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Motivation, Benefits, and Challenges for New Photovoltaic Material & Module Developments

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Abstract

In the last decade and longer, photovoltaic module manufacturers have experienced a rapidly growing market along with a dramatic decrease in module prices. Such cost pressures have resulted in a drive to develop and implement new module designs, which either increase performance and/or lifetime of the modules or decrease the cost to produce them. In this paper, the main motivations and benefits but also challenges for material innovations will be discussed. Many of these innovations include the use of new and novel materials in place of more conventional materials or designs. As a result, modules are being produced and sold without a long-term understanding about the performance and reliability of these new materials. This has led to unexpected new failure mechanisms occurring few years after deployment, such as potential induced degradation or backsheet cracking. None of these failure modes have been detected after the back then common single stress tests. New accelerated test approaches are based on a combination or sequence of multiple stressors that better reflect outdoor conditions. That allows for identification of new degradation modes linked to new module materials or module designs.

1. State of the art in crystalline silicon PV section heading

The general architecture of modern crystalline silicon wafer based photovoltaic (PV) modules was developed in the late 1970s and early 1980s within the Flat-Plate Solar Array Project and has not significantly changed since then [1]. A 2022 standard PV module consists of a number of interconnected solar cells encapsulated by a polymer (encapsulant) and covered on the frontside by glass and at the rear by a polymeric backsheet into a long-lasting multi-material composite. In most cases this panel is surrounded by a frame providing the necessary structural support and means for module mounting. The actual module architecture has a layered encapsulation structure designed to protect the solar cells and their interconnecting wires from the harsh environment in which they are typically used.

Despite most PV modules being constructed according to this rather standardized composition in layers, PV modules can come in a variety of different form factors, architectures and designs using a range of different materials. To enable such variability, the fundamental functional requirements for the materials have to be well understood.

The primary objective of a PV module is to convert as much irradiation into electricity as possible. To achieve this goal, on the one hand high transmission of sunlight to the solar cells is required while on the other hand the optical and electrical components need to be protected from damage from chemical stressors

such as water, corrosive gases, oxygen, and from thermal and mechanical stresses for at least 25 years. In order to be successful in the market, these ambitious objectives must be accomplished using low cost materials and high-volume manufacturing processes.

Over the past decade there has been an enormous growth in the production capacity of PV modules worldwide: in 2020 an estimated 140 GW of PV was produced [2, 3]. With significantly increasing production capacity, PV module prices have fallen dramatically. The current PV market shows an extremely high cost pressure, which is also the driving factor for the development and implementation of new module designs and the use of new materials and components. New technologies, which promise either higher efficiency for the same cost or cost reduction at same efficiency, are very often quickly introduced to the market [4]. With current production capacities, many Gigawatts of modules with new technologies and materials can be produced and installed without having sufficient experience about long term reliability. In the worst case, this has led to unexpected degradation mechanisms several years after field deployment, which were not predicted in laboratory accelerated testing, such as potential induced degradation (PID) [5], light and elevated temperature induced degradation (LeTID) [6, 7], or backsheet cracking [8, 9].

The main objectives of this review paper are to provide a global survey of technical efforts aimed at lowering cost and increasing performance and reliability of PV modules by employing new designs, materials and concepts. The paper aims to (1) reveal motivations and benefits for material innovations in PV, (2) to point out the challenges of new materials and new PV module designs and (3) described the lessons learned in introduction of new materials on the showcase of co-extruded polymeric backsheets.

2. Motivation and benefits for new material and module developments

2.1. Decrease of LCOE: cost reduction and performance increase

Over the past few decades, PV module prices have fallen dramatically, following a price-experience curve (learning curve) with an average learning rate of about 80%, i.e. the average selling price of PV modules fell by 20% for each doubling of production volume. This development was driven not only by technological improvements but also by changed market conditions [2]. Economy of scale was one of the major driving forces of the falling prices, i.e. the huge expansion of production capacities, not only for PV modules but also for all components and materials in the value chain. Furthermore, advances in manufacturing technology (automatization, quality control/statistical process control, lean manufacturing) and material science had a significant impact on price reduction. In the following sections, several strategies applied in order to achieve these historical cost reductions are listed.

2.1.1. Reduction and replacement of expensive materials

One approach to lower PV module prices is reduction and/or replacement of expensive materials. The silicon solar cell was and still is the most expensive component of a c-Si PV module, with the silicon wafer accounting for half of the cells price [4]. The thickness of solar cells was reduced from over 300 μm in the early 2000s down to 180 μm in 2020. Further reduction in thickness to between 140 and 160 μm is foreseen in the next decade, depending on the wafer technology [4].

Also, the amount of silver used in c-Si based PV modules was reduced from 400 mg to 90 mg between 2007 and 2020 by reducing the metal finger width and the busbar area on the cells. The minimum amount of silver needed to ensure current transport within the conductive system is predicted to be almost halved in the next years to approximately 65 mg by 2028. However, a replacement by non-silver-based solar cell metallization solutions (e.g. copper) is not expected to gain significant market share in the next decade [10].

The last few years have seen a reduction in the front glass thickness from 3.2 mm down to values between 1.6 and 3 mm [4].

PV backsheet technology changed significantly in the last 20 years. In the early 2000s, more than 85% of the backsheets used were so-called 'Tedlar' (TPT) backsheets, with a Polyester core layer and inner/outer layers made from PVF [11]. Since then manufacturers are moving to replace the comparably expensive PVF films with more economical fluoropolymers like PVDF or other, fluorine-free, technical polymers like PET, PA, or PE derivatives [12]. In 2010, co-extruded backsheets-types were introduced into the market, based on commodity polymers like PP, PE, and PA [12, 13].

2.1.2. Acceleration of manufacturing processes

The acceleration of the time-consuming PV module lamination process has been a major focus in technology development over the years. The main approach was a reduction of the crosslinking time via adaption of the encapsulant material formulation. Initially, standard cure EVA types needed up to 25 min for the crosslinking reaction [14]. With fast cure and ultra-fast cure types, the crosslinking time was reduced down

to 10 min [14–17]. Alternatively, also thermoplastic encapsulants have been developed, where no crosslinking is needed and the total lamination time was reduced to 10 min [18].

2.1.3. Performance increase

Many new materials and components have been developed to achieve a performance increase. When looking at cell interconnection technologies, a transition from three busbars to layouts with up to 12 busbars can be seen. Also busbar-less technologies like the ‘Smart Wire Interconnection’ are on the rise [4, 19, 20]. The increased number of busbars aims to reduce resistive losses by reducing the amount of current that flows in both, the fingers and the busbars. Additionally, also cell shading is reduced and it coincides with additional reduction of the silver content [4]. New approaches like the use of half cut cells and shingling of partial cells aim at increasing the active area and power output per area while reducing the current and associated resistive losses [21].

Many developments aim at improving or better matching the optical properties of the components allowing an increased number of photons to reach the solar cells. Encapsulant films with new additive formulations allow for transparency in the UV region of the incoming light, resulting in an increased power output of up to 0.5% [18, 22, 23]. Similar effects can be achieved using highly reflective backsheets that act as a diffuse mirror and lead to backscattering of light to the cells [13, 24]. It is now common to use bifacial cells in a monofacial package that is designed to take advantage of the reflective properties of the backsheet. Antireflective coatings for improving the transmission of the front glass have become state of the art in recent years, also resulting in an increase power output of up to 0.5% [25].

