Thèse n° 8789

EPFL

Evaluation of the Effect of Backsheet Properties on PV Encapsulant Degradation under Ultraviolet-Damp-Heat Conditions

Présentée le 1^{er} novembre 2021

Faculté de l'environnement naturel, architectural et construit Laboratoire d'énergie solaire et physique du bâtiment Programme doctoral en énergie

pour l'obtention du grade de Docteur ès Sciences

par

Djamel Eddine MANSOUR

Acceptée sur proposition du jury

Prof. S. Haussener, présidente du jury Prof. J.-L. Scartezzini, Dr A. Schueler, directeurs de thèse Dr P. Gebhardt, rapporteur Dr G. Oreski, rapporteur Dr Y. Leterrier, rapporteur

 École polytechnique fédérale de Lausanne

2021

Wings are a constraint that makes it possible to fly. — Robert Bringhurst

To my parents...

Acknowledgements

First of all, I have been lucky to have **Dr Paul Gebhardt** as my supervisor and **Dr Luciana Pitta Bauermann** as my former supervisor of my PhD. Your guidance is the key to the success of this thesis. I owe deep gratitude to the help, support and countless valuable conversations received from you. Big thanks to **Paul** for the detailed proofreading of this work. Special thanks also go to **Esther Fokuhl**, **Georg Mülhöfer** and **Sandor Stecklum** for the valuable technical and non-technical daily support all along the journey, it's been great pleasure to share the office with you, thank you for sharing so many good memories with mine. They have made my life in Freiburg unforgettably wonderful! I would also like to thank **Daniel Philipp**, for having accepted me into his group and to the projects and offered great opportunities to the research field throughout my last 4 years.

I sincerely thank **Dr Andreas Schüler** and **Prof. Jean Louis Scartezzini** for having offered me the precious opportunity to perform my PhD thesis in the LESO-PB Lab. Your passion, commitment and brilliant helicopter view on the research field have inspired me tremendously in the last 4 years!

I am grateful to all the members of Module Characterization Reliability (MCR) group, for having maintained such stimulating and collaborative environment. Especially, **Jeanette Wolf**, **Patrik Hesse** and **Milena Schiller Nino** are thanked for the excellent logistic and administrative support and **Michael Hohl** for assisting in the problem of lack of data storage capacity that came up during this work!

I would also like to thank **Dr Gernot Oreski** for the technical contribution, proofreading of this work and positive feedback within the last 4 years. I also thank my other jury members, **Dr Yves Leterrier**, **Prof. Tagliabue Giulia** and **Prof. Haussener Sophia** for giving me the honor to have you on my thesis committee!

This work was completed with the continuous financial and technical support from the Solar-Train project and followed by Gepard project. I would like to thank the colleagues in the Solar-Train for their close collaboration, especially **Chiara Barretta**, **Luis Castillon**, **Stefan Mitterhofer**, **Ismail Kaaya**, **Julian Ascencio-Vasquez**, **Aziz Nairi**, and thank you to all **ESRs** for the great memories during the travelling in Europe. Big thanks to **Dr Karl-Anders Weiß**, **Enikö Bedö** and all the **supervisors** for the valuable management of the project!

These 4 years would not have been such a smooth journey without all the assistance from the former and present members of MCR and PV module Technology (PVM) groups. Big thanks go to **Christoph Herzog**, **Martin Wiese**, **Felix Basler**, **Dr Martin Heinrich**, **Dr Max Mittag** and **Dr Torsten Rößler** for the valuable technical contribution, assistance and collaboration. Spetial thanks also go to the **IBBB** PhD members for providing technical support and experience, especially in helping me to improve the presentation skills. I also would like to thank **Laila Veríssimo Mesquita**, **Sandra Kotterer** and **Aksel Kaan Öz** for their wonderful master thesis work. It contributed nicely to the completion of my PhD thesis!

During my industrial stay as my first secondment in Anton Paar GmbH Stuttgart, I received support from **Fabian Swientek** and **Paul Pavlov**. Thank you very much for your great and nice welcome!

During my academic stay as my second secondment at PCCL Leoben, Austria, I received lots of help from colleagues. I want to take this opportunity to sincerely thank **Dr Gernot Oreski**, **Petra Christöfl**, **Chiara Barretta** and **Luis Castillon** for the great experience inside and outside PCCL!

I am very grateful to **Dr Marko Janković** and **Stefan Mitterhofer** from Ljubljana University for the great collaboration and more precisely for providing the laminates incorporated with the digital humidity sensors and performing the aging for the kinetic study in this thesis.

My life would not be full of fun without all my friends around: **Khalid Lahmidi**, **Jose-Alfredo Madrazo**, **Manon Trüper**, **Samia Timtaoucine**, **Sanzidur Rahman**, **Harsono Harsono**, **Amir Shariffudin**, **Ahmed Ridoy**, **Stefan Chantrel**, **Luca Koldeweyh**, **Frieda Anders**, **May Bohmann**, **Maike Vennemann**, **Elisa Bemmerl**, **Malte Jursch**, **Eyüb Ertan**, **Paule Grasy** and many friends in Freiburg. Thank you all! Wish your life full of happiness!

Special thanks to my group in Freiburg, my friends **Ismail Kaaya**, **Sophie Marchand** and **Leonhard Probst** for all the great moment and travels in the last 4 years!

In the process of the thesis work, I also received great support from my friends outside Germany and Switzerland. Sincere thanks go to **Hyejeong Yoo** for the language quality control of this thesis and providing moral support way before and during this journey. Wish you big success and happiness!

At last, I want to express my love to all my family. Specially, **Mum**, **Dad**, **Sisters** and **Brothers**, thank you all for your enormous support and sacrifice in my life, allowing me to join this awesome adventure! **Khaoula Messaoudi**, thank you for entering my life on the perfect time and thank you for your support to keep fighting. I love you all, my family!

Freiburg, 2021

Djamel Eddine Mansour

Abstract

The reliability of photovoltaic (PV) modules is highly determined by the durability of the polymeric components (backsheet and encapsulant). The power degradation and failure of PV modules can be caused by changes in the physical, chemical, and mechanical properties of these polymeric components during the module lifetime. In this thesis, different experimental techniques to investigate changes in PV modules polymeric components were deployed. Apart from the known techniques available in the literature, new methods (e.g. Nanoindentation and Scanning Acoustic Microscopy (SAM)) were also applied and benchmarked with already established methods. PV encapsulation processes were also investigated with the aim to optimize the lamination conditions that can help to improve the reliability of PV modules.

In the first part of the thesis, to investigate the mechanical properties of the polymers, the instrumented nanoindentation method was introduced in this research. Two types of time-dependent indentation cycle modes, the time domain (creep mode) and frequency domain (dynamic mode), were performed to determine the viscoelastic behavior. For each mode, a corresponding model was applied to calculate the main mechanical properties. The general capability of nanoindentation as crosslinking behavior determination with the methodolog-ical advantages over bulk methods were investigated. To this end, a large number of glass/ Poly(ethylene-co-vinyl acetate) (EVA)/backsheet laminates were built using different lamination conditions resulting in different degrees of curing. The dynamic mechanical analysis (DMA) characterization was used as an established method to validate the indentation measurements. Both nanoindentation and DMA tensile mode produce similar quantitative viscoelastic responses, in the form of the damping factor parameter, using three different frequencies at room temperature. A statistical study of the data revealed the advantages for the investigation of multilayer PV laminates by using nanoindentation as a surface method while also being applicable to field aged modules.

Secondly, we demonstrated the use of the SAM as a non-destructive method to estimate the mechanical properties of backsheets and encapsulants inside the PV modules. The acoustic speed inside each individual material was measured and its mechanical properties calculated.

More precisely, the longitudinal modulus was determined acoustically at 30 MHz to obtain more information about aging-induced material changes and degradation. The PV module failure modes associated with backsheet degradation have a high relevance in the operation and maintenance of power plants. Therefore, field-exposed modules were analyzed by SAM to visualize and localize backsheet failure modes in specific layers non-destructively. Acoustic micrographs were collected from different material depths of the backsheet, which allowed the assessment of depth profiles of the embedded PV module components individually. Multiple types of interlayer cracks were identified. These local defects of the backsheet were confirmed by microscopy images of destructively acquired backsheet cross-section samples.

Thirdly, PV modules degradation was strongly influenced by moisture ingress. Previously, most of the investigations of the diffusion properties of encapsulants and backsheets have been carried out on the polymer sheets alone, thereby not accounting for diffusion properties of all involved materials. A part of the thesis was related to kinetic study of the water uptake of the EVA inside the laminate stack. This was performed using incorporated miniature digital humidity sensors at different EVA depths. Samples with different polymeric materials and lamination conditions were aged under damp-heat (DH) conditions while monitoring the humidity inside the laminates. From this data, the respective diffusion rates were calculated to determine how the different materials and lamination conditions affect the mechanism of moisture ingress/egress during the aging tests. The results demonstrated a faster diffusion in the fluoro-polymer based laminated PET backsheet type. With respect to the lamination process, the effective activation energy, calculated assuming an Arrhenius-like behavior showed slower moisture ingress for the shortly laminated sample.

To demonstrate the effects of backsheet permeation properties on encapsulant degradation, one type of EVA was aged in glass/EVA/backsheet laminates in accelerated aging tests (up to 4000 h for Damp-Heat (DH) and up to 480 kWh/m² for Ultraviolet (UV) and UV-DH combined). Firstly, by using samples with different backsheets, the effects of different material combinations on the EVA degradation mechanisms (chemical changes) were investigated. Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) studies identified two different EVA degradation processes. A thermal oxidation was taking place in the glass-EVA-Polyamide (PA)-based backsheet configuration after 500 h DH tests. However other EVA degradation products were observed in the glass-EVA-PET-based backsheet after 1500 h DH tests. Secondly, it has been perceived that a different material combination leads to different EVA degradation rates, by analyzing the EVA thermal and mechanical changes using Differential Scanning Calorimetry (DSC) and Nanoindentation respectively. As a consequence of these findings, the changes in the melting enthalpy and the viscoelastic properties at the EVA surface was more pronounced when PA-based backsheet was used then when PET-based backsheet was used under combined UV-DH aging tests. The comparison of three accelerated aging stress factors revealed that EVA suffers the strongest chemical and optical degradation when high UV, high temperature and high relative humidity are combined simultaneously.

Acknowledgements

Additionally, in current PV module technology research, there exists a missing link between the PV material degradation and the PV performance degradation after accelerated lifetime tests. Therefore, in this research, a contribution towards this missing link was added by investigating the correlation of material degradation to power degradation. To do this, several PV modules were built and subjected to artificial aging tests. The influence of different micro-climates was investigated and changes in material properties were related to the PV performance degradation. Furthermore, a good correlation between the changes in PV performance parameters and PV module optical evolution of the modules with different material combinations was reached.

Moreover, the power output and the series resistance degradation of the PV module was much more severe and stronger under this combined UV-DH aging test than the addition of both factors individually. Based on the experimental measurements, it was shown that moisture has a significant impact on degradation mechanisms driven by combination of UV, relative humidity, and temperature stresses. Under these combined aging conditions, several degradation modes were observed under the visual inspection of the PV modules, including corrosion of the solar cells, backsheet cracking and EVA discoloration. However, the same module types showed none of those degradation modes except a minor corrosion after the dry-UV aging tests. Indeed, SAM proved to be a useful technique to detect backsheet cracks that are otherwise not detectable in the visual inspection. The depth profile analysis indicated that SAM can be applied to detect thickness inhomogeneities within the backsheet and encapsulant layers. The PV modules were analyzed by imaging techniques, including SAM, Electroluminescence (EL) and Dark Lock-In Thermography (DLIT) before and after every aging step, and the images were compared.

Key words: Photovoltaic (PV) Module, Reliability, Degradation modes, Damp-heat (DH) aging, Ultraviolet (UV) aging, UV-DH combined aging, Encapsulant, Backsheet, Humidity sensors, Nanoindentation, Scanning Acoustic Microscopy (SAM)

Zusammenfassung

Die Zuverlässigkeit von Photovoltaik (PV)-Modulen wird zu einem großen Anteil von der Haltbarkeit der verwendeten Polymere bestimmt (Rückseitenfolie und Verkapselungsmaterial). Ein Leistungsverlust oder Ausfall der PV-Module kann durch Änderungen der physikalischen, chemischen oder mechanischen Eigenschaften dieser Polymere während der Lebensdauer verursacht werden. In dieser Arbeit werden verschiedene Techniken zur Analyse von Veränderungen der Polymere innerhalb eines PV-Moduls angewendet. Aufbauend auf den in der Literatur bereits bekannten Analysemethoden werden innovative spezifische Methoden (z.B. Nanoindentation oder Scanning Acoustic Microscopy (SAM)) angewendet und mit den bereits bestehenden verglichen. Zudem werden in dieser Arbeit die Einlaminierungsprozesse untersucht, damit optimierte Betriebsbedingungen für eine Steigerung der Zuverlässigkeit von PV-Modulen gefunden werden können.

Zu Beginn der Arbeit wird die Nanoindentation als Methode zur Untersuchung der mechanischen Eigenschaften der Polymere eingeführt. Zwei Arten der zeitabhängigen Anregungsarten, Zeitbereich (Kriechmodus) und Frequenzbereich (dynamischer Modus), wurden verwendet, um das viskoelastische Verhalten zu bestimmen. Für jeden Modus wurde ein dafür passendes Modell erstellt, um daraus die mechanischen Eigenschaften ableiten zu können. Zuerst werden die Vorteile der Nanoindentation zur Bestimmung der damit in Zusammenhang stehenden Parameter gegenüber den Methoden zur Untersuchung des Volumens dargestellt. Dafür wurden eine große Anzahl von Proben bestehend aus Glas, Poly(ethylene-co-vinyl acetate) (EVA) und Rückseitenfolie zusammen unter unterschiedlichen Bedingungen laminiert, was zu variierenden Aushärtegraden führt. Die etablierte Dynamic Mechanical Analysis (DMA) wird verwendet um die Messung mit der Nanoindentation zu evaluieren. Beide Methoden (DMA und Nanoindentation) ergeben vergleichbare quantitative viskoelastische Antworten, wofür die Dämpfungsfaktoren bei drei unterschiedlichen Frequenzen bei Raumtemperatur herangezogen wurden. Eine statistische Auswertung der Daten zeigt die Vorteile der Nanoindentation bei der Untersuchung von mehrlagigen PV-Laminaten als Oberflächenuntersuchungsmethode, welche gleichzeitig auch bei im Feld gealterten Modulen angewendet werden kann.

Im Anschluss wir die SAM als zerstörungsfreie Analysemethode zur Bestimmung der mechanischen Eigenschaften der Rückseitenfolien und des Verkapselungsmaterials von PV-Modulen vorgestellt. Die Schallgeschwindigkeit innerhalb der unterschiedlichen Materialien wurde gemessen und daraus die mechanischen Eigenschaften abgeleitet. Im Speziellen wurde das Längselastizitätsmodul bei 30 MHz bestimmt um daraus weitere Informationen bezüglich der alterungsbedingten Materialänderungen zu erhalten. Es ist bereits bekannt, dass Fehler von PV-Modulen, welche im Zusammenhang mit der Alterung der Rückseitenfolien stehen, große Auswirkungen auf den Betrieb und die Wartung von Solarparks haben. Deshalb wurden im Feld installierte Module mit SAM analysiert um zerstörungsfrei verschieden Rückseitenfolienfehler darzustellen und in den unterschiedlichen Lagen zu lokalisieren. Akustische Mikrofotos wurden an unterschiedlichen Materialdicken der Rückseitenfolien aufgenommen, womit die Bestimmung der Tiefenprofile der einzelnen PV-Modul-Komponenten möglich ist. Es konnten unterschiedliche Typen von schichtübergreifenden Rissen festgestellt werden. Diese lokalen Materialfehler der Rückseitenfolie wurden mit Mikroskopaufnahmen validiert, wofür jedoch zerstörend aus den Rückseitenfolien Querschnitte herausgeschnitten werden mussten.

Des Weiteren wird die Alterung von PV-Modulen stark von der eindringenden Feuchtigkeit bestimmt. Bisher basierten die meisten Untersuchungen der Diffusionsparameter der Verkapselungsmaterials und der Rückseitenfolien auf der Analyse der einzelnen Polymerlagen, wodurch nicht alle Diffusionsparameter der beteiligten Materialien berücksichtigt werden. Ein Teil der Arbeit beschäftigt sich mit der kinetischen Analyse der Wasseraufnahme des EVAs im laminierten Modul. Dafür wurden digitale eingebettete Miniatur-Feuchtigkeitssensoren an unterschiedlichen Tiefen im EVA verwendet. Proben mit unterschiedlichen Polymeren und Laminationsparametern wurden damit unter feuchter Wärme (engl. Damp Heat; DH) gealtert und gleichzeitig die Feuchtigkeit innerhalb der Laminate überwacht. Aus diesen Daten wurden die jeweiligen Diffusionsraten berechnet, um zu bestimmen wie die unterschiedlichen Polymere und Laminationsparameter den Mechanismus des Ein- und Ausdringens von Wasser während der Alterungstest verändern. Die Ergebnisse zeigen eine schnellere Diffusion in der Fluor-Polymer freien, beschichteten, einlagigem Poly(ethylenterephtalat) (PET) - Rückseitenfolie im Vergleich zur Fluor-Polymer basierten, beschichteten PET – Rückseitenfolie. Beim Laminationsprozess zeigte sich, dass basierend auf der Aktivierungsenergie welche unter der Annahme eines Arrhenius-ähnlichen Verhaltens bestimmt wurde, bei der unter kürzerer Zeit laminierten Probe weniger Feuchtigkeitseintritt zu beobachten war.

Um die Effekte der Durchdringungseigenschaften der Rückseitenfolien auf die Alterung des Einkapselungsmaterials zu zeigen, wurde mit einer EVA-Variante in einem Glas / EVA / Rückseitenfolie-Laminat beschleunigte Alterungstests durchgeführt (bis zu 4000 h mit DH und bis zu 480 kWh/m² für ultraviolettes Licht (UV) und UV-DH kombiniert). Zu Beginn wurde anhand von Proben mit unterschiedlichen Rückseitenfolien die Auswirkungen von unterschiedlichen Materialkombinationen auf die Alterungsmechanismen des EVA (chemische veränderungen) untersuch. Untersuchungen mit der Fourier Transform Infrared Spectroscopy with Attenuated Total Reflection (FTIR-ATR) zeigten zwei unterschiedliche Alterungsprozesse des EVA. Eine thermische Oxidation zeigte sich in der Glas / EVA / Polyamid (PA)-basierten

Rückseitenfolienkombination nach einem DH-Test von 500 h. Allerdings wurden andere EVA-Alterungsprodukte für die Glas / EVA / PET-basierte Rückseitenfolienkombination nach einem DH-Test von 1500 h festgestellt. Des Weiteren wurde entdeckt, dass eine andere Materialkombination zu unterschiedlichen Alterungsraten des EVA führt. Dazu wurden die thermischen und mechanischen Veränderungen des EVA mittels Differential Scanning Calorimetry (DSC) und Nanoindentation untersucht. Aus den Ergebnissen kann geschlossen werden, dass die Änderung der Schmelzenthalpie sowie viskoelastischen Eigenschaften auf der Oberfläche des EVA stärker ausgeprägt ist, wenn PA-basierte Rückseitenfolien anstatt von PET-basierten Rückseitenfolien bei den UV-DH-Alterungstests verwendet wurden. Der Vergleich von drei Alterungsfaktoren zeigt, dass das EVA die stärkste chemische und optische Alterung zeigt, wenn starke UV-Strahlung, hohe Temperaturen und hohe relative Feuchtigkeit gleichzeitig auftreten.

Darüber hinaus besteht in der derzeitigen PV-Modulforschung noch der Bezug zwischen der Alterung der Materialien in einem PV-Modul und den Leistungsparametern nach der Alterung mit den beschleunigten Alterungstests. Deshalb versucht diese Arbeit hier einen Beitrag zu leisten indem der Zusammenhang zwischen Materialalterung und Verlust der Ausgangsleistung des Moduls untersucht wird. Dafür wurden mehrere PV-Module angefertigt und damit beschleunigte Alterungstests durchgeführt. Dabei wurde der Einfluss unterschiedlicher Mikroklimas untersucht und die Änderungen der Materialparameter mit dem Verlust bei den Leistungsparametern der Module in Beziehung gesetzt. Zudem wurde eine gute Übereinstimmung der Veränderungen der Leistungsparameter mit der optischen Alterung bei unterschiedlichen Materialkombinationen festgestellt.

Das alterungsbedingte Abfallen der Ausgangsleistung und des Serienwiderstands der PV-Module ist beim kombinierten UV-DH-Alterungstest deutlich ausgeprägter als die addierten Verluste der Tests mit den einzelnen Alterungsfaktoren. Die bei Experimenten durchgeführten Messungen zeigen, dass die relative Feuchtigkeit eine signifikante Auswirkung für die Alterungsmechanismen besitzt. Mehrere verschiedene Alterungseffekte konnten bei der visuellen Untersuchung der Module bei den kombinierten Alterungstests festgestellt werden, darunter die Korrosion der Solarzellen, Risse in den Rückseitenfolien und Verfärbung des EVA. Jedoch konnte keiner dieser Alterungseffekte, mit Ausnahme einer geringfügigen Korrosion bei den gleichen Modultypen nach einer trockenen UV-Alterung festgestellt werden. SAM stellte sich als eine nützliche Messmethode zum Auffinden von Rissen in der Rückseitenfolie heraus, die mit einer visuellen Inspektion nicht gefunden werden können. Die Tiefenprofilanalyse zeigte, dass mit SAM die Dickeunterschiede in der Rückseitenfolie und im Einkapselungsmaterial gemessen werden können. Die PV-Module wurden vor und nach jedem Alterungsschritt mit bildgebenden Verfahren untersucht, darunter SAM, Elektrolumineszenz (EL) und Dark Lock-In Termographie (DLIT), und anschließend wurden die Aufnahmen miteinander vergleichen.

Stichwörter: Photovoltaik (PV)-Module, Zuverlässigkeit, Alterungseffekte, Damp-heat (DH)-Alterung, Ultraviolett-Alterung, Kombinierte UV-DH-Alterung, Einkapselungsmaterial, Rückseitenfolie, Feuchtigkeitssensoren, Nanoindentation, Scanning Acoustic Microscopy (SAM)

Résumé

La fiabilité des modules photovoltaïques (PV) est fortement déterminée par la durabilité des composants polymères (backsheet et encapsulant). La dégradation de la puissance et la défaillance des modules PV peuvent être causées par des changements des propriétés physique, chimique et mécaniques de ces composants polymères pendant la durée de vie du module. Dans cette thèse, différentes techniques expérimentales pour étudier les changements dans les composants polymères des modules PV sont déployées. Outre les techniques connues disponibles dans la littérature, de nouvelles méthodes avancées (par exemple, la Nanoindentation et la microscopie acoustique à balayage (SAM)) sont également appliquées et comparées avec des méthodes déjà établies. Dans la thèse, les processus d'encapsulation PV sont également étudiés dans le but d'optimiser les conditions de stratification qui peuvent aider à améliorer la fiabilité des modules PV.

Tout d'abord, notre recherche introduit la nanoindentation instrumentée comme méthode pour étudier les propriétés mécaniques des encapsulants polymère. Deux types de modes de cycles d'indentation en fonction du temps, le domaine temporel (mode de fluage) et le domaine fréquentiel (mode dynamique) ont été réalisés pour déterminer le comportement viscoélastique. Pour chaque mode, un modèle correspondant a été appliqué pour calculer les principales propriétés mécaniques. La capacité générale de la nanoindentation à déterminer le comportement de réticulation et les avantages méthodologiques par rapport aux méthodes "bulk" sont étudiés. À cette fin, un grand nombre de laminés verre/Poly(éthylène-co-vinyl acétate) (EVA)/backsheet ont été construits en utilisant différentes conditions de laminage résultant en différents degrés de réticulation. La caractérisation par analyse mécanique dynamique (DMA) est utilisée comme méthode de référence pour valider les mesures d'indentation. La nanoindentation et le mode de traction de la DMA produisent des réponses viscoélastiques quantitatives similaires, sous la forme du paramètre du facteur d'amortissement, en utilisant trois fréquences différentes à température ambiante. Une étude statistique des données révèle les avantages de l'étude des laminés PV multicouches en utilisant la nanoindentation comme méthode de surface, tout en étant également applicable aux modules vieillis sur le terrain.

Deuxièmement, nous démontrons l'utilisation de la SAM comme méthode de caractérisation non-destructive pour estimer les propriétés mécaniques des backsheets et des encapsulants à l'intérieur des modules PV. La vitesse acoustique à l'intérieur de chaque matériau a été individuellement mesurée et ses propriétés mécaniques calculées. Plus précisément, le module longitudinal a été déterminé acoustiquement à 30 MHz pour obtenir plus d'informations sur les changements et la dégradation des matériaux induits par le vieillissement. Il est bien connu que, les modes de défaillance des modules PV associés à la dégradation du backsheet sont très significatifs pour l'exploitation et la maintenance de centrales électriques. Par conséquent, les modules exposés sur le terrain ont été analysés par SAM pour visualiser et localiser les modes de défaillance du backsheet dans des couches spécifiques de manière non destructive. Des micrographies acoustiques ont été collectées à différentes profondeurs du matériau du backsheet, ce qui a permis d'évaluer les profils de profondeur individuels des composants du module PV intégrés. Plusieurs types de fissures entre les couches ont été identifiés. Ces défauts locaux du backsheet ont été confirmés par des images microscopiques de coupes transversales du backsheet obtenues de manière destructive.

Troisièmement, la dégradation d'un module PV est fortement influencée par la pénétration d'humidité. Auparavant, la plupart des études sur les propriétés de diffusion des encapsulants et des backsheets ont été menées sur le polymère seule, sans tenir compte des propriétés de diffusion de tous les matériaux impliqués. Une partie de la thèse est liée à l'étude cinétique de l'absorption d'eau de l'EVA à l'intérieur des couches laminés. Cela a été réalisée, en utilisant des capteurs d'humidité numériques miniatures incorporés à différentes profondeurs de l'EVA. Des échantillons avec différents matériaux polymères et conditions de lamination ont été vieillis dans des conditions de chaleur humide (DH) tout en surveillant l'humidité à l'intérieur des couches laminés. A partir de ces données, les taux de diffusion respectifs ont été calculés et ont permis de déterminer comment les différents matériaux et conditions de lamination affectent le mécanisme d'entrée/sortie d'humidité pendant les tests de vieillissement. Les résultats montrent une diffusion plus rapide dans le backsheet Poly(éthylentéréphtalate) (PET) monocouche enduit sans fluoro-polymère que dans le backsheet PET laminé à base de fluoro-polymère. En ce qui concerne le processus de laminage, l'énergie d'activation effective, calculée en supposant un comportement de type Arrhenius, montre une pénétration de l'humidité plus lente pour l'échantillon peu laminé.

Pour démontrer les effets des propriétés de perméation du backsheet sur la dégradation de l'encapsulant, un type d'EVA a été vieilli dans des laminés verre/E-VA/backsheet dans des tests de vieillissement accéléré (jusqu'à 4000 h pour la chaleur humide (DH) et jusqu'à 480 kWh/m² pour les lumières ultraviolettes (UV) et UV-DH combinés). Les échantillons contenaient différents backsheets. Une première tentative, pour l'étude de l'effet des différentes combinaisons de matériaux sur les mécanismes de dégradation de l'EVA (changements chimiques), les études de spectroscopie infrarouge à transformée de Fourier avec réflectance totale atténuée (FTIR-ATR) ont identifié deux processus différents de dégradation de l'EVA. Une oxydation thermique a eu lieu dans la configuration du verre-EVA-backsheet à base de Polyamide (PA) après 500 h de tests DH. Cependant, d'autres produits de dégradation de

Acknowledgements

l'EVA ont été observés dans du verre-EVA-backsheet à base de PET après 1500 h de tests DH. Deuxièmement, il a été perçu qu'une combinaison différente de matériaux conduit à un taux de dégradation différent de l'EVA, en analysant les changements thermiques et mécaniques de l'EVA utilisant respectivement la calorimétrie à balayage différentiel (DSC) et la nanoindentation. En conséquence de nos résultats, les changements dans l'enthalpie de fusion et les propriétés viscoélastiques à la surface de l'EVA sont plus prononcés lorsque le backsheet à base de PA a été utilisé que lorsque le backsheet à base de PET a été utilisée dans des tests de vieillissement combinés UV-DH. La comparaison de trois facteurs de stress de vieillissement accéléré révèle que l'EVA subit la plus forte dégradation chimique et optique lorsque des UV élevés, une température élevée et une humidité relative élevée sont combinés simultanément.

Actuellement, dans le domaine de la recherche sur la technologie des modules PV, il existe un lien manquant entre la dégradation du matériau PV et la dégradation de la performance du PV après des tests de durée de vie accélérés. Par conséquent, dans cette recherche, une contribution à ce chaînon manquant est ajoutée en étudiant la corrélation entre la dégradation des matériaux et la dégradation de la puissance. Pour ce faire, plusieurs modules PV ont été construits et soumis à des tests de vieillissement artificiel. L'influence de différents microclimats a été étudiée et les changements dans les propriétés des matériaux ont été liés à la dégradation de la performance du PV. En outre, une bonne corrélation entre les changements dans les paramètres de performance PV et l'évolution optique des modules PV avec différentes combinaisons de matériaux est atteinte.

De plus, la dégradation de la puissance de sortie et de la résistance série du module PV est beaucoup plus sévère et forte dans le cadre de ce test de vieillissement combiné UV-DH que dans le cas de l'addition des deux facteurs pris individuellement. Sur la base des mesures expérimentales, il est démontré que l'humidité relative a un impact significatif sur les mécanismes de dégradation induits par la combinaison des stress UV, humidité relative et température. Dans ces conditions de vieillissement combinées, plusieurs modes de dégradation ont été observés lors de l'inspection visuelle des modules PV, notamment la corrosion des cellules solaires, la fissuration du backsheet et la décoloration de l'EVA. Cependant, les mêmes types de modules ne présentaient aucun de ces modes de dégradation, sauf une légère corrosion après les tests de vieillissement par UV sec. En effet, la SAM s'est avérée être une technique utile pour détecter les fissures du backsheet qui ne sont pas détectables lors de l'inspection visuelle. L'analyse du profil de profondeur a indiqué que la SAM peut être appliquée pour détecter les homogénéités d'épaisseur dans le backsheet et les couches d'encapsulation. Les modules PV ont été analysés par des techniques d'imagerie, y compris SAM, Electroluminescence (EL) et Dark Lock-In Thermographie (DLIT) avant et après chaque étape de vieillissement, et les images ont été comparées.

Mots clefs : Module photovoltaïque (PV), fiabilité, modes de dégradation, vieillissement par la chaleur humide (DH), vieillissement par ultraviolets (UV), vieillissement combiné UV-DH, encapsulant, backsheet, capteurs d'humidité, nanoindentation, microscopie acoustique à balayage (SAM).

