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Aging Phenomena of Backsheet Materials of Photovoltaic Systems for Future Zero-carbon Energy and the Improvement Pathway

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Abstract: The insulation degradation in polymeric backsheets has been identified as a main cause of catastrophic accident induced by short circuit or ground faults in photovoltaic module. To ensure quality, the photovoltaic industry is therefore faced with urgent demand in discovering degradation mechanisms. Moreover, the development of environmental-friendly backsheets and the establishment of backsheets recycling specifications are vital to fulfil the requirements of future reliable photovoltaic system with improved productivity. In this review, we innovatively summarize the detection methods of insulation deterioration from the viewpoints of spectroscopic, thermal and mechanical approaches. The corresponding ambient conditions in measurement and their accelerating effect in the degradation of photovoltaic backsheets are discussed. Subsequently, emerging novel materials and structures for enhancing insulation properties, anti-aging performance and optical-electrical energy conversion efficiency of photovoltaic cell are summarized. It offers a comprehensive strategy to design materials with optimal structures in photovoltaic module for a future zero-carbon energy system.

Keywords: Photovoltaic, Polymeric backsheets, Degradation, Environmental-friendly design, Zero-carbon

1. Introduction

The energy crisis and climate change are becoming major challenges as they block healthy and sustainable development worldwide in last decade [1-5]. In sight of dramatic breakthroughs in cost and efficiency of photovoltaic (PV) technology, its own environmental friendliness, and the booms in multi-energy complementary integrated energy systems, solar PV forms the cornerstone of a viable solution [6-12]. PV power generation is therefore strongly supported under the guidance of carbon peak and carbon neutral targets [13,14]. As shown in Fig. 1a, solar PV capacity will reach a record of 6,970 TWh in 2030 according to the International Energy Agency (IEA) [15]. The growing demand for a large PV installed capacity and longer service life in PV modules have brought the aging and maintenance of solar panels into focus in the future [16].

Generally, the service time of the entire system depends on the durability of the individual components. In the case of solar panel, stable long-term operation is determined by the reliability of each component. The PV module mainly consists of a cell based on the PV effect, packaging materials such as front-side glass cover, encapsulant, PV backsheets and an aluminum frame for support and so on [17]. Among them, the backsheets are suitable for a variety of purposes such as critical electrical insulation, mechanical support, environmental protection, and light reflection [18,19]. These durable performances are required for more than 20 years [17,20]. Nevertheless, the actual operation indicates that the service life of these packaging materials is even shorter than design life, which leads to the performance loss of solar panels and affects the safe and stable operation of PV plants [21]. Driven by the degradation of backsheets during service lifetime, the durability of PV backsheets and the mechanisms of failure under real-world operation have attracted considerable interest in both research and industry.

The PV backsheet is in direct contact with the ambient environment and guarantees the electrical output of the cell by shielding it from various external stress factors [22]. During field-exposed, PV backsheets are exposed to various internal and external stress factors that undermine the durability of the protective layers. The internal stress factors are backsheet-encapsulant interactions and partial discharge induced by leakage current. While external stressors are related to environmental conditions, which include ultraviolet (UV) radiation, mechanical stress, salt-mist exposure, moisture, heat [23].

During field exposure, PV backsheet continuously suffers from these factors shown in Fig. 1b, which reduce its durability and service time. Specifically, the phenomenon of peeling, cracking, chalking and discoloration of PV backsheet can be observed in the field, which is depicted in Fig. 1c [24,25]. It indicates that the degradation of the backsheet material is closely related to the exposed environment which can be determined by a combination of the climate of the PV module installation site, the PV array structure, and different ground covers. For instance, a floating solar PV will have a different degradation mechanism compared to a PV system on land [26,27]. The water environment is more humid and cooler than the land surface. In addition, the reflectivity of sunlight on the water surface is different from that on the ground. Corresponding seasonal changes and environmental factors can also bring temperature and humidity variations to PV backsheets. These specific environments can result in different temperatures, humidity and UV irradiation levels. Therefore, research on the degradation of PV backsheet under different stresses will help to understand the degradation patterns of backsheet during field exposure. Further discussion of the different stress factors is presented in Section 4.

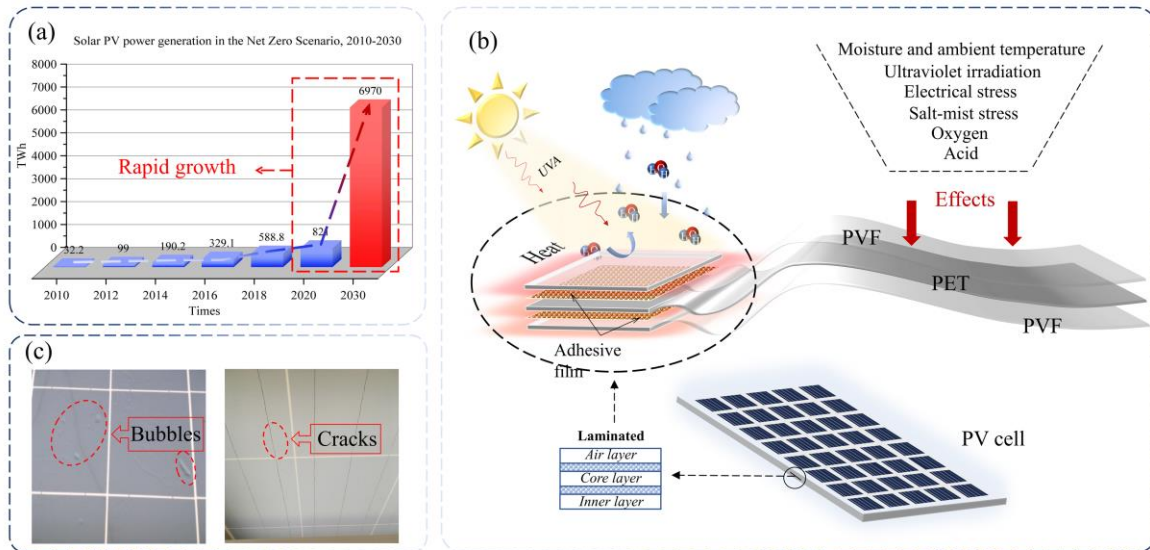


Fig. 1. (a) Solar PV power generation in the Net Scenario, 2010-2030 [15]; (b) Environmental stressors associated with PV backsheet failures. PV backsheet can suffer from several stressors in specific ambient; (c) The two main types of defects on backsheet observed in the field, including blistering (left) and cracking (right). The circles in the images indicate cracks and bubbles respectively.

The great advancements on PV backsheet have been achieved up to now, especially for the analysis of aging mechanism of polymer components applied in PV backsheet. However, it is urgently desired to summarize these works and exhibit a comprehensive research result in the field of PV backsheet. In this paper, we review the literature on various insulating backsheet materials in PV modules and their characteristics. A summary of detection methods of insulation deterioration from the viewpoints of spectroscopic, thermal and mechanical approaches is presented and, the corresponding ambient conditions in measurement and their accelerating effect in the degradation of PV backsheets have been discussed. Subsequently, emerging novel materials and structures for enhancing insulation properties, anti-aging performance and optical-electrical energy conversion efficiency of PV cell are summarized. Finally, the perspective of novel future research directions is highlighted including health monitoring, novel detection methods, correlation between aging mechanisms of backsheet and accelerated testing, and environmental friendliness of PV power

generation. These perspectives and recommendations provide comprehensive ideas for future zero-carbon energy systems. The detailed process flow chart of the paper is shown in Fig. 2.

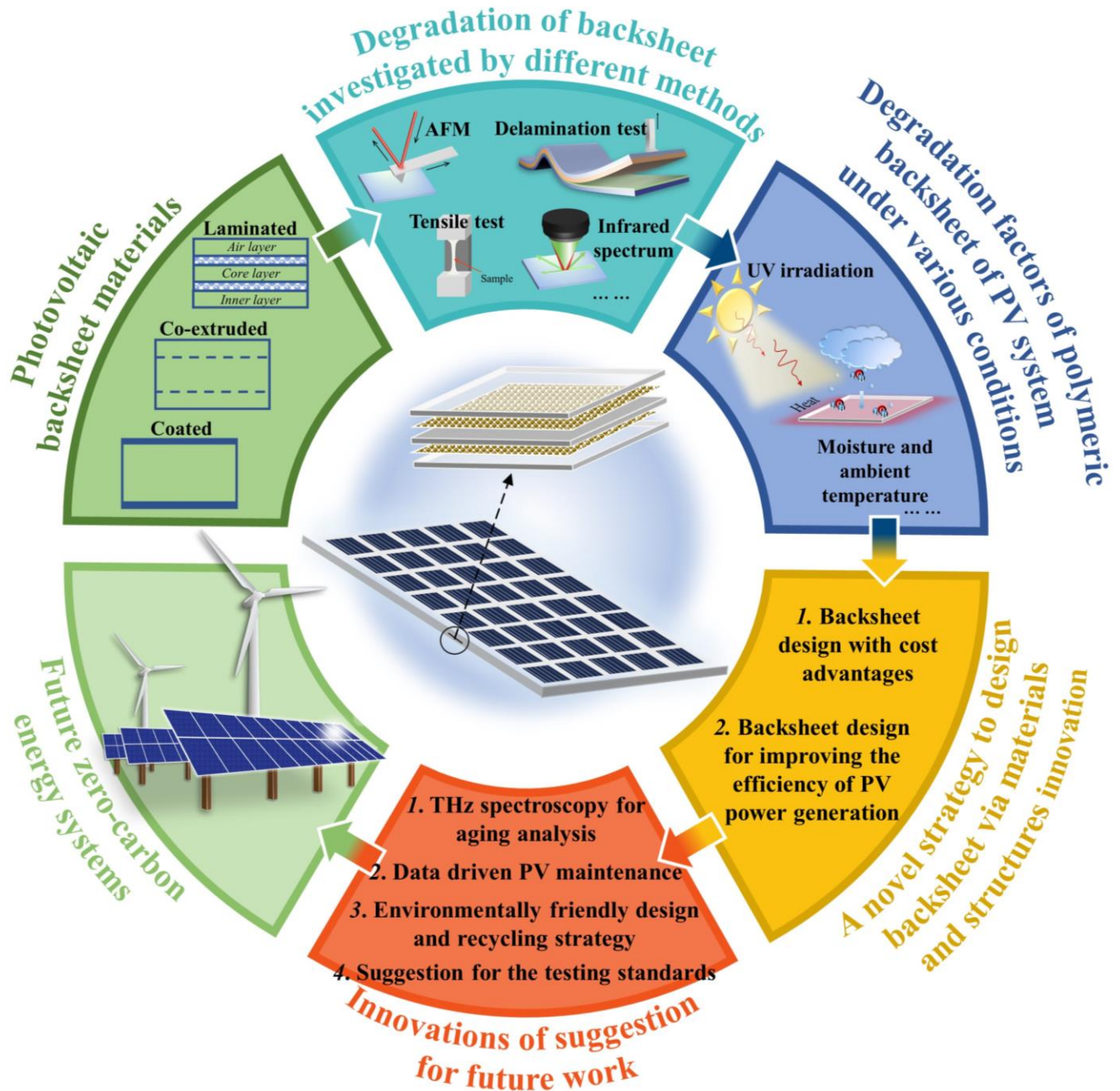


Fig. 2. Process flow chart of this paper.