2.1.4. Production related cost decrease

One important driver for cost reduction since about 2018 is the increase of wafer size. The wafer size has basically been unchanged for decades in the range 156^2 – 156.75^2 mm² but since 2019 two new wafer standard sizes have emerged and are well positioned to soon dominate the silicon wafer market. The two new sizes are the M10 (182^2 mm²) promoted by JA Solar, Jinko and LONGi and the M12 (210^2 mm²) version promoted by Zhonghuan Semiconductor, Trina Solar, Risen Energy, Tongwei, Canadian Solar and others. Since the costs of many wafer- and cell related manufacturing operations scales by the number of pieces rather than the area of the wafer, this increase in wafer size allows for both a decrease in costs and an increase the cell power, the total Wp output of PV manufacturing per year at nearly the same machine and fabrication area costs. Furthermore, the increase in Wp per PV modules reduces the LCOE costs as one needs fewer modules and cables for the same Wp PV system size.

2.2. Sustainability and legal regulations

Awareness regarding sustainability of products is increasing in general. Large deployment of PV installations over the past decade has raised concerns about the environmental impacts of its production and final disposal. Since PV is related to the delivery of renewable ‘green’ energy, customers have very high expectations for the sustainability of the technology [26, 27].

The impact of materials incorporated in PV modules on the ecological footprint of produced PV electricity is significant and twofold: First, there is the direct impact related to the material itself, including effects from producing and transporting the materials, manufacturing related effects and recycling/disposal related effects [28]. Second, there is an effect of the chosen materials on the lifetime and yield of modules and systems. Since the effect of lifetime and lifetime-yield on the ecological footprint of PV electricity is enormous, this also translates to the effects of materials and material quality [29]. To analyse the effects of specific materials or material combinations, a life cycle assessment (LCA) covering all the stages in the lifetime of a PV system can be performed to identify hotspots of environmental burdens and specific effects and influences [30, 31]. Such assessments also should include local (climatic) influences since they have strong effects on the kWh output per Wp. LCA studies can also help to identify the suitability of materials and material combinations for specific applications, locations or module designs. The results illustrate the potential to further reduce the ecological footprint of PV power generation and to identify possible environmental problems during the PV systems life cycle. A recent paper showed the significant environmental improvement in the sc-Si PV system production (between 2015 and 2020) with a reduction of the carbon emissions by 50%, mainly at the wafer stage [30]. Energy payback times of currently installed systems range from 0.6 to 1.3 years, depending on type of installation and climatic conditions [30].

Additionally, sustainability related PV legal regulations and rating systems are expected or have been introduced in several countries in recent years. Such instruments include national regulations such as the product environmental footprint (PEF) as defined by the European Union or French tenders containing the carbon footprint of products. Further multi-national policies are under discussion in the European Union [32] at the moment including legally binding regulations, like ‘Eco Design’ in the EU [33], which sets out

minimum mandatory requirements to remove non-sustainable products. Another regulatory option is 'Energy Labelling' which requires a clear statement regarding the energy related performance of a product [34]. Other possibilities being considered are systems to grant the most sustainable products in the market with a label like the EU 'Eco Label' which aims at marking the best 20% of the products in the market to support manufacturers producing sustainable products [35]. The NSF/ANSI 457 PV sustainability leadership standard establishes measurable criteria for multiple levels of sustainability and environmental leadership achievement and performance throughout the life cycle of the product [36]. In the U.S., several states have implemented or are considering regulations that require PV modules to be recycled at the end of life.

The sustainability and ecologic performance of PV materials is becoming more important and may soon be included in tender regulations and market standards. Information about calculation methods for sustainability assessments of PV systems as well as impact categories and effects of components and materials can be found in reports and publications of IEA PVPS Task 12 [31].

Also, product adherence to ESG criteria set by EPC's and investors are now becoming important aspects of the commercial supplier selection process. In particular, allegations related to the use of forced labour in the Xinjiang based silicon metal industries, have set new focus on the overall supply-chain transparency and the possibilities to verify use of raw materials in up to seven independent processing-steps.

2.3. New technological requirements

2.3.1. Crystalline silicon wafer—the cell substrate

Although this report mainly addresses packaging materials that are used in making the PV module, it is also relevant to reflect on the important developments in materials and performance related to the crystalline silicon wafer which constitutes the substrate of most solar cells today. The manufacturing sequence for crystalline silicon wafers can be divided into three steps, each of which has undergone significant changes during the last decade and thereby contributed to the observed overall cost reductions.

2.3.1.1. Silicon feedstock

In 2000, the only source of feedstock for solar silicon wafers was scrap material from the semiconductor industry. Refinement processes for the hyper-pure silicon material were developed to enable the semiconductor industry. There the objective has been the manufacturing of integrated circuits with nanometre sized transistor elements, where the challenge is to avoid electrical defects (e.g. shunts) originating from impurities in the material. At that time, the solar industry did not have such stringent purity requirements. Less expensive alternative processing routes for solar grade silicon (SGS; e.g. upgraded metallurgical silicon) were developed and production capacities of up to 10.000 MT of SGS were established and in operation for several years. However, with process developments in heat recovery, CAPEX reductions, cost efficiency, and productivity enhancement, new production capacities for high purity silicon feedstock have now been brought online in volumes of 50 000–100 000 MT per plant. This development has taken place mainly in China and located in areas where electricity is cheap. As a result of these process developments and cost-reductions, the world-wide production capacity for pure silicon feedstock has increased by a factor of 12 since year 2000, without compromising the product performance (purity) and still reducing the manufacturing cost by a factor of at least four (from around 30 to <7 USD/kg in 2020) [37].

2.3.1.2. Crystallisation

Although the silicon feedstock comes with purity more than sufficient for solar cells, the brittleness of this material made of many micrometre sized crystals, precludes its direct use as a substrate for solar cell manufacturing. First, the material has to be melted and re-crystallized under controlled conditions to generate larger crystal grains, which also ensure that no (or few) grain boundaries and crystalline defects such as point-, line-, 2D-, or bulk features are present, which may act as recombination centres and limit the solar cell performance.

The technology from the semiconductor industry is able to grow mono-crystals up to 300 mm in diameter and more than 200 kg in weight has been transferred to the PV industry and demonstrated capability to obtain solar cell efficiency close to the theoretical upper limit at the two new standard square wafer sizes of 182² and 210² mm². A simpler and more cost-efficient casting method capable of making multi-crystalline ingots with cm-sized monocrystalline grains, has also been developed and for many years coexisted in the same commercial space [38].

Until recently, the most common solar cell has been based on the aluminium back surface field (Al-BSF) architecture but with today's cell architectures being dominated by cells as PERC, PERT, and Topcon variants, it has become evident that multi-crystalline wafers cannot ensure the same level of cell performance as a monocrystalline counterpart. A very fast transition of the wafer base towards monocrystalline products

is therefore predicted. The most important functional performance parameters of crystalline ingots produced for the PV industry are purity (low level of contamination with impurities into the molten silicon during the crystallization process), lack of crystalline defects (e.g. B–O complexes which will lead to light induced degradation) and stress-control through temperature gradient control while cooling the crystal from the melting temperature. The most important quality assurance characterization parameter of the silicon ingots is the minority carrier lifetime, as determined by the quasi steady state photoconductivity (QSSPC) or microwave detected photoconductive decay (μ -PCD) methods.

2.3.1.3. Wafering

In the early days of the PV industry, the silicon ingots were sliced into 0.3 mm thick round silicon wafers by use of an inner diameter saw, one at a time. Today wafers are sliced to a thickness of 0.18 mm by use of wire saws, where the steel wires are diamond coated by use of electroplated nickel and water is used as a cooling media. This process is about to fully replace the alternative wire cutting method that was developed for the solar industry in the late 1990s which made use of brass wires and an abrasive grit made from silicon carbide particles and polyethylene glycol as cooling media.