Contents

Ac	knov	wledgements		i
Ab	ostra	ct (English/Deutsch/Françai	is)	iii
Li	st of :	figures		xix
Li	List of tables		xxv	
1	Intr	oduction		1
	1.1	Photovoltaic modules techr	10logy	1
	1.2	Reliability of PV modules		2
		1.2.1 PV module failure m	odes	3
	1.3	PV polymer degradation .		9
		1.3.1 Process of EVA therm	nal-oxidation	10
		1.3.2 Process of EVA photo	o-oxidation	11
		1.3.3 Process of PET backs	sheet hydrolysis	12
		1.3.4 Process of PA-based	backsheet cracking and chalking	13
	1.4	The impact of PV module m	nanufacturing on the degradation mechanism	14
		1.4.1 Soldering & tabbing		14
		1.4.2 Lamination process		15
		1.4.3 Integration of junction	on box & bypass diode(s)	16
	1.5	The impact of climatic zone	es on the degradation mechanism	17
2	Mot	tivation and summary of the	e thesis results	19
	2.1	Context and gaps		19
	2.2	Structure of this thesis		21
3	Mat	terials and methods		25
	3.1	Lamination		25
	3.2	Reliability tests		29
		3.2.1 Damp-heat (DH) exp	posure	29
		3.2.2 Ultraviolet (UV) expe	osure	29
		3.2.3 Combined UV/DH et	xposure	30
	3.3	Characterization methods f	for PV polymer components	31
		3.3.1 FTIR-ATR spectrosco	ру	31

		3.3.2	Dynamic Mechanical Analysis	33
		3.3.3	Nanoindentation	34
		3.3.4	Raman spectroscopy	41
		3.3.5	Yellowness Index	42
		3.3.6	Differential Scanning Calorimetry	43
	3.4	Chara	cterization methods for PV Modules failure analysis (non-destructive tech-	
		nique	s)	44
		3.4.1	Visual inspection	44
		3.4.2	PV performance_analysis of light I-V curves	45
		3.4.3	Electroluminescence	45
		3.4.4	Dark Lock-In Thermography	46
		3.4.5	Scanning Acoustic Microscopy	48
4	Adv	anced	methods for PV module polymer mechanical degradation	51
	4.1	Nanoi	ndentation	53
		4.1.1	Creep mode: Ramp and hold indentation	55
		4.1.2	Dynamic frequency sweep: Sinus indentation	56
	4.2	Scann	ing Acoustic Microscopy	57
		4.2.1	Time-of-flight measurements through the EVA and backsheet	57
		4.2.2	Acoustic imaging	61
	4.3	Concl	usion	65
5	Opt	imizin	g the encapsulation process	67
5	Opt 5.1	imizin EVA d	g the encapsulation process egree of curing (DoC) determination	67 68
5	Opt 5.1	imizin EVA d 5.1.1	g the encapsulation process egree of curing (DoC) determination	67 68 70
5	Opt 5.1	imizin EVA d 5.1.1 5.1.2	g the encapsulation process egree of curing (DoC) determination	67 68 70 72
5	Opt 5.1	imizin EVA d 5.1.1 5.1.2 5.1.3	g the encapsulation processegree of curing (DoC) determinationEffect of DoC on the creep response of the EVAEffect of DoC on the DMA and dynamic indentation of the EVAEffect of DoC on the time-of-flight through the EVA layer	67 68 70 72 77
5	Opt 5.1	imizin EVA d 5.1.1 5.1.2 5.1.3 Monit	g the encapsulation processegree of curing (DoC) determinationEffect of DoC on the creep response of the EVAEffect of DoC on the DMA and dynamic indentation of the EVAEffect of DoC on the time-of-flight through the EVA layeroring of moisture ingress/egress into PV laminates	67 68 70 72 77 79
5	Opt 5.1	imizin EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1	g the encapsulation processegree of curing (DoC) determinationEffect of DoC on the creep response of the EVAEffect of DoC on the DMA and dynamic indentation of the EVAEffect of DoC on the time-of-flight through the EVA layeroring of moisture ingress/egress into PV laminatesBacksheet effect on moisture ingress	67 68 70 72 77 79 80
5	Opt 5.1 5.2	imizin EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2	g the encapsulation process egree of curing (DoC) determination	67 68 70 72 77 79 80 83
5	Opt 5.1 5.2 5.3	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl	g the encapsulation process egree of curing (DoC) determination	67 68 70 72 77 79 80 83 84
5	Opt 5.1 5.2 5.3 Enc	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl apsula	g the encapsulation process egree of curing (DoC) determination	 67 68 70 72 77 79 80 83 84 85
5 6	Opt 5.1 5.2 5.3 Enc 6.1	imizin EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl capsula Mater	g the encapsulation process egree of curing (DoC) determination Effect of DoC on the creep response of the EVA Effect of DoC on the DMA and dynamic indentation of the EVA Effect of DoC on the time-of-flight through the EVA layer oring of moisture ingress/egress into PV laminates Backsheet effect on moisture ingress Correlation between EVA DoC and moisture ingress usion nt degradation analysis: effect of backsheet ial combination comparison	 67 68 70 72 77 79 80 83 84 85 86
5	Opt 5.1 5.2 5.3 Enc 6.1	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl capsula Mater 6.1.1	g the encapsulation process egree of curing (DoC) determination	 67 68 70 72 77 79 80 83 84 85 86 86
5	Opt 5.1 5.2 5.3 Enc 6.1	imizin EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl capsula Mater 6.1.1 6.1.2	g the encapsulation process egree of curing (DoC) determination Effect of DoC on the creep response of the EVA Effect of DoC on the DMA and dynamic indentation of the EVA Effect of DoC on the time-of-flight through the EVA layer oring of moisture ingress/egress into PV laminates Backsheet effect on moisture ingress Correlation between EVA DoC and moisture ingress usion nt degradation analysis: effect of backsheet ial combination comparison Detection of EVA decomposition Determination of EVA melting enthalpy	 67 68 70 72 77 79 80 83 84 85 86 86 88
5 6	Opt 5.1 5.2 5.3 Enc 6.1	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl capsula Mater 6.1.1 6.1.2 6.1.3	g the encapsulation process egree of curing (DoC) determination	 67 68 70 72 77 79 80 83 84 85 86 86 88 90
5 6	Opt 5.1 5.2 5.3 Enc 6.1	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl capsula Mater 6.1.1 6.1.2 6.1.3 Interfa	g the encapsulation process egree of curing (DoC) determination Effect of DoC on the creep response of the EVA Effect of DoC on the DMA and dynamic indentation of the EVA Effect of DoC on the time-of-flight through the EVA layer oring of moisture ingress/egress into PV laminates Backsheet effect on moisture ingress Correlation between EVA DoC and moisture ingress usion nt degradation analysis: effect of backsheet ial combination comparison Detection of EVA decomposition Determination of the viscoelastic properties of EVA ace comparison	 67 68 70 72 77 79 80 83 84 85 86 86 88 90 92
6	Opt 5.1 5.2 5.3 Enc 6.1	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl apsula Mater 6.1.1 6.1.2 6.1.3 Interfa 6.2.1	g the encapsulation process egree of curing (DoC) determination Effect of DoC on the creep response of the EVA Effect of DoC on the DMA and dynamic indentation of the EVA Effect of DoC on the time-of-flight through the EVA layer oring of moisture ingress/egress into PV laminates Backsheet effect on moisture ingress Correlation between EVA DoC and moisture ingress usion nt degradation analysis: effect of backsheet ial combination comparison Detection of EVA decomposition Determination of the viscoelastic properties of EVA ace comparison Detection of EVA decomposition	 67 68 70 72 77 79 80 83 84 85 86 86 88 90 92 92
6	Opt 5.1 5.2 5.3 Enc 6.1 6.2 6.3	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl apsula Mater 6.1.1 6.1.2 6.1.3 Interfa 6.2.1 Aging	g the encapsulation process egree of curing (DoC) determination Effect of DoC on the creep response of the EVA Effect of DoC on the DMA and dynamic indentation of the EVA Effect of DoC on the time-of-flight through the EVA layer oring of moisture ingress/egress into PV laminates Backsheet effect on moisture ingress Correlation between EVA DoC and moisture ingress usion Detection of EVA decomposition Determination of the viscoelastic properties of EVA Detection of EVA decomposition Detection of EVA decomposition the viscoelastic properties of EVA the viscoelastic properties of EVA the transmission test comparison	 67 68 70 72 77 79 80 83 84 85 86 86 88 90 92 92 93
6	Opt 5.1 5.2 5.3 Enc 6.1 6.2 6.3	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl apsula Mater 6.1.1 6.1.2 6.1.3 Interfa 6.2.1 Aging 6.3.1	g the encapsulation process egree of curing (DoC) determination Effect of DoC on the creep response of the EVA Effect of DoC on the DMA and dynamic indentation of the EVA Effect of DoC on the time-of-flight through the EVA layer oring of moisture ingress/egress into PV laminates Backsheet effect on moisture ingress Correlation between EVA DoC and moisture ingress usion nt degradation analysis: effect of backsheet ial combination comparison Detection of EVA decomposition Determination of the viscoelastic properties of EVA Detection of EVA decomposition Detection of EVA decomposition	 67 68 70 72 77 79 80 83 84 85 86 86 88 90 92 92 93 93
6	Opt 5.1 5.2 5.3 Enc 6.1 6.2 6.3	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl apsula Mater 6.1.1 6.1.2 6.1.3 Interfa 6.2.1 Aging 6.3.1 6.3.2	g the encapsulation process egree of curing (DoC) determination Effect of DoC on the creep response of the EVA Effect of DoC on the DMA and dynamic indentation of the EVA Effect of DoC on the time-of-flight through the EVA layer oring of moisture ingress/egress into PV laminates Backsheet effect on moisture ingress Correlation between EVA DoC and moisture ingress usion nt degradation analysis: effect of backsheet ial combination comparison Detection of EVA decomposition Determination of the viscoelastic properties of EVA ace comparison Detection of EVA decomposition Detection of EVA decomposition Detection of EVA decomposition Detection of EVA decomposition Quantification of the EVA decomposition	 67 68 70 72 77 79 80 83 84 85 86 86 88 90 92 92 93 93 96
6	Opt 5.1 5.2 5.3 Enc 6.1 6.2 6.3	imizing EVA d 5.1.1 5.1.2 5.1.3 Monit 5.2.1 5.2.2 Concl apsula Mater 6.1.1 6.1.2 6.1.3 Interfa 6.2.1 Aging 6.3.1 6.3.2 6.3.3	g the encapsulation process egree of curing (DoC) determination Effect of DoC on the creep response of the EVA Effect of DoC on the DMA and dynamic indentation of the EVA Effect of DoC on the time-of-flight through the EVA layer oring of moisture ingress/egress into PV laminates Backsheet effect on moisture ingress Correlation between EVA DoC and moisture ingress usion nt degradation analysis: effect of backsheet ial combination comparison Detection of EVA decomposition Determination of the viscoelastic properties of EVA ace comparison Detection of EVA decomposition Detection of EVA decomposition Detection of EVA decomposition Quantification of the EVA fluorescence background Vellowness index measurement	 67 68 70 72 77 79 80 83 84 85 86 86 88 90 92 93 96 97

		6.3.4 Determination of EVA melting enthalpy	99
	6.4	Conclusion	100
7	Cor	relation between failure imaging and power output degradation	101
	7.1	Relative humidity effect on performances	103
		7.1.1 Correlation between backsheet cracking and corrosion	105
		7.1.2 Correlation between yellowing and corrosion	108
	7.2	Material combination effect on performances	110
	7.3	Correlation between acoustic, thermal and electroluminescence imaging \ldots	111
	7.4	Conclusion	118
8	Gen	eral conclusions and perspectives	119
	8.1	General conclusions	119
	8.2	Perspectives	121
A	App	pendix	125
Bi	bliog	graphy	154
С	urric	ulum Vitae	155

List of Figures

1.1	The price of electricity from new power plants - 2009 vs. 2019 [1]	1
1.2	PV module's energy and material transport mechanisms	3
1.3	Encapsulant-backsheet discoloration in PV module	4
1.4	Delamination of EVA from glass-EVA interface	5
1.5	Corrosion of soldering ribbons in PV module	5
1.6	Elecroluminescence (EL) image (a) and photography image (b) of a snail trails	
	affected PV module	6
1.7	Elecroluminescence (EL) images before (a) and after (b) PID test in a PV module	7
1.8	Elecroluminescence (EL) image of a cell cracking affected PV module	8
1.9	Hot spot detected by IR camera	8
1.10	Oxidative degradation mechanism of EVA [51]	11
1.11	Proposed photo degradation mechanism of EVA [30]	12
1.12	Hydrolytic Degradation of PET [57]	13
1.13	Photograph of PV backsheet degradation in the field cracking (left) and chalking	
	(right)	13
1.14	Quantification of Climatic Stresses (Global Mapping) [114]	18
2.1	Polymeric materials present in the PV modules in the field in 2021 [138]	21
2.1	Polymeric materials present in the PV modules in the field in 2021 [138]	21
2.1 3.1	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding	21
2.1 3.1	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet _ Bight: Assembled samples after lamination with an external	21
2.1 3.1	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader.	21 26
2.13.13.2	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	21 26
2.13.13.2	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	21 26 27
 2.1 3.1 3.2 3.3 	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	21 26 27
 2.1 3.1 3.2 3.3 	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	21 26 27 27
 2.1 3.1 3.2 3.3 3.4 	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	21 26 27 27
 2.1 3.1 3.2 3.3 3.4 	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	21 26 27 27 28
 2.1 3.1 3.2 3.3 3.4 3.5 	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	21 26 27 27 28 29
 2.1 3.1 3.2 3.3 3.4 3.5 3.6 	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	21 26 27 27 28 29 30
 2.1 3.1 3.2 3.3 3.4 3.5 3.6 3.7 	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	21 26 27 27 28 29 30 30
 2.1 3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 	Polymeric materials present in the PV modules in the field in 2021 [138] Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader	 21 26 27 27 28 29 30 30 32

Chapter 0

3.9	Schematic depiction of the investigated laminate during the sample preparation	
	for characterizations	32
3.10	Schematic illustration of the DMA assembly applied to the multilayer EVA-BS	
	film for the shear mode (left) and to the EVA sheet for the tensile mode (right) $\ .$	34
3.11	(a) Schematic indentation load-displacement curve with the slope S of the un-	
	loading curve used in the Oliver and Pharr analysis. (b) Cross section of a conical	
	indenter tip [146]	35
3.12	Microscopic image of the three-side pyramid indented on the PET-based back-	
	sheet [149]	37
3.13	Schematic illustration of the Ultra Nanoindentation Head Assembly applied to	
	the multilayer EVA-BS film	38
3.14	Two Kelvin-Voigt bodies model	38
3.15	Dynamic mechanical model of viscoelastic material [160]	40
3.16	Microscopic image of the spherical imprints performed on the EVAs surface after	
	indentation	41
3.17	Typical Raman spectra of a c-Si PV module with EVA encapsulation before and	
	after outdoor aging [166]	42
3.18	Chromaticity Diagram and Chromaticity Coordinates [170]	43
3.19	Typical DSC thermograms of uncured and laminated EVA [139]	43
3.20	Photography of the front side (left) and rear side (right) of PV module of type IV	44
3.21	Typical I-V curve of an illuminated PV module [16]	45
3.22	Electroluminescence images of PV module - front side – before (a) and after	
	reliability test (b)	46
3.23	DLIT imaging setup an IR camera collects thermal images from a PV module of	
	type IV reflected on a mirror	46
3.24	DLIT images of a PV modules of type IV . $S^{0^{\circ}}$ (a), $S^{-90^{\circ}}$ (b), amplitude (c), and	
	phase (d) [181]	47
3.25	Measurement principle of the SAM in reflection mode [137]	48
3.26	Schematic illustration of the SAM assembly applied to the multilayer PV module	50
3.27	SAM imaging setup an 30 MHz transducer scans acoustic images from a PV	
	module of type IV immersed in water	50
4.1	Combined curves of load versus indenter displacement used for the calculation	
4.1	of hardness of hacksheet (a) and EVA (b) [149]	53
12	Microscopic images of the cross-section of the laminates after indentations on	55
4.2	the backsheet 1 (a) and backsheet 2 (b) [149]	54
13	Changes in hardness of backsheets after different intervals of DH aging [149]	54
4.5	Creen load-displacement-time curves on the EVA surface obtained using a maxi-	54
7.7	mum load 40 mN duration of creen 200 s	55
45	Dynamic load-displacement-time curves on the FVA surface obtained using a	55
1.5	frequency sweep during the hold	56
46	Photo of PV module being scanned from the front side by SAM	57
1.0	There of the module being seamled from the none by 0.101	51

4.7	Left: TOF-amplitude reflectograms of a PV module of type IV measured at 30	
	MHZ. Right: Image of the back side of the module from the SAM software with	50
	the measurement areas (A1 on the edge and A2 at the center of the module) .	58
4.8	Changes in Time-of-flight of the backsheet (left) and EVA (right) in the PV mod -	- 0
	ule of type IV as a function of sequential aging duration	59
4.9	Longitudinal modulus of the backsheet (left) and EVA (right) in the PV module	
	of type IV as a function of sequential aging duration	60
4.10	Acoustic micrographs (SAM images) generated from the different spectral re-	
	gions ("gates") from a Full size PV module of type V	61
4.11	Microscopic images of Backsheets cross-sections. The letters a, b and c indicate	
	the interfaces shown in the SAM images. Case 1 (left), destroyed PP inner layer;	
	Case 2 (right), Cracks in outer PA layer	62
4.12	TOF-amplitude reflectogram of a PV module case 1 (left) and case 2 (right)	62
4.13	SAM images of Case 1, a. outer layer surface. b. core-inner layers interface. c.	
	inner layer bulk	63
4.14	SAM images of Case 2, a. outer-core layers interface. b. core layer bulk. c.	
	core-inner layer interface	63
4.15	Acoustic cross-sections Case 1	64
4.16	Acoustic cross-sections Case 2	64
5.1	Correlation between the Degree of curing of the processed samples and the	
	lamination parameters time and temperature	70
5.2	Image of mounted samples with exposed surfaces of interest (EVA with linear	
	circles and backsheet (CPC) with dashed circles) for nanoindentation tests	70
5.3	Creep data on the same surfaces with max load 40 mN, duration of creep 200 s	71
5.4	Elastic creep modulus (calculated from the creep curves) of the EVA surface as a	
	function of DoC as measured by DSC	71
5.5	Storage modulus (calculated from the sinus part of the dynamic curves) of the	
	EVA surface as a function of DoC as measured by DSC	72
5.6	Data of storage modulus (top). Loss modulus (mid) and Damping factor (bottom)	
	calculated from tensile-DMA of the EVA bulk as a function of 30 different DoCs	73
5.7	NHT ² Nano Hardness Tester	74
5.8	Data of storage modulus (top), loss modulus (mid) and damping factor (bottom)	
0.0	calculated from DMA tensile mode of the EVA bulk (a) and nanoindentation	
	dynamic mode of the EVA surface (b) as a function of 5 different DoCs	75
59	Data of damping factor calculated from DMA shear mode of FVA-BS laminates	10
0.0	as a function of 5 different DoCs	76
5 10	TOE-amplitude reflectograms of a laminate of type I measured at 30 MHz	78
5.10	Evolution of A TOE in the EVA layer with the DoC	79
5.11	Monosured moisture ingress in laminate #a for DLL cycle at 05 °C	00
5.12	Magnung moisture ingress for position #1 in lowington #2 and #b at 1:00 minutes	00
5.13	ivieasured moisture ingress for position #1 in faminates #a and #b at different	00
	constant temperatures	80

5.14	Arrhenius plots describing the rate of moisture ingress during damp-heat aging. The calculated E_A^{eff} are presented for each RH setting	82
5.15	Digital microscopy images of the cross-section of the two backsheets used in the	
	study	82
5.16	6 Measured moisture and temperature in the chamber and in the laminate #a and	
	#b	83
5.17	⁷ Measured moisture ingress in laminate #a and #c at 40 °C, 65% RH	83
0.1		
6.1	Digital microscopy images of the cross-sections to illustrate the sample's struc-	
	interface)	86
62	Typical ATP ETIP spectra of a fresh EVA	90
0.2	ATD FTID execting of the FVA at the class interface hefers and ofter DU tests with	00
6.3	AIR-FIIR spectra of the EVA at the glass interface before and after DH tests with	
	offset in the v direction for clarity	87
C 4	DCC Thermoerree of EVA (c). (First heating) two sevelageed on dathermain	07
6.4	DSC Thermograms of EvA. (a): (First heating), two overlapped endothermic necks are 45° C and 60° C. (b): (second heating), one remaining endothermic	
	peaks are 45 C and 60 C. (b). (second nearing), one remaining endomerning	88
с г	Franktion of the anthology of the and otherweighter in the DCC Therman	00
6.5	evolution of the enthalpy of the endothermic transition in the DSC Thermograms	
	different backsheets used in the laminates during the aging tests)	89
66	Digital microscopy images of the sample cross sections to illustrate the sample's	05
0.0	structure during indentation on the EVA surface (glass/EVA interface)	90
67	Ontical microscopy image of indented EVA surface (glass, EVA interface)	01
0.7	Demois a factor (coloridate d from the since port of the demonsion surres) hefere	91
6.8	and after IW-DH combined aging	91
6.0	ATD ETID experts of the EVA at close interface and at healthback interface with	51
6.9	PET based backsheet 2 in (a c) and PET based backsheet 1 in (b d). All curves	
	are offset in the v direction for clarity	92
6 10	ATD ETID spectre of the EVA at the glass and at heaksheat interfaces before and	52
0.10	after dry-IIV tests. All curves are offset in the v direction for clarity	94
6 1 1	ATE ETIP spectra of the EVA at glass interface before and after DH (a) and IW	51
0.11	DH combined (b) tests with a PA based backsheet. All surves are offset in the v	
	direction for clarity	95
6.12	CL of EVA with different aging tests for various peak shifts from ETIP spectra	06
0.12	Demonstration of the low-instance in standard different spin a set ditions. Dil tests (1)	90
6.13	in blue, LW tests (2) in orange and LW DH tests (3) in purple	97
C 1 4	Molece ov tests (2) in orange and ov-Dri tests (3) in purple	51
0.1 4	aging condition tests. DH tests (1) in high LW tests (2) in orange and LW DU	
	aging continuon tests. Diff tests (1) in diffe, $0 v$ tests (2) in drange and $0 v$ -DH tests (3) in purple	00
		30

6.15	(A) Thick red-model fit, dotted red measured data, thick blue-model prediction, dotted blue measured data calibrated data. (B) Sensitivity analysis of yellowing index change to relative humidity and UV doses.	99
6.16	Evolution of the enthalpy of the endothermic transition in the DSC Thermograms of the EVA before and after different aging condition tests	100
7.1 7.2	Simulated photo degradation rate map (top) and relative humidity (bottom) [113 Measured P_{MPP} (a) and Rs (b) for M-AAA and M-APA_Al under different aging]104
7.3	Photography and EL images for PV modules of type IV with <i>AAA</i> backsheet after 2500 h of DH, after 240 kWh/m ² and after 420 kWh/m ² in UV-dry (up) and in combined UV-DH (bottom). SAM images of both aged backsheets showed outer layer structure (left)	104
7.4	Acoustic micrographs of a PV module of type IV using <i>AAA</i> before and after UV-DH combined aging test at the backsheet/EVA interface (#1) and EVA/cell interface (#2)	107
7.5	Left. Time of flight (TOF)-amplitude reflectogram of PV module of type IV measured at 30 MHz. Right. TOF from water-backsheet to EVA-Cell interfaces.	107
7.6	Photography and EL images for PV modules of type IV with <i>APA_Al</i> after 2500 h of DH, after 240 kWh/m ² followed by 420 kWh/m ² in UV-dry (up) and in	107
	combined UV-DH (bottom)	108
7.7 7.8	Measured <i>Y I</i> for M-AAA and M-APA_AI under different aging conditions Measured P_{MPP} (a) and Rs (b) for different material combination under UV-DH	109
7.9	Measured <i>YI</i> for different material combination under UV-DH combined aging	110
7.10	SAM (a), DLIT (b) and EL images (c) of a <i>CPC</i> 02 module after sequential reliabil-	111
7.11	SAM (a), DLIT (b) and EL images (c) of a <i>TPT</i> 05 module after sequential reliabil-	112
7 1 2	ity tests	113
1.12	ity tests	114
7.13	SAM (a), DLIT (b) and EL images (c) of a <i>AAA</i> 09 module after sequential reliabil- ity tests	115
7.14	SAM (a), DLIT (b) and EL images (c) of a <i>APA_Al</i> 11 module after sequential reliability tests	116
7.15	SAM (a), DLIT (b) and EL images (c) of a <i>APA_Al</i> 12 module after sequential reliability tests	117
8.1	Single reflectograms (left) and continuous reflectograms data for a defined area	
8.2	in the module (right)	122 122

Chapter 0

A.1	Visual inspection of module <i>CPC</i> 02 after sequential reliability tests — front side	
	(a) and rear side (b)	126
A.2	Visual inspection of module <i>TPT</i> 05 after sequential reliability tests — front side	
	(a) and rear side (b)	127
A.3	Visual inspection of module AAA08 after sequential reliability tests — front side	
	(a) and rear side (b)	128
A.4	Visual inspection of module AAA09 after sequential reliability tests — front side	
	(a) and rear side (b)	129
A.5	Visual inspection of module APA_Al11 after sequential reliability tests — front	
	side (a) and rear side (b)	130
A.6	Visual inspection of module APA_Al12 after sequential reliability tests — front	
	side (a) and rear side (b)	131

List of Tables

3.1	Different setup of the lamination and backsheet type used	26
3.2	Backsheets used to laminate the PV modules	27
3.3	Summary of sample configuration of PV laminates and aging conditions	31
3.4	Summary of sample configuration of PV modules and aging conditions	31
4.1	Indentation parameters for creep mode	55
4.2	Indentation parameters for dynamic frequency sweep mode	56
4.3	Density and thickness of the laminated backsheet and EVA foils $\ldots \ldots \ldots$	60
5.1	Extracted coefficient of determination for the fit functions shown in Figure 5.6	74
5.2	Comparative summary of the investigated approaches and their correlation to	
	DoC	77
6.1	FTIR absorption bands undergoing change in ethylene vinyl acetate copolymer	
	(EVA) from Figure 6.3	88
6.2	FTIR absorption bands undergoing change in EVA from Figure 6.9	93
6.3	Extracted parameter of the yellowing index model	98

1 Introduction

1.1 Photovoltaic modules technology

With an increased attention to the environment and the limited supply of fossil fuels, production of electricity through harnessing of renewable energy sources is critical to meeting future energy demands. Although energy needs will likely be met through a variety of renewable sources, electricity produced through solar photovoltaics (PV) will be a significant contributor.



Figure 1.1 – The price of electricity from new power plants - 2009 vs. 2019 [1].

Despite the new technological development and the on-going market penetration, PV will need contribute more significantly to the global electricity supply because power generation costs is reduced. In order to make this technology more cost-effective, PV module output must maintain high performance for long periods of time. By increasing the life time of the PV module, the levelized cost of electricity (LCOE) will decrease [2]. The LCOE captures the cost of building the power plant itself as well as the ongoing costs for fuel and operating the power plant over its lifetime. As shown in Figure 1.1, solar has become the cheapest form of electricity with a declined price by 89 % between 2009 and 2019 [3].

Additionally, a longer PV module lifetime is a major driver for sustainability. In this perspective, the system lifetime and degradation rate stand amongst the factors that directly influence the economics of PV modules [4, 5]. Therefore, reliability and failure analysis are key elements involved in the economic feasibility of PV [6] as far as advancement on material and manufacturing quality, and research on degradation mechanisms will extend the lifetime of PV systems, thus driving generation costs down [5, 7].

1.2 Reliability of PV modules

In the last decade, the solar market has grown very fast and it is becoming a non-subsidized market with increased demand for performance certainty. The expected life time performance and degradation of PV modules is a major issue when trying to drive down the LCOE and therefore making PV technology more competitive in energy market. Some manufacturers guarantee that the performance loss of PV modules will not exceed 20 % of their nameplate power after 25 years of field operation for some manufacturers cases. However, to estimate the profitability of the investment it is essential to accurately quantify and define all the relevant risks in order to mitigate the uncertainties of long term performance loss.

There are several failure modes and degradation mechanisms which reduce the PV modules' power output or even cause its complete failure. The PV system's operating life time is mainly determined by the stability of the PV modules. Their stability is strongly dependent on different physical and chemical degradation mechanisms which are at the same time strongly influenced by the specific mass and energy transport from external factors (see Figure 1.2). It has been documented that modules in hot and humid climates show considerably higher degradation rates, for some degradation mechanisms, than those in desert and moderate climates [8]. From a technical point of view, it is important to understand and define better those degradation mechanisms that could eventually lead to module failures. The performance loss of PV modules during their life time is still not completely documented, and the mechanisms behind it and their specific impact on the module power output still needs to be uncovered.



Figure 1.2 - PV module's energy and material transport mechanisms.

1.2.1 PV module failure modes

There are several PV module failure (degradation) modes and degradation mechanisms which may reduce the power output or cause the module to fail. Nearly all of these mechanisms are related to the weather (rain, hail, and snow...), high temperature, UV, humidity, and thermal cycling. It has been well documented that the energy production of a PV module will decrease over time as a result of one or more degradation modes [9, 10, 11, 12]. These degradation modes depend both on the module construction and environment. The most important PV failure modes which are linked to the polymeric encapsulation material and backsheet degradation are presented below:

Discoloration

Chemically, the EVA discoloration rate is affected by a number of external factors, but more strongly by the additive types in its formulation and the lamination conditions. The additives and curing generated chromophores and their concentrations show a synergistic discoloring effect. Moreover, Discoloration can also be produced by UV/T/Humidity. Also, the chromophores are not always degraded additives but could also be the EVA polymer chains themselves. The discoloration can be reversed by photo-bleaching reactions that occur in presence of oxygen. The EVA is then further degraded but the yellowing is "bleached" because of oxidative destruction of the chromophores. The overall process of color change of EVA is therefore the sum of the effects due to discoloration and photo-bleaching reactions [13].



Figure 1.3 – Encapsulant-backsheet discoloration in PV module.

Backsheet discoloration is also known as a result of the migration of additives and degradation compounds into backsheet-encapsulant interfaces are the main cause for backsheet yellowing [14], as shown in Figure 1.3.

Besides discoloration, the EVA degradation products such as acetic acid and acetaldehyde could induce other side reactions on the solar cell components in the presence of moisture high temperature and oxygen. The overall degradation of the encapsulant is an even more important phenomenon to study than its yellowing alone. Indeed, oxidation and corrosion (by acetic acid as one of the reactants) could increase the series resistance, reduce the current collection efficiency, cause mismatching, and decrease the power output of the module.

Due to chemical interaction between EVA and the other module compounds (glass, solar cell and backsheet), the adhesion can be reduced and delamination risk is increased. It can also be noted that the discoloration induces a reduction of the light spectrum that reaches the solar cells, if the discolored encapsulant is in front of the cells, reducing the system yield [15]. Typically, the power losses induced by the yellowing of the encapsulant follow initially a constant loss rate and this degradation rate increases with time as the EVA absorption coefficient increases and more photo degradation occurs, leading to faster degradation [8].

• Delamination

The delamination is defined as a gap formation caused by debonding and adhesion loss between different materials or components (encapsulant, glass, backsheet, solar cell...). These mechanisms can find their root cause, during the lamination process, if non-optimal lamination parameters (temperature, pressure, duration and cooling) are applied. Delamination can also be a result of debonding mechanism due to heat and moisture exposure.



Figure 1.4 – Delamination of EVA from glass-EVA interface.

Due to the delamination, water vapour and reactive gas may diffuse in the hollow spaces and cause contacts and cell interconnectors' corrosion. After delamination, new interfaces are created, e.g. glass/air and air/EVA in the case of glass/EVA delamination [16], as shown in Figure 1.4. For these latter interfaces, the interfacial reflectance is about 4%. This reflection loss, for long time field exposures of PV modules, causes a drop in power and therefore reduction of the short-circuit current.

• Corrosion

The corrosion of the metallic components within a module could be facilitated by delamination, which can expose the metallization to moisture and oxygen. The corrosion of the cell interconnectors and cross-connectors is also observed near cell edges, due to water vapor ingress.



Figure 1.5 - Corrosion of soldering ribbons in PV module.

In addition, the degradation of EVA may accelerate metallization corrosion due to the production of acetic acid [16]. The corrosion of the soldering ribbons (see Figure 1.5) can reduce the power output by increasing the series resistance of the electrical interconnects. By joule effect, corroded ribbons overheat and can provoke hot-spots. • Snail trails

Snail tracks (or snail trails) are grey/black line shaped discoloration of the silver paste of the front metallization of solar cell as shown in Figure 1.6. The origin of this phenomenon is still under discussion. Several studies proved this snail trails formation due to a chemical reaction between the additives composition and the degradation products of the EVA and the silver salts on the metallic surface. Moreover snail trails tend to appear at the cracks and at the edges the solar cells, indicating a predominant role of moisture ingress and oxygen in their formation. The choice of the backsheet material due to its permeation of oxygen and moisture seems to be important as well for the snail trails occurrence [17].



Figure 1.6 – Electoluminescence (EL) image (a) and photography image (b) of a snail trails affected PV module.

In addition to the cosmetic discoloration, modules with lots of snail trails often show under performance, which is assumed to be related to cell cracks. Systems affected by snail trails show a tendency to high leakage currents.

• Potential Induced Degradation (PID)

The Potential Induced Degradation mode results from the high potential difference between the cells and the module frame during operation (see Figure 1.7). The interaction between encapsulation material, glass and frame has shown to be the major influencing factor at the module level [16]. At the cell level, they are encapsulant material properties (e.g. water vapour transmission rate and volume resistivity), production processes and module layout [17]. Environmental factors, for example elevated temperature, high humidity and soiling, can further hasten the process [18].



Figure 1.7 – Electoluminescence (EL) images before (a) and after (b) PID test in a PV module.

Different types of degradation are possible, with various impacts on module power. Potential induced shunting (PID-s) is caused by shunting of the pn-junction by sodium ion ingress along stacking faults [19]. It can lead to a significant loss of power output (up to 80%). Electrochemical corrosion of the metallization and cell interconnectors can lead to an increase in the series resistance [20]. The surface polarization effect (PID-p) is a reduction of the effectiveness of the surface passivation caused by an accumulated charge on the cell's surface, leading to an increased recombination current [21]. The PID-p effects are generally reversible, the exception being induced corrosion caused by the accumulation of electric charges. Finally, the influence of the EVA film age on PID was investigated. Moreover, the modules with aged EVA films exhibit a severe degradation of solar cells and silver line corrosion [22].

Cell cracks

The cell defects related to cell cracks and/or breakages are usually caused by mechanical or thermal stress during module manufacturing, transport or installation. The most important cell cracks are cross and vertical μ -cracks, cracks with partial cell inactivation and dendritic or branched cracks (see Figure 1.8). Cracks do not necessary lead to a strong power loss of the module directly after the crack initiation [23]. However, more recently, the impact of micro cracks on the performance of PV modules prior to installation phase, as well as testing operating samples from the field has been evaluated. It is found that the μ cracks have impacted power loss differently [24].

The effects of the cell cracks can lead to power losses and a localized temperature increase in the active part of the cell by creating what is called "hotspot".


Figure 1.8 – Elecroluminescence (EL) image of a cell cracking affected PV module.

• Hot spots

A hot-spot consists of a localized overheating in a PV module. It appears when, due to some anomaly (possibly induced by previously described degradation modes), the short circuit current of the affected cell becomes lower than the operating current of the whole module, giving rise to reverse biasing thus dissipating the power generated by other cells as heat (see Figure 1.9).



Figure 1.9 – Hot spot detected by IR camera.

The hot spot is one of the common defects which occur in PV modules during long-term outdoor exposure. It mainly occurs due to thermal expansion/contraction of interconnects or solder bonds, shadowing, faulty cell or cells in a string and low shunt resistance cell. When current produced by the faulty cell or shadowing cell is less than the strings current in a PV module [25]. The temperature of the solar cell increases and hot spot creates a cascaded effect on the efficiency of the PV module.

1.3 PV polymer degradation

The polymeric components of the PV module will age over time due to a number of internal and external factors by setting in motion several physical and chemical processes that will have reversible or irreversible effects on the polymer properties [26]. Aging can be expressed as the increase (or decrease) of a property over time, and degradation being the negative scenario or impact on properties of the material which are relevant to its application or function to eventually reach its end of lifetime [26].

Polymer degradation is a change in the properties—tensile strength, color or chemical structure of a polymer under the influence of one or more environmental factors such as heat, light or chemicals such as acids. In PV modules a series of processes that leads to their polymeric components degradation takes place. It has been reported in literature that several PV module degradation mechanisms are connected to the polymer degradation. Additionally, micro-climatic conditions and load parameters play important roles in polymer degradation.

EVA degradation has been the topic of many research projects and effort in the understanding of this encapsulant's degradation behavior in PV modules [13, 27, 28, 29, 30, 31]. EVA is a copolymer where ethylene (Et) and vinyl-acetate (VA) units repeat randomly, where the ratio is usually higher for Et units leading to commercial EVA with a VA content around 28-33%. Regardless the ratio, EVA for PV applications contains crosslinking agents, UV stabilizers, etc. In a finished PV module manufactured with EVA, some crosslinking agents remain in the form of peroxides. These peroxides are thought to be the responsible for several degradation modes related to the encapsulant such as discoloration of encapsulants [13, 32].