2. Photovoltaic backsheet materials

To fulfil long-lasting performance, a typical backsheet generally laminates several layers of material. In addition, stabilizers and additives are added to polymeric materials to enhance the properties of the backsheet [28,29]. The outer layer of the multilayer structure provides weatherability [25]. Fluoropolymers such as polyvinyl fluoride (PVF), polyvinylidene fluoride (PVDF) ethylene chlorotrifluoroethylene (ECTFE) and tetrafluoroethylene hexafluoropropylene vinylidene fluoride (THV) are generally selected for this layer due to their excellent resistance to hydrolysis and UV radiation [19,22]. In contrast, polyethylene terephthalate (PET), an engineering thermoplastic, is a common core layer material that ensures the mechanical support and electrical insulating ability [30]. For the inner layer, PVF, thermoplastic ethylene vinyl acetate copolymer (EVA) and other materials can be selected [24]. KPK (PVDF, PET, PVDF) and TPT (PVF, PET, PVF) are representatives of laminate backsheet [20]. Moreover, manufacturers have also developed other polymeric materials such as polyamide (PA), polypropylene (PP) and manufacturing process range from coating processes to single-step coextrusion method [31-33]. At present, backsheet manufacturers are actively exploring materials that allow for lower-cost, lower environmental impacts. However, being relatively new on the market, the long-term weathering stability and material compatibility of novel backsheets still needs to be explored [34]. Further discussion of the novel backsheet is presented in Section 5.

3. Degradation of backsheet investigated by different methods

The degradation of polymeric backsheet is usually accompanied by the fracture and recombination of polymer molecular chains, the change of crystallinity and the change of surface roughness. The study of these changes helps to analyze the degradation process of the backsheet, which is tough work as the microstructural change cannot be identified with naked eyes. **As a consequence,**

this section illustrates methods for detecting material degradation from the viewpoints of spectroscopic, thermal and mechanical approaches, which greatly reduces the restrictions in explaining the degradation mechanism of PV backsheets at the microscopic level.

As shown in Fig. 3 from the viewpoint of spectroscopic and thermal approaches, these changes can be determined by a variety of methods, including atomic force microscopy (AFM), cross-sectional scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), fluorescence spectroscopy, X-ray transmission imaging, differential scanning calorimetry (DSC) and so on [35,36,37]. For instance, information on the degradation of polymeric packaging materials is also expressed in the surface and interface properties of the materials, for which the surface microstructure mainly involves SEM and AFM. In addition, both FTIR and Raman spectroscopy are known to be non-destructive for samples, and are powerful tools for analyzing the degradation behavior of different backsheets materials. Normally, researchers measure the spectroscopy of the aged samples as well as a non-aged reference sample. Since different substances have different chemical groups, this difference will be reflected in the spectroscopy with different spectral peaks. Therefore, by comparing their spectroscopy, the differences in the compounds contained in the samples or the differences in the structures of the compounds can be obtained, and thus the material degradation of different samples can be determined. By comparing the spectroscopy before and after the reaction, it is possible to determine the chemical bonds involved in the reaction and to infer the corresponding chemical reactions. However, these techniques are mainly used in the laboratory and are not entirely suitable for field inspection of the degradation state of PV backsheets [38]. Portable near infrared (NIR) spectroscopy provides a promising outdoor inspection method for evaluating the degradation of PV backsheets quantitatively [39] because of its non-destructive testing characteristic. Furthermore, it is

indicated that the spectrum from NIR has high correlation with peel strength and tensile strength tests by using multiple linear regression analysis.

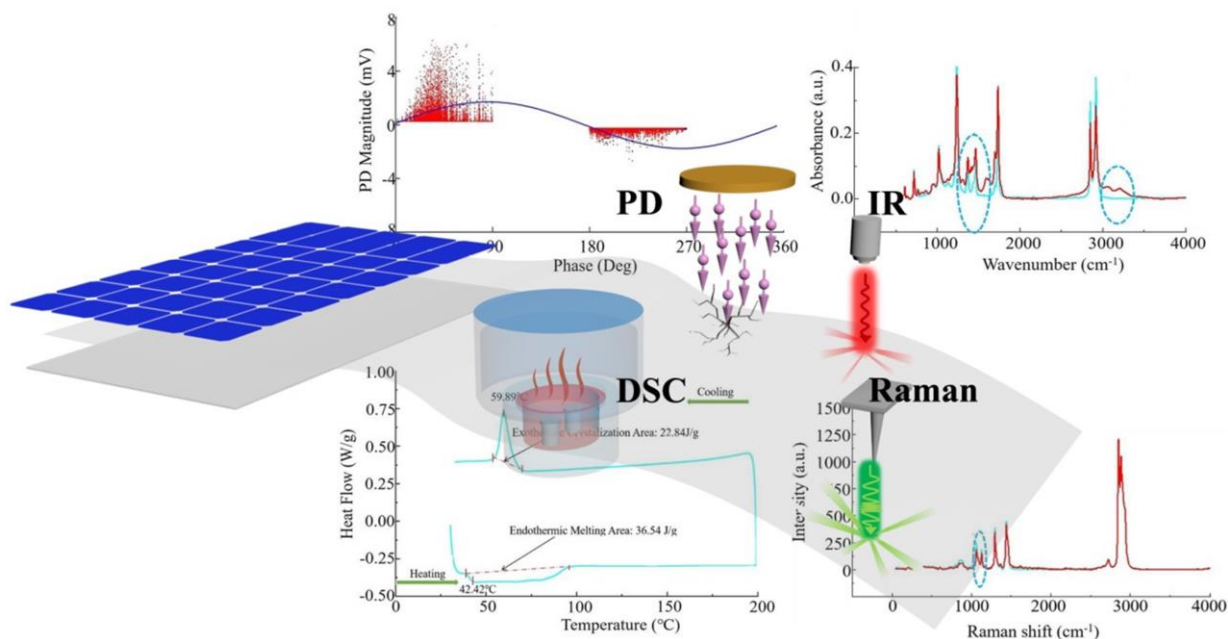


Fig. 3 Different methods for detecting PV backsheet [37].

The degradation of backsheet brings about changes in its own mechanical properties, which can be investigated by mechanical tensile test and adhesion test [18,25,36,40-42]. However, the current means to assess degradation are not perfectly appropriate for assessing the cracking propensity of commercial backsheet. To deal with this situation, a fragmentation test method was proposed which successfully assessed the propensity for cracking of PV backsheet [24]. By observing the crack characteristics during the deformation of the backsheet, the relationship between formation of the surface cracking, aging conditions and polymer degradation can be concluded systematically. Moreover, indentation enables the mechanical properties at the surface of material to be quantified, which identifies the degree of deterioration of the backsheet [36]. Besides characterizing cracking, Julien et al. demonstrated a strategy for characterizing the degradation degree of the backsheet by the adhesion energy. The single cantilever beam (SCB) adhesion test proposed in their works provided

suggestions for enhancing the service time of backsheet [43]. In practice, the degradation of PV backsheet is usually pointed out by manual inspection. However, sometimes subjective human operation may produce errors. In view of this, Zhang et al. demonstrated a fully convolutional deep neural network architecture (F-CNN) to detect degraded patterns and offered solutions in identifying the type of PV backsheet degradation automatically [44].

With the development of photonics and electronics, terahertz (THz) spectroscopy ranging from 0.1 to 10 THz enables the defects detection of the material from an attractive perspective, which could provide significant research value and application prospects [45,46]. THz waves have been successfully applied in the food industry, medical business, and characterization of materials [47-50]. For instance, using THz technique to identify simulated gaps with different widths similar to cracks [51]. Zhang et al. demonstrated a terahertz tomography system designed for nondestructive testing of polymer materials [52]. Furthermore, the dielectric properties of five commonly insulation materials were investigated based on THz wave measurement [53]. These successes significantly boost confidence in the application of the technology for non-destructive testing of insulating backsheet. Here, we put forward it is possible to use THz technology for the nondestructive detection of cracks resulting from the aging of the PV backsheet. Also, terahertz time-domain spectroscopy (THz-TDS) could provide abundant information concerning intermolecular, which can be used to obtain the molecular information of the backsheet material after aging. Fig. 4 shows an example of the THz-TDS for molecular information acquisition of PV backsheet materials. In view of the above-mentioned analyses, a summary of different detection methods used in the degradation of backsheet is given in Table 1.

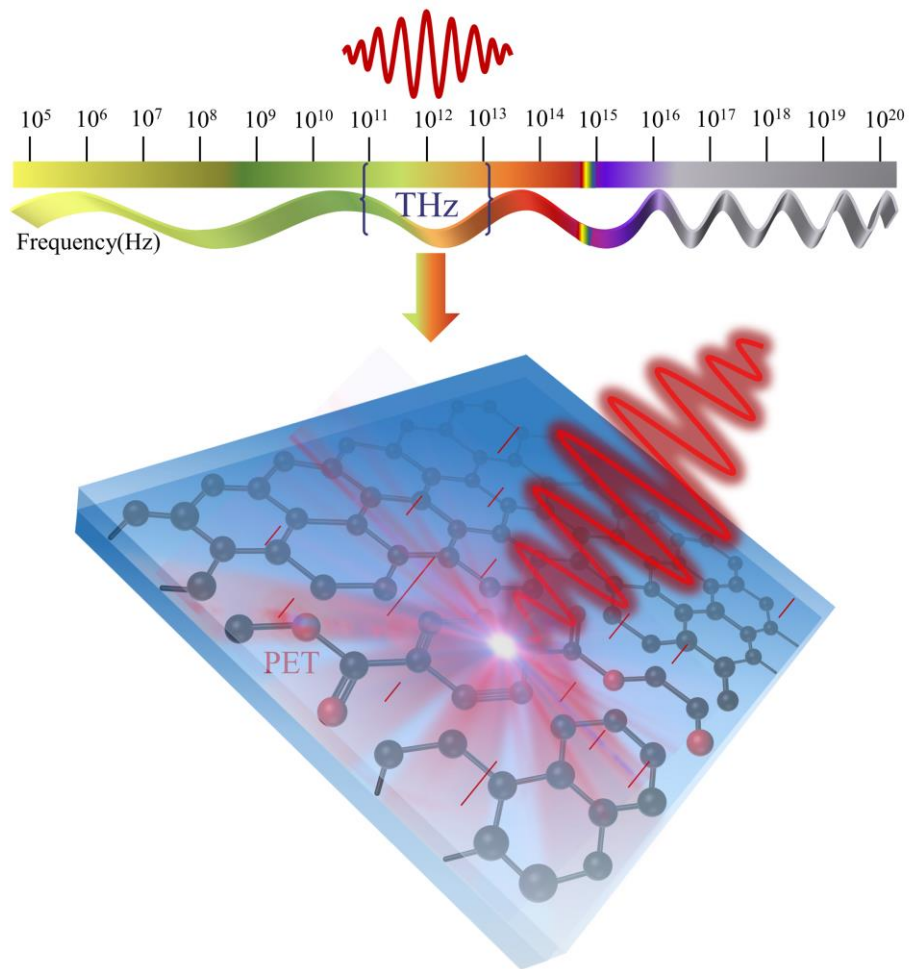


Fig. 4. Terahertz wave spectroscopy for non-destructive testing of PET-based backsheet [46,53].