The wafer thickness is mostly determined by the solar cell manufacturing specifications, as the wire saw can easily cut even thinner wafers. Thinner wafers however, will become ductile and cannot as easily be transported between cell process steps and inserted into cassettes. After the cutting process wafers are cleaned in a wet chemical process, which also removes saw damage and subsurface microcracks in order to enhance the optical performance of the finished cell [39, 40].

For many years, the standard size of both, mono- and multi-crystalline wafers were the same (wafer side length of 156 mm being the most common), which also facilitated full flexibility among wafers in use between cell processing equipment. Within the last few years, this consensus on wafer size has been challenged by major Chinese wafer, cell, and module manufacturers. More efficient cells mean that higher currents are generated per solar cell. Therefore, a simple method to limit the current and related electrical loss is to cut the cell into half and double the number of half-cells per electrical string within the module. Once this new concept of divided cells became viable, the opportunity for dividing cells into 1/3 or even 1/4 is possible and relevant since both the current and resistive losses increase as the area and power of the individual cells increase. The most important functional performance parameters of wafers to be used in the PV industry are surface morphology and subsurface damage to the crystal, geometrical parameters such as total thickness variation, bow & taper and internal stress and fracture strength.

2.3.2. New cell and interconnection technologies

New cell architectures often require new cell interconnection approaches. As a consequence, interactions between encapsulation and connecting wires/ribbons also must be considered (e.g. thermo-mechanical stresses imposed by the encapsulant as well as chemical interactions or incompatibilities, causing corrosion or discoloration [41, 42]). It is of primary interest to investigate the effect of packaging materials on the type of cell technologies, e.g. aluminium back surface field (Al-BSF) or passivated emitter rear contact (PERC), and study their interaction at the interfaces (potential degradation modes) in greater detail.

Silicon heterojunction cells (SHJ) are a promising concept for increasing cell efficiency [43, 44]. However, SHJ cells cannot withstand temperatures above 250 °C, so standard soldering process using SnPb coated ribbons are not feasible [43, 45]. Therefore, different interconnection approaches, such as lead-free low-temperature solders based on bismuth [43], electrically conductive adhesives [46], or smart-wire technology (e.g. SWCT) [47] have to be used (see figure 1). Although currently Cu-ribbons coated with lead based solders are commonly used, lead free solder ribbons, conductive adhesives and multi-wires are expected to gain market share in the near future [4], in parallel with the rise of SHJ cells.

For back contacted solar cells (e.g. IBC, MWT) it is difficult to apply ribbon-based interconnection technologies with standard production equipment [48]. Furthermore, cell warpage during ribbon attachment is an issue that needs to be overcome [49]. Therefore, it is common for structured conductive foils to be used. Here the inner layer of this backsheets is either copper or aluminium. The connection to the cells is then achieved either via laser welding or electrically conductive adhesives. Also here, compatibility between the conductive backsheets, the ECA and the encapsulant has to be ensured [50, 51].

2.3.3. New module designs

New technological requirements for module materials and components also can originate from application driven module concepts with very specific challenges, where conventional module designs with standard components do not meet the specifications.

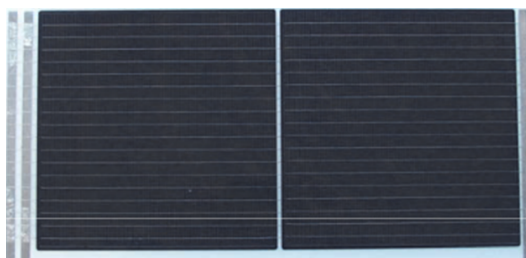


Figure 1. Multi-wire interconnection. Reprinted from [52], Copyright (2016), with permission from Elsevier.

The development of modules for special environmental conditions has become a trend in R&D, as PV modules perform and degrade differently in different climate zones [42, 53–56]. For desert environments soiling and abrasion, high UV radiation and high temperature cycling are the main challenges [57]. One mentionable initiative is the development of PV modules for the Atacama desert in Chile [58], which has one of the harshest operating conditions worldwide [59]. Here different approaches for glazing, cell and interconnection technology, and encapsulant are being tested in order to find the right combination with the required durability [57, 58, 60]. Modules for tropical climates have to withstand higher humidity levels [54, 55] and also higher temperature cycling loads due to partial shading caused by often cloudy skies [61]. PV modules for arctic or alpine regions are often produced with thicker glazing and silicone based encapsulants in order to reduce stress impact and breaking of the solar cells under heavy snow, wind loads and very low temperatures, when common encapsulants cross the glass transition region and become brittle.

Next to climatic stress impacts, also micro-climatic loads can be relevant, e.g. for PV modules in agricultural environment or for floating PV systems. Resistance of PV modules against ammonia from agriculture has been widely researched [62–64]. For floating PV humidity ingress, corrosion, and soiling are known issues [65] that need to be addressed. However, such dedicated modules currently only represent a small share of the overall market [4].

As building integrated PV modules (BIPV) are not only energy producing electrical elements but also building products, special requirements need to be met with respect to fire resistance, strength (especially in facades of multi-storey houses thicker glass panes are required), safety in case of glass breakage (security glass, mostly combined with PVB encapsulants) but also long-term reliability. As roofs or facades typically have a lifetime of 50 years, BIPV is also required to have a comparable lifetime to the rest of the building. As BIPV often is used in the urban environment, the aesthetic appearance of the modules is also an important point. Thus, BIPV modules often come in differing shapes, colours and appearance (surface modification of the glass panes e.g. sandblasting) than standard modules. Changes of the colour have a negative impact on the performance with printed or coated front glass or coloured encapsulants causing a performance loss of 10%–15% (5%–50% are possible see [66]). The reliability of the coloured coatings and prints as well as of pigmented polymers still is subject of long-term studies. Interactions of PV components with attached building materials, adhesives, and mounting compounds also need to be tested for comparability and reliability.

For some PV applications, the weight of PV modules is an obstacle. This is obvious for some special applications such as solar panels for satellites. The requirements for such special applications are typically quite specific and the products are often based on costly materials and custom designs. However, there are also broader fields of application for lightweight PV modules. Numerous commercial buildings are designed with little to no spare structural capacity due to cost constraints. Therefore, lightweight modules may address this market segment by achieving weights, which still allow an installation on such roofs. For some innovative PV system solutions, e.g. PV elements for parking roofs or building Integrated PV (BIPV) [67], but also vehicle integrated PV, lightweight modules can be beneficial.

The main challenge for light-weight PV modules is replacing the glass frontsheet while maintaining the mechanical stability and hail resistance [68–70]. For crystalline silicon cells, various approaches from glass-fibre reinforced composite structures [71–73] to support lattices [68] have been implemented. For thin film technologies like CIGS flexible substrates and polymer frontsheets have been applied [74, 75]. Whereas flat lightweight modules are mostly used for PV installations attached to building roofs with static weight limits, curved or free-formed panels are used in building integration and vehicles.

The common challenge for all module designs is to ensure adhesion of all layers over the whole lifetime as well as compatibility of the materials used. In the worst case, large scale delamination or new material degradation effects caused by unwanted interactions can happen after some years of installation.