Backsheet degradation having recently identified as a one of the major causes of defects in PV modules [33]. Typical degradation patterns start with a loss of mechanical and thermal stability, electrical insulation and moisture and gas ingress. Later on, the backsheets can fail by delamination [34, 35, 16], interdelamination and cracking [36, 37, 38]. Yellowing of backsheets it is also a possibility [39, 40, 41]. It has been reported that several field-exposed PV modules were affected by backsheet degradation within the polymeric layers. Most of the backsheets have a multilayer architecture with a core layer usually of composed of polyethylene terephthalate (PET) and outer layers made with other type of polymers, typically fluoropolymers; but also backsheets with outer layers based on polyamides (PA) and PET have been manufactured [42]. Because of the diversity of requirements a backsheet must fulfill, the different layers in the backsheet should perform specific functions such as electrical insulation, protection against moisture and gas ingress. For example, the presence of severe cracks like in the protective PA layer in the PET-based backsheets or with the decrease in the insulation resistance like in the PET-polypropylene (PP) based backsheets [38]. More recently, the multilayer polyamide composites known as AAA backsheet have shown severe failures due to cracking, delamination or photo-degradation of the outer PA surface [43, 44, 45, 46]. Furthermore, the degradation of AAA has resulted in the photo-degradation of the neighboring EVA encapsulant during a combined Ultraviolet-damp heat (UV-DH) accelerated aging test [47].

The multilayer configuration of backsheet it is intended to take advantages of individual polymers properties like barrier and chemical resistance properties, but creates a problem when doing a failure analysis since it is hard to assign in which layer the degradation or failure started. The impact of backsheet type, i.e., breathable or impermeable, on the moisture induced degradation has been discussed for more reliable PV construction [48]. In general, backsheet degradation due to interactions with the encapsulant are possible and it has not been reported in the literature, however, this is a topic of research also within this thesis. Four examples of degradation mechanisms are shown in this part: (a) EVA thermal-oxidation, (b) EVA photo-oxidation, (c) PET backsheet hydrolysis and (d) PA-based backsheet cracking and chalking.

1.3.1 Process of EVA thermal-oxidation

In general, EVA can be degraded in several ways, but mostly thermo-oxidative. The thermaloxidation mechanism of EVA with high VA content is exemplified in the work of Rimez et al. In their study, the degradation of EVA starts with the so called non-catalytic deacetylation and formation of polyenes (repeating units with C=C bonds) is proposed where acetic acid, inactive and active double bonds are formed. The formation of acetic acid enables the catalytic deacetylation mechanism, and this first step in the EVA degradation stops in the formation with a termination step where all active bonds form inactive bonds. Later on, the degradation of polyenes takes place via chain scission reactions where the inactive bonds forms aromatic compounds and the ethylene units from the EVA produce aliphatic volatiles. Then the degradation goes on at higher temperatures and the presence of oxygen in which the inactive bonds produce now solid aromatic compounds, hydroxyl radicals, water and aromatic volatiles, and the ethylene units produces more volatiles. This step is ultimately degraded when the solid aromatic compounds are further oxidized to carbon dioxide at high temperatures [49].

Allen et al., found that the thermal-oxidation of EVA at high oxygen concentrations produced colored chemical compounds with different functional groups such as hydroxyl/hydroperoxide species, ketone, alpha and beta unsaturated carbonyl groups, conjugated dienes and lactones, different substituted vinyl types as well as anhydrides [50]. Gagliardi et al., also describes schematically the oxidative degradation of EVA at damp heat and environmental conditions aimed for simulations of EVA degradation in PV modules in a similar way to Rimez et al [49]. Both descriptions have the same elements: hydrogen abstraction, oxidation, loss of acetate units, chain cleavage and chain termination [51]. The degradation pathway shown in the work of Gagliardi starts with the parallel degradation of the Et and VAc units in which the acetate units degrade by the abstraction of a hydrogen atom in the Et unit producing a macroradical and a hydrogen radical (Reaction 1 in Figure 1.10). This reaction proceeds, from one side with the formation of a double bonds in the polymer chain and more hydrogen radicals (Reaction 2 in Figure 1.10), and from other side, in the presence of oxygen the formation of carbonyl groups in the polymer chain and the formation of water (Reaction 3 in Figure 1.10). The degradation of the VAc unit can go in two directions, via Norrish type I reaction and Norrish type II. In the first case the Acetate unit is detached from the main chain via C-O bond breakage and the remaining unpaired oxygen from the chain recombine to form a C=O bond and acetaldehyde (Reaction 4 in Figure 1.10). The Norrish type II reaction shows that both hydrogen and the C-O bond will create a double bond and acetic acid as shown in Reaction 5 in Figure 1.10 [51].



Figure 1.10 – Oxidative degradation mechanism of EVA [51].

1.3.2 Process of EVA photo-oxidation

The photo-oxidation mechanism of EVA was proposed in the work of Isarankura et al., via the chain-scission step. In the first step, the formation of free radicals occurs on the tertiary carbon in the EVA molecules. This tertiary carbon radical is rather inert because of a steric effect and stable because of an inductive effect provided by the acetate side groups. Consequently , this reaction pathway is thermodynamically favorable. Subsequently, monomolecular breakdown of the macroradical occurs, resulting in a shorter polymeric chain and primary radical species as shown in Figure 1.11 [30].



Figure 1.11 – Proposed photo degradation mechanism of EVA [30].

1.3.3 Process of PET backsheet hydrolysis

Polyethylene terephthalate (PET) is a polyester thermoplastic polymer. It is the most used polymeric component in photovoltaic backsheets due to it cost-properties ratio and known low water vapor and oxygen transmission rates [52, 53]. This polymer can be used in a multilayer configuration as the core layer and a core-outer layer. In PV backsheets, the PET polymer film is known to be sensitive to hydrolysis at a certain temperature [41, 54, 36, 55]. This degradation occurs by the hydrolytic cleavage of the ester linkage, during which each chain scission consumes one water molecule and generates one carboxyl and one hydroxyl end group as shown in Figure 1.12 [56].

It is mostly affected by moisture content, temperature, initial morphology and crystallinity, and initial carboxylic end group content in the polymer and results in decreased molecular weight, increased crystallinity, increased elastic modulus, which yield embrittlement, and increased carboxylic acid end group concentration [56].



Figure 1.12 – Hydrolytic Degradation of PET [57].

PET hydrolysis mechanisms have been investigated by many research groups [58, 59, 60, 61, 62] for various chemical environments, i.e., acidic, neutral, and basic conditions. Moreover, PV modules and thus PET in the backsheet structure mostly face moisture and humidity caused by rain or dew at normal temperatures during outdoor deployment.

1.3.4 Process of PA-based backsheet cracking and chalking

Backsheet cracks have been recently identified as a one of the major causes of defects in PV modules [33]. Typical degradation patterns start with a change of properties which hamper the fulfilment of the backsheet's basic functions, such as mechanical and thermal stability, electrical insulation and prevention from moisture and gas ingress. It has been reported that several field-exposed PV modules were affected by backsheet chalking within the polymeric layers [38, 63].



Figure 1.13 – Photograph of PV backsheet degradation in the field cracking (left) and chalking (right).

Although this chalking effect doesn't lead to further module degradation modes including

electrical performance degradation, there are some examples where the presence of this white powder in backsheet layers coincides with severe cracks like in the protective polyamide (PA) layer in the PET-based backsheets (Figure 1.13) or with the decrease in the insulation resistance like in the PET-PP based backsheets [64]. More recently, the multilayer polyamide composite known as AAA backsheet attracted interest due to its remarkable cracking degradation, including core layer defect, delamination between inner/core layer and a photo-degradation of the outer PA surface [44].

1.4 The impact of PV module manufacturing on the degradation mechanism

The c-Si PV module fabrication process can be divided into three primary areas; (#1) stringing and tabbing, (#2) lamination, and (#3) integration of junction box and bypass diode(s) [65]. Each of these processing steps can impact the reliability and durability of PV modules during its service lifetime in the field. The ultimate goal of this part is to identify appropriate techniques and characterization methods that can be utilized within a module manufacturing facility to improve the reliability and durability of the final product.

1.4.1 Soldering & tabbing

In the soldering and tabbing process, tin plated copper ribbon (or tabs) are soldered to the cell busbars on the front side, with sufficient length extending beyond the edge of the cell to provide contact to the rear of the adjacent cell. A string is then formed when several cells are placed in series and the excess ribbon from one cell is soldered to the metallic back contact of the adjacent cell [65]. Conventional interconnects are soldered in the cell busbars, extending much of the length along the busbar to improve the conductivity [66]. Furthermore, a combined stringing and tabbing "tabber stringer" was developed for the reduction of the additional damage to the cells [67].

Several different failure modes can develop during or as a result of the cell interconnection processes. The failure modes identified are micro-crack formation and cell fracture, solder bond failure [68], ribbon or inter connect failure [69], and corrosion [70, 71, 72]. Micro-cracks, which may lead to cell fracture and increased module series resistance, can develop due to stresses caused by differences in coefficient of thermal expansion or applied pressure from soldering.

Methods to avoid cell damage during soldering include using a low yield strength ribbon to allow for expansion during cooling and simultaneous stringing and tabbing reducing the thermal stress induced from the two soldering processes. Increased resistance also results from solder bond failure, which can be a result of poor solder-ability of the cell metallization incompatible solder metal alloys, inappropriately sized solder joints, or metal diffusion from the solder.

Introduction

Ribbons can fail as a result of thermally-driving stresses, resulting in increased resistance and current crowding. Corrosion, although driven generally by moisture and other contaminants within the laminate has also been linked to the laminate conductivity and both negative and positive biases during operation.

A number of analysis techniques including methods for individual component as well entire modules have been used to characterize and predict durability issues during the stringing and tabbing process step.

Interconnect degradation can be determined through measurements of module series resistance, which can be measured using illuminated or dark I–V curves, a cell line checker tool in the field [73, 74, 75], or qualitatively through electroluminescence imaging, which has also been used to identify grid-finger failures and cell fracture [76, 77, 78, 79]. Infrared thermography, both steady state and lock-in, can be used to evaluate hot spots that form due to weak or failed solder bonds resulting in Joule heating of the solder ribbon [80, 81, 82]. Additionally, thermal cycling can be used as a method to stress solder bonds and interconnects, to screen modules for issues related to thermal expansion [83].

There are also several component level tests that can be used to quantify properties of materials used and determine the quality of solder bonds or interconnects. The peel test can be used to determine the adhesion between the cell interconnect and the cell metallization [84]. The pull test can be used to determine the maximum stress level before failure [85]. Cycling fatigue test is useful in determining ribbon cycle life time [86]. Information about solder bond morphology and micro structure can be obtained through electron microscopy as well as x-ray spectroscopy techniques [87, 88].

1.4.2 Lamination process

The lamination step is the process of encapsulating interconnected cells to provide mechanical support, offer protection from environmental stresses as well as from the produced voltage, and ensure safe and reliable operation in the field. A typical packaging scheme, or laminate, utilizes a glass front cover, multilayer polymer backsheet, and internal encapsulant such as EVA. Failure of the fundamental functions of the module packaging can lead to safety hazards, degradation of internal components or complete failure of the module. The failure modes identified for the module packaging itself were discoloration, delamination, mechanical failure and backsheet degradation.

The laminate also has a significant influence on degradation mechanisms of the active internal components including potential induced degradation within the cell and corrosion of the cell interconnects, metallic front or rear contacts, and cell anti-reflection coatings [65].

For understanding materials interactions after lamination, and for failure analysis or aging studies, methods for extraction of various properties of the encapsulation materials have been identified. That include: chemical analysis for determination of critical glass transition

temperatures, curing temperatures, level of crosslinking or curing [89, 90, 91, 92, 93, 94], chemical structure [28, 41, 95, 96, 50], morphology, impurity content (e.g. moisture, acetic acid), and moisture/oxygen transmission and diffusion rates [97, 52, 53]; mechanical analysis for determination of hardness, storage modulus [89], elastic modulus [98, 91], viscosity, tensile strength, fracture strength, glass surface stress and laminate stress state [99, 100]; electrical analysis for volume resistivity, dielectric strength, and module insulation resistance [65]; and finally interfacial adhesion analysis through various adhesive strength measurement techniques [101, 102].

More recently, the Coefficient of Thermal Expansion (CTE) of different backsheets were measured and used in the Finite Element Analysis (FEA) [103]. As a result, because of an anisotropic CTE behavior of the backsheet the probability of cell fracture is increased during lamination.

There is a wide range of techniques available, however a comprehensive series of tests or thorough quality assurance protocol is required to ensure materials and lamination processes being used will provide adequate performance over the operational lifetime of the module. There are several groups working to identify the key metrics required to evaluate potential materials or processing conditions prior to incorporation into the lamination step of the module manufacturing line. Therefore, a detailed study is discussed in this thesis for the contribution to the research field of the lamination process.

1.4.3 Integration of junction box & bypass diode(s)

Breakdown of the basic functionality of the junction box and included protective bypass diodes can have a significant impact on the reliability and durability of the PV module. Junction box delamination can result in electrical shorting, ground faults, or corrosion. Series arcing with in the junction box is also a potential result when there is an open circuit condition between two nearby points. This can be caused by poor solder joints between string interconnects or module connector leads, failure of bypass diodes, corrosion of electrical contacts, or degradation of electrical insulation.

There are a number of mechanisms that result in bypass diode failure, which include electrostatic discharge (ESD) [104], thermal runaway [105], and thermal fatigue [106, 107]. Bypass diodes are sensitive to ESD, which can occur within a module manufacturing facility and lead to premature failure of a PV module if proper ESD precautions are not taken. The properties of the diode must also be considered, including the current–voltage characteristics and junction operating temperature, to avoid thermal runaway when the diode rapidly returns to reverse bias from a high temperature forward bias state and to avoid thermal fatigue if extended hot spot conditions occur in the field [65].

In the field, the operating condition of bypass diodes can be identified (including identification of failed diodes), through the use of infrared thermography [81, 108], module current–voltage measurements, or with an on contact voltage tester (i.e. diode checker).

Until only recently, reports on the field performance and reliability of by pass diodes have been missing from the literature. As an example, the Adhesion loss between junction box and backsheet is attributed to an unspecified alternative adhesive. Several techniques have been discussed that allow one to monitor the functionality of bypass diodes in order to prevent catastrophic failure of the module through over heating or arcing. Additionally, new techniques to monitor the performance of bypass diodes in the field, prior to failure, need to be developed. There is also a need to qualify the use of diodes based on their resistance to failure as well as their compatibility with the junction box system and module electrical characteristics [65].

1.5 The impact of climatic zones on the degradation mechanism

Regardless the type and nature of each polymer, it is also common to differentiate them by their application, namely the function, and therefore the implied environment in which they will operate or being used during their service lifetime. Polymeric materials will be exposed to specific and controlled environments or free and uncontrolled environments, the latter depending mainly on weather conditions.

The speed or rate in which these polymers degrade is still not completely known and can be estimated experimentally. Whether the same polymer will degrade slower or faster in a controlled or uncontrolled environment is also unknown, but experiments can be done to find correlations [109]. In controlled environments, the degradation mechanisms and degradation rate of a polymer may be attributed to a single factor, load or stress e.g. temperature, radiation and humidity [26, 110]. In uncontrolled environments, the degradation mechanisms and degradation rate of a polymer it is not so trivial and can't be attributed to a single factor, stress or load, but to their superposition or combinatorial effect and material interactions, making the natural weathering of polymer a difficult task to study [110]. Climate is the resulting combination of atmospheric factors such as temperature, relative humidity and light measured over a long period of time, and weather is the short-term description of these combined atmospheric factors [26].

Within a certain climate, different sub-climate conditions can coexist. In fact, regions characterised by peculiar atmospheric conditions with respect to the rest of the climate can develop their own subclimate, which is relatively different from the climate. A sub-climate can be as big as a city or as small as a backyard or a rooftop. This concept makes the location of weather stations relevant. In material science, a microclimate is decisive for aging, and the localized climatic conditions are not the temperature, humidity, etc. values of the surrounding atmosphere, but the values at the boundary layer on the exposed surface [26].

An updated world Köppen-Geiger climate map was deeply investigated and made freely available [111]. To evaluate the performance of PV systems globally and assess risk due to different climate conditions, a methodology for the global Köppen-Geiger-Photovoltaic (KGPV) climate classification that divides the globe into 12 zones with regard to the temperature was proposed.

A set of electrical and thermal performance indicators of crystalline silicon PV modules in different KGPV zones is analyzed and their evolution over time due to climate changes caused by high greenhouse gas emissions discussed. Results show that the KGPV scheme proves to be a convenient methodology to relate the KGPV climate zones with PV performance [112]. The impact of combined climatic loads on the PV module's maximum power output using a mathematical approach was studied [113]. Three degradation precursor reactions, namely, hydrolysis, photo-degradation, and thermomechanical degradation, are assumed to be necessary for service lifetime prediction.

Furthermore, the climate analysis data set was processed to extract and model the climatic stresses necessary for the calculation of degradation rates. These stresses are then applied to evaluate the three degradation mechanisms (hydrolysis-degradation, photo-degradation and thermomechanical-degradation) and the total degradation rate of PV modules due to the combination of temperature, humidity, and ultraviolet irradiation. [114]. The results of the calculated worldwide degradation rate combining the three degradation mechanisms based on the main climate degradation factors are shown in Figure 1.14.



Figure 1.14 - Quantification of Climatic Stresses (Global Mapping) [114].

By choosing a good degradation model, and understanding the different degradation patterns, an algorithm for degradation trend evaluation was proposed, where a new concept of multiple "time- and degradation pattern-dependent" degradation factors. The model has been benchmarked against existing statistical models evaluating 11 experimental PV systems with different technologies [115]. A more specific rate dependence model employing the modified Arrhenius equations to predict the degradation rate for encapsulant discoloration in different climates was investigated [116]. As the last example, the experimental results have already shown a decrease in properties of EVA in natural field exposure due principally to the specificity of the region characterised by hot and dry climate of Algerian Sahara as specific desert climate [31].

2 Motivation and summary of the thesis results

2.1 Context and gaps

PV modules are multi-layer structured devices in which the solar cells and circuitry are embedded in transparent polymeric encapsulants. These materials are further laminated between glass or polymeric backsheets for additional protection. A careful combination of materials is employed to ensure a service lifetime of 25–30 years: To reach a long-term reliability of PV modules, it is important that each layer retains its properties and functionality over the module lifetime. The power degradation and failure of PV modules can be caused by changes in the mechanical properties of the polymeric components during the module lifetime.

Aging of polymeric materials will occur to some degree—regardless of the selected weathering conditions. Indoors tests or outdoors aging factors (e.g., ultraviolet (UV), temperature, relative humidity (RH) and their combinations) will set in motion a series of processes that leads to degradation. It has been reported that several PV degradation processes are associated with polymer degradation: Discoloration of encapsulants [13, 32] and backsheets [41], backsheet cracking and chalking [37, 38], and delamination [34, 35, 117]. It is therefore critical to understand which aging factor(s) influence the polymer degradation and to what extent. Especially, micro-climatic conditions and load parameters play important roles in polymer degradation.

It has previously been found that small molecules, such as water vapor and oxygen, permeate through the backsheet and initiate degradation processes inside the PV modules [16, 17, 15, 52, 53]. The ingress of such gases is governed by the permeation properties of the polymeric backsheets and/or encapsulation materials used. Significant permeation backsheet selectivity has been observed [53]. For example, backsheets with a PET (polyethylene terephthalate)-core layer represent a relatively strong barrier against oxygen and acetic acid permeations. In contrast to that, PA (polyamide) core layer backsheets typically have much higher oxygen and acetic acid transmission rates (OTR and AATR) at the beginning of the module lifetime [52, 53]. A correlation between the aging behavior of the backsheets and the electrical performances of PV modules has been reported [118, 119, 14, 120].

These results raise the question of how the backsheet permeation properties affect other PV module components, such as the commonly used encapsulant ethylene vinyl acetate (EVA). Different EVA degradation processes have been proposed: via thermal oxidation under dampheat (DH) aging [100, 121, 50, 122, 123, 28] or via the chain-scission mechanism provoked by EVA photo-degradation under UV irradiation [29, 124, 30, 125]. The effect of different microclimates on the aging behavior of the encapsulant has been studied [109]. Moreover, a comparative study of the stability and degradation behavior characteristics of two different types of emerging encapsulant materials for PV modules is investigated. Where a thermoplastic polyolefin (TPO) and a polyolefin elastomer (POE) are compared to the EVA upon exposure to two different artificial aging tests (UV and DH exposure tests) [126]. Nevertheless, the reason for differences in the degradation of EVA in the most predominant aging tests DH and UV remain to be clarified. Additionally, a recent study of combined accelerated aging tests has drawn attention [127].

When it comes to reliability and failure analysis of PV modules, destructive and nondestructive testing techniques are often applied to investigate the root cause of failures. Although destructive techniques are common since they require simple sample preparation, they may prevent further testing on the same samples. Nevertheless, testing PV components individually or embedded in a PV module is a challenging compromise: While the former often requires destructive testing, it does not fully address material interactions during the module's service lifetime [7]. On the other hand, the non-destructive investigation of components at module level still faces the restriction of only few available methods [128]. Therefore, the combination of different destructive and non-destructive methods for the analysis of PV modules is key to collect reliable information and ensure that the modules remain intact [15].

The results of most studies indicate that despite the investigation of EVA degradation using Fourier Transform Infra-Red spectroscopy (FTIR-ATR) [50, 122, 123, 28, 125, 109, 129], Raman spectroscopy [109, 130], Differential Scanning Calorimetry (DSC) [100, 124, 125, 109, 90, 89, 102, 131, 132, 133, 134, 135] and tensile tests [125, 136, 137], the correlation between EVA chemical, thermal, optical and mechanical properties with stress factor changes remains unclear. Furthermore, the effect of the backsheet's permeation properties and material interactions on the encapsulant degradation has not been completely investigated. Particularly, with all the polymeric materials present in the in the PV modules in the field in 2021 (Figure 2.1) [138], all material composition should be tested and well classified.

In this thesis, different backsheets from all categories in Figure 2.1 were analyzed to understand their influence on different EVA encapsulant degradation processes. Subsequently, chemical, thermal, optical and mechanical characterization methods were used to detect and understand the degradation of the encapsulant caused by applying both dry-UV and DH aging tests separately and simultaneously. Furthermore, the need of the UV-DH combined test is very crucial to be able to age samples further and do interim characterization. Therefore, Kinetic information on the aging mechanism is then investigated.



Figure 2.1 – Polymeric materials present in the PV modules in the field in 2021 [138].

2.2 Structure of this thesis

This thesis analyzes multiple critical aspects of the encapsulation process and reliability of PV modules. Specifically, the long-term reliability of crystalline silicon PV modules with EVA encapsulant and different backsheets is selected as a model system. **Chapter 3** presents the experiment methodology and applied techniques. This includes the lamination of the different structures and systems, the indoor reliability tests and large amount of characterization methods for the polymer components as well as the PV modules failure analysis.

Chapter 4 covers the two advanced characterization methods for PV polymer component degradation (nanoindentation and scanning acoustic microscopy (SAM)) by providing detailed information on the theoretical background of both techniques and by using some examples such as, analysis of field-degraded polymeric materials in the PV modules. The thesis highlights i) the development of nanoindentation for a fast, reduced scale and an accurate determination of viscoelastic changes of the polymeric materials in PV module and ii) a nondestructive ultrasonic method for detection of polymer defects inside PV modules.

Chapter 5 to 7 present the main results of the experiments. **Chapter 5** covers the changes in the mechanical properties of the polymeric components during the lamination step and their correlation to the curing process. Those material properties are deduced from the two new techniques and procedures developed in **Chapter 4**. Additionally, a comprehensive study showing the correlation between encapsulant degree of crosslinking and moisture ingress into PV laminates during the accelerated aging tests is presented. In **Chapter 6**, the focus is shifted to the different encapsulant degradation mechanisms under the influence of different back-sheets used in the laminates as well as the different aging tests applied. After the discussions on the encapsulant's chemical, mechanical, thermal and optical changes, in **Chapter 7**, the thesis explores the correlation between critical parameter changes in the polymers and module performance characterization (e.g. IV curves) under the influence of the different backsheet used in the modules as well as the different reliability tests performed. Moreover, defects in degraded PV modules are analyzed by SAM and the results are compared with well-established non-destructive methods: Dark Lock-In Thermography (DLIT) and Electroluminescence (EL). Finally, **Chapter 8** draws the conclusions and perspectives of further research.

This thesis contributes to the research field with the main findings as below:

- Based on nanoindentation analysis, the mechanical parameters of the EVA encapsulant is found to be capable of optimizing the module encapsulation process as well as the environmental impact of the PV module. Furthermore, the results of dynamic mechanical analysis (DMA) testing have validated the nanoindentation on the encapsulants as a robust and fast technique for the viscoelastic properties determination. This thesis is the first research to detect the EVA surface's viscoelastic changes using time-dependent cycle modes nanoindentation.
- The work has used incorporated miniature digital humidity sensors at different EVA depths in PV laminates to identify the correlation between EVA's degree of crosslinking and the monitored moisture ingress. A short lamination results in a weakly crosslinked EVA and enhances a higher degree of crystallinity which acts as a diffusion barrier for the moisture ingress.
- The research presents the verification of SAM as a reliable and nondestructive method for the measurement of the acoustic and mechanical properties of the polymeric foils (backsheet and encapsulant) separately inside PV modules. Thus, to obtain more information about aging-induced material changes and degradation. The thesis further demonstrates that this is the most suitable methodology for major PV module configurations (glass-glass and glass-backsheet modules) over the existing testing methods that are time-consuming, destructive, or limited to specific module configurations.
- We investigated SAM as a reliable and complementary technique to dark lock-in thermography and electroluminescence techniques in PV modules. SAM can precisely locate defects such as backsheet cracking and delamination in specific interlayers without destructing the PV module. We demonstrated the vertical profile visualization of PV modules which can be applied to detect thickness variations within the polymeric layers.
- Backsheet properties have different impact on the PV module encapsulation degradation. The research presents how different material combinations influence different EVA degradation mechanisms (chemical changes) leading to different EVA degradation rates (thermal and mechanical changes).
- EVA suffers the strongest chemical and optical degradation when high UV, high temperature and high relative humidity are combined simultaneously. Moreover, the performance degradation of the PV module is much more severe and stronger under this combined UV-DH test than the addition of both factors individually. Based on experimental measurements, it is shown that moisture has a significant impact on degradation mechanisms driven by combination of UV, relative humidity and temperature stresses which is consistent with the simulations that have been done in previous studies.

- The research has achieved laboratory-produced backsheet cracking (e.g., in the case of AAA backsheet and coated PET backsheet) to simulate field-degraded backsheets. This demonstrates the role of moisture inside a PV module in catalyzing the photodegradation in the formation of backsheet cracking.
- The research detected the need to bridge material combination and module long-term reliability and launched the attempt to set up the missing link. The effects of various backsheet types on the module reliability in UV-DH combined accelerated test are first studied in this thesis.

All the results presented in this thesis are original, unless otherwise mentioned or referenced.

3 Materials and methods

3.1 Lamination

Laminates of type I were manufactured for the investigation of new methods for the detection of the encapsulant degree of curing (DoC) after lamination (see **Chapter 5**). The samples of 20 x 20 cm² were prepared by laminating a layer of commercially available backsheet, 2 layers of 450 µm EVA: PHOTOCAP® 15580P/UF, Specialized Technology Resources, Inc. as encapsulant and a low-iron transparent solar glass cover using different lamination processes: curing temperature from 120°C to 160°C in 10°C steps and curing time from 2 to 12 min in 2 min steps. Using a MEIER ICOLAM 10/08 vacuum laminator, a pressure of 10 mbar was held in the lamination chamber. Upon reaching the set temperature, a pressure of 800 mbar was applied via a membrane to the lamination stack. During the lamination process the temperature was recorded using 2 type-K thermocouples with a measurement error of 1.5 K.

Simultaneously samples for the DoC measurements by Differential Scanning Calorimetry (DSC) (section 3.3.6) [139] and Dynamic Mechanical Analysis (DMA)-tensile tests (section 3.3.2) were laminated according to the following setup using the same lamination cycle: 1 Teflon based release sheet (50 μ m), 2 layers of EVA: PHOTOCAP® 15580P/UF, Specialized Technology Resources, Inc., 1 Teflon based release sheet (50 μ m) and a transparent solar glass cover (20x20 cm²). After removing of the EVA sheet from the release sheets, samples were punched using a 6 mm x 20 mm punch machine for DMA-tensile tests (section 3.3.2) and 4 mm diameter punch machine for DSC measurements (section 3.3.6).

Laminates of type II were manufactured for a kinetic study of the moisture ingress/egress under the influence of material combination and lamination condition (see **Chapter 5**). Three samples of 20 x 15 cm² were assembled by incorporating miniature temperature and humidity sensors. In this study, three laminates were prepared. The following components were used (see Table 3.1):

- Two different PET-based backsheets from different manufactures.
- Four layers of EVA from the same manufacturer and one glass plate for each laminate.
- Flexible sensor stripes with 4 humidity sensors for each laminate.

Three of the sensors were laminated between the EVA layers at different distances from backsheet and the fourth was left outside the laminate for air humidity measurement (Figure 3.1). Sensor #1 was placed between the EVA and the glass, sensor #2 was laminated in the middle of the sample between two EVA layers on each side and sensor #3 was installed between the EVA and the backsheet. Since the moisture enters perpendicular to the backsheet surface, the lateral displacement of the sensors does not affect the humidity concentration.

Laminates	#a	#b	#c
Backsheet	TPT	CPC	TPT
Lamination time [min]	10	10	5
Degree of Curing (DoC) [%]	High	High	Low
Thickness [µm]*	350	150	350
water vapour permeation [g/m ² .d]*	0.7	3.9	0.7

Table 3.1 – Different setup of the lamination and backsheet type used.

*Supplied in the product's datasheets

@23°C/85% RH for #a #c and @38°C/90% RH for #b.



Figure 3.1 – Left: Schematic representation of the sensor positions in the laminate. Middle: Overview of the components used for assembling the laminates before adding the backsheet. Right: Assembled samples after lamination with an external digital acquisition reader.

The sensor strips containing miniature temperature (T) and relative humidity (RH) sensors were encapsulated in various laminates. The sensors used were Sensirion SHT-25 and SHT-W2. Both have been shown to be resistant to the high temperature and able to measure the humidity in the encapsulant accurately [140]. The strips were connected to a printed circuit board (PCB) containing the necessary readout electronics. Custom software is used to evaluate the measurement results.

10/08 vacuum laminator.

20 cm

20 cm

Laminates of type III were manufactured for the investigation of The EVA degradation under the effect of different backsheets properties (see **Chapter 6**). To this end, five different types of commercially available backsheets were used in the laminates. These laminates were prepared by adding to each backsheet two layers of EVA:PHOTOCAP® 15580P/UF, Specialized Technology Resources, Inc., as encapsulant and a low-iron transparent solar glass cover (as shown in Figure 3.2 and illustrated in Figure 3.3) in one lamination run using a MEIER ICOLAM

Clasmation method PO Image spin Color (mag) Image scale(meth) 1144-1144 Image scale(meth) 1445-1440 Color:the Amer 1444/14100000 Color:the Amer 1444/14100000 Color:the Amer 1444 Total magnetication: 1344	Glass ~ 3	3000 µm	
1	11.11		
	EVA ~ a	800 µm	
	Backsheet	t ~ 200 μm	
200 µm			-

Figure 3.2 – Digital microscopy image of the sample cross-section to illustrate the sample's structure after lamination.

Backsheet type	Thickness [mm]*	Comp (outer/core/inner)
AAA_White	0.35	PA/PA (Co-extruded)/PA
CPC_White	0.17	Coating/PET/Coating
TPT_White	0.35	PVF/PET/PVF
APA_White	0.39	PA/PET/Al/PA
DyMat-Transparent	0.30	Pet-Pet-Primer
* Supplied in the product's datasheets.		
Polymeric backsheet Encapsulant Encapsulant PV glass		Polymeric backsheet Encapsulant Solar cell Encapsulant PV glass

Table 3.2 – Backsheets used to laminate the PV modules.

Figure 3.3 – Schematic representation of the **Laminate of type III** (left) and the **PV module of type IV** (right).

20 cm

20 cm

PV modules of type IV was manufactured for the investigation of induced failure and degradation by using non-destructive imaging techniques (This study is presented in **Chapter 4** and **Chapter 7**). The modules were prepared using four different backsheets, EVA: PHOTOCAP® 15580P/UF, Specialized Technology Resources, Inc., monocrystalline silicon cells (15.7 x 15.7 cm², 243.6 cm²), and PV glass according to the layout presented in Figure 3.3. The interconnect ribbons were soldered onto the busbars of the cells. The lamination settings applied were standard lamination conditions for regular EVA: curing time and temperature of 10 min at 160 °C, respectively, at 900 mbar pressure, total lamination duration of 25 minutes. All the modules were laminated in the same laminator as for **Laminates of type I** and **Laminates of type III** (see Figure 3.4).



Figure 3.4 – Encapsulant preparation for the lamination (left), PV components for **PV modules of type IV** laid out on a MEIER ICOLAM laminator (Right).

Finally, **Full size PV modules of type V** from different power plants, exhibiting features that suggest an advanced stage of backsheet degradation, were analyzed and compared (see **Chapter 4**):

- **Case 1**: Field aged PV module with damaged white polypropylene (PP) inner backsheet layer.
- **Case 2**: Field aged PV module with backsheet cracking between the cells and backsheet chalking.

To confirm the observations from scanning acoustic microscopy (SAM) imaging, samples of backsheets were carefully extracted from the rear side in between the cells and embedded in epoxy resin, ground and polished to allow subsequent analysis of the backsheet cross sections with a Olympus reflected-light microscope.

3.2 Reliability tests

This section describes the aging tests carried out to induce failures and defects on the PV laminates and modules. The artificial aging tests selected are described as follows.

3.2.1 Damp-heat (DH) exposure

The damp-heat aging test (DH) was conducted according to IEC61215-2:2016 (MQT 13) [141]. The test conditions are: 85% relative humidity (RH) at 85 °C. The **Laminates of type III** were then subjected to indoor accelerated aging tests under the (1) DH tests in time intervals of 500 h (Step 1) up to 4000 h (Step 8) (see **Chapter 6**). In parallel, the **PV modules of type IV** were aged under the same DH test conditions for 1000 h, 1500 h and 2500 h (see **Chapter 4** and **Chapter 7**).