Table 1 Methods used to evaluate the degradation of backsheet.

Methods	Advantages	Physical changes	Chemical changes	Field survey	Surface roughness
Mechanical tensile	Related to chemical and physical changes	√			
Gel permeation chromatography	An useful analytical tool for monitoring the molecular weight and its distribution of polymers (Especially hydrolytic degradation)		√		
DSC	Characterize the thermal Changes in crystallinity of polymers	√	√		
FTIR	Fast inspection speed, low operation difficulty, high measurement sensitivity		√		

Melt rheological measurement	As a good verification of changes in molecular mass	√		
Roman Spectroscopy	Study the molecular structure		√	
AFM	The change of surface morphology			√
NIR	Quick, easy and nondestructive		√	√
F-CNN	Automated inspection Decrease the errors and uncertainties in manual inspection			√
SCB	Quantified adhesion energy Solve the defect of traditional peel test	√		
THz	Nondestructive Abundant information concerning intermolecular		√	

4. Degradation factors of polymeric backsheets of PV system under various conditions

The Renewable Energy Sources Act (EEG) was implemented on April 1, 2000, and then, solar energy has been promoted in Spain, Japan and other countries [54]. There has been a considerable increase in studies of degradation on PV backsheets caused by environmental stress factors since 2002. Summarizing the degradation of PV backsheets caused by these stress factors provides a feasible way to grasp the aging process.

4.1 UV radiation

UV light (200–400 nm) induces the deterioration of the PV backsheet step by step by breaking the polymer chains and producing free radicals at the micro level [55]. Different wavelengths mean different energies carried by light and different degrees of penetration, which leads to a complex photodegradation of polymer films when exposed to the UV light [56]. Eventually, it results in loss of mechanical property and color change.

This section of research focuses on PET films and multilayer backsheets with PET as the core layer. These polymeric backsheets occur yellowing after long-term UV radiation, and the degree of yellowing is closely related to the dosage of UV exposure [22,57,58]. The changes in color can be measured by Delta E apart from the yellowness index (YI) [57]. These indexes provide important reference for accurately measuring the color change of backsheet after UV degradation. The color changes of the backsheet during the degradation are attributed to the chemical changes that occur during the degradation process. Specifically, the bonds in the molecular chains that make up the material are broken and other products are produced during the process [22,59]. Furthermore, the changes in molecular weight due to chain breakage cause a loss of mechanical properties of the material [28,60]. The deterioration of mechanical properties is reflected in the appearance of cracks on the surface of the film, which makes the inside of the backsheet available for further degradation and ultimately brings about embrittlement [57]. Usually, the degradation caused by UV radiation starts at the surface of the backsheet and gradually penetrates [57,60]. However, this degradation is not uniform [22]. Horne et al. simulated the photodegradation reaction with narrower wavelength range of light and analyzed more degradation products on the basis of previous experimental results and related theories [59]. The results showed that light at 302 nm acts on the PET surface, while light at 365 nm penetrates the PET film to cause damage. In addition, the combination of moisture will also make the degradation of the backsheet more serious [22,58]. In view of analysis of depth profile of backsheet degradation, the degree of degradation can be investigated effectively.

To slow down a range of photodegradation, various types of light stabilizers, such as Tinuvin 1577, carbon black, mixture of titanium dioxide (TiO₂) and barium sulfate (BaSO₄), have emerged in the realization of PV backsheet, allowing for the improved UV aging resistance in PV backsheet [28]. Fechine et al. conducted preliminary work based on the aging behavior of PET incorporated with

different additives and presented that UV absorber as an effective stabilizer. In a follow-up study, with the major focus on the mechanism of resistance of stabilizers against UV, his research team revealed that UV absorber can slow down the degradation of PET by reducing the formation of carboxyl end-groups [60]. Another approach towards mitigating UV damage to the backsheet is to modify surface properties of material by plasma treatment [61]. More specifically, surface modification can change the optical properties such as reflectivity in the UV. The increase in UV albedo reduces the damage in polymeric materials.

The UV dose in the weathering exposure also correlates with the degradation of backsheet [62]. An established lifetime model based on UV dose from different regions can ensure reliable operation of PV backsheets over long periods of time. There is no doubt that the spectral UV albedo of the PV module installation site, the spectral sensitivity of backsheet degradation, latitude, seasonal, weather factors and usage of UV absorber create considerable difficulties in predicting the accurate lifetime of PV backsheet [63]. Furthermore, with the gradual destruction of the ozone layer, UVB (280-320 nm) and even UVC (200-280 nm) may reach the surface of earth in increased amounts [64,65]. So far, no work has provided a more precise lifetime prediction model of UV damage. Future research is to consider the impact of these factors on the degradation of backsheet and provide precise life predictions of UV irradiance.

4.2 Moisture and ambient temperature

Apart from UV radiation, moisture ingress and heat within the backsheet can result in metal corrosion, delamination of multi-layer backsheet, cracking, discoloration, and acetic acid from EVA [42]. In addition, humid and hot conditions can damage the optical properties of the backsheet resulting in a reduction in output of the solar panel [66].

While the silicone oxide barrier layer used in the backsheet weakens the effect of moisture, the polymeric backsheet cannot completely obstruct the ingress of gases. Due to the presence of ester bonds in PET molecules, water and temperature will lead to significant hydrolysis and eventually delamination and tearing appear [18,29]. The debond energy of PV backsheet under moisture temperature and mechanical loads can be quantitatively characterized with the method of single cantilever beams [41]. A fracture-kinetics model can be established by quantifying the debond energy of PV backsheet, which forms the basis of reliability prediction of PV backsheet. However, the initial peeling energy does not correlate with the bonding performance after the DH test. To ensure a high performance after deterioration, a reasonable combination of backsheet and encapsulant film needs to be selected [67]. Temperature cycles and moisture result in brittleness of the backsheet and differences in the thermal expansion of the material between the layers eventually leading to cracking. Tearing energy varies significantly with DH exposure. A very detailed study on the tearing behavior of multi-layer backsheet was conducted by Yuen et al. By exposing the backsheets of six polymers to damp heat (85 °C/85%RH), they developed a model to describe the tearing energy of multilayer backsheets [35]. Additionally, they further proposed that interaction of mechanical constraint between different layers should be considered when designing a reliable backsheet. Benefit from the polymeric materials, modified polyolefin backsheets produced by the co-extrusion process can effectively reduce cracking and delamination. Coextruded polyolefin-backsheet had better thermal and mechanical stability compared with polyester-based backsheet through damp heat test (85°C/85%RH) and simulation test under the sun [18]. Based on these experimental results, the MPO backsheet is promising and could replace PET-based backsheet prone to crack and embrittle under damp heat conditions.

Due to the long test time for damp heat exposure, the PV industry needs shorter and more reliable test cycles to accelerate products to market [42,68]. The aging pattern under pressure cooker tests

(PCTs) may correlate with the failure pattern after damp heat testing. Based on PV industry standards and previous work, PCTs have been proved to be effective in reducing damp heat (DH) test cycles.

There is a good correlation between the performance of the material in autoclave and DH tests at 120°C. Therefore, PCTs are believed to save material testing time and improve the quality of PET-based backsheets materials.

According to IEC 61215 and IEC 61730 standards, DH testing is the most commonly used test in the PV community [18,35,41]. However, it is often the case that single test procedure does not represent the real service conditions of outdoor PV module under multiple environmental stresses. For instance, DH tests are not sufficient to exactly predict the durability of PV backsheets, especially when the UV degradation is ignored. Thus, both DH and UV accelerated tests are necessary to be taken into consideration simultaneously, in order to accordance with the actual operational conditions.

4.3 Salt-mist exposure

PV systems installed in tropical and offshore areas are vulnerable to salt-mist exposure apart from exposure to high humidity. Moisture and salt-mist may cause delamination of the packaging materials, which provides a pathway for further corrosion of the metal within the solar module. Moreover, it also reduces the insulation properties of the PV module and eventually accelerates the degradation. Scholars have noted the effects of salt mist on PV modules, yet research on PV backsheets after salt-mist exposure remains limited. Salt spray exposure will accelerate the potential-induced degradation (PID) phenomenon in PV modules [69]. The combined effects of salt-mist stress and high-voltage loading are easy to cause PID. However, the mechanism of salt-mist stress accelerating PID effect still needs to be further understood. Specifically, understanding of the transport processes of sodium ion is needed to reduce the degradation of PV backsheets near the coast. Solar PV technology can realize greater

potential in sunny tropical regions. Salt-mist and high humidity hinder the expansion of PV technology in sunny tropical regions. Thus, Illya et al. put forward quantitative characterization technique used to examine the delamination strength of PV backsheet after exposed to salt damp heat conditions [70]. According to experimental results, salt-mist exposure weakened the interface adhesion strength between backsheet and encapsulant. Additionally, the single cantilever beam test depicted in Fig. 5 can effectively study the degradation of backsheet and encapsulant. Salt-mist exposure is associated with PD activity. Through analyzing the relationship between PD activity and salt spray exposure, it is possible to evaluate the electrical and chemical changes induced by PD activity after salt spray exposure and to explore the causes of crystallinity changes. Salt-mist condition and PD activity can affect the degradation rate of PET material [71].