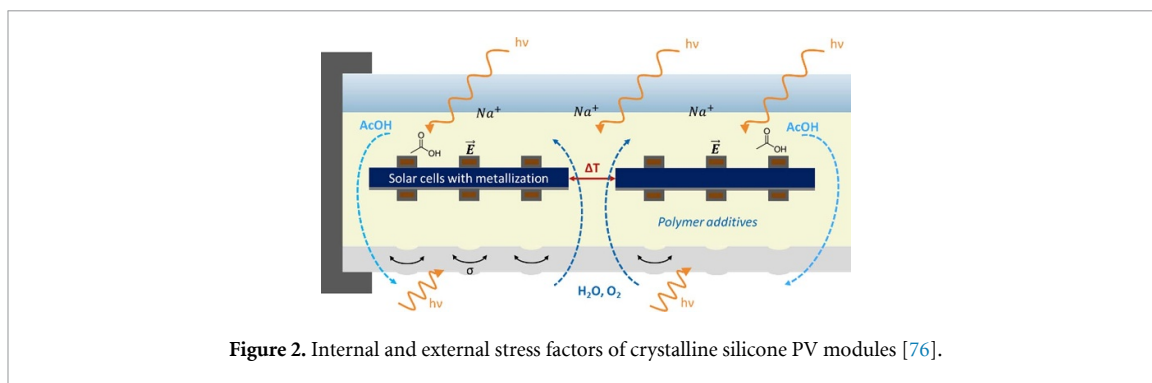


Figure 2. Internal and external stress factors of crystalline silicon PV modules [76].

3. Challenges for new material & module developments

3.1. Emergence of new degradation modes

The process of material innovation for PV is complicated by the complex interactions of the materials/components within a PV module with internal and external stressors, see figure 2. A specific benefit of a new material may be outweighed by its unfavourable interactions with another component [76]. For instance, EVA has become the industry standard for solar cell encapsulation because of its favourable properties such as high transparency, ease of processing and high mechanical damping, as well as its low cost. However, during degradation of EVA acetic acid is formed which can cause corrosion of the metallization and interconnection if it is not allowed to escape the module package in the case when an impermeable backsheets is used [14]. New materials must work within the whole module stack and in concert with all the other materials present and their potential degradation by-products [76].

Many common PV module degradation modes are not the result of a single stressor, but of a combination of external stressors such as UV, humidity, temperature, and/or mechanical loading (e.g. wind, snow, hail). Internal stress factors arising from a specific combination of the different materials used in a PV module may also affect the kinetics of degradation and the activated pathways [41, 42, 76, 77]. It is not only that certain module materials are incompatible with each other, but also that degradation by-products, such as acetic acid produced due to hydrolysis of the EVA encapsulant, can strongly influence individual degradation modes and pathways, for example interconnect or screen printed silver gridline corrosion or cell PID-s [23, 41, 42].

In general, PV module failure modes are well described in the literature [42, 76, 78], including their main driving factors. It is also well known that the right combination of materials reduce failures or degradation rates [42]. However, more importantly, the wrong combination of materials also can lead to new degradation mechanisms, prominent recent examples in the past years have been the occurrence of PID or backsheets cracking [76].

Overall there are no common rules or acceleration factors related to stress conditions which apply generally for all PV modules. On the one hand, the degradation modes depend on the bill of materials and components and may be unique to a particular PV module brand and model. However, it is common for manufacturers to use several bills of materials (BOM) in the same model number due to supply chain constraints. On the other hand, there are typically several degradation modes and pathways activated simultaneously and these may have synergistic or antagonistic effects, making it challenging to correlate observed effects with single degradation mechanisms or a single stressor.

3.2. Impact on module testing procedures and standardization

The development of standardized tests for qualifying PV module performance and safety started in the 1970s (US JPL Block Buys I–V) and early 1980s (EU Spec. 501-503), see [79]. The International Electrical Committee (IEC) established the Technical Committee ‘Solar Photovoltaic Energy Systems’ TC 82 in 1981. Because PV is a global market, most of the PV standards are developed in a top-down fashion, so the TC 82, backed by 43 national committees as full members proposes, develops and issues the vast majority of PV related standards, which then are adopted by supranational and national standardization bodies. More than 500 experts from Asia-Pacific, the Americas, and Europe cooperate within TC 82, with industry as well as research groups involved.

The IEC’s central office standardization management board states: ‘It appears that TC 82 has the largest program of work in IEC (in terms of number of projects). TC 82 were observed to be the second highest number of publications sold among all IEC TCs/SCs from July 2018 to June 2019 in IEC CO sales statistic.’ [80]. As of January 2022, 175 published PV standards exist and 63 are currently under development.

Almost half of all PV standards focus on modules, one third of the published, and one quarter of the standards under development focus on component and materials characterization and durability. The high number of active standardization projects—new standards, as well as new editions of already existing ones—indicates that PV, and PV module development is a very active evolving field. In general, PV standards focus on quality and reliability along the whole value chain from cells, materials and components to systems and grid integration, including traceable and reproducible measurement and characterization procedures. Nevertheless, well established, test procedures for PV modules have their shortcomings:

- Tests primarily are able to detect early failure modes (e.g. design flaws, infant failures) but are only loosely related to failures that might occur in long-term outdoor applications under different climatic and operating conditions;
- Tests were designed to detect failures from known and established materials. New materials may have failures that the tests do not detect;
- The tests were initially designed for applications with non-restricted heat dissipation under moderate climatic conditions only [81];
- Changes in module manufacturing, BOM and assembling (e.g. cell interconnect technology) may provoke new failure modes as well, not covered by existing test procedures.

Optimum PV module test design was assumed to have each test procedure specified in a way, that it exactly covers or provokes one distinct failure mode. If new failure modes were observed in field applications, new test procedures shall be designed, and added to the test specifications. In [82], a table lists common module failure modes and how standard sequential testing routines are able to detect such failures.

Table 1 replicates this and expands the list by additional failures and test procedures. From this table it is obvious, that a 1:1 relation between field failures and test procedures is only rarely achieved. The actual versions of the module type and safety qualification standard series IEC 61215 [83–87] and IEC 61730 [88, 89] were issued in 2016. At that time, mainly the structure was changed to better handle evolution of technologies and test procedures, and to align requirements with horizontal standards, e.g. the insulation coordination IEC 60664-1 [90]. In parallel, new test procedures for materials in the IEC 62788 series [91–99], as well as for known and newly detected module field failure modes, that are not covered by existing standards were developed, e.g. the IEC TS 62804 series [100, 101] for PID issues, or a test procedure for dynamic mechanical load stresses, IEC TS 62782 [102]. The original intention was that a single PV module design shall be for all purposes and environments, but implicit application was focused on (standard) open rack mount in moderate climates. A proposed standard series, IEC 62892, intended to have four parts to a rank of module designs in different climates. Three parts were cancelled and only a single document related to local climate and temperature variations, IEC 62892 *Extended thermal cycling of PV modules—Test procedure*, was issued and is practically useful only for thermo-mechanical fatigue of solder bonds [103].

Although modules with non-restricted air flow operate even in very hot climates at temperatures below 85 °C, the test temperature used in many of the module qualification tests, an additional standard for high(er) temperature applications, IEC 63126 *Guidelines for qualifying PV modules, components and materials for operation at high temperatures* [104], was developed, providing modified test procedures for modules operating at higher temperature levels, Levels 1 and 2. These levels are defined by a 98% quantile operating temperature, i.e. the temperature a module exceeds for 175.2 h per year. If this 98% quantile is not exceeding ≤ 80 °C, the standard tests are sufficient without modification, Level 1 is for a 98% quantile up to 80 °C and Level 2 for applications where the 98% quantile is not exceeding 90 °C.