The **Laminates of type II** were subjected to a different DH tests, where for three constant temperatures (T) (40, 60 and 85 °C), the relative humidity (RH) in the climatic chamber was varied as shown in Figure 3.5. The RH was kept constant until equilibrium of the sensors was reached (see **Chapter 5**).



Figure 3.5 – RH cycle for each constant temperature.

3.2.2 Ultraviolet (UV) exposure

The dry-UV test was conducted according to IEC61715-2:2016 (MQT 10) [141]. The test conditions are performed with fluorescence tubes (UV-B : 15%) at 60°C and at a relative humidity below 5%. The spectral irradiance of the fluorescence tubes which were used for the UV aging test is shown in Figure 3.6. The temperature was measured behind the laminates with a PT100 temperature sensor. The temperature was found to be 60 °C on average. The relative humidity was not controlled in the climatic chamber and can be estimated to < 5% RH. The **Laminates of type III** were subjected to indoor accelerated aging tests under the (2) dry-UV tests in dose intervals of 60 kWh/m² (Step 1) up to 480 kWh/m² (Step 8) (see **Chapter 6**). The **PV modules of type IV** were sequentially aged after DH tests under the same dry-UV test conditions for 240 kWh/m² and then for 420 kWh/m² (see **Chapter 4** and **Chapter 7**).



Figure 3.6 – UV chamber TLPV, spectral distribution.

3.2.3 Combined UV/DH exposure

The combined UV-DH (air 60°C/ 85% RH) test (see the climatic chamber in Figure 3.7) was conducted with the same aging intervals as for the dry-UV test. This combined test (3) aims at a more realistic representation of degradation by simulating multiple factors simultaneously, where the UV irradiation is comparable to the dry-UV test using the same type of UV fluorescence tubes [47]. A summary of the specifications of the backsheets used and aging conditions for Laminates of type III (see Chapter 6) and PV modules of type IV (see Chapter 4 and Chapter 7) can be seen in Table 3.2 and Table 3.4 respectively.



Figure 3.7 – UV-DH combined chamber.

Backsheet type	Total DH duration (1) [h] (Step 8)	Total Irradiation Dose (2) [kWh/m²] (Step 8)	Total Irradiation Dose- DH (3) [kWh/m²] (Step 8)
CPC_PET-based BS_1	4000	-	480
TPT_PET-based BS_2	4000	480	480
AAA_PA-based BS	4000	-	480
APA_Alu-based BS	-	480	480
PPP_transparent BS	-	480	480

Table 3.3 – Summary of sample configuration of Laminates of type III and aging conditions.

Table 3.4 – Summary of sample configuration of **PV modules of type IV** and aging conditions.

Backsheet type	Total DH duration [h] -> Total Irradiation Dose [kWh/m²]	Total DH duration [h] -> Total Irradiation Dose-DH [kWh/m ²]
CPC_PET-based BS_1	-	2500 -> 420
TPT_PET-based BS_2	-	2500 -> 420
AAA_PA-based BS	2500 -> 420	2500 -> 420
APA_Alu-based BS	2500 -> 420	2500 -> 420

3.3 Characterization methods for PV polymer components

3.3.1 FTIR-ATR spectroscopy

Changes in the chemical composition (e.g. functional groups) of EVA surfaces were investigated using Fourier transform infrared spectroscopy (FTIR) by monitoring the appearance or disappearance of functional groups using a PerkinElmer Spectrometer equipped with a Diamond crystal detector in Attenuated Total Reflection (ATR) mode.

FTIR is sensitive to dipole moments of the vibrations of chemical bonds. Mid-Infrared (IR), absorption spectroscopy technique was used with a broadband source and a Michelson interferometer to modulate the optical path difference and thus collect spectra from a number of wavelengths simultaneously (see Figure 3.8). This reduces scan time and increases resolution (higher signal-to-noise ratio). The ATR technique measures the absorption of the evanescent wave created at the interface of the sample and the ATR crystal, measuring < 2 μ m depth.



Figure 3.8 – Principle of ATR operation

The evaluation was obtained by averaging three repeated measurements over the spectral range between 4000 cm⁻¹ and 750 cm⁻¹ for each sample in **Laminates of type III**. The initial samples and the aged samples were prepared for FTIR-ATR spectroscopy measurements (see **Chapter 6**) as follows: The glass-encapsulant interface was separated using a chisel type blade which allowed the extraction of 20x20 mm² backsheet-encapsulant films (see Figure 3.9). This sample preparation is designed for nanoindentation (**Section 3.3.3**) and shear tests at Dynamic Mechanical Analysis (DMA) (**Section 3.3.2**) characterizations, where the results are discussed in **Chapter 5** and for FTIR-ATR characterization, where the results are discussed in **Chapter 6**. Using this latter, the EVA surfaces were analysed at glass interface by peeling off the polymer film and at backsheet interface by peeling off the EVA from the backsheet.



Figure 3.9 – Schematic depiction of the investigated laminate during the sample preparation for characterizations

3.3.2 Dynamic Mechanical Analysis

Dynamic Mechanical Analysis (DMA) is an established method for studying the viscoelastic behavior of EVA PV encapsulants [91]. After each lamination of the **Laminates of type I**, the polymer film samples were measured by a Netzsch 242 E DMA for the determination of the storage modulus (E') and the loss modulus (E'') at room temperature at varying frequencies.

The storage and loss moduli represent the elastic portion or stored energy (storage modulus E') and viscous part or dissipated energy (loss modulus E'') of the material, respectively [142]. They are defined by the Eqn 3.1 and Eqn 3.2.

$$E' = \frac{\sigma_0}{\epsilon_0} \cos\delta \tag{3.1}$$

$$E'' = \frac{\delta_0}{\epsilon_0} \sin \delta \tag{3.2}$$

Where σ_0 and ϵ_0 are stress and strain, respectively and δ is the phase shift between stress and strain. The strain lag δ is often used in form of $(tan\delta)$, which is called the damping factor and is defined by the following Eqn 3.3.

$$tan\delta = \frac{E''}{E'}$$
(3.3)

The damping factor ($tan\delta$) describes the materials ability to disperse and absorb energy in relation to the stored potential energy in the material viscoelastic behavior of the polymers (see **Chapter 5**). In this thesis, two analytical modes of DMA were used:

- Shear mode: 3 samples (backsheet-EVA laminates) of **Laminates of type I** have been prepared as described in **sections 3.1 and 3.3.1** for shear mode measurements (Figure 3.10). From these laminates 9 mm diameter samples were punched.
- Tensile mode: 3 samples (EVA films) of **Laminates of type I** have been prepared as described in **section 3.1** for tensile mode measurements as shown in Figure 3.10. EVA sheet was removed from the release sheets and was punched using a 6 mm x 20 mm punch.



Figure 3.10 – Schematic illustration of the DMA assembly applied to the multilayer EVA-BS film for the shear mode (left) and to the EVA sheet for the tensile mode (right).

3.3.3 Nanoindentation

The instrumented indentation technique involves pressing an indenter of known geometry into the material while both normal load and penetration depth are monitored. From the obtained force-displacement curve, the indentation hardness (*HIT*), elastic modulus (*EIT*) [143, 144], viscoelastic properties of polymers [145, 146] and other mechanical properties [147] can be obtained.

The analysis of indentation curves is mostly done by the method of Oliver and Pharr as presented in Figure 3.11 [143]. The unloading curve of the load penetration curve can be fitted [148] according to Eqn 3.4, where h_p is the permanent indentation depth, h_c is the contact depth of the indenter with the sample at the maximum force F_{max} , h_{max} is the maximum indentation depth and *m* is a fitting parameter. The parameters h_p , h_{max} and h_c are illustrated in Figure 3.11.

$$\frac{F}{F_{max}} = \left(\frac{h - h_p}{h_{max} - h_p}\right)^m \tag{3.4}$$

34



Figure 3.11 - (a) Schematic indentation load-displacement curve with the slope S of the unloading curve used in the Oliver and Pharr analysis. (b) Cross section of a conical indenter tip [146].

$$S = \left(\frac{dF}{dh}\right)_{max} \tag{3.5}$$

The contact stiffness *S* is the slope of the fit for the beginning of the unloading curve (see Eqn 3.5). Where $A_p = f(h)$ is the contact area of the indenter tip for a given indentation depth *h* and β is the geometry factor of the indenter tip. Based on Oliver and Pharr method, the hardness (*H*) is defined as the pressure the material will support under load and is calculated from the peak indentation load (*F*_{max}) divided by the projected area (*A*) according to Eqn 3.6.

$$H = \frac{F_{max}}{A} \tag{3.6}$$

35

The reduced modulus E_r can be calculated [148] by Eqn 3.7. E_r is obtained by the slope of the unloading curve assuming that the unloading is purely elastic. Eqn 3.8 defines the relationship between the elastic modulus E_i the reduced modulus E_r and E_i , the elastic modulus of the indenter ($E_{diamond}$ =1141 GPa). v_i as Poisson's ratio of the indenter tip with $v_{diamond}$ =0.07. For the following experiments we assumed v_s =0.3 for EVA and backsheet.

$$E_r = \frac{\pi S}{2\beta \sqrt{A_p(h_c)}}$$
(3.7)

$$\frac{1}{E_r} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu_i^2)}{E_i}$$
(3.8)

First, the nanoindentation tests were carried out on the cross-sections of the **Laminates** of type III (Figure 3.2). The objective of this study was to identify the mechanical/hardness properties changes along the thickness of the polymeric layers inside PV modules (see **Chapter** 4). For the **Laminates of type III**, the cross-sections were extracted at a distance of at least 3 cm from the edge, to avoid effects from lateral humidity transmission, by using a glass cutter to cut the glass followed by a sharp scalpel to cut the polymer layers. The cross-sections were then embedded in epoxy resin and polished with polycrystaline diamond suspension. In this part, nanoindentation was used to investigate the changes in hardness occurred during accelerated aging of the backsheet and EVA layers cross-section in the **Laminates of type III** with a high spatial resolution.

Nanoindentation on the cross-section experiments were performed using the Nano Hardness Tester NHT³ from Anton Paar GmbH. The system has load and displacement resolution of up to 500 mN and 200 μ m, respectively. A three-side pyramid with an area-to-depth function similar to a Vickers diamond indenter geometry, was used in all experiments as shown in Figure 3.12. The data analysis is instrumented and can be done automatically via Anton Paar's indentation 8.0.26 software. This is an advantage compared to classical hardness measurements in which each imprint has to be precisely measured separately with a microscope.

The indentations were performed at a distance of $44 \,\mu\text{m}$ between each point. The possible distance between the indentations is inversely proportional to its depth. A deeper indentation affects a larger area of the polymer and the distance between the measurements have to be large enough to avoid an overlapping. Moreover, the impact of the embedding and the mechanical polishing on the mechanical response of the cross-sections might be significant after the nanoindentation tests.





Moreover, the nanoindentation was used as to investigate the changes in the viscoelastic properties of the encapsulant that occurred during the lamination process and accelerated aging. The force-displacement-time information of the instrumented nanoindentation were interpreted and discussed in **Chapter 4**, **Chapter 5** and **Chapter 6**. Changes in the viscoelastic properties of EVA surfaces were investigated using instrumented nanoindenter machines manufactured by Anton Paar GmbH:

- The Ultra-Nanoindentation Testing (UNHT³) (Figure 3.13) with sphero-conical indenter tip geometry load ranges from 10 μ N up to 100 mN and a penetration depths of a few nm up to 100 mN.
- The Nanoindentation Testing (NHT²) with flat punch-end conical indenter tip geometry has a maximum load of 500 mN.

Figure 3.13 shows a schematic illustration of the head of the indenter, where a reference ball used to monitor the surface of the sample continuously during the measurements using a piezoelectric actuator. This setup allows for an extremely low thermal drift during the indentation tests [150]. The thermal drift of the instrument is usually calculated and calibrated before the measurement [151, 152].

In this work, we focus on flat punch-end conical (a tip diameter of 100 μ m and an opening angle of 60°) and sphero-conical (a tip radius of 0.1 mm and an opening angle of 90° [146]) blunt tip geometries i.e. for shallow indentations. Tip calibration was performed on a fused silica reference sample from Anton Paar with a thermal drift of ~ 0 μ m/N [153]. A distinct advantage of the flat punch geometry is that even in the presence of creep behavior, the contact geometry remains the same, and hence, the amplitude of the oscillation stays stable.



Figure 3.13 – Schematic illustration of the Ultra Nanoindentation Head Assembly applied to the multilayer EVA-BS film.

During nanoindentation creep measurements, typical evolution of the EVA creep h(t) can be approximated by a model consisting of a spring with stiffness C_0 in series with two Kelvin-Voigt bodies (Figure 3.14) (see Eqn 3.9). A priori assumptions can be made in the correspondence solutions regarding linear viscoelastic material behavior and the creep function [154]. The experimental data can be then fitted to the spherical indentation ramp–creep solutions to calculate the values of time-dependent elastic modulus in a Hertz contact model, where the elastic modulus is replaced with creep compliance as function of time [155, 156, 157].



Figure 3.14 – Two Kelvin-Voigt bodies model.

$$(h(t))^{m} = KP\{C_{0} + \Sigma C_{j}[1 - \rho_{j}\exp(-\frac{t}{\tau_{j}})]\}$$
(3.9)

Where *m* is 3/2 for spherical indenter, *K* is $3/(4\sqrt{R})$, *P* is load and the term ρ_j is the ramp correction factor [156, 151]. The Eqn 3.10 describes the creep at the ramp load phase and the Eqn 3.11 describes the creep at the constant load phase.

$$(h(t))^{\frac{3}{2}} = \frac{3P}{4\sqrt{R}} \{ C_0 t + \Sigma C_j \tau_j [1 - \exp\left(-\frac{t}{\tau_j}\right)] \}$$
(3.10)

$$(h(t))^{\frac{3}{2}} = \frac{3P}{4\sqrt{R}} \{ C_0 t_R + \Sigma C_j \tau_j \exp\left(-\frac{t}{\tau_j}\right) (\exp\frac{t_R}{\tau_j} - 1) \}$$
(3.11)

At instantaneous time, the elastic modulus (E_0) is described in terms of all the coefficients C_j : compliances and τ_j : retardation times) (Eqn 3.12) and at infinite long time the relaxed elastic modulus (E_∞) is described using only the elastic coefficient (C_0) (Eqn 3.13) [156, 151, 153].The creep ration (CR) (Eqn 3.14) measures the extent of viscoelasticity, describing how much is the material creeping.

$$E_0 = E(0) = \frac{1}{J(0)} = \frac{1}{(C_0 + \Sigma C_j)}$$
(3.12)

$$E_{\infty} = E(\infty) = \frac{1}{C_0} \tag{3.13}$$

$$CR = 1 - \frac{E_{\infty}}{E_0} \tag{3.14}$$

During a sinus measurement, small load oscillations (amplitude and frequency) are controlled. This load generates displacement oscillations with a phase angle. When testing viscoelastic materials with such a similar oscillatory methods, there is a lag (phase shift) δ in strain compared to force oscillations.

The dynamic mechanical testing method has also been applied to indentation testing. Several research papers summarize the implementation of the model and analysis of oscillatory indentation [158, 159]. Within the limits of linear viscoelasticity (i.e. displacement amplitude should be much smaller than the indentation depth), the indentation storage and indentation loss moduli (E' and E") are given in Eqn 3.15 and Eqn 3.16, respectively [145].

$$\frac{E'}{1-\nu^2} = \frac{\sqrt{\pi}}{2\beta\sqrt{A_p}} (\frac{F_0}{h_0}\cos\delta + m\omega^2 - K_i)$$
(3.15)

$$\frac{E''}{1-\nu^2} = \frac{\sqrt{\pi}\omega}{2\beta\sqrt{A_p}} \left(\frac{F_0}{\omega h_0}\sin\delta - D_i\right)$$
(3.16)

Where v is Poisson's ratio, β is geometrical term, A is projected contact area, F_0 and h_0 are force and displacement amplitudes, respectively and δ is phase shift between force and displacement. K_i and D_i are stiffness and damping coefficient of the instrument respectively, $\omega = 2\Pi f$ where f is the Sinus frequency and m is the mass of the indenter. The oscillation properties of the instrument (stiffness, indenter mass, etc.) are determined during dynamic calibration procedure. This procedure is launched by the user and it is completely automatic.

The viscoelastic response of the tested samples is modeled using a spring with stiffness *S* in parallel with a dashpot with damping factor *D*. Using the half amplitude of load and displacement signals, the measured phase angle and angular frequency of oscillation are used for the calculation of *S* and *D* (Figure 3.15). These two parameters are then used for the determination of (E') and (E'').



Figure 3.15 - Dynamic mechanical model of viscoelastic material [160].

The samples of **Laminates of type I and III** were prepared as described in **sections 3.1 and 3.3.1** for nanoindenation measurements at the EVA surfaces (glass-EVA interface) and outer backsheet surfaces (the results are discussed in **Chapter 5** and **Chapter 6**). The samples require a flat surface with a very low surface roughness, and a support underneath. The loading-holding-unloading parameters for both cycle modes were kept constant for all samples and are presented in **Chapter 4**, where a matrix of 9 measurements with a x and y spacing of 200 µm was performed (Figure 3.16).



Figure 3.16 – Microscopic image of the spherical imprints performed on the EVAs surface after indentation.

3.3.4 Raman spectroscopy

Raman spectroscopy is used to determine vibrational modes of molecules, as well as rotational and other low-frequency modes of systems [161]. For polymer analysis, the application of Raman spectroscopy is widely investigated. Besides material identification, including copolymer composition and structure analysis, a conformational analysis can carried out by Raman spectroscopy. This polymerization analysis is mostly based on the observation of the decrease in the C=C bond vibration of the reactant [130]. Furthermore, the degree of crystallinity of polymers can be determined via certain vibrations which are characteristic for the amorphous or the crystalline phase. One example can be the Raman-spectroscopic crystallinity determination in polypropylene [162]. Another example can be the investigation of polyethylene terephthalate (PET) polymer morphology by the determination of information on molecular orientation and crystallization using Raman spectroscopy [163, 164].

Figure 3.17 shows an example of a Raman spectrum of EVA in a PV module, before and after an outdoor aging test. Before the aging procedure the spectrum shows the typical Raman peaks of EVA. After aging, a broad fluorescence background is present in the whole spectral range. Besides this fluorescence background, also small peaks of the EVA vibrations can be found. The fluorescence in Raman spectra of polymers is mostly caused by presence of chromophores with a $\pi \rightarrow \pi^*$ character. Those compounds have a low energetic state and therefore, low excitation energies are sufficient to promote the molecules [165, 130].

After each aging step of the **Laminates of type III**, the samples were measured non-destructively through the glass using a Raman microscope WiTec Alpha 500 to determine the change in fluorescence background intensity caused by EVA degradation (the results are described in **Chapter 6**). A green laser with a monochromatic wavelength of 532 nm was used for all samples as an excitation source within a Raman shift range from 0 cm⁻¹ to 3800 cm⁻¹.



Figure 3.17 – Typical Raman spectra of a c-Si PV module with EVA encapsulation before and after outdoor aging [166]

3.3.5 Yellowness Index

The Yellowness is defined as the deviation in chroma from whiteness in the dominant wavelength range and the Yellowness index is the magnitude of yellowness relative to a white standard under illumination by a standard light source. The Yellowness Index is a measure for the quantification of the subjective perception of colors by the human eye. This index is most commonly used to evaluate color changes in a material, e.g. caused by accelerated aging. It can be determined via different standards given by the Commission Internationale de l'Ecleirage (CIE) or by the American Society for Testing and Materials (ASTM) [130, 167, 168]. The yellowness index (*Y I*) was calculated using Eqn 3.17.

$$YI = 100.\frac{C_x X - C_z Z}{Y}$$
(3.17)

In which X, Y and Z are the so called 'tristimulus values'. Where X (red), Y (green) and Z (blue) are the specified amounts of each light which are primarily required to match the color of a sample [169]. C_X , and C_Z stand for the chromaticity coordinates. These can be easily obtained by using the diagram shown in Figure 3.18, and the Eqn 3.18 [166].

$$C_x + C_y + C_z = 1 \tag{3.18}$$

As a non-destructive technique, optical changes in the **Laminates of type III** and , due to degradation, were monitored by means of spectral reflectance measurements with a portable ColorLite sph900 spectrophotometer. The measurements were performed according to the standard EN ISE 11664-4 [171], using the CIE L*a*b color scale and calculated values for *YI*.



Figure 3.18 - Chromaticity Diagram and Chromaticity Coordinates [170]

3.3.6 Differential Scanning Calorimetry

Differential Scanning Calorimetry (DSC) measures the enthalpy released by the residual additives in the EVA using a calibration curve to provide the relation between the DSC and Soxhlet methods and it can determine the structural changes in the polymer, e.g. (re-)crystallization. Changes in the curing state behavior of the EVA bulk in the **Laminates of type I** were monitored by means of Differential Scanning Calorimetry (DSC) method after each lamination. The characterization was performed on a TA Instruments DSC Q200 system. The EVA samples were placed in an Al crucible. Thermograms were recorded under constant nitrogen flow and at a heating rate of 10°C/min from 25°C to typically 250°C [172]. The degree of curing (DoC) was calculated using the enthalpy of the crosslinking reaction of the cured samples (H_{sample}) as well as an uncured sample as reference ($H_{uncured}$) [139] as shown in Eqn 3.19.



Figure 3.19 – Typical DSC thermograms of uncured and laminated EVA [139]

$$X(DoC) = 1 - \frac{H_{sample}}{H_{uncured}}$$
(3.19)

43
Figure 3.19 show two DSC exemplary thermograms where the enthalpies of partially cured EVA ($(H_{sample}) = 0.6 \text{ J/g}$) and uncured EVA ($(H_{uncured}) = 20.0 \text{ J/g}$) are deduced, resulting in a DoC of 96.8 %. The complete results are discussed in **Chapter 5**.

Furthermore, changes in the melting enthalpy and temperature as well as crystallization behavior of the EVA bulk in the **Laminates of type III** were monitored by means of DSC before and after the exposure to accelerated aging tests (see **Chapter 6**). The EVA layers were extracted from the laminates and prepared as ~ 500 μ m-thick circular discs and placed in an Al crucible. At least 5 samples per aging step were used and the measurement results were averaged. Thermograms were recorded under constant nitrogen flow and at a heating rate of 10 °C/min using three temperature evolution phases: (1) a first heating phase from 40 °C to typically 180 °C (2) a cooling phase to 40 °C and (3) a second heating phase from 40 °C to 180 °C to identify the reversible processes [47].

3.4 Characterization methods for PV Modules failure analysis (nondestructive techniques)

3.4.1 Visual inspection

Visual inspection was performed before and after accelerated aging tests on **PV modules of type IV** (see **Chapter 7** and **Appendix**). Usually, each module component is inspected separately, and every visible defect is described as precise as possible. Some defects and failures that can be detected visually include burn marks, delamination, corrosion, EVA browning, snail trails, backsheet delamination, bent, and misaligned components, cracks, bubbles, and blisters, loosened parts, scratches, and glass breakage, amongst others. Because other significant defects cannot be detected visually, other advanced methods must, therefore, be employed [16]. A photograph is taken of each **PV module of type IV** front and rear side and more to document the inspection (Figure 3.20). If appropriate, detailed views of damages or changes due to the stress tests are taken.



Figure 3.20 – Photography of the front side (left) and rear side (right) of PV module of type IV

3.4.2 PV performance_analysis of light I-V curves

The I-V curve essentially provides key parameters about the module quality, such as series and shunt resistances, heterogeneity effects, and cell degradation, for example. The measurement conditions consist of providing the modules with a natural or artificial light source under STC (1000 W/m², 25 °C, AM 1.5). A reference module with a similar spectral response is used to measure the current and voltage across the module when an external power supply is applied.

Figure 3.21 presents a schematic illustration of a typical I-V curve of a PV module and the main parameters obtained, including the open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), and the maximum power point (P_{MPP}). The V_{OC} is the maximum voltage achieved by the module when current = 0, and the I_{SC} is the maximum current when V = 0. The point on the curve at which the product of current (I_{MPP}) and voltage (V_{MPP}) is highest is defined as the P_{MPP} . From this, the fill factor (FF) can be derived, which determines the quality of the module. The FF compares the actual maximum power P_{MPP} to a virtual power PT, taken as the product of V_{OC} and I_{SC} if these were the V_{MPP} and I_{MPP} , respectively. The FF is easily calculated as the ratio between the blue and green rectangles in Figure 3.21 [16]. Moreover, the conversion efficiency of a module can be derived from these parameters, and it is defined as the ratio of the maximum power, P_{MPP} , to the incident power In = 1000 W/m² [173] (see **Chapter 7**).



Figure 3.21 – Typical I-V curve of an illuminated PV module [16].

Near the open-circuit voltage, the IV curve is strongly affected by the series (*Rs*). A straightforward method of estimating the series resistance from PV module is to find the slope of the IV curve at the open-circuit voltage point.

3.4.3 Electroluminescence

Electroluminescence (EL) imaging remains one of the main techniques applied for PV module quality testing, in addition to visual inspection and performance measurements [128]. Inactive areas and cell cracks and other failures are easily detected because these will appear dark in the EL image [16, 174].

An EL image is taken while applying current to the module and collecting the radiation it emits. EL images can reveal inhomogeneities and defects like micro cracks on the cell and defective electrical interconnections and ribbons as seen in the example in Figure 3.22.



Figure 3.22 – Electroluminescence images of PV module - front side – before (a) and after reliability test (b).

EL imaging was carried out at the LOANA Solar Cell Analysis System (pv-tools GmbH). The **PV modules of type IV** were measured before and after accelerated aging tests from the glass side. The results are discussed in **Chapter 7**.

3.4.4 Dark Lock-In Thermography

Dark Lock-In Thermography (DLIT) is a consolidated non-destructive technique for solar cell research, and can be applied to analyze shunts and areas of high series resistance [175, 176]. Additionally, other defects detected through DLIT include edge isolation shunts, broken interconnects, bubbles within the encapsulant material, different types of cell cracks [16], and delamination. The **PV modules of type IV** were supplied with a 9 A current signal at f = 0.5 Hz, and the thermal images were acquired by an IR camera (IRCAM Quadriga® 1310 k SM pro), sensor size of 1280 x 1024 pixels, InSb FPA detector, 1.5 to 5 µm spectral response, and 107 Hz full frame rate. Image processing was carried out using Argos PV with LockIn software version 1.1.5 (IRCAM GmbH, Germany). The **PV modules of type IV** were measured from the rear side (backsheet) (Figure 3.23). The results are discussed in **Chapter 7**.



Figure 3.23 – DLIT imaging setup an IR camera collects thermal images from a **PV module of type IV** reflected on a mirror.

Lock-in thermography works by exciting the sample periodically by applying a pulsed voltage or a light source at a given lock-in frequency and recording the resulting surface temperature distribution by an IR-camera. Defects or irregularities within the sample that lead to an inhomogeneous heat distribution can be detected down to a few μ K when a pulsed voltage is employed [177, 178].

In DLIT measurements, four images are generated for the **PV modules of type IV** (see Figure 3.24). The S^{0^0} and S^{-90^0} images display the signal in phase with the sine and cosine functions, respectively; from these, two additional images are derived:

- The amplitude image displays the amplitude of the surface temperature detected.
- The phase image *θ*, given in degrees, shows the local phase shift between the reference and detected signal; in other words, it provides information on the rate at which the heat spreads from source to the surface.

By measuring at different frequencies and current, heat sources at different depths along the material are detected and displayed in the amplitude image. The amplitude, S^{0^0} , and S^{-90^0} images are scaled in K [16, 179, 180, 181].



(a)

(b)



Figure 3.24 – DLIT images of a **PV modules of type IV**. S^{0^0} (a), S^{-90^0} (b), amplitude (c), and phase (d) [181].

The measurement setup includes a mirror, from which the thermal images are first reflected and then captured by the IR camera. Because of this, the DLIT images presented in this work were mirrored to match the EL images [181].

3.4.5 Scanning Acoustic Microscopy

The basic principle of Scanning Acoustic Microscopy (SAM) is illustrated in Figure 3.25. A sound pulse propagates into the sample through the coupling fluid (e.g. water). An echo arises as the acoustic wave front strikes the specimen's top surface s1. Part of the acoustic wave propagates through the material's bulk and a second echo arises once the wave front reflects from its back surface s2. The time delay between both top and back surface echoes is called the time-of-flight (*TOF*).



Figure 3.25 – Measurement principle of the SAM in reflection mode [137].

Scanning Acoustic Microscopy (SAM) allows the investigation of PV modules at any depth range selected by the user, thus enabling a detailed analysis of the backsheet, encapsulant, and the cell individually without carrying out destructive tests. The acoustic micrographs can be acquired at high spatial resolution and enabled a clear visualization of the vertical profile of the PV module components, and defects within the backsheet and EVA, and the cell.

Another field of application of acoustics is the measurement of the mechanical and the elastic properties of materials, including a wide range of polymers. Although different experimental setups for this purpose are reported in the literature, the mechanical characterization commonly involves the analysis of shear and longitudinal wave excitation modes, which can then be used to derive the bulk K and shear moduli G. From these two moduli, the longitudinal and shear sound speeds, as well as the Young's modulus E, and the Poisson ratio v can be calculated, thus enabling a complete characterization of the mechanical behavior of a material [182, 183, 184, 185, 186, 187].

Moreover, research on determining the cross-linking degree of EVA encapsulant by acoustic methods have been reported [188, 91]. Using the acoustic reflectogram, the speed of sound c (m/s) as a material property can be calculated from the round-trip travel time of the acoustic wave across the thickness of the layer according to the Eqn 3.20 [189].

$$c = \frac{2d}{t_1 - t_2}$$
(3.20)

Where d is the layer's thickness and $(t_2 - t_1)$ is the *TOF* between the echoes from the back s_2 and top surfaces s_1 of the layer.

Because a given propagation mode, e.g., longitudinal or shear waves, relates to a particular speed of sound, the wave mode then determines the corresponding elastic constant, such that the longitudinal and shear sound speeds relate to the longitudinal and shear modulus as presented in Eqn 3.21 and Eqn 3.22, respectively. The relation between the two moduli is given in Eqn 3.23.

$$L = \rho . c_l^2 \tag{3.21}$$

$$G = \rho . c_{\delta}^2 \tag{3.22}$$

$$L = K + \frac{4G}{3} \tag{3.23}$$

Where *L* is the longitudinal, *G* is the shear and *K* is the bulk Modulus. In isotropic materials including polymers, these two propagation modes and the density of a given material can be used to determine the material's elastic constants, particularly the Young's modulus (*E*) [190]. This last can be calculated from Eqn 3.24 [190, 191, 189, 192].

$$E = 3K(1 - 2\nu) = 2G(1 + \nu) \tag{3.24}$$

Where v represents the Poisson's ratio. Because the transducer is scanned perpendicularly to the material surface and liquids or very soft materials do not support shear wave propagation [193, 191], our approach is therefore based on the analysis of longitudinal waves only.

Therefore, the experimental results refer to the longitudinal modulus L only [137].

The **Laminates of type I**, **PV modules of type IV** and **Full size PV modules of type V** (as it will be discussed in **Chapter 4**, **Chapter 5** and **Chapter 7**) were placed flat in a water tank and scanned by SAM 500 HD2, PVA TePla Analytical System GmbH, Westhausen, Germany. The measurements were carried out in pulse-echo mode, at a normal incidence angle at the 30 MHz acoustic frequency and at the water temperatures of ~ 20°C (see Figure 3.26).



Figure 3.26 - Schematic illustration of the SAM assembly applied to the multilayer PV module.

The reflection of the acoustic waves at the concerned interfaces yields discernible echoes and the resulting peaks are not overlapping. The received echoes were digitized at asampling rate of 1.25 G Samples/s. The experimental setup is shown in Figure 3.27. The reflectograms and acoustic images were interpreted and it will be discussed in **Chapter 4** and **Chapter 7**.



Figure 3.27 – SAM imaging setup an 30 MHz transducer scans acoustic images from a **PV module of type IV** immersed in water.

4 Advanced methods for PV module polymer mechanical degradation

Abstract: The power degradation and failure of photovoltaic (PV) modules can be caused by changes in the mechanical properties of the polymeric components during the module lifetime. The first part of this chapter introduces instrumented nanoindentation as a method to investigate the mechanical properties of module polymeric components. Previously most of the investigation of the mechanical changes due to the aging were carried out with the polymeric materials as bulk. With nanoindentation the change in hardness of encapsulant and backsheet can be spatially resolved with a high lateral resolution. The nanoindentation tests at first place were carried out on the cross-section of Laminates of type III after sequential aging steps of 500 h damp-heat (DH) at 85 °C and 85 % r.h. The results show an increase in hardness (up to 40 MPa from 500 h to 2000 h DH) for the fluoro-polymer free coated monolayer Poly(ethylenterephthalat) (PET) backsheet type (CPC) with the highest water vapor permeation rate, which suggests a high degree of hydrolysis of the PET core layer. For the softer polymeric layer (encapsulant), advanced nanoindentation tests were carried out on ethylene vinyl acetate (EVA) surfaces, which had been separated from the glass panel. Two types of timedependent indentation cycle modes, the time domain (creep tests) and frequency domain (dynamic tests) were performed to determine the viscoelastic behavior. For each mode, a corresponding model was applied to calculate the main mechanical properties.

As a second part of this chapter, we demonstrate the use of the scanning acoustic microscopy (SAM) as a nondestructive characterization method to estimate the mechanical properties of polymeric multi-layers (backsheet and encapsulant) in PV modules. The acoustic speed inside each individual material was measured and its mechanical properties calculated. More precisely, the longitudinal modulus was determined acoustically at 30 MHz to obtain more information about aging-induced material changes and degradation. PV module failure modes associated with backsheet degradation have a high relevance in the operation and maintenance of power plants. Therefore, field-exposed modules were analyzed by SAM to visualize and localize backsheet failure modes in specific layers non-destructively. Acoustic micrographs were collected from different material depths of the backsheet, which allowed the assessment of depth profiles of the embedded PV module components individually.

Multiple types of interlayer cracks were identified. These local defects of the backsheet were confirmed by microscopy images of destructively acquired backsheet cross-section samples.

Keywords: Encapsulant, backsheet, nanoindentation, creep measurement, frequency sweep, Scanning Acoustic Microscopy (SAM), time-of-flight (TOF), acoustic micro-graph

The viscoelastic properties of the encapsulation materials have been shown to have a direct influence on the imposed strains (and therefore degradation potential) of the solder bonds. The mechanical behavior for each encapsulant is dependent on the absolute temperature and the rate of change of temperature, as expected of viscoelastic materials [194].

