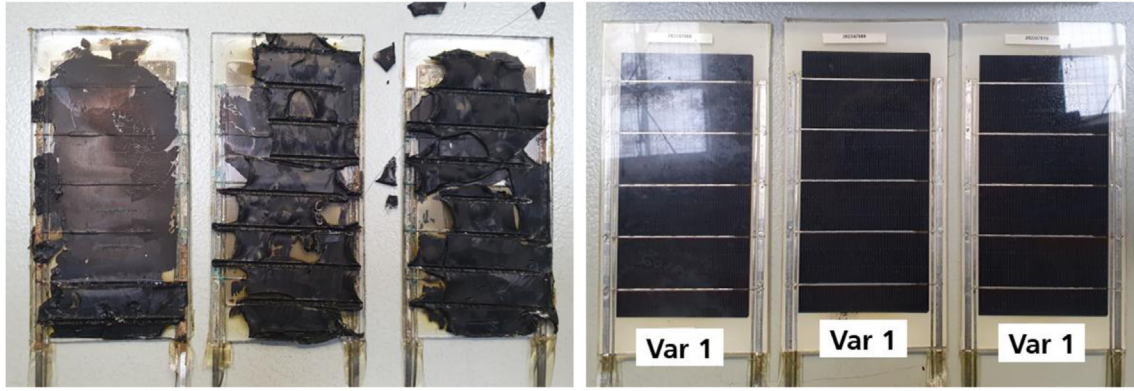


Fig. 11. Photos after DH aging, left) Var 4 after DH500, right) Var 1 shows yellowing after DH1000.