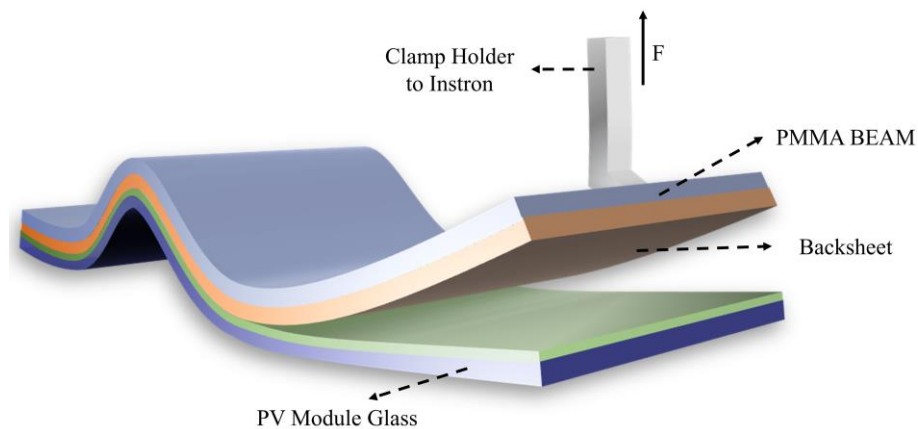


Fig. 5. Cartoon of single cantilever beam test method [43,70].

In the future, there are still numerous works that deserve consideration. (1) Investigating the adhesion property between different layers of typical commercial multilayer backsheets after salt spray exposure and the effect of PD activity on the durability of the backsheet after salt spray exposure. (2) Analyzing the tearing behavior of the backsheet after salt spray exposure (3) In order to realistically simulate the environment of offshore area, the combined effect of salt-mist and additional stress factors such as UV, temperature cycles still need to be investigated.

4.4 Electrical aging stress

Electrical-induced degradation is also an important factor that affects PV backsheets easily during the operation of PV system. Since 2011, the influence of electrical-induced degradation on the performance of PV backsheet has received considerable attention, which provided significant theories and methods for subsequent research.

The impact of the electric field leads to changes in the surface chemistry, crystallinity and surface roughness of these backsheets [20,72-75]. These changes eventually appear as a decrease in insulation performance. The crystallinity of PET backsheet after the application of electric field is proportional to the discharge time. The electrical aging behavior of the backsheet can be analyzed by measuring the crystallinity. Multilayer backsheets have stronger insulating ability compared to PET backsheets. By applying an electric field to the multilayer backsheet, it can be found that the KPK and TPT backsheets have similar resistance to partial discharge, but the KPK backsheet is more resistant to corona discharge after corona discharge. In addition, the electric field on the on the backsheet is also affected by temperature. The increase of temperature will accelerate the effect of electric field on the electrical aging of backsheet.

Material modification could weaken the effect of electric field on properties of polymer materials [76]. By studying the partial discharge (PD) activities of PET films doped with different additives including TiO_2 as well as BaSO_4 , it was found that the PET with additives exhibited better PD resistance and lifetime than untreated PET, which could be confirmed from micro perspective via surface chemistry analyses.

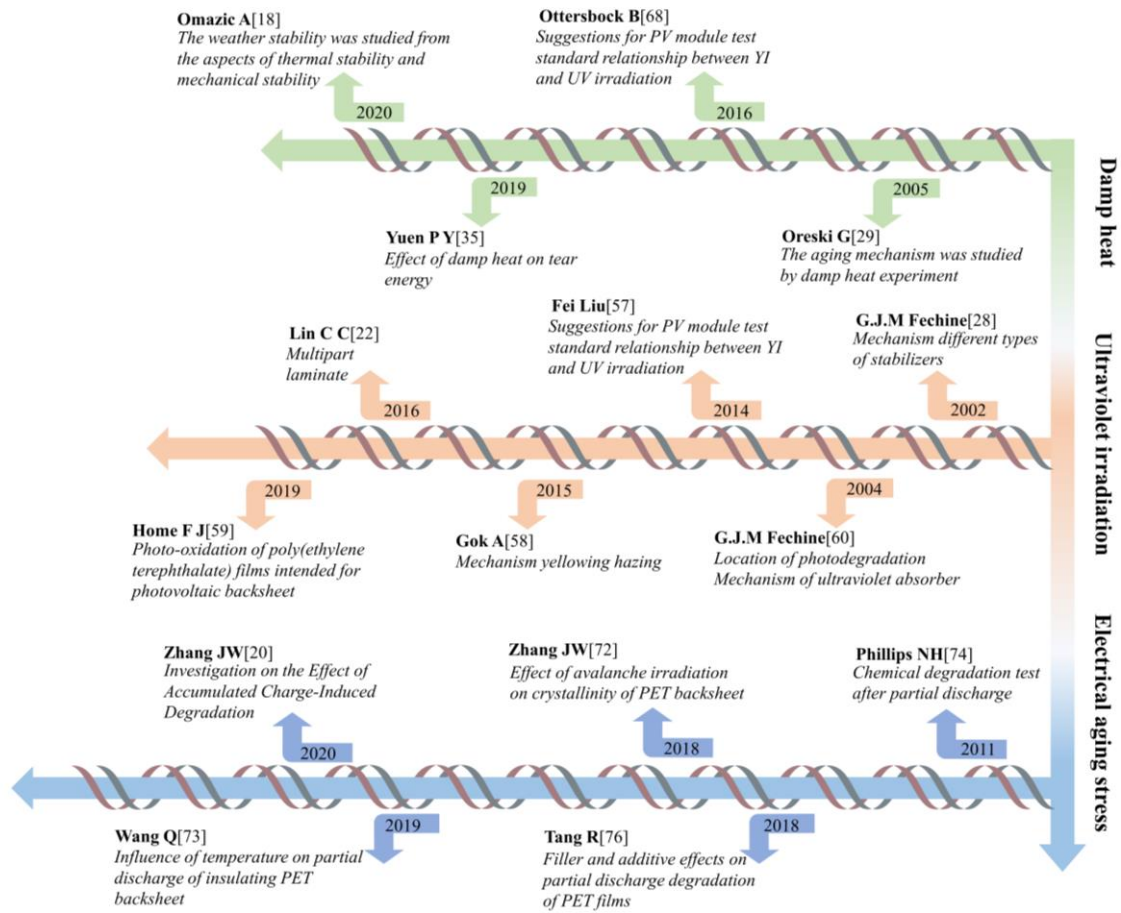


Fig. 6. Flow chart of reviews on degradation in PET backsheet [18,20,22,28,29,35,57-60,68,72-74,76].

Overall, a history of different backsheet tests and further understanding of the aging mechanism in the literature has been reported. As demonstrated above, a variety of indoor tests of PET backsheet was summarized, as illustrated in Fig. 6. Additionally, the following research advance in polyamide-based backsheets, as shown in Fig. 7. It can be seen from the above contents that the research on the aging mechanism of PV backsheet usually applies aging factors sequentially (usually one or two) or uses standardized qualification tests such as IEC61215. However, it is not adequate to reliably predict the long-term performance of PV backsheets in different regions with specific climates. The aging mechanisms could be much profound and complex in the actual operational environment, and these mechanisms may be interrelated. For example, different defects are observed in the polyamide

backsheet after aging under different climatic conditions [77]. To reliably assess the lifetime of backsheet, a combined-accelerated stress test (C-AST) method has been introduced [36,78,79]. Although relevant research has informed the accelerated laboratory weathering, the C-AST lacks consideration of partial discharge caused by leakage current which is a key factor for aging of backsheet. The future design of reasonable accelerated aging tests is the focus of work, which will help understand the degradation mechanism of backsheet and reliably predict the PV backsheet durability [80,81].

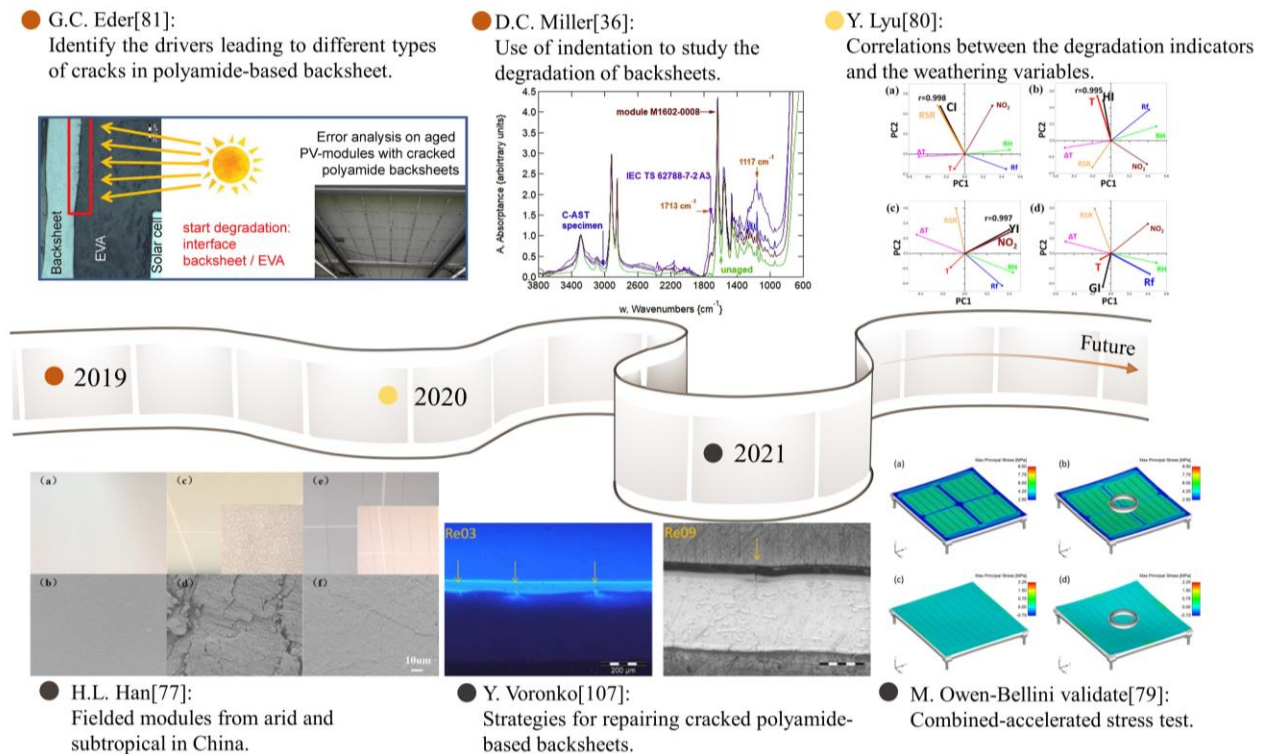


Fig. 7. Flow chart of reviews on fundamental research on PA-based backsheet. [36,77,79-81,107]

5. Novel strategies to design backsheets via materials and structures innovation

Following the advancements made with PV technology, new backsheet materials with broad market prospects have attracted more and more attention. Innovations in materials and structural design are covered in these new designs of backsheet. Consideration of durability is a fundamental concept

throughout the design of backsheet. On this basis, further considerations such as cost reduction, module power generation performance and material recovery potential should be taken into account. In the following section, the emerging novel materials and structures that reduce module costs, improve backsheet durability, or increase the efficiency of PV power generation are summarized. A tree diagram of reviews of novel backsheet structure and materials can be found in Fig. 8.