Chemical aging processes can influence the chemical structure of polymers, induce the formation of new functional group and cause removal of small molecules (with effect on the optical and mechanical properties). Examples of chemical processes during polymer aging are thermal degradation, oxidation, hydrolysis and photolysis. The main characteristic of these processes is that they are not reversible. Physical aging processes, on the other hand, have a major influence on polymer morphology and might be reversible. Mechanical, thermo-mechanical and thermal properties are subject to changes due to the aforementioned processes. There are several characterization techniques and evaluation concepts able to describe changes in polymer properties and therefore chemical and physical changes. Two advanced methods for the PV module polymer mechanical degradation were investigated as follow:

- Destructive method (Nanoindentation)
- Non-destructive method (Scanning Acoustic Microscopy)

The first method was applied to materials, namely polymer films (unprocessed, processed and aged) as well as to materials laminated into modules. It is called destructive because it irreversibly changes the original samples, which lose their functions and cannot be used anymore after the test. Moreover, when the destructive technique is applied at the module level, it is necessary to break the module and extract some material for further characterizations. The second method was applied at any level without damaging the sample and without compromising its function. For this reason, this method can be applied at any stage (unprocessed, processed and aged materials as well as modules). Non-destructive characterization methods are very powerful tools because they can be potentially applied even in the field, on operating modules to detect and assess material degradation. The objective of SAM is to find suitable methods to describe material interactions with the more ambitious aim to advance the state of the art of non-destructive techniques useful during the PV modules operation.

4.1 Nanoindentation

In order to obtain a coherent value of hardness of the polymers and remove the influence of the exposed surface after the sample preparation, a pre-measurement was conducted to find the ideal depth of the nanoindentation tip. A load is applied until the hardness value stays constant. The values of maximum load were fixed at 50 mN for backsheet and 100 mN for EVA. A typical graph of load versus indenter displacement used for the calculation of hardness of backsheet and EVA is shown in Figure 4.1. For similar load (~ 50 mN) the indent in the backsheet (~ 3,500 nm) is much shallower than in the EVA (~ 30 μ m). The hardness is calculated from Eqn 3.6 by maintaining the load constant and measuring the indenter displacement or the indented area left after the unloading of the indenter as described in **section 3.3.3** in **Chapter 3**.



Figure 4.1 – Combined curves of load versus indenter displacement used for the calculation of hardness of backsheet (a) and EVA (b) [149].

The **laminates of type III** were aged for 4 intervals of 500 h DH each. The hardness was measured after each interval. Figure 4.2 shows the deformations left on the backsheet crosssection after the indentations. In this work the hardness of the core layer of the backsheets was calculated on the middle of the PET layer. The measurement of the hardness of two backsheets at different aging steps is shown in Figure 4.3. Five indentations were performed on each line parallel to the interfaces and an average value was calculated. The initial hardness values of backsheet_1 are lower than those of backsheet_2, due to the difference of PET polymers formulation. The change in hardness during the DH aging is much higher for backsheet_1, due to which the hydrolysis could happen to a higher extent. Hydrolysis of PET is mostly affected by moisture content, temperature, initial morphology and crystallinity, and initial carboxylic end group concentration [56]. In the recent study, a direct dependence between the hardness and the degree of crystallinity of the polymer is observed [195].



Chapter 4

Figure 4.2 – Microscopic images of the cross-section of the laminates after indentations on the backsheet_1 (a) and backsheet_2 (b) [149].



Figure 4.3 - Changes in hardness of backsheets after different intervals of DH aging [149].

More recently, the instrumented indentation testing was used to distinguish different PV backsheets and quantify the effect of aging [196].

As the encapsulant is more elastic than the backsheet, its deformation after the indentation is barely visible. The hardness for the EVA after aging showed unexpected values. We suppose that the displaced EVA area through the indenter was very large and its mechanical properties are modified due to the sample preparation of the cross-section. Therefore, the alternative way of using nanoindentation on the EVA is to perform the tests on the EVA surface at the glass-EVA interface as described in **sections 3.3.1 and 3.3.3**.

The geometry of the indentation tip plays a critical role for the experiment. Depending on the mechanical properties of the material under test, differently shaped tips - usually made from diamond - can be used. It was shown that the radius of a ball indenter varies, while it can be considered as constant for larger depths [151].

The advantage of using a blunt indentation tip with low loads on time-dependent materials (e.g. polymers) is essentially for the avoidance of plastic deformation of the sample. Therefore, the contact problem can be easily solved by Hertz equations, modified for the calculation of the viscoelastic properties of the polymer [197, 198, 199]. Moreover, the stresses in the indentation tests should be lower using blunt indenter geometry than a sharp tip [155]. In order to describe the creep and viscoelastic behavior of the material, two time-dependent indentation cycle modes are performed.

4.1.1 Creep mode: Ramp and hold indentation

As one option to vary the measurement with respect to the time domain, creep measurements are used to describe the long-term viscoelastic properties. The material is assumed to be linearly elastic but the stiffness is changing as a function of time [146]. The example cycle in Figure 4.4 consists of fast loading of 10 s up to 40 mN followed by a long lasting hold of 200 s at constant force, where the increase of depth (creep) is then monitored (see Table 4.1). For the example shown in Figure 4.4, the creep compliance function, and for the ramping part (load 1 \rightarrow 2) can be expressed as Eqn. 3.10 and for the creeping part (hold 2 \rightarrow 3) can be expressed as Eqn. 3.11. By fitting a function to the constant load segment (creep 2 \rightarrow 3), the coefficients and time constants in Figure 3.14 can be found. The results of this study is used in **Chapter 5**.



Figure 4.4 – Creep load-displacement-time curves on the EVA surface obtained using a maximum load 40 mN, duration of creep 200 s.

Table 4.1 – Indentation parameters for creep mode.

Loading / Unloading rate	$0.004 \ s^{-1}$
Maximum load	40 mN
Holding time	200 s

4.1.2 Dynamic frequency sweep: Sinus indentation

Figure 4.5 illustrates the load-displacement-time cycle used for the sinus mode. To ensure similar loading conditions during measurements for all samples, a constant strain rate is used (up to 40 mN). The loading phase is followed by 15 seconds break at constant load to obtain an equilibrium state. Oscillations are then applied at a fixed load for 65 seconds. The mean and standard deviation of storage and loss moduli at a given depth during the oscillations are then calculated using the Eqns. 3.15 and 3.16, respectively showed in **section 3.3.3** in the **Chapter 3**. Note that when plotting these results, the values are plotted against the Sinus oscillations (Sinus cycles) because the depth is not expected to be (significantly) increasing during the pause since most of the creep has occurred during the preceding hold period. All dynamic measurements are performed at room temperature using the same indentation parameters as seen in Table 4.2. The results of this study is used in **Chapter 5**.



Figure 4.5 – Dynamic load-displacement-time curves on the EVA surface obtained using a frequency sweep during the hold.

Table 4.2 – Indentation parameters for dynamic frequency sweep mode.

Constant strain rate	$0.05 \ s^{-1}$
Maximum load	40 mN
Break before Sinus	15 <i>s</i>
Sinus duration	65 <i>s</i>
Sinus frequency	5 <i>Hz</i> , 40 <i>Hz</i> and 100 <i>Hz</i>
Amplitude	4 A

4.2 Scanning Acoustic Microscopy

SAM is a non-destructive technique that offers the possibility of analyzing the compliance of PV module components (see Figure 3.20) because it can provide real-time acoustic high spatial resolution information from the internal structure of materials [200]. As a validation of SAM, it was shown that the calculated longitudinal modulus in the backsheet and the EVA have a similar trend with temperature. Moreover, the change of the longitudinal modulus of these materials at 15 MHz has a good correlation with the Young's modulus calculated from the tensile tests [137]. Furthermore, it was reported that SAM delivers complementary information to electroluminescence (EL) imaging and dark lock-in Thermography (DLIT) on the quality of PV modules [201]. Moreover, SAM was proved to be in good agreement with EL [128] and DLIT.



Figure 4.6 - Photo of PV module being scanned from the front side by SAM [64].

4.2.1 Time-of-flight measurements through the EVA and backsheet

Different methods are available to measure acoustic and mechanical properties of polymeric materials, for example, by using the amplitude, phase, and power spectra derived from the Fourier transform [183, 186, 187]. On the other hand, the amplitude and time-of-flight (TOF) analysis of the demodulated echoes is often applied for deriving acoustic properties directly as described in **section 3.4.5** in the **Chapter 3**. Yet, defining the time interval correctly could be challenging depending on the output echoes, and advanced signal processing techniques may be required, for example, when peaks appear overlapped or distorted [202, 203]. Often, the Hilbert transform (HT) has been applied in acoustic investigations to define the pulse peak in the time domain through the generation of an amplitude envelope as a TOF measurement method [202, 184, 204]. The HT itself represents a 90° phase shift of the original (in-phase) signal, thereby increasing the accuracy of the system by generating twice the number of signals. Therefore, the HT is commonly applied as an efficient technique in signal modulation and demodulation, as well as for envelope detection because it is more accurate than the indirect waveform detection [205]. Figure 4.7 left illustrates the principle of the HT envelope detection by the root-mean-square sums of the original signal y(t) and its Hilbert transform $\hat{y}(t)$.



Chapter 4

Figure 4.7 – Left: TOF-amplitude reflectograms of a **PV module of type IV** measured at 30 MHz. Right: Image of the back side of the module from the SAM software with the measurement areas (A1 on the edge and A2 at the center of the module).

Previously it has been validated that the TOF of the backsheet and EVA can be measured not only individually, but also when they are laminated together. Two reasons might explain the difference in TOF values between foils and modules [137]. The first might result from the variation in mechanical stability of EVA as a freestanding foil and laminated between glass and backsheet. The second might be related to local variations in the thickness of the EVA foil since this foil melts and fills in gaps between the solar cells during the lamination, which might ultimately lead to uneven thickness across the foil inside the module [206]. Therefore, acknowledging the influence these two factors might have on TOF measurements, this topic remains as the subject of further research.

The Time-of-flight measurements were calculated based on the peak maxima of the Hilbert transform of the signals. signals 1, 2 and 3 represent the water/backsheet, backsheet/EVA and EVA/cell interfaces respectively. In this section, one example of the effect of aging on the Δ TOF in the backsheet and EVA is discussed using the **PV module of type IV** with a CPC backsheet type. The Δ TOF changes in the CPC (between signal 1 and 2) and EVA (between signal 2 and 3) in Figure 4.7 left for the CPC-EVA module before and after the sequential accelerated aging tests.

First, acoustic images of the whole module area were carefully examined for any structural imperfections within the foils and between their interfaces that could affect TOF measurements, such as air gaps, bubbles, impurities, microcracks and other material discontinuities (Figure 4.7 right). Since these imperfections reflect the acoustic wave, they give rise to echoes at positions that do not correspond to the foil boundaries, which ultimately masks the real-delay time, that is, the TOF, of the foils and hence their longitudinal modulus. Because SAM is a very thickness sensitive technique, particularly the variation of EVA thickness at the edge of laminated modules and cell gaps must be taken into consideration since different thickness also means different TOF for the same material [201, 206]. Assuming the same foil thickness at regions of changing TOF ultimately yields wrong modulus values. Therefore, the areas (A1 and A2) as shown in Figure 4.7 right, were selected for the acoustic measurements.

The stress of the high frequency ultrasound (MHz range) is exerted in the material for a very short time, leaving short-length scales for the relaxation of molecular chains [182]. However, the Δ TOF in the CPC and EVA layers in the **PV module of type IV** show a trend. Each data point is the average of five random points collected from the same area in the module. Two areas were sampled: at the edge (A1) and at the center of the module (A2) (see Figure 4.7 right). The module was measured at an average temperature of 20 °C (± 1.1°C) in order to exclude the effect of significant temperature changes [137].

The results of Δ TOF variation in the CPC and EVA layers in the **PV module of type IV** as a function of aging duration are shown in Figure 4.8. The aging test used in this part is summarized in Table 3.4. After the first DH sequential tests, a slight decreasing Δ TOF in the CPC was observed. This means that the acoustic wave velocity in the CPC increases with DH aging. On the other hand, the Δ TOF in the EVA shows a decreasing trend up to 1500 h, but increases after 2500 h. The data shows a large variation compared to the CPC. After the UV-DH combined test, a significant drop of the Δ TOF in the CPC and the EVA is observed.



Figure 4.8 – Changes in Time-of-flight of the backsheet (left) and EVA (right) in the **PV module of type IV** as a function of sequential aging duration.

The Δ TOF of the foils were obtained from the SAM and the corresponding longitudinal modulus was calculated from the measured Δ TOF, density, and thickness. The density and thickness values used were determined from measurements of the single foils. The sound speed of the foils were calculated from Eqn 3.20 being the Δ TOF between the first and back surface echoes of the polymeric foils. The previous study showed a slight changes in density and thickness, which were assumed negligible in a temperature range from 10°C to 40°C [137].

Therefore, these properties were assumed to be constant across the investigated **PV modules** of type IV before and after aging to calculate the viscoelastic changes of the foils in the PV modules. The values of these parameters at 20°C were chosen. For the backsheet, the density used is 1462 $kg.m^{-3}$ and thickness 173 μ m, for the EVA, the density is 949 $kg.m^{-3}$ and thickness 407 μ m (see Table 4.3).

The longitudinal moduli of the CPC and EVA foils inside the PV module were measured at 30 MHz by determining the thickness of the respective layers and depicted in Figure 4.9. An increasing trend in the longitudinal modulus with the aging duration was observed in the foils inside the module.

|--|

Layer	Backsheet	EVA
ρ (g/cm ³)	1.462	0.949
<i>d</i> (µm)	173	408



Figure 4.9 – Longitudinal modulus of the backsheet (left) and EVA (right) in the **PV module of type IV** as a function of sequential aging duration.

An increasing wave velocity with aging might further suggest an increase in the material's elastic moduli (see Eqns 3.21, 3.22, 3.23 and 3.24). Especially, the results might suggest that the CPC has become stiffer with aging. In fact, studies have shown that single PET-based backsheets become brittle upon DH aging [56]. Embrittlement of the PET component is related to physical and chemical degradation of the polymer chain as discussed in **Chapter 1**, such as post-crystallization and hydrolysis [7, 36, 56].

Similarly, The increase of the longitudinal modulus of the EVA might be related to an increase in stiffness with aging. This behavior can be explained by photo-degradation under UV-DH combined aging [47], which will be discussed in detail in **Chapter 6**. More studies have shown that several PV module encapsulants, including EVA, become stiffer and more brittle after DH and UV-DH exposure [100, 29].

One limitation of using high frequency measurements on polymeric materials is that the latter presents much lower polymer chain mobility at MHz range, which induces a shift in the glass transition temperature (T_g). Therefore, these polymeric materials require higher measurement temperatures in order to increase chain mobility and transition from a glassy to rubbery state [182, 186]. However, SAM measurements at 30 MHz showed good results to evaluate viscoelastic changes in polymeric layers in a PV module caused by aging as long as the temperature during the measurement is controlled.

4.2.2 Acoustic imaging

This study demonstrates the application of SAM for the evaluation of PV backsheet degradation upon weathering. Towards this goal, degraded backsheets of different layer structure from the **Full size PV modules of type V** were analyzed by SAM to understand and localize failure modes such as cracks in specific layers that are otherwise not assessable without destroying the module. The SAM results are validated by microscopy images of destructively acquired backsheet cross-section samples.

The acoustic micrographs in Figure 4.10 were generated from specific gates in the reflectogram, representing different depths inside the fielded PV module. This is desired if individual interfaces between the PV components are inspected. For example, using one SAM scan, three micrographs can be generated: (top image) Backsheet/encapsulant interface, (middle image) ribbons of the backside of the cells. Therefore, the image looks darker and (bottom image) encapsulant/cells interface. Here, the ribbons and silver pads at both sides of the cells are visible.



Figure 4.10 – Acoustic micrographs (SAM images) generated from the different spectral regions ("gates") from a **Full size PV module of type V**.

The backsheet of the Module case 1 could be identified to consist of a fluoropolymer coating (outer layer), polyethylene terephthalate (PET) (core layer) and a damaged polypropylene (PP) (inner layer). This backsheet had previously been inspected visually and no backsheet cracking had been observed of the module. The microscopic images shown in Figure 4.11. represent the backsheet cross-sections of the modules case 1 and case 2 as described in **section 3.1**.

Chapter 4



Figure 4.11 – Microscopic images of Backsheets cross-sections. The letters a, b and c indicate the interfaces shown in the SAM images. Case 1 (left), destroyed PP inner layer; Case 2 (right), Cracks in outer PA layer.

Figure 4.12 left represents the reflectogram of the PV module (case 1) measured from the rear side (backsheet) in the intercellular gaps. The acoustic beam is focused at the backsheet surface (first peak on the left). The assignment of the signals was done based on the knowledge on the present interfaces in the module [201]. The strongest peak on the left at 2.65 μ s TOF corresponds to the water/backsheet surface, the following gates are assumed to correspond to the core/inner layers interface (orange) and the inner/encapsulant interface (red). As observed in the visual inspection, the weathered backsheet outer layer has an intact surface (echo (a) Figure 4.13) between and behind the cells. Inside the backsheet and only between cells, cracks in one direction are observed at the core/inner layers interface (echo (b) Figure 4.13). Deeper inside the inner layer, additional smaller cracks in multiple directions are visible (echo (c) Figure 4.13).



Figure 4.12 – TOF-amplitude reflectogram of a PV module case 1 (left) and case 2 (right).

The second type (case 2) of the PV-field aged module contained a backsheet consisting of a PET core layer sandwiched by two polyamide (PA) layers. By placing three gates in reflectogram in Figure 4.12 right, the acoustic images in the Figure 4.14 were obtained at specific corresponding acoustic depths inside the multilayered backsheet. At the outer PA/core PET layers interface, both cracks in the machine direction can be observed. These are especially pronounced in the cell gap locations, where additional, smaller cracks in different directions are present (echo (a) Figure 4.14).



Figure 4.13 – SAM images of Case 1, a. outer layer surface. b. core-inner layers interface. c. inner layer bulk.



Figure 4.14 – SAM images of Case 2, a. outer-core layers interface. b. core layer bulk. c. core-inner layer interface.

All cracks are difficult to see with the naked eye (almost not visible). The corresponding acoustic image of echo (b) Figure 4.14 shows larger cracks in a gate (b) that is assigned to the bulk of the PET core layer. The cracks appear with high contrast since no interface was detected in this region (no peak reflectogram, Figure 4.12 right). The last image at echo c, Figure 4.14, represents the core/inner layers interface.

Both cases of backsheet cracking presented earlier are observed only along the intercellular spacing where the front UV irradiation can be absorbed during operation. The structure of these cracks can be clearly visualized and quantified by SAM analysis. In case 2 both cracking types mainly affect the outer PA layer and the Inner PET layer. However in case 1, both crack types are visible at the inner/EVA layer interface. In a previous study, similar cracks were accompanied by a delamination of the inner PA-layer from one of the adjacent layers [44].

In order to validate the visualization of the location of these cracks and the depth profile of the PV module, an acoustic cross-section along the different positions were nondestructively extracted and is presented in Figure 4.15 for the module in case 1 and in Figure 4.16 for the module in case 2. The backsheet cracks are indicated by arrows.



Figure 4.15 – Acoustic cross-sections Case 1.



Figure 4.16 – Acoustic cross-sections Case 2.

The acoustic cross-sections confirm the same crack positions of the different modules. For the module case 1, the cracks are visible at the 4^{th} interface starting from the top line, which means at the backsheet inner/EVA layer interface. Whereas, For the module case 2, the cracks appears slightly earlier at the 2^{nd} interface, i.e. the outer PA/core PET layers interface after the water/backsheet interface.

4.3 Conclusion

It has been shown that the nanoindenation allows the measurement of mechanical properties of the EVA encapsulation materials with the application of extremely low load. The presented method has been tasted using two time-dependent indentation cycle modes to determine the EVA's surface viscoelastic behavior. A corresponding model was applied for each mode to calculate the main mechanical properties.

The verification of SAM as a non-destructive method for the measurement of the longitudinal modulus of backsheet and EVA foil inside a PV module was presented in this chapter. By assuming that the thickness and density parameters of the foils remain constant across the sequential aging tests, the change in longitudinal modulus can be calculated. First, it was shown that the acoustic response (change in TOF) of the backsheet and the EVA produced similar trends but different absolute values during the aging, and consequently similar trend of the longitudinal modulus in the backsheet and the EVA inside a PV module. Acoustic measurements at a wider frequency range are needed to understand the resulting behavior of these polymeric materials more precisely. Nevertheless, SAM measurements at 30 MHz can be used to evaluate viscoelastic changes in polymeric layers in a PV module caused by aging as long as the temperature during the measurement is controlled.

In this work we demonstrated that SAM can uncover backsheet cracking in specific interlayers non-destructively, as validated with conventional destructive tests. Various types of backsheet cracking were locally distinguished and quantified in the intercellular gap for the field degraded PV modules under the acoustic micrographs. Additionally, the acoustic cross-sections obtained allowed the depth profile analysis of the multilayer backsheets at component level, and the exact position and location of cracks for the confirmation.

5 Optimizing the encapsulation process

Abstract: One of the most important parameter of photovoltaic PV module encapsulation process, the gel content is usually measured by the Soxhlet extraction method. Due to the destructive sample preparation, long turnaround times, hazardous solvents and the limited precision of results, an alternative crosslinking determination technique is needed. The general capability of nanoindentation and Scanning Acoustic Microscopy (SAM), using the approaches discussed in **Chapter 4**, as cross-linking determination methods were investigated. A large number of **laminates of type I** were built using different lamination conditions resulting in different degrees of curing. Both indentation modes and SAM described in **Chapter 4** indicate good sensitivity for following the EVA crosslinking correlation. Additional Dynamic Mechanical Analysis (DMA) characterization is used as an established method to validate the indentation tests. Both nanoindentation and DMA tensile mode produce quantitatively similar viscoelastic responses, in the form of the damping factor parameter, using three different frequencies at room temperature. A statistical study of the data reveals the advantages for the investigation of multilayer PV laminates by using nanoindenation as a surface method.

The degradation of a PV module is strongly influenced by moisture ingress. Previously most of the investigations of the diffusion properties of encapsulants and backsheets have been carried out on the polymer sheets alone, thereby not accounting for diffusion properties of all involved materials. In this work, a kinetic study of the water uptake of the EVA inside the laminate stack was performed, using incorporated miniature digital humidity sensors at different EVA depths. Samples with different polymeric materials and lamination conditions were aged under a damp-heat (DH) and UV-DH combined conditions while monitoring the humidity inside the **laminates of type II**. From this data, the respective diffusion rates were calculated and determined how the different materials and lamination conditions affect the mechanism of moisture ingress/egress during the aging tests. The results demonstrate a faster diffusion in the CPC backsheet than in the TPT backsheet type. With respect to the lamination process, the effective activation energy (E_A^{eff}), calculated assuming an Arrhenius-like behavior showed slower moisture ingress for the shortly laminated sample.

Keywords: Encapsulant, backsheet, nanoindentation, DMA, SAM, humidity sensors

5.1 EVA degree of curing (DoC) determination

Currently, there exists a big interest from the photovoltaic (PV) industry in a fast and nondestructive method for the determination of the encapsulant mechanical properties to ensure the encapsulation quality after lamination and the long-term stability of PV modules. To implement this idea with a non-destructive approach, some studies have proposed using ultrasonic detection [137, 188], optical transmission [135] and indentation [207, 208, 209, 210].

One of the most important influence factors for the EVA's thermo-mechanical properties is the degree of curing (DoC). The polymer chains form a three-dimensional network during lamination through the thermolysis of peroxides, followed by a radical chain reaction, which crosslinks the individual polymer chains resulting in a certain DoC. An insufficient DoC can be the root cause for module degradation in the field, since under-cured EVA can result in lower adhesion strength between layers [211]. Furthermore, the remaining unused crosslinking agents can trigger polymer degradation mechanisms, such as acetic acid production [212, 213, 214]. On the other hand, an over-cured encapsulant might result in delamination and susceptibility to mechanical loads caused by a too high stiffness. Additionally, the EVA encapsulation plays a crucial role in degradation of module power performance. It has been demonstrated that highly crosslinked EVA favoured thermal cycling (TC) stresses, while a low crosslinked EVA performed better under DH stresses. However, under the latter stresses, this highly crosslinked EVA may trap the generated acetic acid within the module [215]. It was also observed that the level of power degradation depends on the degree of EVA crosslinking [216, 119]. The two main parameters influencing the DoC are curing time [91, 212, 139] and curing temperature [216, 119, 139].

There are several methods to determine the DoC of EVA [91]. Soxhlet method is a destructive and time-consuming method [122]. The correlations between the DoC and the other methods were validated using different analytical approaches such as (1) the detection of the actual crosslinks formed during lamination, for instance by means of IR or Raman spectroscopy [135, 212, 217, 95], (2) the calculation of the residual amount of crosslinker present in the material after lamination, for instance by means of Differential Scanning Calorimetry (DSC) [91, 139, 89, 218] or (3) monitoring the changes of mechanical properties, by means of Scanning Acoustic Microscopy (SAM), laser vibrometry or Dynamic Mechanical Analysis (DMA) [91, 212, 89].

DMA has been established as suitable method to detect the viscoelastic properties of the encapsulant [91]. However, the method has considerable drawbacks, including the required specimen geometry as well as a poor comparability of results obtained with different measurement parameters, which may prohibit the use of this technique. Alternatively, indentation testing shows a potential to quantitatively and non-destructively measure the DoC of low, medium, and highly cross-linked laminated solar encapsulants. The detection of the cured EVA's viscoelastic response has been demonstrated previously by means of a compressive stress relaxation measurement. However, this approach was found to be representative only at elevated temperatures [210].

More recently, the instrumented indentation testing was used to distinguish different PV backsheets and quantify the effect of aging [196]. Compared to the previous techniques, the advantages of the instrumented nanoindentation are:

- Small sample size and reduced scale tests.
- Possibility to investigate multilayer material combinations (reduced sample preparation compared to DMA).
- Accurate and advanced tests for time-dependent materials like viscoelastic polymers.
- Spatial resolution allows to study the homogeneity of mechanical parameters along surfaces [219].
- · Automated and Instrumented technique with good reproducibility.

This part introduces an advanced nanoindentation test including the time dependent cycle modes for the quantification of the viscoelastic response of the EVA surface at the polymerglass interface (Figure 3.16). For the best of our knowledge nanoindenation is used for the first time on EVA surface using time-dependent cycle modes . In this approach, first the elastic creep and viscoelastic sweep parameters are measured; then correlated to the EVA's DoC as measured by the DSC method by using the exothermal peak from 110 to 190°C. Furthermore, the viscoelastic properties as determined by the dynamic nanoindentation method are validated by DMA as an established technique.

In the PV community, the EVA gel content represents the weight percentage of the crosslinked part in the EVA after the encapsulation process. Here, the gel contents of EVA samples with different curing times and temperatures are measured by a continuous solvent extraction method (Soxhlet extraction) using toluene [220]. About 1 g of cured EVA was weighed (m_0) and cut into pieces. After extraction at 110 °C for 6 hours, the EVA was dried till the weight stayed constant (m_1) at 80 °C. The gel content was calculated as the ratio of the final weight to the initial weight, as described in Eqn 5.1:

$$\% GelContent = 100.(\frac{m_1}{m_0}) \tag{5.1}$$

The Soxhlet method is only used here to define the standards in the thesis. In the PV industry, DSC is gaining more popularity as a fast tool for determining the EVA gel content [221]. We have verified this method and set up the correlation between DSC and Soxhlet extraction results, as described in **section 3.3.6** in **Chapter 3** and actual EVA gel content measured by Soxhlet extraction. Thus, in this work, the EVA gel content is mainly determined by DSC.



Figure 5.1 – Correlation between the Degree of curing of the processed samples and the lamination parameters time and temperature.

As seen in Figure 5.1 the different times and temperatures for the lamination process result in a variety of DoC ranging from 17.5 % up to 98.7 %. The correlation between the lamination process and the curing of encapsulants has already been studied in detail [139]. In the next section, the main focus lies on the changes of mechanical properties in the encapsulants. The variation of the DoC of one encapsulant allows for a first sensitivity and feasibility analysis of the methods for mechanical characterization to be investigated.

5.1.1 Effect of DoC on the creep response of the EVA

One approach of this study is to correlate EVA's DoC as measured by DSC to the indentation creep of the EVA surface. To this end, comparative evaluations of creep response of the laminates were undertaken using ramp-and-hold protocol as described in **section 3.3.3**. The nanoindentation is a surface characterization method with a penetration depth of less than 0.5 μ m, therefore the EVA-backsheet laminate samples were measured from both sides as shown in Figure 5.2.



Figure 5.2 – Image of mounted samples with exposed surfaces of interest (EVA with linear circles and backsheet (CPC) with dashed circles) for nanoindentation tests.

Creep curves in Figure 5.3 showed that highly cured samples with higher curing temperature (T = 150 °C) yield lower displacement from both surface sides, compared to the lower curing temperature (T = 120 °C). These results indicate the possibility of detecting the EVA cross-linking response non-destructively from the backsheet via nanoindentation at room temperature. However, the influence of lamination conditions on the backsheet mechanical properties has not been considered. Therefore, only results from the EVA surface are discussed in this work, which can be interpreted quantitatively.



Figure 5.3 - Creep data on the same surfaces with max load 40 mN, duration of creep 200 s.

Figure 5.4 shows the creep elastic modulus of the EVA calculated from the experimental displacement-time curves in Figure 4.4 (**section 4.1.1**) and the numerical model in Figure 3.14 (**section 3.3.3**) of 30 samples with different DoCs. These measurements yielded a lower creep elastic modulus (8 MPa) for the lowest cured sample (T 120 °C – t 2 min) and a small increase of the modulus for a degree of crosslinking above 50 %.



Figure 5.4 – Elastic creep modulus (calculated from the creep curves) of the EVA surface as a function of DoC as measured by DSC.

The modulus data from the spherical indentation indicate a reduction of creep with the increasing of DoC. This change is significant for the most poorly crosslinked EVA. The increase of the modulus upon lamination is attributed to the formation of a three-dimensional polymer network. At around 50 % DoC the modulus slightly continue to increase. The overestimated modulus at around 20 MPa (~ 50 % DoC) could have been caused by a tilting of the samples during the measurements.

5.1.2 Effect of DoC on the DMA and dynamic indentation of the EVA

The storage modulus E' of the EVA describes the change of elastic properties of the polymer chains. Figure 5.5 shows E' of the EVA calculated from the sinusoidal part of the dynamic curve at 5 Hz as shown in Figure 4.5 (section 4.1.2) and the numerical model in Figure 3.15 (section 3.3.3) of the same 30 samples. Evaluated against the DoC, the E' from the dynamic nanoindentation shows a similar relationship as for the creep elastic modulus showed in Figure 5.4. The E' values increases strongly over the early phase of crosslinking, but show smaller increase at higher DoCs.



Figure 5.5 – Storage modulus (calculated from the sinus part of the dynamic curves) of the EVA surface as a function of DoC as measured by DSC.

Both nanoindentation approaches (creep and dynamic modes) possess a good sensitivity for following the EVA crosslinking in its early stages, but could not reliably differentiate between samples with higher DoCs [91]. At this DoC range, the polymer might be sufficiently crosslinked and almost all polymer chains are connected. If there are more radicals that result in even more crosslinks, the thermo-mechanical stability might not change significantly. In other words, it might be that the material shows no more detectable changes in mechanical properties after a crosslinking over a certain level. We compared the results of the DMA measurements in tensile mode to the DoC of the EVA to investigate which material properties are sensitive enough for a correlation. The DMA measurements with tensile mode were performed on the EVA bulk using three different frequencies (1, 5 and 50 Hz). All 30 samples were measured once and the resulting values for E', E'' and $tan\delta$ are presented in Figure 5.6.



Figure 5.6 – Data of storage modulus (top), Loss modulus (mid) and Damping factor (bottom) calculated from tensile-DMA of the EVA bulk as a function of 30 different DoCs.

Parameter	Frequency (Hz)	R ²
	50	0,67
storage modulus (E')	10	0,39
	1	0,10
Loss modulus (E")	50	0,95
	10	0,96
	1	0,92
	50	0,96
Damping factor $(tan\delta)$	10	0,97
	1	0,91

Table 5.1 – Extracted coefficient of determination for the fit functions shown in Figure 5.6.

The storage modulus is highly fluctuating for these samples independent of the used frequency. However, for higher frequencies a clear trend can be observed where a higher DoC results in a lower storage modulus. For both values of E'' and $tan\delta$ a stronger correlation and less uncertainty can be observed. This indicates that the changes observed due to crosslinking are mostly impacting the polymers ability to disperse energy.

As a comparative study, a fitting model to quantify the effects of the different DMA parameters on the DoCs is proposed here. The presented fitting model is calibrated on the experimental data to extract the coefficient of determination (R^2) parameter as summarised in Table 5.1. The fits are plotted with the measurements in Figure 5.6. The R^2 values confirm the poor correlation of the E' to the DoC compared to E'' and $tan\delta$, especially at lower frequencies.

Following these measurements, 5 samples of varying DoCs were chosen to investigate the test–retest reliability. Due to the low response of DMA measurements at 1 Hz the frequency range was increased to 5 Hz, 50 Hz and 100 Hz. Here a flat punch indentation measurements was performed at the EVA surface (EVA/glass interface) (see Figure 5.7). Results from three different frequency sweeps in Z-direction (5, 40 and 100 Hz) were compared.



Figure 5.7 – NHT² Nano Hardness Tester.



Figure 5.8 – Data of storage modulus (top), loss modulus (mid) and damping factor (bottom) calculated from DMA tensile mode of the EVA bulk (a) and nanoindentation dynamic mode of the EVA surface (b) as a function of 5 different DoCs.

Figure 5.8 illustrates a direct comparison of E', E'' and $tan\delta$ for the EVA in relation to DoC for each tested frequency as determined by DMA-tensile mode and nanoindentation at room temperature. Each point is an average of three measurements for the DMA and nine for the nanoindentation measurements respectively at a given frequency. As observed before and especially for the nanoindenation, the E' shows a poor correlation to DoC. On the contrary, the correlation quality of E'' to DoC start to increase. Furthermore, a correlation between $tan\delta$ and DoC is observed for all frequencies used.