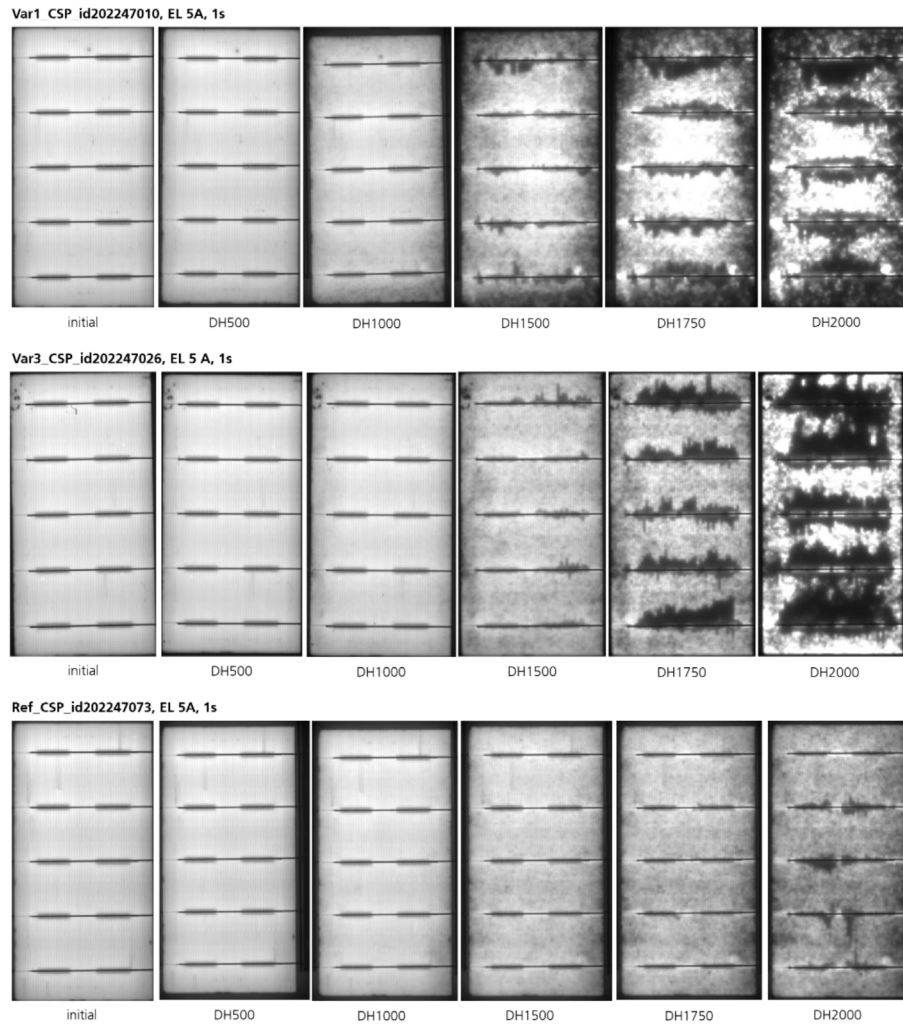


Fig. 12. Selected EL images to analyze the degradation during sequence D (DH).

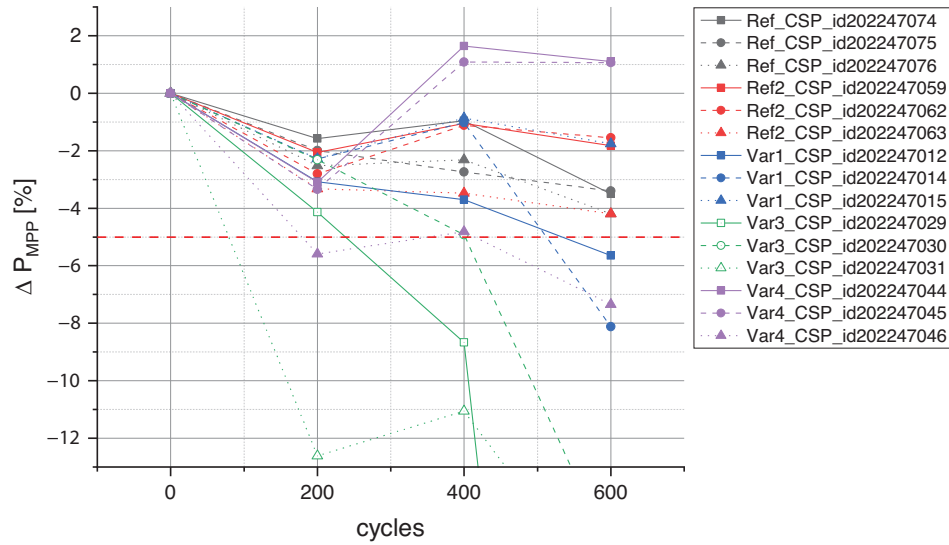


Fig. 13. STC power change of the Mini-module samples during sequence E (TC).