5.1 Backsheet design with cost advantages

The demand for lower-cost PV technologies is driving innovation in materials. The cost of non-fluorinated backsheet has a significant advantage over fluorinated backsheet. After more than 4 years of outdoor exposure, it is testified that degradation often occurs near the edge of the array and at a higher position [82]. Although the durability of such backsheet is not ideal, understanding their behavior in the field is essential for the further development of non-fluoropolymer-based backsheet. Adding natural fiber (NF) as filler to polymeric material can improve material properties. A novel PV backsheet material innovatively utilized a polyvinylidene fluoride-short sugar palm fiber (PVDF-SSPF) was developed. The PVDF-SSPF backsheet which combines well, had good thermal stability [83]. Reducing the use of adhesives can also reduce costs. **A new type of backsheet without the use of adhesives has been reported, which coats the protective layer directly on the surface of a special-grade PET film** [84]. Moreover, this special backsheet (code: FF-backsheet) showed excellent aging resistance compared to conventional backsheet after rigorous accelerated aging tests. Thus, this kind of backsheet, which has both cost advantages and shows high durability, is of high value for future applications in the PV industry. Similarly, the production of polyolefin backsheets through a co-extrusion process does not require adhesive layers [85]. More importantly, the material selected for this backsheet has a recycling advantage over fluorinated backsheets. Nevertheless, the successful promotion and application of such backsheets also requires the consideration of durability. By

exposing PP backsheet and PET-based backsheet to high temperature and humidity, co-extruded backsheet based on polypropylene maintained better mechanical properties while the PET-based backsheet showed a loss of mechanical properties. In addition, the backsheet can allow acetic acid to pass through effectively to reduce internal corrosion, and the excellent optical properties of such backsheets can also improve the output of PV module. The future of the co-extrusion process for the production of backsheets requires a high degree of attention.

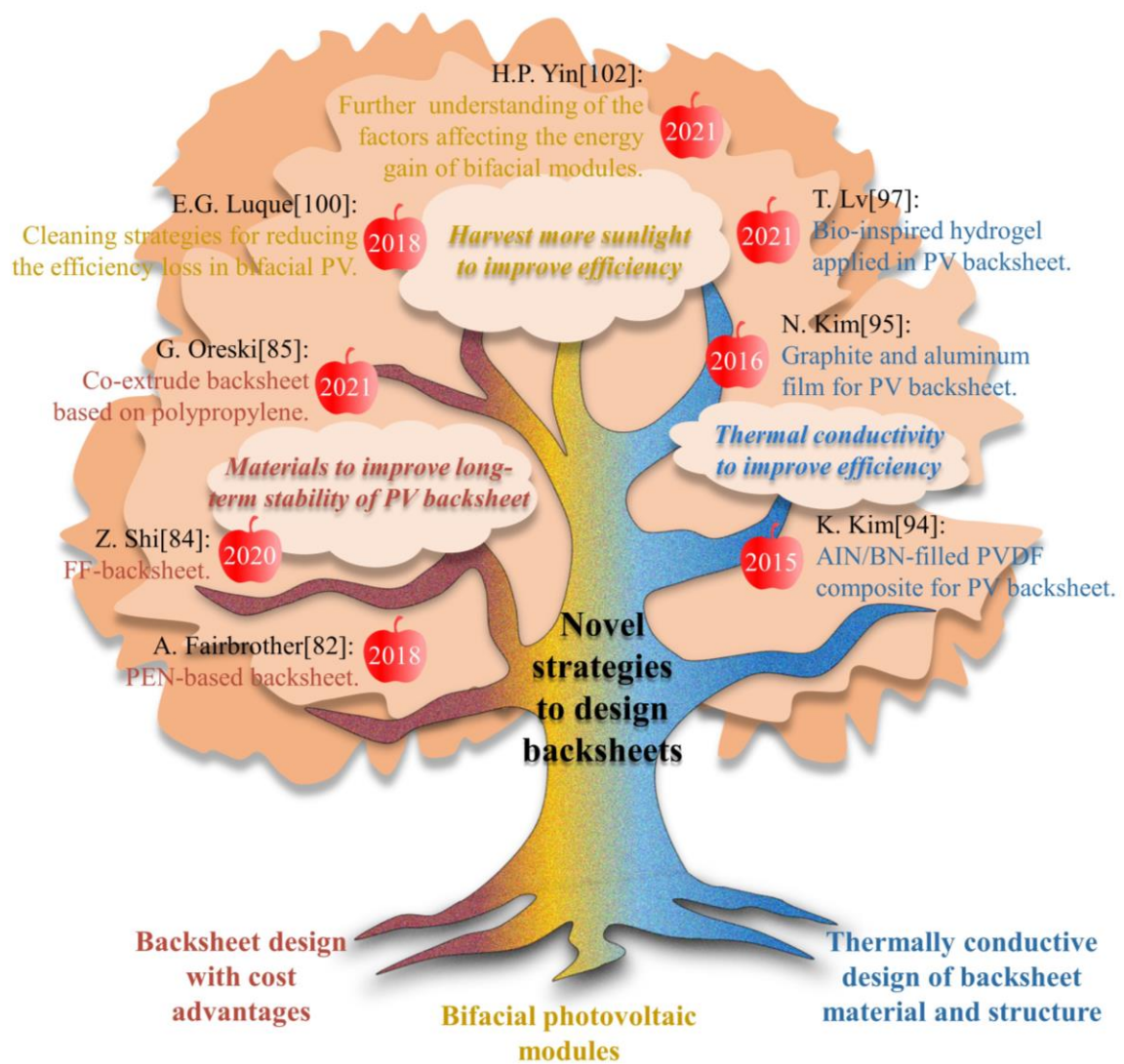


Fig. 8. Flow chart of reviews on novel backsheet structure and materials. [82,84-85,94-95,97,100,102]

5.2 Backsheet design for improving the efficiency of PV power generation

Enhancing the efficiency of solar panels is also a focus of research [86]. For instance, Yuan et al. found that incorporating a ferroelectric polymer layer can improve the efficiency of some organic PV devices, as shown in Fig. 9 [87]. Otherwise, the efficiency contribution from the backsheet has been introduced [88]. Enhancing the thermal conductivity of the backsheet or replacing the backsheet material to increase the amount of light into solar panel can also increase the efficiency of PV power generation.

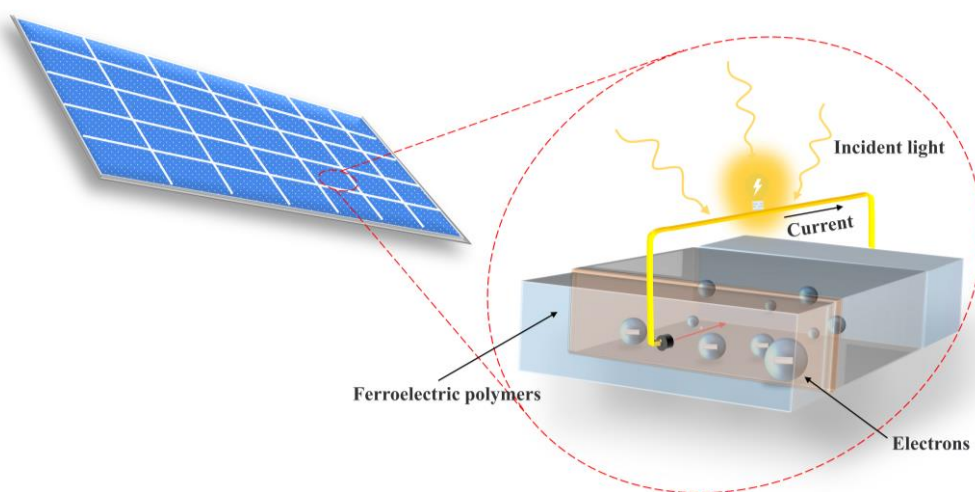


Fig. 9. Structure of polymer PV cell with ferroelectric interfacial layer [87].

Generally, much of the solar radiation entering solar cells will be transformed into heat, resulting in a temperature rise in solar panels, which obstacles working of solar panels in ideal efficiency and causes degradation [89-93]. Therefore, one approach of improving the operation of the solar panel is maintaining the cell at the optimum working temperature. For instance, a single-layer PVDF structure was fabricated using surface-modified AlN and BN as fillers [94]. After testing, the backsheet showed strong thermal conductivity and mechanical properties. Additionally, the excellent hydrophobicity of BN overcame the degradation of materials caused by moisture. Similarly, backsheet laminating graphite with aluminum sheet can also solve the problem of heat dissipation [95]. Notably, researchers

further pointed out that the frame structure of PV module will also affect the path of heat transfer. Likewise, new thermal conductive backsheets (TCBs) can reduce the temperature inside the PV module, and the improved thermal conductivity also helped to enhance the reliability of backsheet and reduce the levelized cost of energy (LCOE) [96]. In addition to adding thermal conductive fillers in the backsheet, an organic-inorganic hydrogel with adhesion and refrigeration functions provides a new idea for solving the heat dissipation problem of PV backsheet. The backsheet combined with the phase change material can achieve adjustable cooling capacity under the condition of moisture [97]. It also has the characteristic of reuse.

Compared with conventional glass/backsheets PV modules, glass/glass modules can utilize both front and back sides of the PV cell for light absorption, which increase power generation efficiency [98,99]. Regarding durability, strict aging conditions are imposed on the double-glazed modules by extending the IEC 61215 standard test. Compared to the conventional structure, the P_{max} attenuation of the bifacial PV module under different stress sources is significantly lower due to the impermeability for water vapor. However, the loss of transmittance of the double-sided module and the loss of efficiency due to contamination of the surface of the double-sided module are issues that need to be addressed [100-102]. Therefore, Luque et al. compared the soiling rate of bifacial module as well as traditional single-sided module, and modified the cleaning optimization model by taking bifaciality into consideration. It was also provided that ignoring cleaning on the rear could be an acceptable strategy on the soiling effect of bifacial PV module. Additionally, the transmission loss can be minimized by coating the rear glass of the double-sided module with an infrared reflective layer combined with a white reflective layer. Yin et al. further discussed how to balance the front and rear side power and pointed out that enhancing the front-side power should be considered first in the design of bifacial modules.