We would like to point out that the observed decrease in $tan\delta$ corresponds to an increase of crosslinking bonds density, which also increases the molecular weight of the material. The strongest decrease of $tan\delta$ was found between the values corresponding to DoCs of 48 % and 67 %. This might be caused by a change in crystallinity.

A second interesting result is that the two methods (dynamic nanoindentation and DMAtensile mode) yield quantitatively comparable $tan\delta$ values despite the different volume of the material response: The DMA in tensile mode represents the response of the EVA bulk, while the nanoindentation represents the response of the EVA surface, where the volume considered is several orders of magnitude smaller than in the DMA. This is surprising when comparing results obtained with techniques using different measuring material dimensions. However, it demonstrates the validity of both methods in this application.



Figure 5.9 – Data of damping factor calculated from DMA shear mode of EVA-BS laminates as a function of 5 different DoCs.

Figure 5.9 shows the evolution of the effective damping factor $(tan\delta_{eff})$ of the material combination backsheet-EVA calculated from DMA-shear mode measurements in relation to the EVA's DoC from the chosen laminates with five different lamination temperatures. These results show overestimated damping factors with high error bars , which could originate from the additional influence of the backsheet as well as the relatively high aspect ratio of the EVA for a shear experiment. A sample with a ratio of 0.8 mm thickness to 10 mm diameter needs high forces to achieve a reasonably measurable deflection. Therefore influences of plastic deformation or increased errors due to the low deflection might occur. The thickness of ~ 800 µm was chosen to represent a geometry typically found in commercial PV modules. Nevertheless, the same trend of $tan\delta_{eff}$ is observed independently of the frequency.

Table 5.2 summarizes the analytical methods discussed earlier for the test-retest reliability of EVA viscoelastic properties. For each method/approach, information is given about the mechanical material response, applicability to the components after sample preparation, the measured viscoelastic variable which can be assessed and the test-retest reliability for correlation quality of the mechanical parameters to DoC.

To obtain a quantitative comparison of the $tan\delta$ measured at 100 Hz (taken as an example) using the three approaches, the coefficient of variation (CV) is used here, where it represents the ratio of the standard deviation to the mean values of each measured sample. This is a useful statistic for comparing different methods or measured values regarding their repeatability. A lower CV for repeated measurements using a certain method indicates a more reliable method. As can be seen in Table 5.2, the CV of $tan\delta$ measured from nanoindentation shows the smallest value.

Characterization Method - mode	Material response	Applicability to PV components	Measured Variable	Coefficient of variation**	
NI - dynamic	EVA surface	laminates*	tanδ	0,4 %	
DMA - shear	laminate bulk	laminates	$tan\delta_{eff}$	8,4 %	
DMA - tensile	EVA bulk	EVA sheets	tanδ	1,9 %	
*lominatos: Paakshoot EVA films					

Table 5.2 - Comparative summary of the investigated approaches and their correlation to DoC.

*laminates: Backsheet-EVA films.

**The Degree of variation is taken from samples with 67 % of DoC.

Our data reveal the possibility to investigate multilayer material by using nanoindenation with strongly reduced labor as well as simpler sample preparation compared to DMA. Therefore, this provides the possibility of the application of nanoindentation for investigating the viscoelastic changes of the encapsulant from field modules or modules from accelerated aging tests. As a consequence of the nanoindenation validation result by DMA technique, only results from nanoindentation tests are discussed in the next aging part in **Chapter 6**. After this validation, the nanoindenation method is applied to investigate the influence of the choice of backsheet on the mechanical aging behavior of EVA.

5.1.3 Effect of DoC on the time-of-flight through the EVA layer

Like the nanoindenation technique, the scanning acoustic microscopy method proposed in this chapter uses the relationship between the EVA's mechanical properties and the degree of curing. When sound propagates through a stiff structure it is attenuated less than when it passes through a more loosely coupled structure. By measuring this attenuation the SAM quantifies the stiffness (e.g. the degree of crosslinking) of the EVA layer [188]. The 30 **laminates of type I** with transparent backsheet were also measured by means of SAM. By using the HT envelope signals for determining the correct maximum point of the acoustic signals as described in **section 4.2.1** and showed in Figure 5.10. The Δ TOF in the EVA layer in **laminates of type I** as a function of DoCs is shown in Figure 5.11. Each data point is the average of 5 points sampled from the same region at room temperature. The echoes considered for the measurements are those indicated in Figure 5.10. i.e. the distance between the BS/EVA and EVA/Glass interface. The BS/EVA interface signal is at the focal plane.



Figure 5.10 – TOF-amplitude reflectograms of a laminate of type I measured at 30 MHz.

An increasing Δ TOF in the EVA with DoC as measured by DSC was observed. However a large scatter can be seen, especially at lower DoC. This could be improved by collecting a continuous data for the whole surface to investigate the homogeneity of the Δ TOF over the samples surface.



Figure 5.11 – Evolution of \triangle TOF in the EVA layer with the DoC.

In this work we have presented a novel inspection technique that can measure the degree of crosslinking of EVA sheets in fully assembled PV modules within a few seconds without damaging the samples. These initial results show that the SAM technique therefore has considerable potential as an online inspection system and it should be regarded as one of the most promising method for inline crosslinking determination.

5.2 Monitoring of moisture ingress/egress into PV laminates

Ingress of moisture into PV modules has a major influence on the long-term reliability. The influence of the poorly crosslinked EVA on the moisture ingress of PV modules has been investigated [213, 214]. Discoloration has been observed at soldering ribbons on modules with short lamination times upon accelerated aging [212], which is a strong indication for moisture ingress as a main driver of corrosion [16, 17].

The diffusion properties are determined by the polymeric layers (backsheet and encapsulant) which both have only a partial moisture barrier. In the case of EVA encapsulants, moisture can react at elevated temperatures with the VA content, forming acetic acid which then reacts with the metallic components of the cells, causing corrosion [222].

In order to predict the moisture ingress into the PV modules, different theoretical models have been proposed: e.g. via Finite Element Analysis (FEA) for the prediction of the moisture content in the laminate structures based on the Fickian diffusion model [223, 48, 224]. A more accurate model based on FEA using dual moisture transport mechanisms has been recently developed for different encapsulation materials [225].

These last calculations were validated experimentally using measurement setup based on miniature temperature and humidity sensors [226, 140]. Using the same sensors, this work investigated the rates and patterns of moisture ingress into and egress out of PV laminates based on external humidity changes, utilizing measurements at different material depths. The results were compared with depth profiling measurements of the encapsulant inside **laminates of type II**. As shown in Table 3.1 and explained in **section 3.1** in **Chapter 3**, three laminates were prepared using two types of backsheets and two different lamination processes resulting of different degrees of crosslinking.

The moisture ingress was measured during DH (see **section 3.2.1**) and UV-DH combined (see **section 3.2.3**) exposure tests. This last combined test aims at more realistic representation of degradation by simulating multiple environmental stress factors simultaneously [47].

Figure 5.12 shows an example of the measured RH of all positions inside the laminates and one outside during the RH cycle applied in the chamber. As expected, the sensor encapsulated closer to the glass (pos. #1) detects the moisture ingress and egress with larger delay than the sensor embedded closer towards the backsheet (pos. #3). Furthermore, the water uptake inside the laminate describes a reversible behavior for all sensors positions at 85°C.


Figure 5.12 – Measured moisture ingress in laminate #a for RH cycle at 85 °C.

5.2.1 Backsheet effect on moisture ingress

All sensors showed higher RH values in laminate with CPC backsheet (see Figure 5.13). The equilibrium was reached faster, after ~ 15 h using CPC and after ~ 32 h using TPT at 85°C. This behavior indicates a higher moisture diffusion rate through the backsheet as indicated by the higher Water Vapor Transmission Rate (WVTR) from the backsheet's data sheet (see Table 3.1 in **Chapter 3**).



Figure 5.13 – Measured moisture ingress for position #1 in laminates #a and #b at different constant temperatures.

Since the data were acquired at three different temperatures, the effective activation energy (E_A) was determined assuming an Arrhenius-like behavior Eqn. 5.2.

$$D = D_0 \cdot \exp\left(-\frac{E_A}{RT}\right) \tag{5.2}$$

80

Where D is the diffusion coefficient, D₀ is a factor gathering various constants as well as entropy considerations, E_A is the activation energy commonly expressed in J/mol, R is the universal gas constant (8.314 J mol⁻¹ K^{-1}) and T is the temperature in K.

$$D = A \exp\left(-\frac{E_A}{RT}\right) [H_2 O]$$
(5.3)

$$D = A \exp\left(-\frac{E_A}{RT}\right) R H \exp\left(-\frac{H_s}{RT}\right)$$
(5.4)

$$D = D_0 \cdot \exp\left(-\frac{E_A^{eff}}{RT}\right) RH$$
(5.5)

$$\ln(D) = -E_A^{eff} RT + \ln(A) + \ln(RH)$$
(5.6)

The concentration of water in a polymer at a given temperature is equal to the product of saturation solubility S and the relative humidity: $[H_2O] = S \cdot RH$ [55]. The solubility usually is proportional to an Arrhenius-like expression where E_A is replaced by the enthalpy of solvation Hs allowing Eqn. 5.3 to be expressed as Eqn. 5.4. The two empirically determined values of activation energy and solubility enthalpy can be combined and expressed as effective activation energy (E_A^{eff}) to give Eqn. 5.5. The E_A^{eff} summarizes the diffusion properties. It is important to note that the key parameter is relative humidity at the sample temperature, not the vapor pressure of water.

Figure 5.14 shows the Arrhenius plots for all sensors of the laminates #a, #b and #c, where the y-axes specifies the time required to reach the equilibrium in RH. The corresponding temperature is indicated on the x-axes Eqn. 5.6.

Using different backsheet types between laminate #a and #b as shown in Figure 5.15, the E_A^{eff} presented in Figure 5.14 showed lower values at 65% RH for laminate #b, which confirm the higher water vapor transmission rates in Table 3.1 taken from the datasheet.



Figure 5.14 – Arrhenius plots describing the rate of moisture ingress during damp-heat aging. The calculated E_A^{eff} are presented for each RH setting.



Figure 5.15 – Digital microscopy images of the cross-section of the two backsheets used in the study.

To visualize the pathway of moisture during UV-DH combined test, the moisture and the temperature in the encapsulant is plotted at the three various depths for both laminates #a and #b (see Figure 3.1 in the **section 3.1**), as shown in Figure 5.16.



Figure 5.16 – Measured moisture and temperature in the chamber and in the laminate #a and #b.

In the beginning, all sensors measure same initial RH value. As the chamber humidity drops (i.e. at around 30 h), The diffusion of moisture through backsheet and EVA changes strongly, the sensor in pos. #3 shows a decrease in moisture as expected, while the sensor in pos. #1 shows an unexpected rise in relative humidity. For both laminates (#a and #b), the RH values close to the backsheet change quickly with the environmental conditions. The reasons for this behavior is still up for discussion to this date.

5.2.2 Correlation between EVA DoC and moisture ingress

The diffusion seems to exhibit dependence on the lamination time (see Figure 5.17); due to different degree of curing of the EVA [212, 139]. More precisely, the laminate with partially crosslinked EVA (laminate #c) showed slower moisture ingress (higher E_A^{eff} values in the laminate #c in Figure 5.14) at all sensor positions.



Figure 5.17 – Measured moisture ingress in laminate #a and #c at 40 °C, 65% RH.

During the lamination, the EVA curing process results in the consumption of the crosslinking additives (peroxide agent for EVA). Crosslinking or branching interconnects the polymer chains and reduces its crystallinity [131]. Therefore, a short lamination results in a weakly crosslinked EVA which has a higher degree of crystallinity. The dense packaging of the EVA in the crystallites acts as a diffusion barrier for the moisture ingress, which consequently, reducing the speed of diffusion through the material [91].

5.3 Conclusion

Generally, a better understanding of the crosslinking progress, especially at the onset of the PV module lamination, can help shortening PV module lamination times as well as optimizing the encapsulant formulation. It has been shown that the nanoindenation allows the measurement of mechanical properties of the EVA encapsulation materials with the application of extremely low load.

The presented method has been tested using two time-dependent indentation cycle modes to determine the EVA's surface viscoelastic behavior. A corresponding model was applied for each mode to calculate the main mechanical properties. The elastic response of the EVA surface from the creep measurement and the storage modulus from the viscoelastic sweep tests were then correlated to the EVA's DoC as measured by the DSC method. Additionally, in comparing the nanoindenation and DMA with tensile mode data, both characterization techniques produce very nearly the same quantitative damping factor, despite the different volume of the material response.

Furthermore, the dynamic nanoindentation was examined as a novel and suitable method to determine the change of the EVA viscoelastic property with higher test-retest reliability applicable for PV modules after its production as well as after its service lifetime. It will be good to develop the correlation equation between the extent of the damping factor used as a critical parameter and the module performance such as the power output.

Finally, a comparison of the effect of the backsheet permeability and degree of crosslinking of the EVA on (a) initial moisture uptake and (b) time required for saturation were demonstrated. This shows the importance of material properties and therefore material choice when making lifetime predictions. The periods at various RH and temperatures can be related back to reference conditions if the kinetics is known, specifically, the activation energy and the kinetic order of the moisture diffusion. The results demonstrate differences in diffusion rate in dependence of the backsheet type as well as degree of crosslinking of the encapsulant. A slower moisture ingress and higher effective activation energy (E_A^{eff}) could be obtained for the encapsulation with a lower degree of curing. Furthermore, the combined UV-DH seems to generate opposite pathways of diffusion between the sensor positions near the glass and near the backsheet before the equilibrium [227]. These findings are up to discussion and have to be analyzed in more detail in future investigations, where the interfacial behavior between EVA and either glass or backsheet materials need to be better explained.

6 Encapsulant degradation analysis: effect of backsheet

Abstract: The reliability of photovoltaic (PV) modules is highly determined by the durability of the polymeric components (backsheet and encapsulant). This chapter presents the result of experiments on encapsulant degradation influenced by the backsheet permeation properties. Towards this goal, one type of ethylene vinyl acetate copolymer (EVA) was aged in glass/EVA/backsheet laminates (laminate of type III) in accelerated aging tests (up to 4000 h for Damp-Heat (DH) and up to 480 kWh/m² for Ultraviolet (UV) and UV-DH combined). Firstly, by using samples with different backsheets, the effects of different material combinations on the EVA degradation mechanisms (chemical changes) were investigated. Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) studies identified two different EVA degradation processes. A thermal oxidation was taking place in the glass-EVA-Polyamide (PA)-based backsheet configuration after 500 h DH tests. However other EVA degradation products were observed in the glass-EVA-Poly(ethylenterephthalat) (PET)-based backsheet after 1500 h DH tests. Secondly, it has been perceived that a different material combination leads to different EVA degradation rates, by analyzing the EVA thermal and mechanical changes using Differential Scanning Calorimetry (DSC) and Nanoindentation respectively. As a consequence of these findings, the changes in the melting enthalpy and the viscoelastic properties at the EVA surface was more pronounced when PA-based backsheet was used then when PET-based backsheet was used under combined UV-DH aging tests. The comparison of three accelerated aging stress factors revealed that EVA suffers the strongest chemical and optical degradation when high UV, high temperature and high relative humidity are combined simultaneously.

Keywords: Encapsulant degradation; backsheet properties; accelerated aging; Damp-heat (DH); ultraviolet (UV); UV-DH combined; Nanoindentation; material combination

6.1 Material combination comparison

6.1.1 Detection of EVA decomposition

One approach of this study was to analyze the chemical changes of the EVA upon accelerated aging due to the influence of different backsheet properties. Towards this goal, a comparative analysis of the state of degradation after DH exposure (Test (1) in Table 3.3 in **section 3.2.1**) was undertaken using FTIR-ATR spectroscopy as described in **section 3.3.1** in **Chapter 3**. Since the FTIR-ATR spectroscopy is a surface characterization method with a penetration depth of only a few µm, EVA samples were pressed on the surface on the glass side (opposite from the backsheet layer) after peeling off the polymer film from the glass (see Figure 6.1)



Figure 6.1 – Digital microscopy images of the cross-sections to illustrate the sample's structure during FTIR measurements using ATR crystal on the EVA surface (glass/EVA interface).



Figure 6.2 – Typical ATR-FTIR spectra of a fresh EVA.

All expected peaks for intact EVA, representing ethylene (Et) and vinyl acetate (VAc) segments were observed in the spectra, as shown in Figure 6.2, including the different aliphatic CHx vibrations (continuous arrows) and the characteristic C–O, C=O bands (dashed arrows), respectively.

Using both PET-based backsheets, two noticeable new peaks at 744 cm⁻¹ and 829 cm⁻¹ on the EVA surface start to appear after 1500 h DH aging (Figure 6.3. a,b). These peaks can be associated with di- and tri-alkyl substance patterns which can be formed via additive degradation and can be responsible for the yellowing of EVA [50].



Figure 6.3 – ATR-FTIR spectra of the EVA at the glass interface before and after DH tests with PET-based backsheet_1 in (a,b) and PA-based backsheet in (c,d). All curves are offset in the y direction for clarity.

In contrast, when using PA-based backsheet, the ATR-FTIR spectrum of the EVA surface exhibits a narrowing of the peaks at 1642 cm⁻¹ and 3281 cm⁻¹ after the first DH test interval (500 h), as shown in Figure 6.3. c,d. The peak at 1642 cm⁻¹ corresponds to a ketone band shift which is consistent with the formation of unsaturated carbonyl products. In parallel, hydroxyl formation is also observed at 3281 cm⁻¹ (see Table 6.1).

IR [cm ⁻¹]	Group	Remark	
744	Diene	CH out-of-plane def. vib.	
829	$R^1 R^2 C = C H R^3$	CH out-of-plane bending	
1642	Unsaturated esters	double bonds of a vinyl group	
3281	Hydroxyl	Oxidation products	

Table 6.1 – FTIR absorption bands undergoing change in ethylene vinyl acetate copolymer EVA from Figure 6.3.

These degradation products may be formed by the breakdown of hydroperoxides. Alternatively, they could also be derived from the decomposition of additives whose initial components cannot be detected by FTIR. In this case, the EVA spectral changes are consistent with thermal oxidative degradation processes [228, 229, 230].

6.1.2 Determination of EVA melting enthalpy

DSC is often performed to determine differences in the crystallization of the EVA bulk. Here, we used it as a complementary technique to quantify the influence of different backsheet materials and aging stresses (summarized in Table 3.2 in **section 3.2.3**) on the EVA degradation. DSC thermograms of the EVA before and after long DH (1) and UV-DH combined (3) tests are shown in Figure 6.4 for the example of PET-based backsheet. During the first heating cycle from 40 to 70°C, two partially overlapping endothermic peaks are observed (Figure 6.4 (a)).



Figure 6.4 - DSC Thermograms of EVA. (a): (First heating), two overlapped endothermic peaks are $45^{\circ}C$ and $60^{\circ}C$. (b): (second heating), one remaining endothermic peak. All curves are offset in the y direction for clarity.

The peak at 45°C shows an increase in area after DH and combined UV-DH tests. The origin of this peak corresponds to the melting of small crystallites formed during lamination (for fresh EVA) and during the aging tests (for aged EVA) as a reversible process [90].

The position of the second peak shifts from 69°C to 66.5°C and 64°C after DH and combined UV-DH tests, respectively, which corresponds to the melting of the ethylene segments of the EVA [90, 89, 134]. The temperature of the melting peak is related to the average size of the crystallites in the EVA encapsulant [132, 133, 135]. The same peak is also present during the second heating cycle shown in Figure 6.4 (b). The temperature of the melting peak around 67°C indicates a clear dependence on the aging stress. This phenomenon can be explained by the decrease in the initial molecular mass of the EVA after the different aging tests via chain-scission degradation process.

The decrease in the melting enthalpy is a good indicator for material/polymers degradation [131]. The enthalpy measured in the EVA decreased after the first step of DH aging (500 h), indicating a decrease in the average size of the crystallites of aged EVA, and then remained constant independently of the backsheet type used (see Figure 6.5 (a)). The enthalpies gradually decreased with the increase in UV doses in the UV-DH combined tests (see Figure 6.5 (b)).

Furthermore, only small variations were observed when PET-based backsheets were used, while stronger drops in enthalpy were observed with the PA-based backsheet. The error bars represent the standard deviation of the average enthalpies taken per aging step. The large errors after combined UV-DH tests may indicate an inhomogeneity of the EVA degradation caused by additive distribution. Thus, the results provide evidence that different material combinations (backsheet/encapsulant) lead to different degradation rates [52]. More precisely, a significant chemical degradation of EVA was observed when the PA-based backsheet was used, which is in good correlation with the results discussed earlier in the section FTIR-ATR spectroscopy results. The cause for this observation could be that PA-based backsheets have a much higher OTR, and therefore with higher oxygen content we see more degradation.



Figure 6.5 – Evolution of the enthalpy of the endothermic transition in the DSC Thermograms of the EVA before and after DH aging (a) and UV-DH combined aging (b) (three different backsheets used in the laminates during the aging tests).

Chapter 6

6.1.3 Determination of the viscoelastic properties of EVA

Two different backsheets were used in PV laminates to understand the influence of material combination on EVA degradation. Samples were prepared according to **section 3.3.1** and nanoindentation measurements were performed at the EVA surfaces (see Figure 6.6), using the frequency sweep cycle mode as described in **section 3.3.3** in **Chapter 3** and in **section 4.1.2** in **Chapter 4**. The mechanical changes on the EVA due to the influence of the different backsheet properties were investigated.

First, we would like to point out that our situation is indentations of soft film (EVA) on the hard substrate (backsheet). Another important consideration, is that the maximum indentation penetration (~ 35 μ m) is less than 10 % of the total EVA thickness (~ 800 μ m) to avoid substrate influence. Therefore, in this study, the viscoelastic response is considered only of the EVA film assuming a negligible effect from the mechanical response of the backsheet. However, is it important to emphasize that the properties of PA backsheets change dramatically after weathering [231, 44].



Figure 6.6 – Digital microscopy images of the sample cross-sections to illustrate the sample's structure during indentation on the EVA surface (glass/EVA interface).

Figure 6.7 shows the matrix of 9 imprints from the spherical indentation with a x and y spacing of 200 μ m each. An average of 9 measurements per sample were taken and evaluated regarding their *tan* δ as shown in Figure 6.8. At small UV doses under 180 kWh/m², both EVA surfaces showed no changes in their viscoelastic behavior, as marked by the constant value of *tan* δ . After 180 kWh/m², the modules based on a PET backsheet still showed no changes in the viscoelastic properties of its EVA on the glass-polymer interface. However, the PA backsheet-based modules showed strong changes upon aging: The *tan* δ increases significantly with increasing UV doses.

Using a PA-based backsheet, the increase in $tan\delta$ reveals changes in the viscoelastic response of the EVA surface after UV-DH combined, which indicates a change in the molecular structure and a degradation of the EVA. The current analysis confirms the hypothesis that for PA-based backsheet/EVA combination, the susceptibility to degradation is higher than for the PET-based backsheet/EVA combination.



Figure 6.7 - Optical microscopy image of indented EVA surface (glass-EVA interface).

This example provides evidence that the permeation properties of the different backsheets are of great importance. As stated, PA-based backsheet allow high oxygen permeation, which diffuses through the EVA and increases the oxygen concertation at the EVA/glass interface during the UV-DH treatment which could enhance the photo-oxidation of the EVA surface [47]. After these weathering conditions and by using both backsheets, EVA samples were degraded to obtain discolorations extending from yellow to brown as seen in the example of using PET-based backsheet in Figure 6.8.



Figure 6.8 – Damping factor (calculated from the sinus part of the dynamic curve) before and after UV-DH combined aging.

6.2 Interface comparison

6.2.1 Detection of EVA decomposition

Previous studies have shown the role of silane-based coupling agents as adhesion promoters for the glass/EVA interface [232, 233], where the silane reacts with hydroxylated glass to create siloxane bonds [234]. A recent study has shown that increasing silane content increases the EVA's chemical stability against DH aging [129]. In addition to the comparison of the backsheet influence, the chemical changes of the EVA surfaces between the glass/EVA and EVA/backsheet interfaces were compared after the same DH exposure using FTIR-ATR spectroscopy.



Figure 6.9 – ATR-FTIR spectra of the EVA at glass interface and at backsheet interface with PET-based backsheet_2 in (a,c) and PET-based backsheet_1 in (b,d). All curves are offset in the y direction for clarity.

Firstly, we would like to point out that independently of the backsheet used, the broad peak at 1600 cm^{-1} due to conjugated diene (C=C) started to broaden at the glass/EVA interface after the first DH aging tests (step 1) (500 h) (see Figure 6.9 (a),(b)).

For laminates with both PET-based backsheets, four noticeable new peaks on the glass/EVA interface (see Figure 6.9, (a) (b)), and one noticeable new peak on the EVA/backsheet interface (see Figure 6.9, (c) (d)), started to appear after 1500 h DH aging. All of these peaks can be associated with di and tri-alkyl substance patterns as discussed earlier and listed in Table 6.2.

IR [cm ⁻¹]	Group	Remark
480	$cis-R^1C = CHR^2$	-
680	trans- $R^1C = CHR^2$	-
744	Diene	CH out-of-plane def. vib.
829	$R^1 R^2 C = C H R^3$	CH out-of-plane bending
880*	R - CH = CH - R	CH out-of-plane bending
1600	Conjugated diene	C = C stretch

Table 6.2 – FTIR absorption bands undergoing change in EVA from Figure 6.9.

*It only appears at the EVA-backsheet interface.

No signals from the silane compounds could be identified in the ATR-FTIR spectra (see Figure 6.9), which is in line with the reportedly low concentration under the detection limit of the instrument [129]. At the EVA/backsheet interface, without reaction to glass, the impact of silane on EVA degradation is negligible, even under 4000 h of damp heat aging. At the glass/EVA interface, the glass seems to act as a catalyst for EVA chemical changes demonstrated by the effect of damp heat exposure.

6.3 Aging test comparison

Photo-degradation due to UV stress exposure has been reported to cause a number of degradation modes. It could, for example, cause discoloration of the encapsulant material [235], delamination of the glass/encapsulant or cell/encapsulant interfaces [236]. Indeed, the effect of UV aging has been quantified using the Schwarzschild law which models the effect of UV independently without other contributing stresses [237]. However, a new study of combined accelerated aging tests has achieved recent attention [127]. Furthermore, it was demonstrated that UV irradiation plays a significant role in generating acetic acid from the EVA with the presence of relative humidity that can cause power degradation of PV modules [238].

6.3.1 Detection of EVA decomposition

The same types of laminates (**laminates of type III**) were irradiated with dry-UV light with a wavelength of 280 nm – 400 nm (UV-A). An irradiance of 250 W/m² was not exceeded. The sample temperature was approx. 60°C during the test as described in **section 3.2.2**. The FTIR-ATR spectroscopic results of the UV tests demonstrate a good chemical stability of the EVA at glass and backsheet interfaces as shown in Figure 6.10, where no EVA's chemical changes were observed at both glass and at backsheet interfaces after the long dry-UV tests.



Figure 6.10 – ATR-FTIR spectra of the EVA at the glass and at backsheet interfaces before and after dry-UV tests. All curves are offset in the y direction for clarity.

Based on the previous results of EVA chemical changes through damp-heat aging and the latest dry-UV aging tests, we further studied the influence of Vinyl Acetate (VAc) content on the combined UV-DH aging behavior of EVA, comparing with other standard tests, DH and dry-UV separately. According to the prevalent literature, the VAc units are more vulnerable to heat, oxygen, and UV light radiation than the ethylene group, and therefore could easily form reactive radicals or unstable hydroperoxides and thereby trigger further irreversible chemical reactions. EVA photo-degradation has been reported to cause a number of degradation modes. It has been demonstrated that UV irradiation plays a significant role in generating acetic acid in the presence of relative humidity, which can cause corrosion and power degradation of PV modules [238].

Quantitative results of the effects of combined UV-DH conditions (see **section 3.2.3**) are described and interpreted hereinafter (Figure 6.11). In comparing these results with the standard dry-UV tests, we conclude that the latter alone would have a minor influence on the EVA photo-degradation. During this test, the chamber's relative humidity usually accounts for 20–38%.

In the combined UV-DH test, however, the humidity level was set to 85% and the temperature to 60°C, while the latter slightly increased at the sample surface due to the UV irradiation. Note that the temperature in the chamber has an impact on the humidity level, which is a bit lower at the sample surface. After the combined UV-DH test on the laminates with PA-based backsheet, the FTIR spectra of the EVA surface show a growth of a shoulder at 1715 cm⁻¹ and a broad band at 1178 cm⁻¹ (see Figure 6.11 (b)), unlike after the DH test (see Figure 6.11 (a)). These peaks represent C=O stretching of ketone functions. These might have formed during the acetaldehyde evolution in Norrish III reaction [50, 125].



Figure 6.11 – ATR-FTIR spectra of the EVA at glass interface before and after DH (a) and UV-DH combined (b) tests with a PA-based backsheet. All curves are offset in the y direction for clarity.

In parallel, lactone formation was also observed through the absorption band around 1780 cm⁻¹ in Figure 6.11 (b), indicating a back-biting process in the polymer chain [125, 239]. These degradation products may have formed after chain-scission caused by photo-oxidation. To obtain a quantitative comparison of specific functional groups formed during the three aging types (DH (1), UV (2) and UV-DH combined (3)), the intensity ratio between the methylene (–CH2–) in-plane deformation rocking at 2850 cm⁻¹ and the absorbance of the selected carbonyl, also known as the carbonyl index (CI) [28, 240], were measured. As can be seen in Figure 6.12, the ratios referring to ketone formation, describes an initially small drop before growing upon further aging. Variations in A_{2850}/A_{1710} taken as an example, indicate that:

- DH: No carbonyl formation from the EVA chain is observed after 4000 h DH exposure.
- UV: Minor changes in the CI until 300 kWh/m² irradiation, and then it remains stable.
- UV/DH combined: A gradual increase in the CI with longer aging and stabilization after 300 kWh/m² irradiation.

Samples submitted to the combined UV-DH test showed a higher degree of carbonyl formation than those with a lower moisture exposure. We conclude that the effect of UV exposure on EVA's photo-oxidation combined with high temperature is highly influenced by the moisture level.



Figure 6.12 - CI of EVA with different aging tests for various peak shifts from FTIR spectra.

6.3.2 Quantification of the EVA fluorescence background

The Raman spectra of all aged **laminates of type III** showed an intense fluorescence background which increased in the Raman spectra upon further aging (see Figure 6.13). The fluorescence background was correlated with the chemical degradation of the EVA. More precisely, the fluorescence intensity increased due to the formation of chromophores [52] at high Raman shift ranges for DH (green spectra), whereas dry-UV tests (spectra in blue in Figure 6.13) showed a maximum increase mainly between 1400 cm⁻¹ and 2200 cm⁻¹. Furthermore, the combination of both stress factors (combined UV-DH spectra in red in Figure 6.13) showed a similar fluorescence range to the UV degradation process, albeit at a higher intensity. The different spectral regions of the fluorescence provide evidence that DH and UV aging cause different EVA degradation processes and that the process caused by UV aging is further accelerated by the moisture present in the combined UV-DH test to result in faster EVA photodegradation.



Figure 6.13 – Raman spectra of the **laminates III** after different aging conditions. DH tests (1) in blue, UV tests (2) in orange and UV-DH tests (3) in purple.

6.3.3 Yellowness index measurement

The non-destructive determination of yellowness index was used to measure the optical degradation and compare the effect of different aging tests. Figure 6.14 depicts a moderate discoloration of the EVA after DH test, which is in the same range as after dry-UV test (curves in blue and orange). More importantly, EVA yellowing is accelerated with a factor of 10 by combined UV-DH exposure. Degradation products, such as C=O and C=C double bonds are induced by a thermo-oxidative or photo-oxidative processes, for DH and UV, respectively [29, 125]. Additionally, The hypothesis is that the yellowing is caused by degradation products of the antioxidant [241].



Figure 6.14 – Yellowness index (YI) of EVA incorporated in the test **laminates III** upon different aging condition tests. DH tests (1) in blue, UV tests (2) in orange and UV-DH tests (3) in purple.

A model to quantify the effects of combined UV-DH conditions is proposed here. In developing the model, we assume that UV stress alone would influence some degradation modes but also some other modes might be influenced with a combined UV and moisture stresses.

Therefore, to take into account the effect of UV alone and the combined UV and moisture, the following degradation model is proposed. The latter was applied to evaluate the change in *YI* due to combination of UV-DH or dry-UV stresses. The model is done as follows in Eqn 6.1:

$$YI = YI_0 + A.UV^{\mathcal{Y}}(1 + RH^{\mathcal{X}}).\exp\left(-\frac{E_A}{kT}\right)$$
(6.1)

Table 6.3 – Extracted parameter of the yellowing index model.

Mode parameter	А	У	х	E_A (eV)
Value	1.75	2.05	1.24	0.43

Where $Y I_0$ is the initial yellowing index. To demonstrate its application, the experimental measurements on the **laminates of type III** were used. As explained earlier, the dry UV and UV-DH combined tests were carried out at T = 60°C for different UV doses (60, 120, 180, 240, 300, 360, 420, 480 kWh/m²).



Figure 6.15 – (A) Thick red-model fit, dotted red measured data, thick blue-model prediction, dotted blue measured data calibrated data. (B) Sensitivity analysis of yellowing index change to relative humidity and UV doses.

Since during this test the sample's relative humidity usually reads > 30%, in this case we assumed the sample humidity as 25%. In the second experiment, the humidity level in the climatic chamber was set to 85%, but a bit lower at the laminate surface, around 70%. The temperature to 85°C and the UV doses remained the same as in the first experiment. The proposed yellowing index model is parametrized on the experimental data at T = 60°C and RH = 85% to extract the model parameters presented in Table 6.3. The model is then applied to predict the change in yellowing index at T = 60°C and RH = 25%. The predictions are plotted with the measurements in Figure 6.15 (a). This predictions correlate well with the experiments and help for a better sensitivity analysis of *Y I* change to RH and UV doses (see Figure 6.15 (b)).

6.3.4 Determination of EVA melting enthalpy

It has been demonstrated that the aging behavior of the crystalline structures of EVA between DH and UV aging tests is different. Higher doses of UV stress cause faster aging than DH on crystallization of EVA as well as on the EVA/Glass adhesion strength [41]. To investigate the effect of heat dissociation in the EVA chains formed during the different aging test conditions (DH, UV-DH: using the PA-based backsheet. UV: using PET-based backsheet_1), the enthalpy of the endothermic peak during the second heating cycle was integrated and depicted in Figure 6.16 as a function of the different steps of aging. As the aging time increases, the enthalpy decreases and results in EVA crystals with smaller molecular weight of EVA.