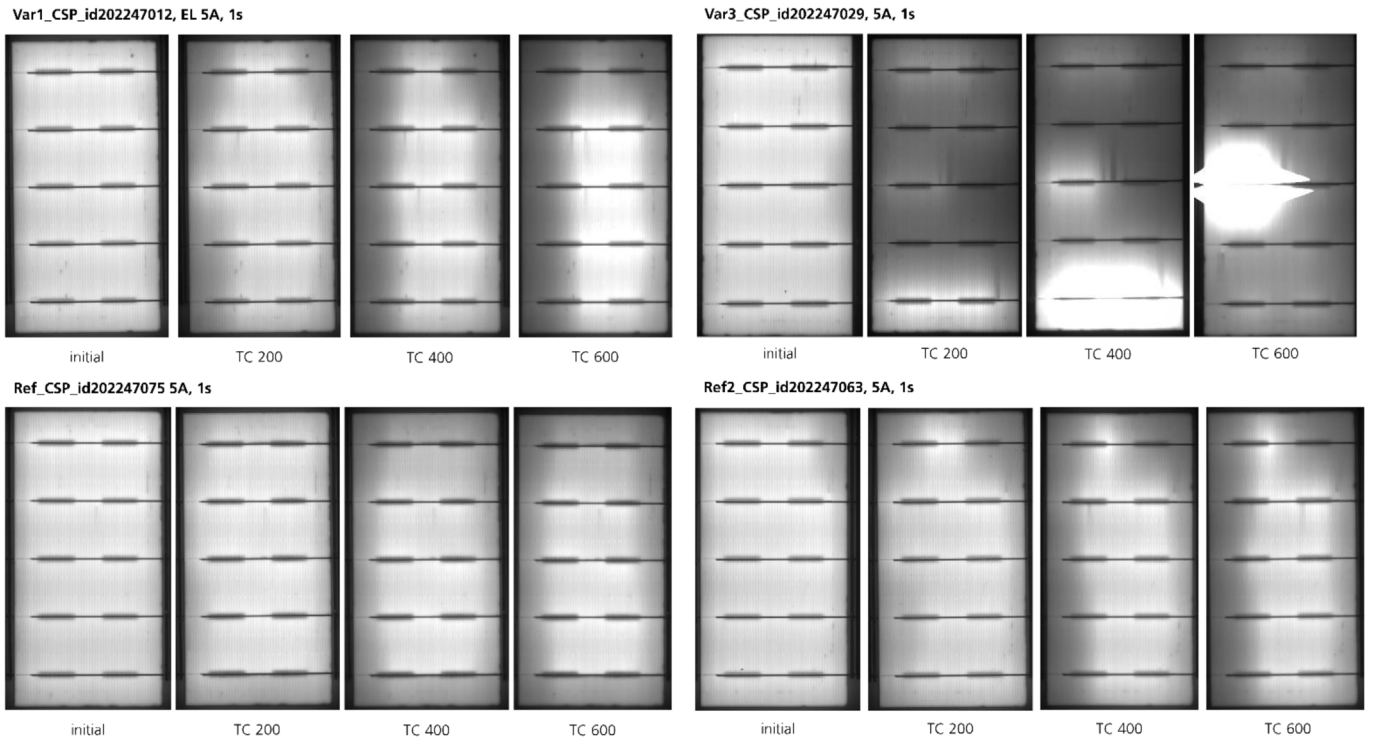


Fig. 14. Selected EL images to analyze the degradation during sequence E (TC).

connection. If particularly bright areas appear, as in Var 3, this is probably an indication of interruptions in the cross-connection. In the case of CSP_id202247029, the entire current is conducted via only one conductor after TC600, which increases the local current density and thus the brightness.

4 Discussion

The selected wood-based alternative frame material has proven to be resistant in the aging tests carried out. With this material, the dependence of the properties on the

Table 4. Evaluation of the mini-module test results.

Test	Var 1	Var 2	Var 3	Var 4	Var 5	Var 6	Ref	Ref 2
Seq B	Pass	–	Pass	Fail	Fail	Fail	Fail*	Fail*
Seq C	Pass	–	Pass	Fail	–	–	Pass	Pass
Seq D	Fail*	–	Pass	Fail	–	–	Pass	Pass
Seq E	Pass	–	Fail*	Fail	–	–	Pass	Pass
Overall	Suitable	Not suitable	Suitable	Not suitable	Not suitable	Not suitable	Suitable	Suitable

* Degradation at the limit and not all samples affected.

moisture content must be considered. In the design process the fracture behavior of the material must be taken into account and appropriate safety factors must be chosen. Compared to aluminum, there are some disadvantages in terms of ductility, which is why a minimum safety factor of 1.5 is recommended, as overloading must be avoided in any case. In concrete terms, this means that the material load-bearing capacity determined from the bending tests is reduced by this factor for the design (e.g. elongation at break of 1.1% must not exceed 0.7% when dimensioning). Note that test loads from IEC standards already have a safety factor of 1.5. Based on the existing load-bearing capacity, a wooden frame will be thicker and heavier compared to aluminum. An improvement of the mechanical properties through fiber reinforcement is possible and may change the fracture behavior but may then affect the recyclability. Despite current disadvantages a wood-based frame offers other possibilities for integration, such as easier processing and fastening with screws.