6. Innovations of health monitoring, maintenance and environmental recycling of PV module

In order to comprehensively and effectively investigate and monitor the aging behavior of PV backsheets and make contribution to establishing a zero-carbon energy system, several emerging technologies relating to the health monitoring, fault detection and environmental recycling procedure for the future zero-carbon emission system, for the development of photovoltaic module are proposed as follows [103].

6.1 Health monitoring and maintenance

As the scale of PV cells and PV penetration in the electric power grid increases, the proportion of fluctuating power sources such as PV power generation connected to the electrical grid becomes more and more dominant [104]. Thus, the stability of PV generation associated with the insulation properties of PV backsheets must be enhanced. Also, the leakage current of the insulation backsheets needs to be monitored accurately in real time in order to maintain the security of large scale of solar panel group in the future zero carbon energy system [105]. A comprehensive testing system orienting to the AI monitoring, as shown in Fig. 10, offers a solution for automatic leakage current measurement of the insulating backsheets, which includes optical fiber sensor based on Fabry-Perot (F-P) interference principle and computing in memory (CIM) unit based on resistive random-access memory (RRAM) array. The optical fiber sensor can realize the real-time measurement of leakage current, and the CIM unit can realize the data collection, initial computation and storage. This comprehensive system which could real-time measure the leakage current of PV backsheets allows Edge Computing Systems (ECS) with higher efficiency and lower power consumption compared with the traditional central server with the function of training data and machine learning. By this means, the health condition of the PV station could be recognized by AI algorithm and transmitted to the mobile edge of the technicians to arrange the repairing of the faults or maintenance works in PV station efficiently. Consequently, maintenance

efficiency and stability of PV power plants could be upgraded. Moreover, this novel technique based on CIM technology and AI could decrease the labor cost, power consumption and computation burden of central server for data learning and operation pattern recognition, and provide strong support for the safe operation and maintenance of large-scale PV power station in the future green energy system.

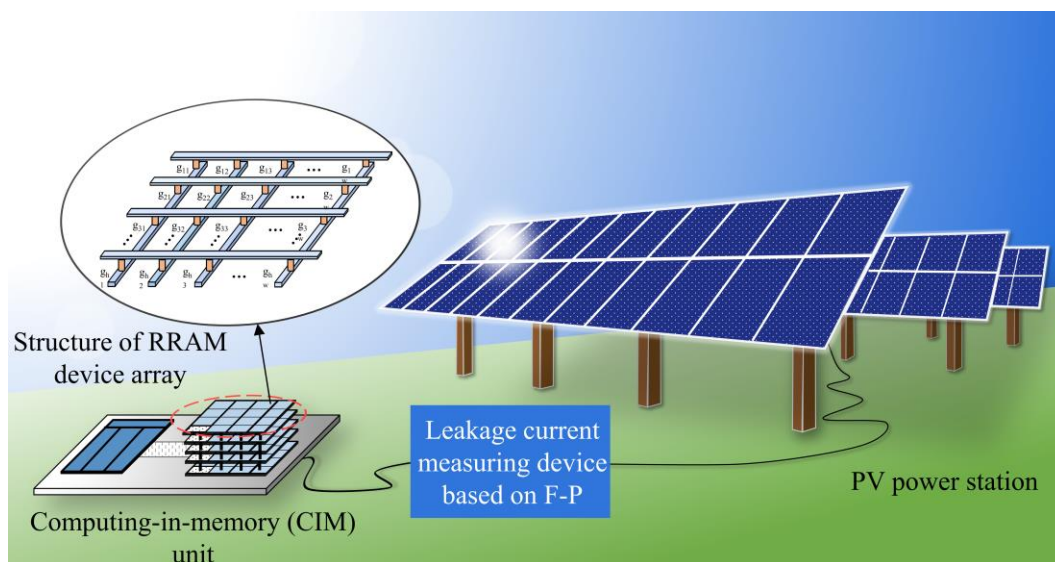


Fig. 10. CIM unit based on RRAM for measuring leakage current of insulation backsheet.

6.2 Novel detection method

THz wave spectroscopy offers a different perspective on the aging of PV backsheets. The combination of different analytical tools can provide different perspectives of information on the aging of PV backsheets and enhance the accurate understanding of the aging state. Due to the instinct merits of detection with ultrahigh sensitivity of moisture and temperature, the application of THz spectroscopy is expected to be extended to analyze the ageing process of encapsulant of PV module. The moisture, salt mist and other contaminants which could accelerate the deterioration of polymeric backsheets and EVA or POE bonding layer in PV module, could be shown in THz spectroscopy.

6.3 Data driven photovoltaic maintenance system (DDPMS)

Synthesizing health monitoring of PV plants and novel detection method for degradation of PV backsheets mentioned in section 6.1 and 6.2, here we propose a Data Driven PV Maintenance system (DDPMS). Combined with the monitoring data from PV plant, the system firstly locates the degraded PV backsheets roughly, then uses the F-CNN, THz spectroscopy, near-infrared transmission spectra and other means to assess the aging degree of the backsheets and can automatically detect the degradation pattern. Finally, the DDPMS confirms whether to repair or replace the backsheets and other operations.

6.4 Environmentally friendly design and recycling strategy

Environmental friendliness is an advantage of solar PV over traditional energy, and it should be raised to a higher level in the future [106]. At a more advanced level, more attention should be paid to developing the potential of PV system for carbon emission reduction in the aspects of efficiency, repair and recycling. Firstly, the efficiency of power generation needs to be further improved. Secondly, in terms of maintenance, replacing a large number of cracked backsheets is neither economic nor environmentally friendly [107,108]. Therefore, repair solutions for damaged backsheets need further investigation. As well, further explorations of the reliability of the restoration material. At present, many backsheets using fluoropolymers to enhance weather resistance need to be recycled after they are scrapped. However, the end-of-life (EoL) processing of PV waste will produce harmful substances and pose risks to human health and the environment [109,110]. Thus, on the recycling side, it is recommended that PET-based or co-extruded polyolefin-backsheets can avert environmental concerns more effectively than backsheets using fluoropolymers. Moreover, developing easy-to-recycle backsheets which can alleviate the pollution from microplastics to the marine system more effectively than backsheets using fluoropolymers and other insulating polymeric backsheets. Fig. 11 is a schematic diagram of the green and sustainable cycle for the backsheets materials. It can be anticipated that the

exploitation of backsheet materials will also be evaluated in terms of the efficiency of the PV cells as well as the maintenance and recycling of the backsheet materials.

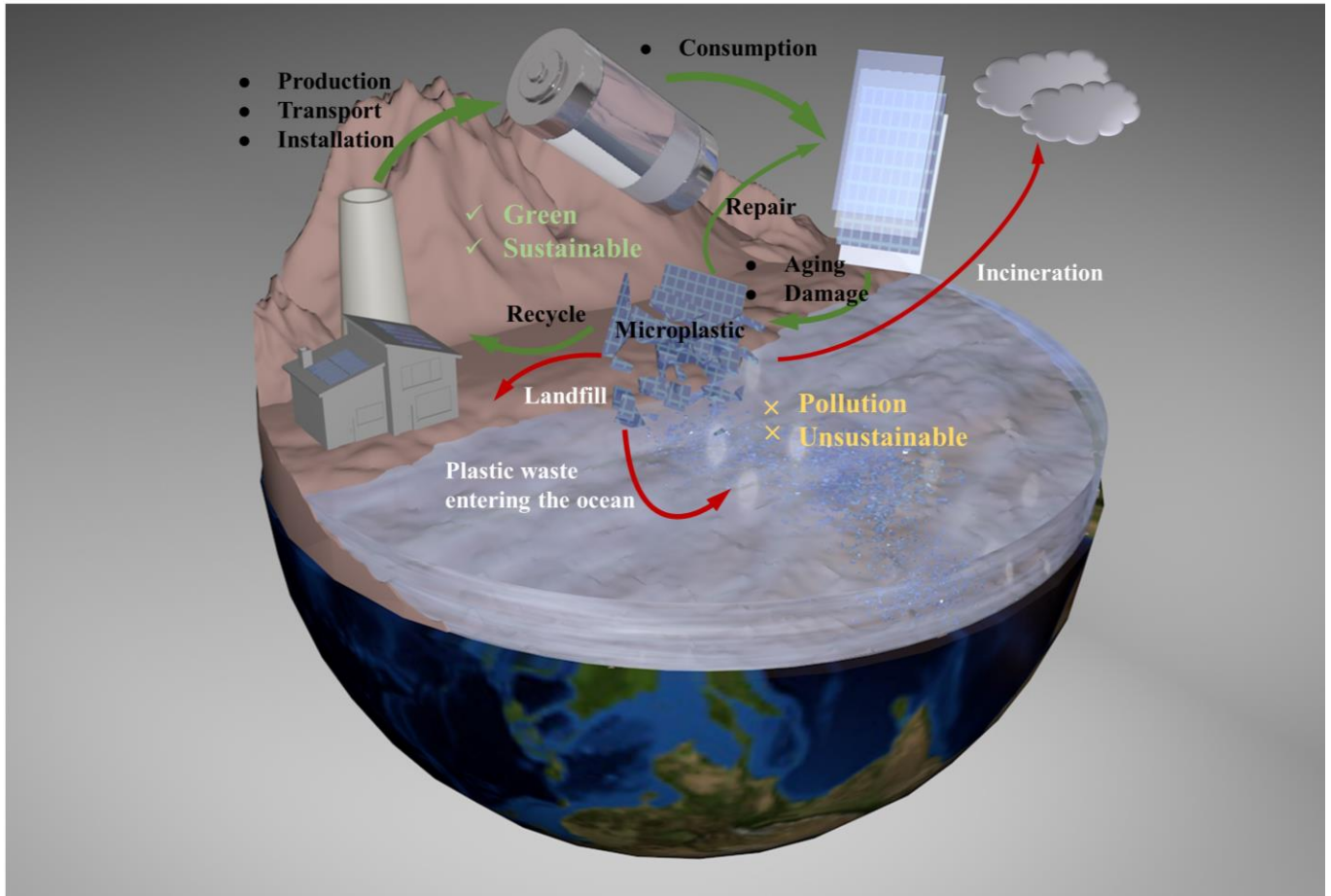


Fig. 11. Green and sustainable recycling solutions for backsheet materials.