The system of module type and safety qualification is well established, with the necessary equipment available at test labs and manufacturers. Several ‘*extended testing*’ procedures were proposed from different test houses, manufacturers, reinsurance and engineering companies, see e.g. [105], DuPont [106] and the Product qualification Program of PVEL [107] having both eight parallel test sequences, but different ones.

Currently in development, IEC TS 63209(–1) *Extended-stress testing of photovoltaic modules for risk analysis* [108], aims to standardize the variety of existing extended test protocols, and has (at present) five parallel test sequences for TC, (D)ML, UV, DH, and PID. In the mechanical load and UV sequences, also TC and HF are applied to open-up possible cracks and to force delamination by thermo-mechanical stresses, and frost if humidity is able to enter the package.

Part 2, IEC TS 63209-2 *Durability characterization of polymeric component materials and packaging sets* [109], shall support the module (or mini-module) tests by component and coupon level tests, as e.g. UV testing by Xe-arc lamps, as defined in relevant module material standards within the IEC 62788 series, needs

Table 1. Sequential module testing procedures and correlation with common failure modes. From [82], updated.

Standard	IEC 61215-2 Ed2, IEC 61730-2 AMD 1 Ed2									61701 62716	62979	NP 82 1771
	TC	DH	HF	UV	ML	DML	Hail	BPT	62804 PID	NaCl NH ₃	BPR	LeTID
Delamination		×	×	×					×			
Encapsulant adhesion & elasticity		×		×								
J-Box adhesion	×	×	×									
Cell breakage c-Si	×				×	×	×					
Broken interconnects, ribbons	×				×	×						
Glass breakage	×				×	×	×					
Open Connections (potential arcing)	×											
Solder bonds (potential arcing)	×				×	×						
Corrosion (all technologies)		×								×		
Electrochemical corrosion (TE)		×										
Inadequate edge delamination (TF)		×	×									
Encapsulant & backsheet discoloration				×								
Ground fault due to backsheet degradation				×								
Structural failures					×							
Bypass diode failure								×			×	
BPD overheating								×			×	
degradation of encapsulant & backsheet materials												
Specific corrosion (deicing, etc)									×			
LeTID												×
PID									×			
Bifacial coefficient degradation		×							×			

very long testing time (2000, 4000, up to 16 000 h, i.e. 2 years) to achieve relevant dose when compared to outdoor applications under high irradiation conditions.

Both parts of IEC TS 63209 [108, 109] focus only on module designs using crystalline silicon cells and are not intended to use in combination with pass/fail criteria, but all data shall be reported.

In contrast to the extended testing procedures and the ones for higher operating temperatures, a market for non-standard PV modules exists, where the reliability requirements may differ and often be lower than for long-term outdoor applications in PV power systems. Therefore, work on a standard for PV consumer products [110] was started, that may ease—depending on applications—some of the module type qualification tests, and add others, e.g. a drop test.

The actual drafts for a new Ed. 2 of the IEC 61215 series Ed. 2 [111–116] and IEC 61730 series Ed. 3 [117, 118], are close to being submitted as final drafts (FDIS) to the IEC central office, therefore publication can be expected in 2021. These drafts now include:

- For bifacial modules requirements and test procedures including nameplate specifications based on the IEC TS 60904-1-2 [119] measurement, using a bifacial nameplate irradiance BNPI (1000 W m⁻² front,

135 W m⁻² back irradiance), and test levels based on BNPI and a bifacial stress irradiance BSI (1000 W m⁻² front, 300 W m⁻² back irradiance);

- A performance test for flexible module designs;
- Includes PID and dynamic mechanical load testing.
- Adds requirements based on component tests, for junction boxes [120], connectors [121] and for back (and frontsheets) [122].

It was planned also to integrate in the new IEC 61215 a test for Light and elevated Temperature Degradation (LeTID) of PERC [123], but now a separate test procedure using current injection at 75 °C is developed, that possibly will be incorporated in the IEC 61215 test flow by an amendment later.

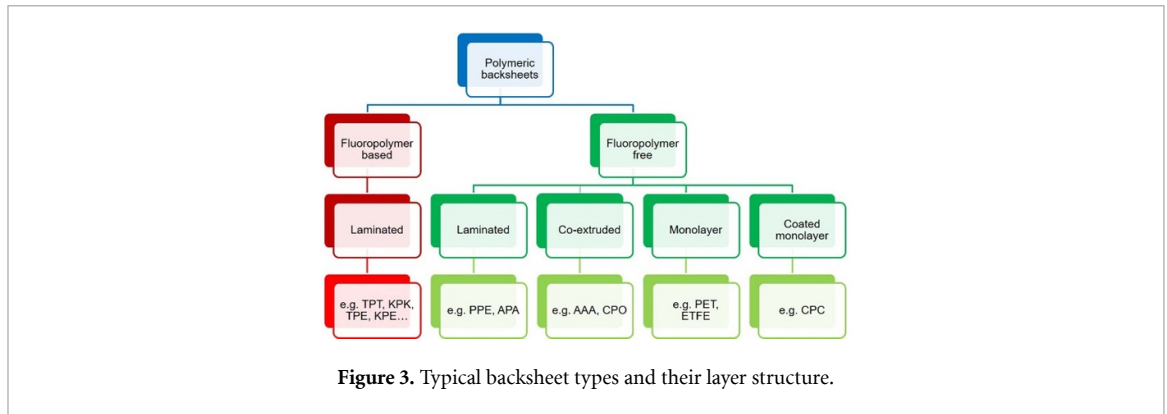
A shortcoming of the standard and extended test procedures is that tests were performed at single stress levels, and combinations of such, so that it is not possible to derive models how e.g. the degradation rate is depending on the temperature, with the other stressors held constant. Therefore, test chamber performance cannot be extrapolated to outdoor service lifetimes under changing environmental conditions. Performing a whole matrix of tests, as, e.g. done within the European SOPHIA Research Infrastructure project, is extremely elaborate, because many modules have to be moved between different climatic chambers, and many interim measurements have to be performed. The status of PV module service life prediction SLP is matter of the Task 13 Subtask 1.4 [124].

Module BOM and manufacturing technologies are rapidly changing and are brought to market quickly in high quantities. It is questionable to design special tests to provoke distinct and field relevant failures by sequential tests with long test durations, even if they are highly accelerated. With the aim to reduce risk in the application of new designs and technologies, within the International PV Quality Assurance Task Force PVQAT, www.pvqat.org/ and the Durable Module Materials Consortium, www.duramat.org/ a new approach was developed, combining multiple stress factors of the natural environment in a single test (cabinet) instead of targeting specific failure mechanisms [125, 126]. A TR was issued giving an overview of 16 approaches of sequential and cyclic sequential test methods used for provoking distinct failure modes, with the same schematic applied to characterize them, and on which levels from materials, coupons, mini, or full-size modules the test procedures were used.

The new approach, called Combined and Accelerated Stress Testing, C-AST uses newly developed test equipment, at present for parallel testing of several 2 × 2 cell mini modules [127, 128]. It is based on a modified weathering test chamber, allowing for applying temperature, humidity and light in a wide range: -40 °C—+90 °C, 5% to >95% relative humidity, and a 2-sun xenon arc irradiance source. The possibility for a water spray on front and back, light reflective troughs underneath the modules, mechanical load and equipment for electrical stresses (1500 V system voltage and reverse bias, resistive load) was added. *In situ* measurement equipment for module status monitoring for illuminated and dark *I-V* curves, power measurement, leakage current monitoring and electroluminescence imaging is implemented.