Due to measurement uncertainties as indicated by error bars, it is difficult to compare between the heat dissociation rate in the EVA chains under the DH (blue bars in Figure 6.16) and dry-UV (orange bars in Figure 6.16). In other words: The aging stress has little effect on the DSC results compared with the measurement uncertainty. More importantly, the experiments reveal that the chemical properties are degrading most strongly when the factors of high UV, high temperature and high relative humidity are combined (purple bars in Figure 6.16).



Figure 6.16 – Evolution of the enthalpy of the endothermic transition in the DSC Thermograms of the EVA before and after different aging condition tests.

6.4 Conclusion

This study examined the EVA degradation influenced by the backsheet properties after performing different accelerated aging tests. The FTIR-ATR spectroscopic studies identified two different EVA degradation processes. A thermal oxidation was taking place in the glass–EVA–PAbased backsheet configuration after 500 h DH tests. However other EVA degradation products were observed in the glass–EVA–PET-based backsheet after 1500 h DH tests.

Furthermore, the dynamic nanoindentation is examined to be a novel and suitable method to show the change of the EVA viscoelastic properties in a PV module after its service lifetime. As a consequence of our findings, the change in the viscoelastic properties at the EVA surface is more pronounced when PA-based backsheet was used then when PET-based backsheet was used under combined UV-DH tests. This technique has the potential to improve PV module analysis by allowing rapid mechanical response detection of the EVA after aging.

Additionally, the EVA degradation during DH was investigated at different interfaces. At the glass-EVA interface, the glass seems to act as a catalyst for EVA chemical changes of DH aging, independent of the type of backsheet used.

Finally, strong EVA degradation was observed when UV light, high temperature and high relative humidity were combined in the aging tests. As confirmed by FTIR-ATR and Raman spectroscopies, Yellowness Index and DSC measurements, the degradation under combined UV-DH was higher than both individual stresses. The UV irradiation plays a significant role in generating photo-oxidation products which, in the presence of high moisture level, cause chain-scission of EVA inside a laminate.

7 Correlation between failure imaging and power output degradation

Abstract: The aging behavior of materials in photovoltaic (PV) modules is strongly affected by the climatic conditions that influence the micro-climate that the polymer actually experiences. The micro-climate also depends on the materials that are used for module production, because e.g. backsheet with different transport properties might lead to different behavior as discussed in **Chapter 6**. Understanding how materials degrade upon the application of different external stress factors (temperature, humidity and UV radiation) is of fundamental importance to understand if those processes result in a PV module power decrease.

In this work, the **PV modules of type IV** were built and subjected to artificial aging tests. The influence of different micro-climates was investigated and changes in material properties were correlated to performance degradation. Furthermore, a good correlation between the changes in PV performance parameters and PV module optical evolution of the modules with different material combinations was reached. Moreover, the power output and the series resistance degradation of the PV module was much more severe and stronger under this combined UV-DH aging test than the addition of both factors individually. Based on the experimental measurements, it was shown that moisture has a significant impact on degradation mechanisms driven by combination of UV, relative humidity, and temperature stresses. Under these combined aging conditions, several degradation modes were observed under the visual inspection of the PV modules, including corrosion of the solar cells, backsheet cracking and EVA discoloration. However, the same module types showed none of those degradation modes except a minor corrosion after the dry-UV aging tests. Indeed, Scanning Acoustic Microscopy (SAM) proved to be a useful technique to detect backsheet cracks that are otherwise not detectable in the visual inspection. Additionally, by means of different techniques, it is possible to learn different information, but not all of them can be related to changes in performances. The modules were analyzed by imaging techniques, including SAM, Electroluminescence (EL) and Dark Lock-in Thermography (DLIT) before and after every aging step, and the images were compared.

Keywords: PV modules; backsheet cracking; damp-heat (DH); ultraviolet (UV); UV-DH combined; electrical performances, material combination; SAM; EL; DLIT

Chapter 7 Correlation between failure imaging and power output degradation

PV modules undergo different degradation mechanisms when exposed to different aging stress combinations. On the one hand, mathematical modelers develop kinetics models of degradation mechanisms to quantify the effects of applied stress combinations basing on physical/chemical assumptions [113]. On the other hand, by applying controlled conditions in the climatic chambers, it is possible to observe the dominating degradation mechanism using different characterization techniques [242].

The two approaches complement each other, for example, the developed mathematical models, recently introduced [113, 115], need to be validated with experimental observations and when validated, mathematical models which are utilized to simulate the rates degradation mechanisms under different stress conditions in shorter period hence reducing the amount of time and costs of experiments. The models can be also applied to map the specific degradation mechanisms indifferent climates [113]. The motivation of this study is based on the previous study [114] were mathematical model were used to map the global degradation rates.

For the experimental part, before and after applying the stress tests on each **PV modules of type IV**, a number of characterization measurements were carried out, as showed in the list below, in order to monitor the degradation in performance or safety.

- Performance at STC (Initial).
- Visual inspection.
- Electroluminescence imaging.
- Dark-lock-In Thermography imaging.
- Scanning Acoustic Microscopy imaging.
- Stress test 1 (Damp-heat -> dry-UV or UV-DH combined).
- Performance at STC.
- Visual inspection.
- Electroluminescence imaging.
- Dark-lock-In Thermography imaging.
- Scanning Acoustic Microscopy imaging.
- Stress test 2.
- ...

The PV modules of type IV with different backsheets are under investigation. All modules consist of mono-crystalline silicon cells with EVA as encapsulant and are laminated using similar standard conditions as discussed in **section 3.1**. The modules were first subjected to DH for 2500 hours (h) with electrical measurements and visual characterization taken at 1000 h, 1500 h and 2500 h intervals as described in **section 3.2.1**. The modules were then sequenced by (1) a dry-UV (420 kWh/m² at 60°C) and (2) combined UV-DH (420 kWh/m² at 60°C /85% RH). Measurements during UV stress were taken after 240 kWh/m² and 420 kWh/m² as described in **section 3.2.3**, respectively.

In the following Figures A.1, A.2, A.3, A.4, A.5 and A.6 which contain the respective photographs, the results of the inspection are shown. Peculiar visual changes or degradation as a result of the stress tests are given.

Based on all characterizations mentioned before in the list, the **PV modules of type IV** which were subjected to DH tests did not present major degradation modes or defects, such as corrosion, delamination or yellowing, even after they were aged for 2500 h (about 3.5 months). Therefore, a comparison of defects amongst the non-destructive techniques addressed in this work may not seem optically interesting at first, but it is no less meaningful. Nevertheless, relevant data concerning changes in the acoustic behavior – linked directly to the elastic properties – of the polymeric layers due to aging tests have been collected and discussed previously in the **Chapter 4**.

7.1 Relative humidity effect on performances

When researching PV degradation kinetics, the effect of relative humidity is usually neglected. In this part we shall evaluate how relative humidity affects the performance degradation using experimental data. This analysis will be used to validate previous works where global degradation rates were mapped [113, 115, 114].

On that study, it was surprising that stronger degradation rates where predicted for photodegradation mechanism in areas with higher UV irradiance and temperatures (e.g in the northern part of Africa, see Figure 7.1 top [114]). It was found that the reason to this observation was because of the very low relative humidity values in this region (see Figure 7.1 bottom [114]). These findings opened further investigations to carry out experiments to verify the simulations. Therefore, in this section we show the results of the experimental investigations. More precisely, we investigate the effects of combined temperature, relative humidity and UV conditions basing on the electrical performance and imaging techniques.

In this part we present results of two of these **PV modules of type IV** with *AAA* and *APA_Al* backsheets. This results shows the measured performance data before and after each stress test. Figure 7.2 plots the change in the maximum power (P_{MPP}) as well as the change of in the series resistance (*Rs*), calculated from the measured IV curves as explaned in **section 3.3.2**, of the tested **PV modules of type IV** in dependence of the different sequential reliability tests.



Figure 7.1 – Simulated photo degradation rate map (top) and relative humidity (bottom) [114].



A higher series resistance results in a voltage drop and therefore loss of output power.

Figure 7.2 – Measured P_{MPP} (a) and Rs (b) for M-AAA and M-APA_Al under different aging conditions.

First, we would like to point out that the 2500 h DH tests does not incur enough performance degradation. However, differences in performance degradation of the **PV modules of type IV** with *AAA* and *APA_Al* backsheets are observed during the extended different reliability tests (after DH tests) as shown in Figure 7.2, which plots the maximum power (P_{MPP}) and the series resistance (*Rs*) over the aging duration.

Deviations of the intermediate and final measurements from the initial measurement are given. Figure 7.2 showed that after the tests, the output power relatively to initial showed a deviation of -2,7 % and -10,5 % for the module *AAA*09 after dry-UV tests and for the module *AAA*08 after UV-DH combined tests respectively, and a deviation of +1,7 % and -23,4 % for the module *APA_Al*12 after dry-UV tests and for the module *APA_Al*11 after UV-DH combined tests respectively.

According to the electrical characterizations of the two **PV modules of type IV** with *AAA* and *APA_Al* backsheets, it is visible that moisture has a big impact on UV-RH-T induced mechanisms. For example both modules showed a stronger P_{MPP} and *Rs* degradation in conditions of extended UV-DH combined in comparison to conditions of extended dry-UV after 2500 hours of DH tests.

Moreover, a destabilization phase is visible in the P_{MPP} measurements for the DH followed by UV-dry conditions of the both modules types. It has been shown in literature, that the monocrystalline PV modules based on the so-called PERC technology, can become susceptible to Light Induced Degradation (LID) during damp heat testing. This effect, which is referred to as destabilization can lead to significant LID at room light after damp heat testing [243, 244].

7.1.1 Correlation between backsheet cracking and corrosion

The *AAA* backsheet was used for the production of **PV modules of type IV**. As discussed in **Chapter 1**, this type of backsheet is known to show outer layer cracks in the field depending on the climatic conditions, other material combination and/or possibly lamination parameters. This type of degradation was not detected from the visual inspections and SAM images after the application of dry-UV aging for 240 kWh/m². However, outer layer polyamide cracks, similar to one from the fielded PV modules, were obtained after a 240 kWh/m² UV irradiation, elevated temperature and elevated relative humidity were combined in the aging tests (UV-DH) (see Figure 7.3).

The images in the left were taken by SAM for the quantification of the micro-structure of the polyamide outer layer. Note that the cracks are more propagated with the duration of the UV-DH combined accelerated aging test as showed in Figure A.3. However, The same module type showed no visible backsheet defect after the dry-UV tests (Figure A.4).

This acknowledges that moisture plays a synergistic role with UV in the formation of surface backsheet cracking [47, 37]. The same failures have been also recently reproduced by an indoor accelerated aging test utilizing simultaneous combined stresses (UV, humidity, temperature and thermo-mechanical load) [231].

The electroluminescence (EL) images (see Figure 7.3) confirm the observation discussed earlier. From the EL images it is visible that there is more electrical faults on the solar cell under UV-DH conditions in comparison to UV-dry conditions.



Figure 7.3 – Photography and EL images for **PV modules of type IV** with *AAA* backsheet after 2500 h of DH, after 240 kWh/m² and after 420 kWh/m² in UV-dry (up) and in combined UV-DH (bottom). SAM images of both aged backsheets showed outer layer structure (left).

Acoustic images in the Figure 7.4 were taken by applying gates to peaks (#1) and (#2) as indicated in Figure 7.5 left, before and after a UV-DH combined accelerated aging test. The acoustic beam can be focused to increase the amplitude of specific signals and thereby increase the image quality for a chosen interface. The images at echo #2 show the main elements at the back surface of the cell, such as the back ribbons and cross-connector. Naked eye visual and additional non-visual cracks (orange arrows) are detected with SAM image after the aging test.

An additional feature of SAM is the visualization of layer thickness. Figure 7.5 right shows an acoustic measurement from the water/backsheet to EVA/Cell interfaces, recorded, where the colors represent the depth information in combination with the speed of sound. Specifically, blue corresponds to a long time-of-flight (TOF), green is shown when the TOF is shorter and red corresponds to the shortest TOF.



Figure 7.4 – Acoustic micrographs of a **PV module of type IV** using *AAA* before and after UV-DH combined aging test at the backsheet/EVA interface (#1) and EVA/cell interface (#2).





Figure 7.5 – Left. Time of flight (TOF)-amplitude reflectogram of **PV module of type IV** measured at 30 MHz. Right. TOF from water-backsheet to EVA-Cell interfaces. Red (short) to blue (long) shows different polymer thickness.

With the TOF being proportional to the thickness of a given homogeneous material, this image reveals details on the backsheet and EVA thickness inhomogeneities due to the arrangement of other module components, such as the cross-interconnects at the top and bottom edges of the module, the rear side ribbons, and the cell boundaries.

7.1.2 Correlation between yellowing and corrosion

The *APA_Al* backsheet was used as a second example for the production of **PV modules of type IV**. This type of backsheet has an aluminium interlayer as a barrier against moisture ingress.



Figure 7.6 – Photography and EL images for **PV modules of type IV** with *APA_Al* after 2500 h of DH, after 240 kWh/m² followed by 420 kWh/m² in UV-dry (up) and in UV-DH (bottom).

On contrary of the The *AAA* backsheet, the *APA_Al* backsheet showed no cracking after a 480 kWh/m² UV irradiation at elevated relative humidity (UV-DH). However stronger electrical faults along the ribbons in the form of corrosion of the cell, were observed under the EL images, whereas a weaker electrical faults were detected after the application of dry-UV aging for 480 kWh/m² (see Figure 7.6).

In parallel to the electrical faults, from the images of the front side of the modules, as shown in the Figure 7.6, it is visible that there is more yellowing under UV-DH conditions in comparison to UV-dry conditions.

In Figure 7.7, after dry-UV aging test for 480 kWh/m², both modules types showed on the front side, a lower Yellowness Index (*Y I*) in contrast to the modules aged under UV-DH combined test for 480 kWh/m² UV dose. Especially for the **PV modules of type IV** with *APA_Al* backsheet, the measured *Y I* value was 23% lower after the dry-UV test than after the UV-DH combined test. Under the latter condition, a significant discoloration were also observed on the back side of the module. i.e. the *APA_Al* backsheet was getting yellow after UV-DH combined tests as shown in Figure A.5 in the appendix. While the same module show quite consistent optical stability under the dry-UV test as shown in Figure A.6 in the appendix.



Figure 7.7 – Measured YI for M-AAA and M-APA_Al under different aging conditions.

Therefore, the combined accelerated tests might have caused chemical changes in the backsheet material which in turn led to the high YI values. As it was observed in the **Chapter 6**, this acknowledges that moisture plays a synergistic role with UV in the encapsulant and backsheet chemical and optical degradation. It is also known that the chemical degradation after the migration of additives into backsheet-encapsulant interface are one the main cause for backsheet yellowing [14].

7.2 Material combination effect on performances

By using the **PV modules of type IV** different backsheets from all categories in Figure 2.1 in **Chapter 2** on the same lamination run with the same other PV components, the electrical performance parameters were measured before and after applying the simultaneous UV-DH combined aging tests. Similar sens of evolution of the P_{MPP} and Rs degradation was also observed by all **PV modules of type IV** after indoor accelerated aging test utilizing simultaneous combined stresses (see Figure 7.8).

Once again the data reveals that the 2500 h DH tests does not incur enough degradation to discriminate the effect due to backsheet properties. Whereas, a clear dependence of the module reliability in UV-DH combined accelerated test on the backsheet properties is observed. More precisely, it is shown that the modules with different backsheet types yield to different performance degradation rates.



Figure 7.8 – Measured P_{MPP} (a) and Rs (b) for different material combination under UV-DH combined aging conditions.

The color measurements of the four modules with different material combinations were performed and the *YI* after the UV-DH combined tests are presented in Figure 7.9. The results correlate well with the P_{MPP} and *Rs* compared values between the modules after the last aging step. As an example, by using *TPT* backsheet, the module shows the strongest P_{MPP} (a) and *Rs* (b) degradation with 32% and 60% relative change, respectively. The same module shows the strongest discoloration of 80% *YI*. In this example, the *YI* can be considered as one of the critical material parameters to be related to the module performance.



Figure 7.9 – Measured *YI* for different material combination under UV-DH combined aging conditions.

7.3 Correlation between acoustic, thermal and electroluminescence imaging

The comparison of SAM images with DLIT and EL images for all **PV modules of type IV** was investigated and is presented in Figures 7.10, 7.11, 7.12, 7.13, 7.14 and 7.15 after reliability tests. On the EL image (on the right of the Figures), when charge carriers recombine in the p-n junction, then electroluminescence radiation is emitted. Therefore, the areas where radiative recombination takes place will look bright in the images, i.e., where the solar cell is functioning. Bright areas on the DLIT (in the middle of the Figures) amplitude images represent warmer surface temperature. Therefore, ribbons are bright because of the increased heat they produce as they carry electric current. The DLIT phase image shows the local phase shift of the signal. Both EL and DLIT imaging techniques demonstrate that, as the aging progresses, the busbars surrounding areas become darker.

The SAM images in all Figures 7.10, 7.11, 7.12, 7.13, 7.14 and 7.15 left, were taken by applying gate to peak (#2) in Figure 7.5 left, as explained earlier in **section 7.1.1**. The SAM images display different material structures depending on the backsheet used in the material. Therefore, the detection of contrast changes that correspond to changes due to aging in the SAM images is particularly challenging, given the differing contrast patterns observed, especially at the active layer of the module (The solar cell, the ribbons and cross-connector). Sometimes these structures can also appear on the DLIT images. These are due to the backsheet's thickness and structure or/and the nonuniform module surface, which sensitively affects the contrast of the images.

Additionally, shunts in all Figures 7.10, 7.11, 7.12, 7.13, 7.14 and 7.15 were detected by EL and DLIT, but these were not detected by SAM. The likely reason is that shunts do not represent a particular polymeric material property or change in elastic property, which could then be detected by the acoustic waves. However, the SAM images reveal other module components failure compared to the DLIT and EL images, such as the encapsulant degradation. For all module types, the regions around ribbons at which after UV-DH combined tests (Figures 7.10, 7.11, 7.12, and 7.14) turn dark in the DLIT and the EL images. This indicates the electrical faults which does disturb the functionality of the ribbon. After the dry-UV tests (Figures 7.13 and 7.15), this degradation patterns is too weak.



Figure 7.10 – SAM (a), DLIT (b) and EL images (c) of a *CPC*02 module after sequential reliability tests.

The SAM images in Figure 7.10 (a) already depict a contrast change of the polymeric layers before aging. This shows the EVA thickness inhomogeneities due to the arrangement of other module components during the lamination. This contrast can appear only with this module type, where the *CPC* backsheet contain a thin PET layer coated from both sides. Moreover, after UV-DH combined aging, the DLIT images depict a distinct brighter phases, which means the heat propagation is delayed because of the backsheet cracking as observed on the SAM.



Figure 7.11 – SAM (a), DLIT (b) and EL images (c) of a *TPT*05 module after sequential reliability tests.

Figure 7.11 shows that the strongly dark areas around ribbons due to the aging on the DLIT (b) and EL (c) images can also be detected on the SAM image (a) only after 420 kWh/m² UV doses of UV-DH combined test.

This can be explained by the absence of the contrast due to the thicker PET layer in the *TPT* as in the *CPC* and/or the material micro-structure of the fluoropolymer layers used in the *TPT* backsheet.



Figure 7.12 – SAM (a), DLIT (b) and EL images (c) of a *AAA*08 module after sequential reliability tests.

Figure 7.12 shows weaker dark areas around ribbons on the DLIT (b) and EL (c) images on samples with *AAA* backsheet after the UV-DH combined tests, in comparison to the other backsheet types (*CPC*, *TPT* and *APA_Al* backsheets used). This results are consistent with the material combination effect on performance as discussed in **section 7.1.2**, where different material combinations lead to different performance loss rates.





Figure 7.13 – SAM (a), DLIT (b) and EL images (c) of a *AAA*09 module after sequential reliability tests.

Figure 7.13 shows almost no dark areas around ribbons on the DLIT (b) and EL (c) images, for modules with *AAA* backsheet after the dry-UV tests in comparison to the degradation after UV-DH combined (Figure 7.12). This correlates well with the relative humidity effect part on performance as discussed in **section 7.1.1**, where higher moisture inside the module lead to faster performance loss. Moreover, the DLIT (b) and EL (c) images show, after DH aging tests, a significant crack at the lower right part of the cell, which runs diagonally from the edge towards the center of the cell. It likely arose due to inadequate module production.
This cell crack cannot be detected with the SAM images (a) because of the structure of the *AAA* backsheet again. However, the detection of this cell cracks was possible with different measurement parameters, which is not presented here, since the set of SAM parameters to expose backsheet and cell cracks is different.



Figure 7.14 – SAM (a), DLIT (b) and EL images (c) of a *APA_Al*11 module after sequential reliability tests.

Figure 7.14 shows a strong dark areas around ribbons on the DLIT (b) and EL (c) images, by using the *APA_Al* backsheet after the UV-DH combined tests. The blurry image on the DLIT can be explained that, the heat transmission propagates from the cell up to the inner layer of the backsheet and blocked by the Aluminium interlayer.



Figure 7.15 – SAM (a), DLIT (b) and EL images (c) of a *APA_Al*12 module after sequential reliability tests.

After 420 kWh/m² dry-UV

(a)

Figure 7.15 shows weaker dark areas around ribbons on the DLIT (b) and EL (c) images, by using the *APA_Al* backsheet after the dry-UV tests in comparison to the degradation after UV-DH combined (Figure 7.14). This correlates well with the relative humidity effect on performance as mentioned in **section 7.1.1**.

The DLIT images (b) of all **PV modules of type IV** in Figures 7.10, 7.11, 7.12, 7.13, 7.14 and 7.15 show an increase in the temperature transport on the module surface along the busbars with aging: strong dark areas after UV-DH combined tests and weak dark areas after dry-UV tests. These areas particularly correspond to the dark areas seen in the EL images (c).

Moreover, as the aging progresses, the busbars surrounding areas become darker in both DLIT and EL images. This adds the observation of the discoloration of the soldering ribbons with UV-DH combined aging as shown in Figures A.1, A.2, A.3 and A.5 in the appendix, which suggests a corrosion on the solar cells. In contrast, the two dry-UV aged modules (Figures A.4 and A.6) did not show a clear discolouration effects around the ribbons.

The acoustic images (SAM images (a)) of the solar cells did not show the defects on the corrosion after UV-DH combined tests. This can be explained by the effect of the backsheet structure hindering the propagation of ultrasound completely. At these conditions, one can hardly make any precise assumptions on this depth profile of the modules. However, as an exception, the SAM image (a) after the last period of aging in the Figure 7.11 shows the same features as for the DLIT (b) and EL (c) images. This may suggest that the *TPT* backsheet can allow the propagation of the acoustic waves using the 30 MHz frequency transducer at room temperature.

7.4 Conclusion

The UV-DH combined aging test resulted in decreased power output, compared to UV-dry, caused by several degradation modes, including yellowing of the encapsulant and corrosion. Based on the experimental measurements, it was shown that moisture has a significant impact on degradation mechanisms and therefore on the power output and the series resistance degradation, driven by combination of UV, relative humidity, and temperature stresses.

Moreover, backsheet cracking were reproduced in the laboratory under UV-DH combined condition tests, whereas, the cracks were absent by the conventional dry-UV test. Additionally, SAM proved to be a useful technique to detect the backsheet cracks that are otherwise not detectable in the visual inspection. The depth profile analysis indicated that SAM can be applied to detect thickness inhomogeneities within the backsheet and encapsulant layers.

Certain electrical faults like corrosion could not be detected by SAM because of the particular absence of a feature to which the acoustic waves should respond [191]. That is, if the defect does not incur elastic changes of material, then it will likely not be detected. This is why shunts, inactive cell parts and/or corrosion of the soldering ribbons could not be imaged by SAM, as opposed to DLIT and EL. However, the detection of this cell part could be possible with different measurement parameters. Therefore, the results help to decide which of these methods are more relevant and suitable for a specific failure and material investigation, or how they can be applied in combination. For example, the SAM can be implemented to investigate not only backsheet and encapsulant defects, but also TOF (time-of-flight) changes.

8 General conclusions and perspectives

8.1 General conclusions

The conclusions listed below are drawn based on the technical chapters $(4 \rightarrow 7)$ within the framework of this thesis.

- 1. The nanoindenation technique is a useful tool to gain knowledge of the mechanical parameters of the PV encapsulant. This information can provide insights into the viscoelastic properties of the EVA encapsulant after the lamination, which can help understanding and optimizing the PV module encapsulation process as well as the environmental impact of the PV module. Through two time-dependent cycle modes of nanoindentation (creep and dynamic modes), the crosslinking degree of the EVA after lamination can be determined. Furthermore, the results of dynamic mechanical analysis (DMA) testing have validated the nanoindentation on the encapsulants as a robust and fast technique for the damping factor ($tan\delta$) determination, as a critical parameter for the viscoelastic change. This technique has the potential to improve PV module analysis by allowing rapid mechanical response detection of the EVA after aging.
- 2. The Scanning Acoustic Microscopy (SAM) allows the possibility to study the relationship between the Time-of-Flight (TOF) and the elastic constants of polymeric layers in PV modules (encapsulant and backsheet) non-destructively. Firstly, an analysis of the EVA's Degree of Curing (DoC) dependence of the acoustic waves revealed that the TOF increases in response to DoC, i.e., the acoustic wave velocity in the polymers decreases with increasing DoC. This is important for the correction of acoustic data that has been collected at different lamination conditions. Secondly, it has also been shown that the TOF in the BS and EVA start to decrease with the first DH aging tests. For both layers, the decrease in the TOF was stronger, after the UV-DH combined aging test. Because of the relationship between the acoustic wave velocity and the elastic constants (e.g. the longitudinal modulus), these findings might further indicate an increase in stiffness of the polymers upon the accelerated aging tests.

- 3. Moreover, because of the possibility to obtain a single reflectogram for every point in the module, SAM allows a full scrutiny of the material depth. By applying gates at the desired depths in a reflectogram, several individual images of the PV module can be generated. Therefore, SAM was also used to uncover backsheet cracking in specific interlayers non-destructively, as validated with conventional destructive tests. Various types of backsheet cracking were locally distinguished and quantified in the intercellular gap for the field degraded full-size PV modules under the acoustic micrographs. Additionally, the acoustic cross-sections obtained allowed the depth profile analysis of the multilayer backsheets at component level, and the exact location of cracks which are not optically visible from the outside.
- 4. The effect of the backsheet permeability and degree of crosslinking of the EVA on (a) initial moisture uptake and (b) time required for saturation were demonstrated using embedded moisture sensors. The results show the importance of material properties and therefore material choice when making lifetime predictions. The periods at various relative humidity and temperatures can be related back to reference conditions if the kinetics is known, specifically, the activation energy and the kinetic order of the moisture diffusion. by applying the humidity sensors inside the PV laminates during the DH aging tests, differences in diffusion rate in dependence of the backsheet type as well as degree of crosslinking of the encapsulant was demonstrated. Furthermore, a slower moisture ingress and higher effective activation energy (E_A^{eff}) of the moisture's diffusion rate could be obtained for the encapsulation with a lower degree of curing.
- 5. An intensive study has been made to establish the missing link between the criteria for the material combination and the module long-term reliability. In this part, the EVA degradation influenced by the backsheet properties after performing different aging tests was evaluated. A first attempt, for the different material combinations effect on the EVA degradation mechanisms (chemical changes), Fourier transform infrared spectroscopy with attenuated total reflectance (FTIR-ATR) studies identified two different EVA degradation processes. A thermal oxidation was taking place in the glass–EVA–PA-based backsheet configuration after 500 h DH tests. However other EVA degradation products were observed in the glass–EVA–PET-based backsheet after 1500 h DH tests. Secondly, it has been concluded that, different material combinations lead to different EVA degradation rates, by analysing the EVA thermal and mechanical changes using Differential Scanning Calorimetry (DSC) and Nanoindenation respectively. As a consequence of our findings, the changes in the melting enthalpy and the viscoelastic properties at the EVA surface is more pronounced when PA-based backsheet was used then when PET-based backsheets were used under the combined UV-DH aging tests.
- 6. Additionally, a comparative study of the stability and degradation characteristics of the EVA encapsulant under the influence of three different artificial aging tests was carried out. In summary, our results clearly show that the EVA suffers the strongest chemical and optical degradation when high UV, high temperature and high relative humidity are combined simultaneously.

- 7. Moreover, the performance degradation (the power output and the series resistance measured from the IV curves) of the PV module is much more severe and stronger under this combined UV-DH aging test than the addition of both factors individually. Based on the experimental measurements, it is shown that moisture has a significant impact on degradation mechanisms driven by combination of UV, humidity and temperature stresses. Under these combined aging conditions, several degradation modes where observed under the visual inspection of the PV modules, including corrosion of the solar cells, backsheet cracking and EVA discoloration. However, The same module types showed non of those degradation modes except a minor corrosion after the dry-UV aging tests.
- 8. Furthermore, good correlation between the changes in PV performance parameters and PV module optical evolution of the four modules with different backsheets is reached, after the UV-DH combined aging tests. As an example, the module with the strongest P_{MPP} and *Rs* degradation of 32% and 60% relative change, respectively, shows the strongest discoloration of 80% Yellowing Index (*Y I*). This finding provide the evidence that the *Y I* could be considered as one of the critical material parameters to be related to the module performance.
- 9. Finally, in studying solar cell defects in PV modules non-destructively, three imaging techniques were compared including SAM, Dark Lock-In Thermography (DLIT) and Electroluminescence (EL) methods. We conclude that, SAM did not successfully locate the electrical faults along busbars, which were easily detected by DLIT and EL for all modules types after the UV-DH combined aging tests. This is because of the particular absence of a feature to which the acoustic waves should respond with the SAM analysis at 30 MHz and at room temperature. Therefore, the results help to decide which of these methods are more relevant and suitable for a specific failure and material investigation, or how they can be applied in combination.

8.2 Perspectives

1. The feasibility study on the advanced nanoindentation (creep and dynamic modes) for fast and easy determination of EVA degree of curing at room temperature after the lamination process was successful and may be developed into an in-line diagnostic tool for PV module production. The next step of this study would be the realization of the measurement from the backsheet side on the PV modules non-destructively. A similar device indicates the possibility of detecting the EVA cross-linking response non-destructively from the backsheet via nanoindentation with a relaxation mode that works in the similar manner. However, the influence of lamination conditions on the backsheet mechanical properties has not been considered and the qualitative correlation of the mechanical response and the EVA's degree of crosslinking was found to be representative only at elevated temperatures.

- 2. In this thesis, the SAM methodology was applied to gain insights into the elastic changes of polymeric layers (Encapsulant and backsheet) upon aging when they are laminated together in a PV module. However, due to the polymeric material properties a wider frequency and water temperature range, at which acoustic measurements should be conducted, are needed to understand the resulting behavior of these polymers more precisely. For the extraction of the mechanical properties like the longitudinal modulus (transducer is scanned perpendicularly to the material), further research should focus on deriving the thickness and density of these polymeric materials simultaneously, for example using multiple transducers, to eliminate the need to input variables, which must be determined elsewhere. Furthermore, in order to generate the shear waves to determine the shear modulus, the system should be more adapted, for example, by scanning with different angles. This may enable a full characterization of the mechanical properties of PV module backsheet and encapsulation foils nondestructively.
- 3. Since we estimate the mechanical changes using TOF calculation, It would be practical to develop a process software to generate a continuous reflectograms data of a defined area quickly and directly, instead of a single reflectogram for every point in the module as illustrated in Figure 8.1. This approach presented is simple, since it only requires direct TOF measurements. Therefore, the goal would be to create a mapping of the mechanical parameters at each depth profile, which can then be compared to the acoustic images (see Figure 8.2) to check weather the change in the TOF is due to the mechanical property or/and thickness inhomogeneities of laminated EVA and backsheet within a PV module.



Figure 8.1 – Single reflectograms (left) and continuous reflectograms data for a defined area in the module (right).



Figure 8.2 - SAM images with different frequency-domains from topside of cell.

- 4. The kinetic study of the water uptake of the EVA inside the laminate stack was performed by using incorporated miniature digital humidity sensors at different EVA depths. The knowledge gained in this work serves well to the further development of simulation tools. These results emphasize the need for further work on the mathematical model, and the differences between the mechanisms of humidity ingress in various polymers. Moreover, similar kinetic study of aged samples would help to understand the mechanism of moisture ingress/egress after PV longterm reliability.
- 5. In the **Chapter 6**, various analytical tools (chemical, thermal, mechanical and optical characterizations) and methodologies have been applied to gain insights into different degradation mechanisms of EVA encapsulants influenced by different backsheet types under different accelerated aging conditions. As the degradation processes of other PV encapsulants, such as PDMS, POE, PVB, ionomers and TPO are mostly similar, insights provided by studies into EVA can also be used to study the degradation processes of the other encapsulants.
- 6. Through this thesis, we recognize the importance of the UV-DH combined-accelerated stress testing as a capable procedure for reproducing the existing degradation modes, including backsheet cracking, EVA and backsheet discoloration and corrosion, as well as the EVA photo-degradation as a known mechanism degradation. Furthermore, the combined tests can query those modes in a single test, as opposed to multiple parallel tests, which is the case for the certification standards. Therefore, the outlook for future work would be to develop a methodology for a better correlation of the degradation modes observed from the field to those combined-accelerated stress.
- 7. Finally, the effect of different aging conditions as well as different material combinations on the the PV performance degradation as well as on PV module optical evolution and EVA's mechanical changes has been observed. Therefore a correlation between the critical parameters like, Yellowness index or extents of the viscoelastic damping factor of EVA and the module performance, such as the power output, could also be researched.

A Appendix



Figure A.1 – Visual inspection of module *CPC*02 after sequential reliability tests — front side (a) and rear side (b).



Figure A.2 – Visual inspection of module *TPT*05 after sequential reliability tests — front side (a) and rear side (b).



Figure A.3 – Visual inspection of module *AAA*08 after sequential reliability tests — front side (a) and rear side (b).



Figure A.4 – Visual inspection of module *AAA*09 after sequential reliability tests — front side (a) and rear side (b).