6.5 Improvement and optimization of the testing standards

As discussed previously, the actual aging environment may have more complex aging mechanisms, and these mechanisms may be interrelated. Although some test standards such as IEC 61215 have been proposed and are constantly revised, they are not enough to reliably predict the long-term performance of PV backsheet. These standards are mainly proposed for PV modules, which may cause inconvenience to study the aging of backsheet alone. With the development of new backsheet materials and the needs of human exploration of space, it is worth considering whether new test

standards are needed to predict and study the reliability and degradation mechanisms of these newly developed backsheet materials, as well as those already used in aerospace. The relationship between environmental stress is also worthy of deeper understanding. This factor has not been taken into account in the test standards of the PV industry. Improving the test standard and associating the indoor aging accelerated test with the actual outdoor working effect of different backsheet materials is a future direction for PV industry.

7. Summary and suggestion for future work

A comprehensive review on common materials, detection methods of insulation deterioration, correlated ambient aging factors, and novel material developments of PV backsheet has been presented in this paper. It highlights UV radiation, temperature, moisture, salt-mist stress and mechanical stress that affect the durability and reliability of PV backsheet. Likewise, emerging novel materials and structures for enhancing insulation properties, anti-aging performance and optical-electrical energy conversion efficiency of PV cell are also emphasized. Emerging research fields and improvement pathway of photovoltaic modules for zero-carbon solar energy system could be summarized as followings:

(1) Develop PV backsheet standards for different environments and test the reliability of new backsheet materials to enhance PV cell durability. Designing new PV cell structures and collecting novel backsheet materials to improve the efficiency of PV modules.

(2) From the viewpoints of the recycling and environmentally friendly consideration in the disposal of waste material from the PV modules, it is recommended the bio-based backsheets which can alleviate the pollution from microplastics to the marine system more effectively than backsheets using fluoropolymers and other insulating polymeric backsheets.

(3) Utilize DDPMS, an artificial intelligence system, to improve aging assessment accuracy and increase overhaul efficiency.

(4) Use computing in memory (CIM) unit based on RRAM array to measure leakage current of backsheets, which can improve maintenance efficiency and save costs.

(5) Terahertz wave spectroscopy for non-destructive inspection of PV backsheets

(6) More emphasis on environmental protection in the production, transportation, maintenance and recycling of PV backsheets.

Data availability statement

The raw data can be shared on the requirement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this work.

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References

- [1] K.R. Abbasi, M. Shahbaz, J.J. Zhang, M. Irfan, R. Alvarado, *Renew. Energy* 187 (2022) 390-402.
- [2] B.M. Opeyemi, *Energy* 228 (2021) 120519.
- [3] G. Nicoletti, N. Arcuri, G. Nicoletti, R. Bruno, *Energy Conv. Manag.* 89 (2015) 205-213.
- [4] F.P. Perera, *Environ. Health Perspect.* 125 (2017), 141-148.
- [5] L.F.O. Silva, M. Santosh, M. Schindler, J. Gasparotto, G.L. Dotto, M.L.S. Oliveira, M.F. Hochella Jr, *Gondwana Res.* 92 (2021) 184-201.
- [6] B.X. Liu, J.R. Lund, S.L. Liao, X.Y. Jin, L.J. Liu, C.T. Cheng, *Energy Conv. Manag.* 209 (2020) 112628.
- [7] D. Schindler, H.D. Behr, C. Jung, *Energy Conv. Manag.* 218 (2020) 113016.
- [8] H. Akbari, M.C. Browne, A. Ortega, M.J. Huang, N.J. Hewitt, B. Norton, S.J. McCormack, *Sol. Energy* 192 (2019) 144-168.
- [9] X.X. Liu, T.Y. Ji., H. Guo, H. Wang, J.Q. Li, H. Liu, Z.X. Shen, *Electrochem. Energy Rev.* 5 (2022) 401-433.
- [10] C. Breyer, D. Bogdanov, A. Gulagi, A. Aghahosseini, L.S.N.S. Barbosa, O. Koskinen, M. Barasa, U. Caldera, S. Afanasyeva, M. Child, J. Farfan, P. Vainikka, *Prog. Photovoltaics* 25 (2017) 727-745.
- [11] C.C. Boyd, R. Cheacharoen, T. Leijtens, M.D. McGehee, *Chem. Rev.* 119 (2019) 3418-3451.
- [12] M. A. Green, *Nat. Rev. Phys.* 2 (2020) 172-173.
- [13] S. Fawzy, A.I. Osman, J. Doran, D.W. Rooney, *Environ. Chem. Lett.* 18 (2020) 2069-2094.
- [14] H.P. Le, S.A. Sarkodie, *Energy Rep.* 6 (2020) 965-973.
- [15] X. Zhou, Y. Li, C. Fang, S. Li, Y. Cheng, W. Lei, X. Meng, *J. Mater. Sci. Technol.* 31 (2015) 708-722.

- [16] C. Buerhop, O. Stroyuk, J. Zöcklein, T. Pickel, J. Hauch, I.M. Peters, *Prog. Photovoltaics* 30 (2022) 938-947.
- [17] A. Ndiaye, A. Charki, A. Kobi, C.M.K. Kebe, P.A. Ndiaye, V. Sambou, *Sol. Energy* 96 (2013) 140-151.
- [18] A. Omazic, G. Oreski, M. Edler, G.C. Eder, C. Hirschl, G. Pinter, M. Erceg, *J. Appl. Polym. Sci.* 137 (2020) 48899.
- [19] K.J. Geretschläger, G.M. Wallner, J. Fischer, *Sol. Energy Mater. Sol. Cells* 144 (2016) 451-456.
- [20] J.W. Zhang, D.K. Cao, X.Q. Yin, C. Putson, P. Xiao, Q. Wang, *Acs Appl. Energ. Mater.* 3 (2020) 8946-8952.
- [21] O. Stroyuk, C.B. Lutz, J. Hauch, I. M. Peters, *Prog. Photovoltaics* 30 (2021) 851-858.
- [22] C.C. Lin, P.J. Krommenhoek, S.S. Watson, X.H. Gu, *Sol. Energy Mater. Sol. Cells* 144 (2016) 289-299.
- [23] M. Aghaei, A. Fairbrother, A. Gok, S. Ahmad, S. Kazim, K. Lobato, G. Oreski, A. Reinders, J. Schmitz, M. Theelen, P. Yilmaz, J. Kettle, *Renew. Sust. Energ. Rev.* 159 (2022) 112160.
- [24] C.C. Lin, Y. Lyu, D.S. Jacobs, J.H. Kim, K.T. Wan, D.L. Hunston, X.H. Gu, *Prog. Photovoltaics* 27 (2019) 44-54.
- [25] G. Oreski, G. Pinter, *Materials* 15 (2022) 3294.
- [26] M. Kumar, H.M. Niyaz, R. Gupta, *Sol. Energy Mater. Sol. Cells* 233 (2021) 111408.
- [27] K. Moustafa, *Trends Biotechnol.* 34 (2016) 257-259.
- [28] G.J.M. Fechine, M.S. Rabello, R.M. Souto Maior, *Polym. Degrad. Stabil.* 75 (2002) 153-159.
- [29] G. Oreski, G.M. Wallner, *Sol. Energy* 79 (2005) 612-617.
- [30] Y. Voronko, G.C. Eder, M. Knausz, G. Oreski, T. Koch, K.A. Berger, *Prog. Photovoltaics*, 23 (2015) 1501-1515.

- [31] X. Zhou, C. Fang, J. Chen, S. Li, Y. Li, W. Lei, *J. Mater. Sci. Technol.* 32 (2016) 687-694.
- [32] Y. Lyu, J.H. Kim, A. Fairbroyher, X.H. Gu, *IEEE J. Photovolt.* 8 (2018) 1748-1753.
- [33] J.W. Zhang, T.H. Li, W. Zhang, *Surf. Rev. Lett.* 27 (2020) 1950230.
- [34] M.D. Kempe, Y. Lyu, J.H. Kim, T. Felder, X.H. Gu, *Sol. Energy Mater. Sol. Cells* 226 (2021) 111044.
- [35] P.Y. Yuen, S.L. Moffitt, F.D. Novoa, L.T. Schelhas, R.H. Dauskardt, *Prog. Photovoltaics* 27 (2019) 693-705.
- [36] D.C. Miller, M. Owen-Bellini, P.L. Hacke, *Sol. Energy Mater. Sol. Cells* 201 (2019) 110082.
- [37] J.W. Zhang, F. Xu, X.J. Chen, C. Putson, S. Diahm, Q. Wang, *ACS Appl. Energy Mater.* 5 (2022) 5551-5560.
- [38] O. Stroyuk, C.B. Lutz, A. Vetter, J. Hepp, J. Hauch, I.M. Peters, C.J. Brabec, *Prog. Photovoltaics* 30 (2022) 859-868.
- [39] H. Li, R. Kikuchi, M. Kumagai, T. Amano, H.N. Tang, J.M. Lin, K. Fujiwara, N. Ogawa, *Sol. Energy Mater. Sol. Cells* 101 (2012) 166-169.
- [40] J. Tracy, N. Bosco, F. Novoa, R. Dauskardt, *Prog. Photovoltaics* 25 (2017) 87-96.
- [41] F. D. Novoa, D. C. Miller, R. H. Dauskardt, *Sol. Energy Mater. Sol. Cells*, 120 (2014) 87-93.
- [42] N. Kim, H. Kang, K.J. Hwang, C. Han, W.S. Hong, D. Kim, E. Lyu, H. Kim, *Sol. Energy Mater. Sol. Cells* 120 (2014) 543-548.
- [43] S.E. Julien, J.H. Kim, Y. Lyu, D. C. Miller, X.H. Gu, K. Wan, *Sol. Energy* 224 (2021) 637-649.
- [44] B.B. Zhang, J. Grant, L.S. Bruckman, *Sci Rep* 9 (2019) 16119.
- [45] M. Kutas, B. Haase, J. Klier, D. Molter, G.V. Freymann, *Optica* 8 (2020) 438-441.
- [46] I. Duling, D. Zimdars, *Nat. Photonics* 3 (2009) 630-632.
- [47] C. Wang, R. Y. Zhou, Y. X. Huang, L.J. Xie, Y. B. Ying, *Food Control* 97 (2019) 100-104.