Test schematics, accounting for specific climates (e.g. tropical, continental, arctic) and all seasons are developed, with the idea of applying multiple stresses in a way that the upper limits of the stresses in natural environment are not exceeded, but applied that C-AST is like a bad day, every day. In comparison to the previously used tests, it is shown that many field relevant failures will be provoked by this ‘essentially design-agnostic testing philosophy’ approach. The idea was to launch as a next step two NPs: *Method for combined-accelerated stress testing—Part 1: Climatic chambers*, to specify the C-AST equipment, and a *Part 2: Stress Tests*, describing test flows aiming for winter, spring, tropical and high desert environment stresses. Although presented results are very promising so far, because such infrastructure is at present only available as a single device, located at NREL, at the (online) 2020 spring meeting of TC82s Module Working group WG2 was discussed that more experience and from different labs would be necessary before going in the direction of Test Specifications (TS) or International Standards (IS) with the C-AST approach.

C-AST demonstrates that there may be a way to test new designs such that possible failures will be detected before field application. But, because of the very complex changing multi-stress conditions during testing it is not possible to extract parameters useful for degradation modelling by these test procedures. In many industries and applications, a movement is seen in the direction of designing a virtual representation of a device and its manufacturing before it is really built, and to check operational behaviour by comparison of monitoring data with such a ‘digital twin’. So, it is an open question how this can be achieved in the PV industry as well. Digital modelling approaches are necessary in testing, certification, and retesting beyond simple pass/fail statements. Ideas of more flexible certification schemes using man *and* machine-readable documents, e.g. in XML-format, to support industry 4.0 and digitalization in construction are discussed in the IEC Standardization Management Board (SMB) supporting digital transformation and ‘smart manufacturing’, but these discussions are in a very early stage in PV module standardization.



4. Lessons learned from new degradation modes explained by the example of cracked PA backsheets

Backsheet development has been an active area of research for many years with new materials and structures introduced recently, driven primarily by cost and sustainability reasons. Backsheets based on PVF and PET have been used for more than 30 years and have served as good standards for performance and durability in PV applications. Field studies have confirmed its outstanding long-term performance relative to other backsheet materials [106, 129].

Besides the established materials polyester (PET), polyvinyl fluoride (PVF) and polyvinylidene fluoride (PVDF), new materials were introduced into backsheets such as polyamide (PA), fluoroethylvinylether (FEVE), and various types of polyolefins (PO). The backsheet structure has also evolved from the established PVF/adhesive/PET/adhesive/PVF (aka TPT) to TPX structures where the outer layer has high weatherability and protection of the core layer of the backsheet and the inner layer is designed to have good encapsulant adhesion and protection of the core layer from UV exposure from the front side of the module. An overview of typical backsheet configurations is given in figure 3.

4.1. Market entrance and reliability of co-extruded backsheets

In 2010 co-extruded backsheets were introduced into the PV market. The main driving factors for this development were cost reduction and the addition of new features. Moreover, expensive fluoropolymers (PVE, PVDF) are replaced with lower-cost polymers (PET, PA, PP, PE derivatives). Additionally, also processing steps are reduced by using co-extrusion as no lamination steps are needed.

New materials also allow for new features from co-extruded backsheets. Functional properties like selective permeability, i.e. high acetic acid transmission rates (AATR) and low water vapour transmission rates (WVTR) [13, 24, 130], enhanced optical properties [13], where increased reflectivity leads higher power output via backscattering of light, or increased thermal conductivity have been added to the property profile. The main advantages of co-extruded backsheets are that the full back integration allows for easy material modifications regarding additive formulation, fillers, or layer geometry. Also, the backsheet is produced in one step, which also means reduced processing induced material degradation [131]. Also, the likelihood of delamination, which is a major backsheet failure mode, should be significantly reduced.

The first co-extruded backsheet on the market was introduced in 2009/2010 [9, 132] and was based on a symmetrical structure consisting of three layers of PA but with different filler material in the outer/inner and the core layer. The outer/inner layer was filled with TiO_2 particles to increase the reflectivity, whereas the core layer contained PP and about 20% of glass spheres for increased mechanical strength [9].

In n recent years, an increased occurrence of PV module failures with cracked PA backsheets has been reported [27, 28]. Two main types of polyamide backsheet-cracking were observed: (1) tile-shaped, square cracks (along the intercellular spacing) see figure 4: PA cracks. Longitudinal (top) and squared cracks (bottom) of PV modules with PA backsheets [9]. (bottom); and (2) longitudinal cracks (beneath the busbars of the cells) see figure 4 (top).

The cracks revealed after several years of field aging have never been observed in forgoing qualification and reliability tests as they are suggested to be the result of a combination of multiple stresses and might also include unexpected material interactions as drivers. Eder *et al* [9] identified the daily and seasonal temperature changes and their corresponding thermo-mechanical loads/stresses due to different thermal expansion coefficients of the different PV module layers as the main driver for crack propagation. The main factor for crack initiation can be found in a physical aging process of PA12 [9, 133], which significantly



Figure 4. PA cracks. Longitudinal (top) and squared cracks (bottom) of PV modules with PA backsheets [9]. Reprinted from [9], Copyright (2019), with permission from Elsevier.

reduces the ability for plastic deformation of the backsheet, visible in the significant decrease of strain-at-break values. Simulations of tensile stresses building up in standard PV modules yielded a maximum tensile strain of 18%, occurring between the area of the cells and backsheet [134], which is more or less the strain-at-break value of PA backsheets after aging.

Chalking and photo-oxidative degradation of the outermost (only a few micrometre) PA-layer is caused by outdoor weathering and not related to crack formation. It is assumed that microcracks develop randomly at local notches with slightly higher stress concentrations. But these cracks were found to be very short and only in near surface regions (outer PA layer). Sometimes microcracking is accompanied by a partial delamination of the outer layer. The longitudinal cracks (LC) are directly located below the ribbons (busbars), which usually have a height of around 200 μm . This elevation imposes additional tensile stress in the backsheet, resulting in cracking from the airside of the backsheet into the core. These LC mostly are more pronounced in length and broadness and are always aligned with the busbars (MD). LCs can grow with ageing time and passing through the core layer of the co-extruded backsheet leaving the encapsulant protected by only the inner layer from open contact with the atmosphere.

For the squared cracks (SC), however, a different root cause and appearance has been found. SCs start to grow from the interface encapsulant/inner PA-layer into the core and outer layer of the backsheet. In this respect it is important to note that SC are exclusively forming in cell interspaces and only in conjunction with certain EVA types/qualities/stabilizers which are prone to show degradation accompanied by significant acetic acid formation. Sun irradiation seems to be one decisive driver for the beginning degradation of the PA-inner layer and the EVA at their joined interface. An additional environmental stress cracking effect, caused by the formation of acetic acid and the presence of phosphoric additives was suspected by the authors [9].

As the formation of micro- and longitudinal cracks is a two-step process it was not discovered in the predominant single stress tests that were used back in 2010 [9]. Usually the materials and test modules were exposed separately to several thousand hours of damp heat testing, several hundred thermal cycles (according to IEC 61215) and several thousand hours to artificial sunlight weathering (xenon lamps) [84]. After damp heat or prolonged xenon exposure, the decrease in strain-at-break of the backsheet would have

been observable, but without combination with crack initiating thermo-mechanical loads, the specific failures like squared cracks and/or longitudinal cracks could not be detected. Furthermore, during thermal cycling, the thermal load seems to have been too low to induce the physical aging effect of the PA backsheets, which would have induced a reduction in elongation at break.