All Mini-module samples, including the reference, showed weaknesses in the long-term DH tests (>1000 h). Due to the small edge distance of the cell, the contacts of the cells are attacked more quickly than would be the case in a normal module. Therefore, for subsequent studies we intend to use an edge seal to prevent this accelerated diffusion path. Based on the results first mini-module test series, Var 1 and Var 3 were identified as possible candidates for further tests and future developments, with some tests still showing potential for improvement. For Var 1, weaknesses are particularly evident in the DH test. The yellowing causes additional losses but is largely an optical defect and the degradation level after 1000 h is at the limit of acceptable degradation, which is also favored by the sample structure, so that it can be assumed that results at module level should improve. To improve the properties, it would be useful to analyze the additive associated with the discoloration in cooperation with the manufacturer and to adapt the material formulation. Var 3 has the greatest weaknesses during temperature changes. The material is therefore not fundamentally unsuitable, but its use as a plate is not advisable, as the high expansion affects the cross-connection via the rigidity of the plate. Here it is necessary to check whether the use as a thinner film is a more suitable solution. Adding glass fibers or natural fibers would be one way to reduce expansion and

possibly also reduce permeation. The addition of specific diffusion barrier layers, as is the case with aluminum layers in special backsheets, can lead to a significant improvement in DH resistance. Var 4 (PLA) is completely unsuitable, as cracks were already present after production and the material has almost no moisture resistance. Var 5 (PLA) becomes brittle and peels off early on, therefore is unsuitable. Some coatings of Var 6 already showed cracks after production. The PLA variants failed immediately after DH. The PET variants are slightly better but were not examined in more detail due to the initial cracks and low availability. The assessment is summarized in [Table 4](#).

5 Summary and conclusions

In this study, various mini-module structures with bio-based and bio-degradable materials as well as an alternative frame material were examined. The composite wood-based material showed good resistance in the aging tests. There are some manageable disadvantages compared to standard aluminum and there is great potential for optimization through targeted material improvement.

The variants Var 1 (EVA+bio-degradable additive and bio-based PET) and Var 3 (EVA+bio-degradable additive and PA11) were identified as possible candidates for transfer to a next stage of tests. These two variants have each shown weak points in the IEC type approval tests and have the highest potential for use in a module with sustainable materials. The fulfilment is a necessary condition for further evaluation but no sufficient condition for an application. Other variants proved to be unsuitable. One of the main challenges was the stability in the damp heat test as well as the IEC 61730 Sequence B.

The basic applicability of bio-based materials was demonstrated. Further tests will be carried out in the project to confirm their long-term suitability. The use of truly biodegradable materials is considered critical based on the current results, as the biodegradation occurs at low thermal activation and the material have low moisture stability. A degradation during operation leads to loss of the protective function of these materials for the cells and results in unacceptably high degradation. For modules with the property of biodegradability new business models may be developed that have other demand for long-term stability.

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Conflicts of interest

The specific trade names of commercially available materials will only be published in exceptional cases and after consultation to protect the interests of the material suppliers. Poor performance or negative experiences for the specific sample design during this specific research could be generalized and harm the interests of the manufacturers. Otherwise, the material will not be made available, making access to samples for future research projects more difficult. There are no financial conflicts of interest.

Data availability statement

The measurement data analyzed as part of the article can be made available on reasonable request.

Author contribution statement

Matthias Pander: Writing, Methodology, Data analysis and Writing of paper. Bengt Jaekel: Result discussion and Proof reading. Anton Mordvinkin: Writing, Material selection and organization, Result discussion and Proof reading. Ringo Koepge: Writing, Project administration, Sample preparation, Result discussion and Proof reading.

Supplementary material

Table S1. Melting points.

Figure S1. DSC graph of PA11 with 1.5% carbon black. Left: 1. heating cycle, right: 2. heating cycle. Blue and red curves correspond to two different specimens.

Figure S2. DSC graph of PLA#2 +1.5% carbon black. Left: 1. heating cycle, right: 2. heating cycle. Blue and red curves correspond to two different specimens.

Figure S3. DSC data of the PLA#3 Backsheet. Left: 1. heating cycle, right: 2. heating cycle. Blue and red curves correspond to two different specimens.

Figure S4. Gas permeation data for PLA#2. Left: Helium permeation, Right: water vapor permeation.

Figure S5. Test setup of the 3PB test, exemplary image of tested bars after DH2000 and HF10-2 (from left to right).

The Supplementary Material is available at <https://www.epj-pv.org/10.1051/epjpv/2024049/olm>.

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