- [48] H.J. Shin, S.W. Choi, G. Ok, *Food Chem.* 245 (2018) 282-288.
- [49] A. Keshavarz, Z. Vafapour, *IEEE Sens. J.* 19 (2019) 1519-1524.
- [50] J.A. Spies, J. Neu, U.T. Tayvah, M.D. Capobianco, B. Pattengale, S. Ostresh, C.A. Schmuttenmaer, *J. Phys. Chem. C* 124 (2020) 22335-22346.
- [51] R. Bao, Z.K. Wu, F. Wang, X.Y. Miao, C.J. Feng, *Anal. Sci.* 33 (2017) 95-98.
- [52] X.X. Zhang, Q.J. Guo, T.Y. Chang, H.L. Cui, *Polym. Test* 76 (2019) 455-463.
- [53] H.W. Mei, L.X. Li, F.H. Yin, W. Hu, J.B. Liu, L.M. Wang, *IEEE Access*, 8 (2020) 226887-226896.
- [54] M. Bechberger, D. Reiche, *Energy Sustain Dev.* 8 (2004) 47-57.
- [55] R. Fahem, E. Yousif, *J. Thin Films Res.* 1 (2017) 17-23.
- [56] G.J. Clydesdale, G.W. Dandle, H.K. Muller, *Immunol. Cell Biol.* 79 (2001) 547-568.
- [57] F. Liu, L. Jiang, S.Y. Yang, *Sol. Energy*, 108 (2014) 88-100.
- [58] X. Zhou, J. Su, C. Wang, C. Fang, X. He, W. Lei, C. Zhang, Z. Huang, *J. Mater. Sci. Technol.* 46 (2020) 74-87.
- [59] F.J. Horne, J.J. Liggat, W.A. Macdonald, S.W. Sankey, *J. Appl. Polym. Sci.* 137 (2020) 48263.
- [60] G.J.M. Fechine, M.S. Rabello, R.M. Souto Maior, L.H. Catalani, *Polymer*, 45 (2004) 2303-2308.
- [61] P. Esena, C. Riccardi, S. Zanini, M. Tontini, G. Poletti, F. Orsini, *Surf. Coat. Technol.* 200 (2005) 664-667.
- [62] X. Zhou, J. Deng, C. Fang, R. Yu, W. Lei, Y. Song, Z. Zhang, Z. Huang, Y. Li, *J. Mater. Sci. Technol.* 60 (2020) 27-34.
- [63] Y. Lv, D.Q. Fan, M.Q. Kong, *Sol. Energy Mater. Sol. Cells* 230 (2021) 111230.
- [64] Q. Liang, S.E. Strahan, E.L. Fleming, *Science* 358 (2017) 1257-1258.
- [65] S.A. Lloyd, *Lancet* 342 (1993) 1156-1158.

- [66] N.Kim, S. Lee, X.G. Zhao, D. Kim, C. Oh, H.J. Kang, *Sol. Energy Mater. Sol. Cells* 146 (2016) 91-98.
- [67] H. Zhuang, G. Huang, Y. Jiang, G. Sun, X.L. Bai, J.G. Li, Xiamen, China, International Conference on New Energy, Power and Environmental Engineering 696 (2021) 012014.
- [68] B. Ottersböck, G. Oreski, G. Pinter, *J. Appl. Polym. Sci.* 133 (2016) 44230.
- [69] S. Suzuki, N. Nishiyama, S. Yoshino, T. Ujiro, S. Watanabe, T. Doi, A. Masuda, T. Tanahashi, *Jap. J. Appl. Phys.* 54 (2015) 08KG08.
- [70] G. Illya, V. Handara, M. Siahandan, A. Nathania, A.S. Budiman, *Procedia Engineering* 215 (2017) 238-245.
- [71] J.W. Zhang, D.K. Cao, S. Diahm, X. Zhang, X.Q. Yin, Q. Wang, *Sol. Energy* 188 (2019) 475-482.
- [72] J.W. Zhang, D.K. Cao, Y.C. Cui, C. Putson, C. Song, P. Huang, *J. Clean Prod.* 189 (2018) 169-175.
- [73] Q. Wang, C.J. Ji, L. Huang, J.W. Zhang, R. Shi, *Int. J. Mod. Phys. B* 33 (2019) 1950209.
- [74] K. Tian, D. Hu, Q. Wei, Q. Fu, H. Deng, *J. Mater. Sci. Technol.* 134 (2023) 106-131.
- [75] W. Chen, X. Yan, *J. Mater. Sci. Technol.* 43 (2020) 175-188
- [76] T. Rong, J.J. Liggat, W.H. Siew. *Polym. Degrad. Stabili.* 150 (2018) 148-157.
- [77] H.L. Han, J. Xia, H.J. Hu, R.S. Liu, J.F. Liu, K.R. Choudhury, W.J. Gambogi, T. Felder, M. Rodriguez, E. Simon, Z.W. Zhang, H. Shen, *Sol. Energy Mater. Sol. Cells* 225 (2021) 111023.
- [78] M. Owen-Bellini, P. Hacke, D.C. Miller, M.D. Kempe, S. Spataru, T. Tanahashi, S. Mitterhofer, M. Jankovec, M. Topič, *Prog. Photovoltaics* 29 (2020) 64-82.
- [79] M. Owen-Bellini, S.L. Moffitt, A. Sinha, A.M. Maes, J.J. Meert, T. Karin, C. Takacs, D.R. Jenket, J.Y. Hartley, D.C. Miller, P. Hacke, L.T. Schelhas, *Sci Rep.* 11 (2021) 1-7.

- [80] Y. Lyu, A. Fairbrother, M. Gong, J. H. Kim, X.H. Gu, M. Kempe, S. Julien, K.T. Wan, S. Napoli, A. Hauser, G. O'Brien, Y. Wang, R. French, L. Bruckman, L. Ji, K. Boyce, *Sol. Energy* 199 (2020) 425-436.
- [81] G.C. Eder, Y. Voronko, G. Oreski, W. Mühleisen, M. Knausz, A. Omazic, A. Rainer, C. Hirschl, H. Sonnleitner, *Sol. Energy Mater. Sol. Cells* 203 (2019) 110194.
- [82] A. Fairbrother, M. Boyd, Y. Lyu, J. Avenet, P. Illich, Y. Wang, M. Kempe, B. Dougherty, L. Bruckman, X.H. Gu, *Sol. Energy* 163 (2018) 62-69.
- [83] M.H. Alaaeddin, S.M. Sapuan, M. Zuhri, E.S. Zainudin, F.M. AL-Oqla, *Materials* 12 (2019) 3007.
- [84] Z. Shi, T. Ito, *Sustain. Energy Technol. Assess.* 42 (2020) 100885.
- [85] G. Oreski, G.C. Eder, Y. Voronko, A. Omazic, L. Neumaier, W. Mühleisen, G. Ujvari, R. Ebner, M. Edlere, *Sol. Energy Mater. Sol. Cells* 223 (2021) 110976.
- [86] A. Polman, M. Knight, E.C. Garnett, B. Ehrler, W.C. Sinke, *Science* 352 (2016).
- [87] Y. Yuan, T.J. Reece, P. Sharma, S. Poddar, S. Ducharme, A. Gruverman, Y. Yang, J.S. Huang *Nat. Mater.* 10 (2011) 296-302.
- [88] M. Köntges, H.S. Huxel, S. Blankemeyer, M.R. Vogt, H. Holst, R.R. Koch, *Sol. Energy Mater. Sol. Cells* 186 (2018) 175-183.
- [89] A.W. Kandeal, A.K. Thakur, M.R. Elkadeem, M. F. Elmorshedy, Z. Ullah, R. Sathyamurthy, S.W. Sharshir, *Clean Prod.* 273 (2020) 122772.
- [90] A. Shukla, K. Kant, A. Sharma, P.H. Biwole, *Sol. Energy Mater. Sol. Cells* 160 (2017) 275-286.
- [91] R. Hossain, A.J. Ahmed, S.M.K.N. Isiam, N. Saha, P. Debnath, A.Z. Kouzani, M.A.P. Mahmud, *Int. J. Photoenergy* 2020 (2020) 1-6.
- [92] C. Wani, K.K. Gupta, *IOP Conference Series: Earth and Environmental Science* 227 (2019) 022009.

- [93] G. Makrides, M. Theristis, J. Bratcher, J. Pratt, G.E. Georghiou, *Sol. Energy* 171 (2018) 491-499.
- [94] K. Kim, M. Yoo, K. Ahn, J. Kim, *Ceram. Int.* 41 (2015) 179-187.
- [95] N. Kim, D. Kim, H. Kang, H.J. Kang, Y.G. Park, *Energy* 113 (2016) 515-520.
- [96] A. Pavgi, J. Oh, G.S. Tamizhmani, *Energies* 14 (2021) 1252.
- [97] T. Lv, L.D. Sun, Y.H. Yang, J.P. Huang, *Sol. Energy* 216 (2021) 358-364.
- [98] A. Hasan, I. Dincer, *Energy Conv. and Manag.* 220 (2020) 112972.
- [99] Y.B. Zhang, J.M. Xu, J. Mao, J.H. Tao, H. Shen, Y.F. Chen, Z.Q. Feng, P.J. Verlinden, P.X. Yang, J.H. Chu, *Rsc Advances* 5 (2015) 65768-65774.
- [100] E.G. Luque, F.R.A. Antonanzas-Torres, R. Escobar, *Energy Conv. and Manag.* 174 (2018) 615-625.
- [101] M.H. Saw, Y.S. Khoo, J.P. Singh, Y. Wang, *Energy Procedia* 124 (2017) 484-494.
- [102] H.P. Yin, Y.F. Zhou, S.L. Sun, W.S. Tang, W. Shan, X.M. Huang, X.D. Shen, *Sol. Energy* 217 (2021) 245-252.
- [103] D.F. Dominković, I. Bačeković, B. Čosić, G. Krajačić, T. Pukšec, N. Duić, N. Markovska, *Appl. Energy* 184 (2016) 1517-1528.
- [104] J. Yang, C. Zuo, Y. Peng, Y. Yang, X.D. Yang, L.M. Ding, *Sci. Bull.* 65 (2020) 872-875.
- [105] W. Luo, Y.S. Khoo, P. Hacke, V. Naumann, D. Lausch, S.P. Harvey, J.P. Singh, J. Chai, Y. Wang, A.G. Aberle, S. Ramakrishna, *Energy Environ. Sci.* 10 (2017) 43-68.
- [106] R.W. Miles, K.M. Hynes, I. Forbes, *Prog. Cryst. Growth Charact. Mater.* 51 (2005) 1-42.
- [107] Y. Voronko, G.C. Eder, C. Breitwieser, W. Mühleisen, L. Neumaier, S.J. Feldbacher, G. Oreski, N. Lenck, *Energy Sci. Eng.* 9 (2021) 1583-1595.
- [108] G. Beaucarne, G. Eder, E. Jadot, Y. Voronko, W. Mühleisen, *Prog. Photovoltaics* 30 (2022) 1045-1053.

[109] P. Danz, V. Aryan, E. Mhle, *Toxics* 7 (2019) 47.

[110] V. Aryan, M. Font-Brucart, *Prog. Photovoltaics* 26 (2018) 443-459.