Also, other companies started to work on co-extruded backsheets in 2010, when the first patents for PP based backsheets were filed [135]. In 2012 a new backsheet, based on cost effective crosslinked polyolefins was developed for solar modules [136]. The coextruded PE based backsheet consists of three polyethylene (PE) layers with different additive contents (the middle layer is a silane crosslinked PE). The crosslinks are built with Si–O–Si bridges with ~ 5 crosslinks per 1000 C-atoms [137, 138]. It results in a higher thermal stability (120 °C for long-term exposure). Results from artificial weathering on this backsheet revealed a good performance [136, 138]. After 5000 h of damp heat testing and 1500 h of UV and Xenon testing, only slight effects of chemical aging have been observed. By IR spectroscopy, the formation of carbonyl groups due to oxidation was detected. Also, using UV/Vis/NIR spectroscopy, slight changes in the reflection spectra were observed. Nevertheless, the UV stabilization remained effective, and therefore the ultimate mechanical properties were not affected due to the accelerated aging tests. Especially after the damp heat test at 85 °C physical aging effects have been observed. With tensile test an increase in elastic modulus and yield strength was measured. This can be attributed to post- and re-crystallization of polyethylene, which was revealed by DSC measurements. DMA showed that the damping factor is strongly influenced by exposure to elevated temperatures [139]. The polyolefin backsheet also proved to greatly reduce the corrosion by low water vapour transmission and high acetic acid transmission [138]. Another study showed that the PE based backsheet was especially modified for long term durability. This is shown by high temperature aging of up to 170 °C, where an extrapolated lifetime of more than 50 years was calculated [136]. Also, here no yellowing or change in optical properties was observed after 4800 MJ m⁻² of Xenon lamp exposure and 2600 MJ m⁻² of UV fluorescence lamp exposure. According to the paper this corresponded to more than 50 years of outdoor application in a standard module in Germany and Arizona. However, this backsheet was discontinued a few years after for undisclosed reasons and is not available any more.

A new class of co-extruded backsheet based on different combinations of polyamide and polyolefins have been launched into the market starting around 2015 [135, 140–142]. This specific composition claims to have lower WVTR and higher acetic acid permeability than PET based backsheet. First reliability studies on this backsheet showed excellent stability against damp heat and UV exposure [140, 141]. Another study exposed modules with such backsheets to hot and humid climatic conditions in India. After 18 months of outdoor exposure, no visible aging and power degradation was observed [142].

Most recently backsheets based on PP were developed and successfully introduced into the market [13]. The material combines the low WVTR of PET based backsheets, but provides high permeability of acetic acid and oxygen. The general material behaviour of these kind of backsheets is different compared to standard PET based backsheets. Co-extruded PP backsheets have lower stiffness and higher flexibility than laminated backsheets with a PET core layer. Several studies reported excellent stability towards damp heat as well as extensive irradiation exposure [143–145]. None of the studies showed any significant deterioration of mechanical properties or sensitivity for embrittlement and cracking. Only slight yellowing was observed, mostly depending on the different additives used. A recent study investigated the influence of PP-based backsheets on the performance and reliability of PV modules. The higher reflectance of the PP backsheet compared to a reference polyester (PET) based laminate led to an increase in power output between 1.5% and 2.5%. Although no significant power loss was detected after 3000 h of damp heat exposure, the selective permeation properties of PP backsheets prevented humidity from entering the module, but allowed for significantly higher diffusion of acetic acid out of the PV module [13, 130]. Therefore, in contrast to test modules using Ethylene Vinyl Acetate (EVA) encapsulants and PET backsheets, no silver grid corrosion was observed for modules using PP backsheets. Similar findings have also been reported by another research group [146]. Nevertheless, long-term outdoor experience is still missing for PP based backsheets.

4.2. Critical backsheets issues of fielded modules

Fielded module evaluations are critical to assessing material degradation and ultimately informing future material design. Indoor accelerated testing is widely conducted but still lacks the ability to accurately portray the results observed in the field. A prime example of this discrepancy is the prevalence of PA based backsheets cracking. This material, which passed all indoor accelerated testing according to the standard IEC 61215-2 [147], has seen large scale failures in the field [8, 148, 149]. In a follow up examination of testing standards, Kempe *et al* were unable to replicate the cracking observed in the field after 4000 h of A3 exposure [99, 149]. Only upon testing using both UV and thermal cycling crack formation could be reproduced. Lyu *et al* reported that only under the combination of humidity, heat, and light acetic acid did assist in the formation of cracks in polyamide backsheets [8]. These cracks originated from the inner and core layers and propagated



Figure 5. Combined accelerated test setup from NREL. [127] John Wiley & Sons. [© 2020 John Wiley & Sons, Ltd.].

through the material to the outside layer [8]. Field-specific errors have also been observed for other materials. Gambogi *et al* have observed PVDF cracks in backsheets of modules in the field—a failure pattern that could be replicated by sequential interior exposures [106, 149]. These cracking effects have been associated with a change in phase of the PVDF material. In an indoor exposure test, Wang *et al* observed a change from the α -phase to the β -phase [150]. However, other studies reported a change from β -phase to the α -phase after damp heat exposure [151, 152]. It is still unknown what the mechanism for this phase change is. However, regardless of the mechanism, this phase change has been shown to be associated with the loss of ductility of the material.

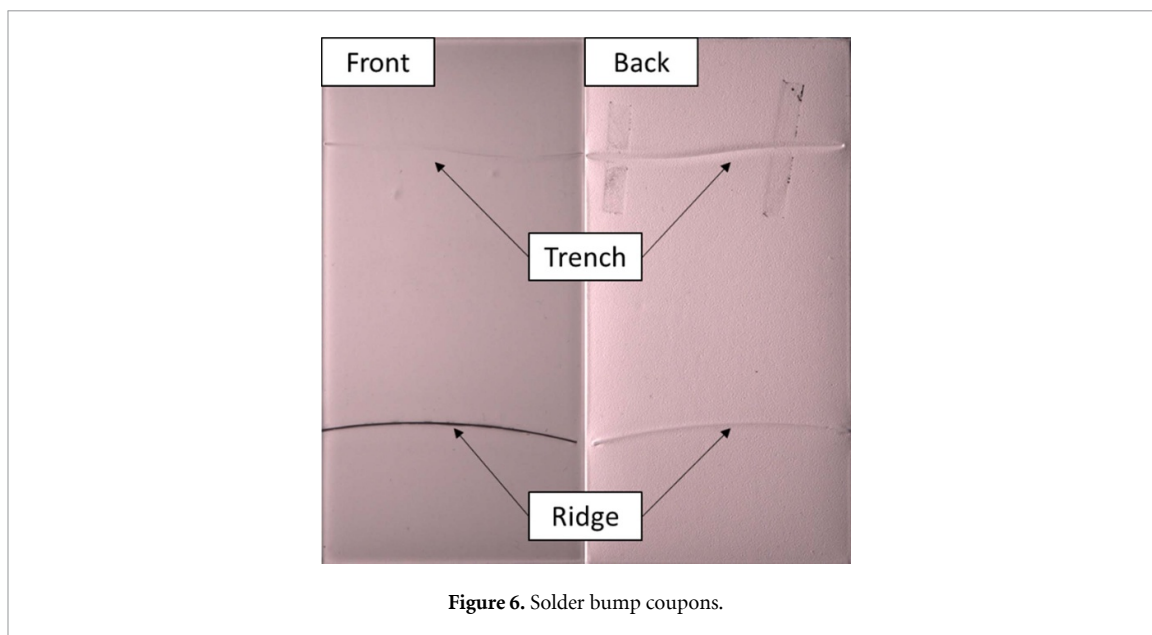
Detailed characterisation and error analysis of fielded modules showing failures are critical for the design of new test procedures that would replicate the stressors and replicate the failure images. Moreover, other types of degradation can only be observed by analysing the field architecture/environment. Fairbrother *et al* have observed a spatial dependence of specific degradation modes on the backside of modules depending on the irradiance distribution [153]. This observation was further expanded on by Wang *et al* in their paper modelling the formation of degradation precursors as a function of their location inside a PV module rack [154]. A statistically significant difference was observed between the formation of degradation precursors between the modules on the rack ends as opposed to those located in the centre of the rack [154]. Additionally the vertical position in the rack also affected the degradation parameters [154]. This macro-scale observations of fielded module conditions elucidate effects that materials may not be exposed to during routine indoor testing. To overcome these issues, new test methodologies have been developed within the PV module test communities and are being adopted within the standards community as an approach to better predict long term performance [155–157].

4.3. New approaches for indoor accelerated aging tests

Only recently for the first time backsheet cracks, as observed for field aged modules using PA and PVDF backsheets [129], have been reproduced by an indoor accelerated aging test utilizing simultaneous combined or sequential stresses (UV, humidity, temperature and thermo-mechanical load) [127, 128, 155, 156, 158, 159]. Simultaneous stresses are required as all damage analysis results show that backsheet cracking (independent of the materials used) results from material degradation caused by UV, humidity and/or temperature combined with thermo-mechanical loads that lead to crack initiation and crack propagation [9, 149, 160]. In recent years, three different approaches have been proposed, all of them leading to cracking of PA backsheets similar to field exposed modules.

A combined-accelerated stress testing (C-AST) capability was presented by Owen-Bellini *et al* [127, 160], that aims to better simulate the effects of the natural environment, to include the effect of unknown, complex, and simultaneous stress interactions and to identify degradation modes not detectable by traditional stress-test protocols. The stress factors include ultraviolet (UV) radiation, humidity, temperature, water spray, thermo-mechanical strain, mechanical loading, and voltage bias. An image of the test setup can be seen in figure 5 [127]. The biggest advantage of the proposed approach is that the test is designed to identify undiscovered failures in new module designs or using new materials, i.e. the test is agnostic to *a priori* known degradation modes [127].

Module accelerated sequential testing (MAST) has been proposed by DuPont [158, 159, 161, 162]. MAST starts with exposure of the samples to 1000 h of damp heat, and 1000 h in a UVA chamber followed by sequence of 200 thermal cycles and additional 1000 h in the UVA chamber [162]. This test sequence mimics the amount of approximately 25 years' worth of humidity, UV and mechanical stress seen in



the field [106, 155, 158, 162]. Using this approach cracking of PA and PVDF based backsheets was successfully replicated.

A different approach was proposed using so-called solder bump coupons was proposed by Kempe et al [149]. Because cracks often appear along surface contours of module, laminated test samples containing glass, encapsulant, backsheet and a round wire are used to duplicate module contours, with the solder wire producing ridges (when situated between encapsulant and backsheet) and trenches (when situated on top of the backsheet), see figure 6. The samples are then exposed to a sequential test consisting of (1) 500 h of xenon exposure and (2) 100 thermal cycles from $-40\text{ }^{\circ}\text{C}$ to $85\text{ }^{\circ}\text{C}$, which was repeated five times.

5. Summary and conclusion

For the last decade or more, PV module manufacturers have experienced a rapidly growing market along with a dramatic decrease in module prices. Such cost pressures have resulted in a drive to develop and implement new module designs, which either increase performance and/or lifetime of the modules or decrease the cost to produce them. Many of these innovations include the use of new and novel materials in place of more conventional materials or designs. As a result, modules are being produced and sold without a long-term understanding about the performance and reliability of these new materials.

There are several motivations for investigating new materials for PV modules. Reducing or replacing expensive materials is important for the overall economics of module production. For example, reducing the use of or replacing silver with copper or aluminium leads to a significant cost reduction for manufacturers. Another example is using thinner glass for top sheets or converting from more expensive PVF to less expensive PVDF materials for backsheets. Accelerating the manufacturing process is another way to decrease production costs. Lamination is typically the slowest step in a module production line and manufacturers are very interested in materials that can speed up this process step. For example, fast or ultra-fast cure EVA encapsulants have reduced the time needed for crosslinking from 25 min to 10 min today. Converting to thermoplastic encapsulants, which do not crosslink, may help reduce these times even further. Increasing performance is an obvious motivation for material innovations. This can be achieved with increasing the number of busbars, increasing the active area by using shingling, or increasing light absorption using antireflective coatings, or increasing internal reflections with highly reflective backsheets or white templates between cells. The trend to increasing wafer size also leads to performance gains. Making modules more sustainable is another strong motivating factor. LCA is a methodology to quantify the environmental impact of a product. Some manufacturers seek recognition of ecologically responsible material choices by using various labelling standards to identify good sustainability practices.

A survey of the PV manufacturing industry today shows that there are clear trends in material improvements. Crystalline silicon wafer sizes are projected to continue to increase over time as silicon production improves and results in larger monocrystals that can reach 300 mm in diameter. Cell sizes are expected to increase up to $210 \times 210\text{ mm}^2$ (M12) in the next several years. New cell interconnection methods are moving to production lines. Manufacturers are instead trying lead-free solder based on

bismuth, electrically conductive adhesives (ECAs), or smart-wire technology. Back contact cells allow the use of conductive backsheets to interconnect cells. This approach has the advantage of minimizing cell warpage and stress on interconnects due to fact that busbars do not need to cross from the back to the front of the cells, which results in a much flatter package design.

Less developed ideas for module improvement include modules designed for specific climates (e.g. desert, tropical, arctic, high wind or snow loads) or environments (i.e. floating, agriculture). Modules for building integrated applications typically value aesthetic properties as much as or more than energy production. For roof-mounted PV modules, weight can be a limiting factor for deployments. Concepts for making lightweight modules using ultrathin glass and glass-fibre reinforced composite structures or support lattices are being investigated. Vehicle integrated PV requires curved modules, which likely will require materials innovations.

The process of material innovation for PV is further complicated by the complex interactions within a PV module. The advantage of one material may be outweighed by its interaction with another component. New materials must work within the whole module package and in concert with the other materials present.

In general, it is challenging to substantiate advantages of new materials without long-term accelerated testing that can be correlated with field data. Consumers and manufacturers rely on international standards, such as those from Technical Committee 'Solar Photovoltaic Energy Systems' TC 82 to ensure that new materials do not result in unexpected performance or reliability problems. Another issue is that module manufacturers do not typically advertise their bill of materials and the BOM for a particular module model can vary depending on when and where it was made.

Unexpected failure modes like PID or backsheet cracking, which have not been detected during material and module qualification in the past, have shaken the confidence in existing standards and test procedures, resulting in huge efforts to implement enhanced accelerated test strategies. Most approaches are defined as so-called agnostic stress tests, which are based on a combination or sequence of multiple stressors that better reflect outdoor conditions. That allows for identification of new degradation modes linked to new module materials or module designs. As a consequence, different accelerated test approaches have been presented that successfully reproduced cracking of backsheets.

Data availability statement

No new data were created or analysed in this study.

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