Figure A.5 – Visual inspection of module *APA_Al*11 after sequential reliability tests — front side (a) and rear side (b).



Figure A.6 – Visual inspection of module *APA_Al*12 after sequential reliability tests — front side (a) and rear side (b).

Bibliography

- [1] Our World in Data. *Why did renewables become so cheap so fast? And what can we do to use this global opportunity for green growth?* URL: https://ourworldindata.org/cheap-renewables-growth.
- [2] SeyedMohsen Mirhassani et al. "Advances and challenges in grid tied photovoltaic systems". In: *Renewable and Sustainable Energy Reviews* 49 (2015), pp. 121–131. ISSN: 1364-0321. DOI: 10.1016/j.rser.2015.04.064.
- [3] International Renewable Energy Agency. *Renewable power generation costs in 2019*. June 2020. ISBN: 978-92-9260-244-4.
- [4] Seth B. Darling et al. "Assumptions and the levelized cost of energy for photovoltaics". In: *Energy Environ. Sci.* 4.9 (2011), p. 3133. ISSN: 1754-5692. DOI: 10.1039/c0ee00698j.
- [5] K. Branker, M.J.M. Pathak, and J. M. Pearce. "A review of solar photovoltaic levelized cost of electricity". In: *Renewable and Sustainable Energy Reviews* 15.9 (2011), pp. 4470– 4482. ISSN: 1364-0321. DOI: 10.1016/j.rser.2011.07.104.
- [6] Wendel Caldwell, T. Paul Parker, and Charlie Hasselbrink. "Using Reliability Modeling and Accelerated Life Testing to Formulate a Cost Model of Photovoltaic Systems with Different Architectures". In: *Eurosensor XXIV ConferenceEurosensor XXIV Conference* 139 (2016), pp. 155–160. ISSN: 1877-7058. DOI: 10.1016/j.proeng.2015.09.237.
- [7] Marlene Knausz et al. "Degradation of photovoltaic backsheets: Comparison of the aging induced changes on module and component level". In: *Journal of Applied Polymer Science* 132.24 (2015), n/a–n/a. ISSN: 0021-8995. DOI: 10.1002/app.42093.
- [8] Dirk C. Jordan et al. "Photovoltaic failure and degradation modes". In: *Progress in Photovoltaics: Research and Applications* 25.4 (2017), pp. 318–326. ISSN: 1099-159X. DOI: 10.1002/pip.2866.
- Patrizio Manganiello, Marco Balato, and Massimo Vitelli. "A Survey on Mismatching and Aging of PV Modules: The Closed Loop". In: *IEEE Transactions on Industrial Electronics* 62.11 (2015), pp. 7276–7286. ISSN: 0278-0046. DOI: 10.1109 / TIE.2015. 2418731.

- [10] Sanjay Mohan Shrestha et al. "Determination of Dominant Failure Modes Using FMECA on the Field Deployed c-Si Modules Under Hot-Dry Desert Climate". In: *IEEE Journal of Photovoltaics* 5.1 (2015), pp. 174–182. ISSN: 2156-3403. DOI: 10.1109/ JPHOTOV.2014.2366872.
- [11] Loredana Cristaldi et al. "Diagnostic architecture: A procedure based on the analysis of the failure causes applied to photovoltaic plants". In: *Measurement* 67 (2015), pp. 99– 107. ISSN: 02632241. DOI: 10.1016/j.measurement.2015.02.023.
- D. C. Jordan and S. R. Kurtz. "Photovoltaic Degradation Rates-an Analytical Review". In: *Progress in Photovoltaics: Research and Applications* 21.1 (2013), pp. 12–29. ISSN: 1099-159X. DOI: 10.1002/pip.1182.
- [13] F. J. Pern. "Ethylene-vinyl acetate (EVA) encapsulants for photovoltaic modules: Degradation and discoloration mechanisms and formulation modifications for improved photostability". In: *Die Angewandte Makromolekulare Chemie* 252 (1997), pp. 195–216. ISSN: 1522-9505.
- G. Oreski et al. "Performance of PV modules using co-extruded backsheets based on polypropylene". In: *Solar Energy Materials and Solar Cells* 223 (2021), p. 110976. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2021.110976.
- [15] Harry Wirth, Karl-Anders Weiss, and Cornelia Wiesmeier. *Photovoltaic modules: Technology and reliability / Harry Wirth, Karl-Anders Weiss, Cornelia Wiesmeier*. Berlin and Boston: DeGruyter, 2016. ISBN: 9783110348286.
- [16] Marc Köntges et al. Performance and reliability of photovoltaic systems: Subtask 3.2: Review of failures of photovoltaic modules : IEA PVPS task 13 : external final report IEA-PVPS. Sankt Ursen: International Energy Agency Photovoltaic Power Systems Programme, March 2014. ISBN: 978-3-906042-16-9. DOI: 10.2314/GBV:856979287. URL: https://edocs.tib.eu/files/e01fb16/856979287.pdf.
- [17] Marc Koentges et al. *Assessment of photovoltaic module failures in the field: Report IEA-PVPS T13-09:2017.* 2017. URL: http://iea-pvps.org/index.php?id=435.
- [18] S. Hoffmann and Michael Koehl. "Effect of humidity and temperature on potentialinduced degradation". In: *Progress in Photovoltaics: Research and Applications* 22.2 (2014), pp. 172–179. ISSN: 1099-159X. DOI: 10.1002/pip.2238.
- [19] V. Naumann. "Analysis of potential-induced degradation at interdigitated back contact solar cells". In: Proceedings of the 4th International Conference on Crystalline Silicon Photovoltaics. 2014.
- [20] G. R. Mon and R. G. Ross. "Electrochemical degradation of amorphous-silicon photovoltaic modules". In: *Proceedings of the 18th IEEE Photovoltaic Specialists Conference*. 1985, pp. 1142–1149.
- [21] R. Swanson et al. "The surface polarization effect in high-efficiency silicon solar cells". In: *Proceedings of the 15th International Photovoltaic Science and Engineering Conference*. 2005.

- [22] K. Brecl et al. "The Influence of the EVA Film Quality on the Degradation of PV Modules under Harsh Test Conditions: 3 pages / 35th European Photovoltaic Solar Energy Conference and Exhibition; 1277-1279 / 35th European Photovoltaic Solar Energy Conference and Exhibition; 1277-1279". In: (2018). DOI: 10.4229/35thEUPVSEC20182018-5CV.3.7.
- [23] M. Koentges et al. "Crack statistic of crystalline silicon photovoltaic modules". In: *Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition*. 2011, pp. 3290–3294. ISBN: 3-936338-27-2. DOI: 10.4229/26thEUPVSEC2011-4EO.3.6.
- [24] Mathhar Bdour et al. "A Comprehensive Evaluation on Types of Microcracks and Possible Effects on Power Degradation in Photovoltaic Solar Panels". In: *Sustainability* 12.16 (2020), p. 6416. ISSN: 2071-1050. DOI: 10.3390/su12166416.
- [25] E. Molenbroek, D. W. Waddington, and K. A. Emery. "Hot spot susceptibility and testing of PV modules". In: *Proceedings of the 22nd IEEE Photovoltaic Specialists Conference*. 1991, 547–552 vol.1. DOI: 10.1109/pvsc.1991.169273.
- [26] Sonja Pongratz. *Resistance and Stability of Polymers*. München: Hanser Verlag, 2013, 2013. ISBN: 978-3-446-43709-8.
- [27] B. Ketola and A. Norris. "The Role of Encapsulant Moisture Permeability in the Durability of Solar Photovoltaic Modules: 5 pages / 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Spain; 4098-4102 / 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain; 4098-4102". In: (2010). DOI: 10.4229/25thEUPVSEC2010-4AV.3.43.
- [28] Miguel Rodríguez-Vázquez et al. "Degradation and stabilisation of poly(ethylene-statvinyl acetate): 1 – Spectroscopic and rheological examination of thermal and thermooxidative degradation mechanisms". In: *Polymer Degradation and Stability* 91.1 (2006), pp. 154–164. ISSN: 0141-3910. DOI: 10.1016/j.polymdegradstab.2005.04.034.
- [29] G. Oreski and G. M. Wallner. "Evaluation of the aging behavior of ethylene copolymer films for solar applications under accelerated weathering conditions". In: *Solar Energy* 83.7 (2009), pp. 1040–1047. DOI: 10.1016/j.solener.2009.01.009.
- [30] Ayutthaya, S. I. A. and J. Wootthikanokkhan. "Investigation of the photodegradation behaviors of an ethylene/vinyl acetate copolymer solar cell encapsulant and effects of antioxidants on the photostability of the material". In: *Journal of Applied Polymer Science* 107.6 (2008), pp. 3853–3863. ISSN: 0021-8995. DOI: 10.1002/App.27428.
- [31] K. Agroui et al. "Quality control of EVA encapsulant in photovoltaic module process and outdoor exposure". In: *Desalination* 209.1-3 (2007), pp. 1–9. ISSN: 0011-9164. DOI: 10.1016/j.desal.2007.04.001.

- [32] David C. Miller et al. "Degradation in PV encapsulation transmittance: An interlaboratory study towards a climate-specific test". In: 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC). Piscataway, NJ: IEEE Service Center, 2015, pp. 1–6. ISBN: 978-1-4799-7944-8. DOI: 10.1109/PVSC.2015.7355607.
- [33] Antonia Omazic et al. "Increased reliability of modified polyolefin backsheet over commonly used polyester backsheets for crystalline PV modules". In: *Journal of Applied Polymer Science* (2020), p. 48899. ISSN: 1097-4628. DOI: 10.1002/app.48899.
- [34] D. Wu et al. Degradation of interfacial adhesion strength within photovoltaic minimodules during damp-heat exposure - Wu - 2014 - Progress in Photovoltaics: Research and Applications - Wiley Online Library. URL: https://onlinelibrary.wiley.com/doi/ epdf/10.1002/pip.2460.
- [35] N. C. Park et al. "The effect of encapsulant discoloration and delamination on the electrical characteristics of photovoltaic module". In: *Microelectronics Reliability* 53.9-11 (2013), pp. 1818–1822. ISSN: 00262714. DOI: 10.1016/j.microrel.2013.07.062.
- [36] G. Oreski and G. M. Wallner. "Aging mechanisms of polymeric films for PV encapsulation". In: *Solar Energy* 79.6 (2005), pp. 612–617. ISSN: 0038-092X. DOI: 10.1016/j.solener. 2005.02.008.
- [37] Chiao-Chi Lin et al. "A novel test method for quantifying cracking propensity of photovoltaic backsheets after ultraviolet exposure". In: *Progress in Photovoltaics: Research and Applications* 89.2-3 (2018), p. 139. ISSN: 1099-159X. DOI: 10.1002/pip.3038.
- [38] P. Gebhardt, L. Pitta Bauermann, and D. Philipp. "Backsheet Chalking Theoretical Background and Relation to Backsheet Cracking and Insulation Failures". In: *Proceedings of the 35th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC); Brussels, Belgium.* 2018, pp. 1097–1100. DOI: 10.4229/35THEUPVSEC20182018-5DO.7.5.
- [39] Thomas C. Felder et al. "Development of backsheet tests and measurements to improve correlation of accelerated exposures to fielded modules". In: *Reliability of Photovoltaic Cells, Modules, Components, and Systems VIII.* Ed. by Neelkanth G. Dhere, John H. Wohlgemuth, and Rebecca Jones-Albertus. SPIE Proceedings. SPIE, 2015, p. 956303. DOI: 10.1117/12.2188627.
- [40] E. Parnham et al. "Yellowing of PV Backsheets in Accelerated Tests Can Be Used as a Realistic Indication of Possible Field Failures – Fact or Fiction? 4 pages / 32nd European Photovoltaic Solar Energy Conference and Exhibition; 1528-1531 / 32nd European Photovoltaic Solar Energy Conference and Exhibition; 1528-1531". In: (2016). DOI: 10.4229/EUPVSEC20162016-5BO.10.1.
- [41] Ethan Wang et al. "Failure Modes Evaluation of PV Module via Materials Degradation Approach". In: *Energy Procedia* 33 (2013), pp. 256–264. DOI: 10.1016/j.egypro.2013.05. 066.

- [42] Klaus J. Geretschläger, Gernot M. Wallner, and Jörg Fischer. "Structure and basic properties of photovoltaic module backsheet films". In: *Solar Energy Materials and Solar Cells* 144 (2016), pp. 451–456. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2015.09.060. URL: https://www.sciencedirect.com/science/article/pii/S0927024815005024/pdfft?md5=4246e76480f1b6c642a0210f8bf3acee&pid=1-s2.0-S0927024815005024-main.pdf.
- [43] Yadong Lyu et al. "Degradation and Cracking Behavior of Polyamide-Based Backsheet Subjected to Sequential Fragmentation Test". In: *IEEE Journal of Photovoltaics* 8.6 (2018), pp. 1748–1753. ISSN: 2156-3381. DOI: 10.1109/JPHOTOV.2018.2863789.
- [44] Gabriele C. Eder et al. "Error analysis of aged modules with cracked polyamide back-sheets". In: *Solar Energy Materials and Solar Cells* 203 (2019), p. 110194. ISSN: 09270248.
 DOI: 10.1016/j.solmat.2019.110194.
- [45] Yadong Lyu et al. "Drivers for the cracking of multilayer polyamide–based backsheets in field photovoltaic modules: In–depth degradation mapping analysis". In: *Progress in Photovoltaics: Research and Applications* 28.7 (2020), pp. 704–716. ISSN: 1099-159X.
 DOI: 10.1002/pip.3260.
- [46] Michael Owen-Bellini et al. "Towards validation of combined-accelerated stress testing through failure analysis of polyamide-based photovoltaic backsheets". In: *Scientific Reports* 11.1 (2021), p. 2019. DOI: 10.1038/s41598-021-81381-7.
- [47] Djamel Eddine Mansour et al. "Effect of Backsheet Properties on PV Encapsulant Degradation during Combined Accelerated Aging Tests". In: *Sustainability* 12.12 (2020), p. 5208. ISSN: 2071-1050. DOI: 10.3390/su12125208.
- [48] M. D. Kempe. "Modeling of rates of moisture ingress into photovoltaic modules". In: Solar Energy Materials and Solar Cells 90.16 (2006), pp. 2720–2738. ISSN: 0927-0248.
 DOI: 10.1016/j.solmat.2006.04.002.
- [49] B. Rimez et al. "The thermal degradation of poly(vinyl acetate) and poly(ethylene-co-vinyl acetate), Part II: Modelling the degradation kinetics". In: *Polymer Degradation and Stability* 93.6 (2008), pp. 1222–1230. ISSN: 0141-3910. DOI: 10.1016/j.polymdegradstab. 2008.01.021.
- [50] N. S. Allen et al. "Aspects of the thermal oxidation, yellowing and stabilisation of ethylene vinyl acetate copolymer". In: *Polymer Degradation and Stability* 71.1 (2000), pp. 1–14. ISSN: 0141-3910.
- [51] M. Gagliardi, P. Lenarda, and M. Paggi. "A reaction-diffusion formulation to simulate EVA polymer degradation in environmental and accelerated ageing conditions". In: *Solar Energy Materials and Solar Cells* 164 (2017), pp. 93–106. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2017.02.014. URL: https://ac.els-cdn.com/S0927024817300673/1-s2.0-S0927024817300673-main.pdf?_tid=d3e75150-bf54-4ee1-b335-3b9ccbe43f3d& acdnat=1521466787_61b2c96afca58f8948b74ed727a70b37.

- [52] C. Peike et al. "Impact of permeation properties and backsheet-encapsulant interactions on the reliability of PV modules". In: *ISRN Renewable Energy* 2012 (2012). DOI: 10.5402/2012/459731.
- [53] Gernot Oreski et al. "Acetic acid permeation through photovoltaic backsheets: Influence of the composition on the permeation rate". In: *Polymer Testing* 60 (2017), pp. 374–380. ISSN: 0142-9418. DOI: 10.1016/j.polymertesting.2017.04.025.
- [54] Dajung Kim et al. "Degradation of Backsheets for Crystalline Photovoltaic Modules under Damp Heat Test". In: *New & Renewable Energy* 12.3 (2016), pp. 36–43. ISSN: 1738-3935. DOI: 10.7849/ksnre.2016.9.12.3.36.
- [55] James E. Pickett and Dennis J. Coyle. "Hydrolysis kinetics of condensation polymers under humidity aging conditions". In: *Polymer Degradation and Stability* 98.7 (2013), pp. 1311–1320. ISSN: 0141-3910. DOI: 10.1016/j.polymdegradstab.2013.04.001.
- [56] ABDULKERIM GOK. "Degradation pathway models of poly(ethylene-terephtalate) under accelerated weathering exposures". PhD thesis.
- [57] Darwin Kint and Sebastián Muñoz–Guerra. "A review on the potential biodegradability of poly(ethylene terephthalate)". In: *Polymer International* 48.5 (1999), pp. 346–352.
 ISSN: 1097-0126. DOI: 10.1002/{\%}28SICI{\%}291097-0126{\%}28199905{\%}2948{\%}3A5{\\%}3C346{\\%}3AAID-PI156{\\%}3E3.0.CO{\\%}3B2-N.
- [58] William McMahon et al. "Degradation Studies of Polyethylene Terephthalate". In: *Journal of Chemical & Engineering Data* 4.1 (1959), pp. 57–79. ISSN: 0021-9568. DOI: 10.1021/je60001a009.
- [59] A. Ballara and J. Verdu. "Physical aspects of the hydrolysis of polyethylene terephthalate". In: *Polymer Degradation and Stability* 26.4 (1989), pp. 361–374. ISSN: 0141-3910. DOI: 10.1016/0141-3910(89)90114-6.
- [60] A. Launay, F. Thominette, and J. Verdu. "Hydrolysis of poly(ethylene terephthalate): a kinetic study". In: *Polymer Degradation and Stability* 46.3 (1994), pp. 319–324. ISSN: 0141-3910. DOI: 10.1016/0141-3910(94)90148-1.
- [61] M. Edge et al. "Physical aspects of the thermal and hydrolytic ageing of polyester, polysulphone and polycarbonate films". In: *Polymer Degradation and Stability* 44.2 (1994), pp. 193–200. ISSN: 0141-3910. DOI: 10.1016/0141-3910(94)90164-3.
- [62] Chris Sammon, Jack Yarwood, and Neil Everall. "An FT–IR study of the effect of hydrolytic degradation on the structure of thin PET films". In: *Polymer Degradation and Stability* 67.1 (2000), pp. 149–158. ISSN: 0141-3910. DOI: 10.1016/S0141-3910(99)00104-4.
- [63] C. Thellen, A. Rothacker, and D. Santoleri. "Co-Extrusion of a Novel Multilayer Photovoltaic Backsheet Based on Polyamide-Ionomer Alloy Skin Layers: 5 pages / 33rd European Photovoltaic Solar Energy Conference and Exhibition; 68-72 / 33rd European Photovoltaic Solar Energy Conference and Exhibition; 68-72". In: (2017). DOI: 10.4229/EUPVSEC20172017-1CO.2.5.

- [64] Djamel Eddine Mansour, Sandra Kotterer, Daniel Philipp, Paul Gebhardt, ed. PV backsheet failure analysis by scanning acoustic microscopy. 37th European Photovoltaic Solar Energy Conference and Exhibition 1014 - 1018. 2020. ISBN: 3-936338-73-6. URL: https://www.eupvsec-proceedings.com/proceedings?fulltext=Mansour&paper= 49325.
- [65] Eric J. Schneller et al. "Manufacturing metrology for c-Si module reliability and durability Part III: Module manufacturing". In: *Renewable and Sustainable Energy Reviews* 59 (2016), pp. 992–1016. ISSN: 1364-0321. DOI: 10.1016/j.rser.2015.12.215.
- [66] A. Luque and Steven Hegedus. *Handbook of photovoltaic science and engineering*.
 2nd ed. Hoboken, N.J.: Wiley and Chichester : John Wiley [distributor], 2011. ISBN: 978-0-470-72169-8.
- [67] A. M. Gabor. "Soldering induced damage to thin si solar cells and detection of crackes cells in modules". In: *Proceedings of the 21st European Photovoltaic Solar Energy Con-ference and Exhibition*. 2006, pp. 2042–2047.
- [68] S. Pingel et al. "Mechanical stability of solar cells within solar panels". In: *Proceedings of the 24th European Photovoltaic Solar Energy Conference and Exhibition*. 2009, pp. 3459–3463. ISBN: 3-936338-25-6. DOI: 10.4229/24thEUPVSEC2009-4AV.3.49.
- [69] Jae-Seong Jeong, Nochang Park, and Changwoon Han. "Field failure mechanism study of solder interconnection for crystalline silicon photovoltaic module". In: *Microelectronics Reliability* 52.9-10 (2012), pp. 2326–2330. ISSN: 00262714. DOI: 10.1016/j. microrel.2012.06.027.
- [70] P. Hacke et al. "Characterization of Multicrystalline Silicon Modules with System Bias Voltage Applied in Damp Heat: 6 pages / 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Spain; 3760-3765 / 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain; 3760-3765". In: (2010). DOI: 10.4229 / 25thEUPVSEC2010-4BO.9.6.
- [71] Peter Hacke et al. "Test-to-Failure of crystalline silicon modules". In: *Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE*. 2010, pp. 000244–000250. ISBN: 978-1-4244-5890-5. DOI: 10.1109/PVSC.2010.5614472.
- [72] Joseph M. Kuitche, Govindasamy Tamizh-Mani, and Rong Pan. "Failure modes effects and criticality analysis (FMECA) approach to the crystalline silicon photovoltaic module reliability assessment". In: *Reliability of Photovoltaic Cells, Modules, Components, and Systems IV.* Ed. by Neelkanth G. Dhere, John H. Wohlgemuth, and Kevin W. Lynn. SPIE Proceedings. SPIE, 2011, p. 81120L. DOI: 10.1117/12.894301.
- [73] D. Pysch, A. Mette, and S. W. Glunz. "A review and comparison of different methods to determine the series resistance of solar cells". In: *Solar Energy Materials and Solar Cells* 91.18 (2007), pp. 1698–1706. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2007.05.026.

- [74] sfuchs6. "Microsoft Word Munich-Bowden2.doc". In: (). URL: https://smartech. gatech.edu/bitstream/handle/1853/26165/Munich-Bowden2.pdf?sequence=1.
- [75] J. L. Crozier, van Dyk, E. E., and F. J. Vorster. "Characterization of cell mismatch in a multi-crystalline silicon photovoltaic module". In: *Physica B: Condensed Matter* 407.10 (2012), pp. 1578–1581. ISSN: 0921-4526. DOI: 10.1016/j.physb.2011.09.090.
- [76] Sarah Kajari-Schroeder et al. "Spatial and orientational distribution of cracks in crystalline photovoltaic modules generated by mechanical load tests". In: *Solar Energy Materials and Solar Cells* 95.11 (2011), pp. 3054–3059. ISSN: 0927-0248. DOI: 10.1016/j. solmat.2011.06.032.
- [77] V. Gazuz and C. Buerhop. "Electroluminescence imaging for detection of power losses in solder contacts between busbar and interconnect in solar cells". In: *Proceedings* of the 25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Energy Conversion. 2010, pp. 4219–4222. ISBN: 3-936338-26-4. DOI: 10. 4229/25thEUPVSEC2010-4AV.3.76.
- [78] P. Chaturvedi, B. Hoex, and T. M. Walsh. "Broken metal fingers in silicon wafer solar cells and PV modules". In: *Solar Energy Materials and Solar Cells* 108.0 (2013), pp. 78–81. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2012.09.013.
- [79] V. Gazuz and C. Buerhop. "Detection of power losses in busbar solder contacts by electroluminescence imaging of solar cells". In: *Measurement Science and Technology* 22.11 (2011), p. 115702. DOI: 10.1088/0957-0233/22/11/115702.
- [80] E. Kaplani. "Detection of degradation effects in field-aged c-Si solar cells through IR thermography and digital image processing". In: *International Journal of Photoenergy* 2012 (2012), pp. 1–11. ISSN: 1110-662X; 1687-529X. DOI: 10.1155/2012/396792.
- [81] D. L. King et al. "Applications for infrared imaging equipment in photovoltaic cell, module, and system testing". In: *Proceedings of the 28th IEEE Photovoltaic Specialists Conference*. 2000, pp. 1487–1490. ISBN: 0-7803-5772-8. DOI: 10.1109/PVSC.2000.916175.
- [82] Miguel García et al. "Observed degradation in photovoltaic plants affected by hotspots". In: *Progress in Photovoltaics* 22.12 (2014), pp. 1292–1301. ISSN: 1062-7995. DOI: 10.1002/pip.2393.
- [83] J. H. Wohlgemuth, M. Conway, and D. H. Meakin. "Reliability and performance testing of photovoltaic modules". In: *Proceedings of the 28th IEEE Photovoltaic Specialists Conference*. 2000, pp. 1483–1486. ISBN: 0-7803-5772-8. DOI: 10.1109/PVSC.2000.916174.
- [84] J. H. Bultman et al. "Interconnection through vias for improved efficiency and easy module manufacturing of crystalline silicon solar cells". In: *Solar Energy Materials and Solar Cells* 65.1–4 (2001), pp. 339–345. ISSN: 0927-0248. DOI: 10.1016/S0927-0248(00)00111-2.
- [85] R. Lathrop and K. Pfluke. "Novel approaches to benchmarking solar cell tabbing solderability". In: *Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition*. 2011, pp. 1403–1408. ISBN: 3-936338-27-2.

- [86] Rico Meier et al. "Reliability of copper-ribbons in photovoltaic modules under thermomechanical loading". In: *Proceedings of the 35th IEEE Photovoltaic Specialists Conference*. 2010, pp. 001283–001288. ISBN: 0160-8371. DOI: 10.1109/pvsc.2010.5614220.
- [87] P. Schmitt et al. "Metallographic preparation of solar cell samples for quality assurance and material evaluation". In: *Energy Procedia* 8 (2011), pp. 402–408. ISSN: 1876-6102. DOI: 10.1016/j.egypro.2011.06.157. URL: http://www.sciencedirect.com/science/article/pii/S1876610211016663.
- [88] P. Schmitt et al. "Intermetallic phase growth and reliability of Sn-Ag-soldered solar cell joints". In: *Energy Procedia* 27 (2012), pp. 664–669. ISSN: 1876-6102. DOI: 10.1016/j. egypro.2012.07.126.
- [89] W. Stark and M. Jaunich. "Investigation of Ethylene/Vinyl Acetate Copolymer (EVA) by thermal analysis DSC and DMA". In: *Polymer Testing* 30.2 (2011), pp. 236–242. ISSN: 0142-9418. DOI: 10.1016/j.polymertesting.2010.12.003. URL: http://www.sciencedirect. com/science/article/pii/S0142941810002126.
- [90] K. Agroui et al. "Thermal stability of slow and fast cure EVA encapsulant material for photovoltaic module manufacturing process". In: *Solar Energy Materials and Solar Cells* 90.15 (2006), pp. 2509–2514. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2006.03.023.
- [91] Ch. Hirschl et al. "Determining the degree of crosslinking of ethylene vinyl acetate photovoltaic module encapsulants—A comparative study". In: *Solar Energy Materials and Solar Cells* 116 (2013), pp. 203–218. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2013.04. 022. URL: http://www.sciencedirect.com/science/article/pii/S0927024813001979.
- [92] Radek Polanský et al. "Mechanical Behavior and Thermal Stability of EVA Encapsulant Material Used in Photovoltaic Modules". In: *Journal of Electrical Engineering* 64.6 (2013), pp. 361–365. ISSN: 1335-3632. DOI: 10.2478/jee-2013-0054.
- [93] B. Rimez et al. "The thermal degradation of poly(vinyl acetate) and poly(ethylene-covinyl acetate), Part I: Experimental study of the degradation mechanism". In: *Polymer Degradation and Stability* 93.4 (2008), pp. 800–810. ISSN: 0141-3910. DOI: 10.1016/j. polymdegradstab.2008.01.010.
- [94] Kamel Agroui and George Collins. "Determination of thermal properties of crosslinked EVA encapsulant material in outdoor exposure by TSC and DSC methods". In: *Renewable Energy* 63 (2014), pp. 741–746. ISSN: 0960-1481. DOI: 10.1016/j.renene.2013.10.013.
- [95] C. Peike et al. "Non-destructive degradation analysis of encapsulants in PV modules by Raman Spectroscopy". In: *Solar Energy Materials and Solar Cells* 95.7 (2011), pp. 1686– 1693. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2011.01.030.
- [96] X.-M. Shi et al. "Effect of damp-heat aging on the structures and properties of ethylenevinyl acetate copolymers with different vinyl acetate contents". In: *Journal of Applied Polymer Science* 112.4 (2009), pp. 2358–2365. ISSN: 0021-8995. DOI: 10.1002/app.29659.

- [97] G. J. Jorgensen et al. "Moisture transport, adhesion, and corrosion protection of PV module packaging materials". In: *Solar Energy Materials and Solar Cells* 90.16 (2006), pp. 2739–2775. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2006.04.003.
- [98] Keiko Matsuda et al. "Microscopic Degradation Mechanisms in Silicon Photovoltaic Module under Long-Term Environmental Exposure". In: *Japanese Journal of Applied Physics* 51 (2012), 10NF07. ISSN: 1347-4065. DOI: 10.1143/JJAP.51.10NF07.
- [99] David C. Miller et al. "Creep in photovoltaic modules: Examining the stability of polymeric materials and components". In: *Photovoltaic Specialists Conference (PVSC), 2010* 35th IEEE. 2010, pp. 000262–000268. ISBN: 978-1-4244-5890-5. DOI: 10.1109/PVSC.2010. 5615832.
- [100] Gernot Oreski and Gernot M. Wallner. "Damp heat induced physical aging of PV encapsulation materials". In: *12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2010.* Piscataway, NJ: IEEE, 2010, pp. 1–6. ISBN: 978-1-4244-5342-9. DOI: 10.1109/ITHERM.2010.5501297.
- [101] C. Balzani et al. "Adhesive joints in composite laminates—A combined numerical/experimental estimate of critical energy release rates". In: *International Journal of Adhesion and Adhesives* (2011). ISSN: 01437496. DOI: 10.1016/j.ijadhadh.2011.09.002.
- [102] V. Chapuis et al. "Compressive-shear adhesion characterization of polyvinyl-butyral and ethylene-vinyl acetate at different curing times before and after exposure to dampheat conditions". In: *Progress in Photovoltaics: Research and Applications* 22.4 (2014), pp. 405–414. ISSN: 1099-159X. DOI: 10.1002/pip.2270.
- [103] Pascal Romer et al. "More Realistic Consideration of Backsheets Coefficient of Thermal Expansion on Thermomechanics of PV Modules". In: *Proceedings of the 37th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC)*. 2020, pp. 772–776. DOI: 10.4229/EUPVSEC202020-4BO.11.4.
- [104] D. C. Wunsch and R. R. Bell. "Determination of Threshold Failure Levels of Semiconductor Diodes and Transistors Due to Pulse Voltages". In: *IEEE Transactions on Nuclear Science* 15.6 (1968), pp. 244–259. ISSN: 0018-9499. DOI: 10.1109/TNS.1968.4325054.
- [105] Cyril Buttay et al. "Thermal Stability of Silicon Carbide Power Diodes". In: *Electron Devices, IEEE Transactions on* 59.3 (2012), pp. 761–769. ISSN: 0018-9383. DOI: 10.1109/ TED.2011.2181390.
- [106] G. TamizhMani et al. "Failure analysis of design qualification testing: 2007 VS. 2005". In: 33rd IEEE Photovoltaic Specialists Conference, 2008. Piscataway, NJ: IEEE, 2008, pp. 1–4.
 ISBN: 978-1-4244-1640-0. DOI: 10.1109/PVSC.2008.4922768.
- [107] Neelkanth G. Dhere et al. "The reliability of bypass diodes in PV modules". In: *Reliability of Photovoltaic Cells, Modules, Components, and Systems VI*. Ed. by Neelkanth G. Dhere, John H. Wohlgemuth, and Kevin W. Lynn. SPIE Proceedings. SPIE, 2013, p. 88250I. DOI: 10.1117/12.2026782.

- [108] Katherine A. Kim and Philip T. Krein. "Reexamination of Photovoltaic Hot Spotting to Show Inadequacy of the Bypass Diode". In: *IEEE Journal of Photovoltaics* 5.5 (2015), pp. 1435–1441. ISSN: 2156-3403. DOI: 10.1109/JPHOTOV.2015.2444091.
- [109] Bettina Ottersböck, Gernot Oreski, and Gerald Pinter. "Comparison of different microclimate effects on the aging behavior of encapsulation materials used in photovoltaic modules". In: *Polymer Degradation and Stability* 138 (2017), pp. 182–191. ISSN: 0141-3910. DOI: 10.1016/j.polymdegradstab.2017.03.010.
- [110] Christopher C. White, Kenneth M. White, and James E. Pickett. Service life prediction of polymers and plastics exposed to outdoor weathering. Plastics design library. Norwich: William Andrew, 2017. ISBN: 9780323497770.
- M. C. Peel, B. L. Finlayson, and T. A. McMahon. "Updated world map of the Köppen-Geiger climate classification". In: *Hydrology and Earth System Sciences* 11.5 (2007), pp. 1633–1644. ISSN: 1027-5606, 1607-7938. DOI: 10.5194/hess-11-1633-2007.
- [112] Julián Ascencio-Vásquez, Kristijan Brecl, and Marko Topič. "Methodology of Köppen-Geiger-Photovoltaic climate classification and implications to worldwide mapping of PV system performance". In: *Progress in Solar Energy 1* 191 (2019), pp. 672–685. ISSN: 0038-092X. DOI: 10.1016/j.solener.2019.08.072.
- [113] Ismail Kaaya et al. "Modeling Outdoor Service Lifetime Prediction of PV Modules: Effects of Combined Climatic Stressors on PV Module Power Degradation: IEEE Journal of Photovoltaics, 9(4), 1105-1112". In: *IEEE Journal of Photovoltaics* 9.4 (2019), pp. 1105– 1112. ISSN: 2156-3403. DOI: 10.1109/JPHOTOV.2019.2916197.
- [114] Julián Ascencio-Vásquez et al. "Global Climate Data Processing and Mapping of Degradation Mechanisms and Degradation Rates of PV Modules". In: *Energies* 12.24 (2019), p. 4749. ISSN: 1996-1073. DOI: 10.3390/en12244749.
- [115] Ismail Kaaya et al. "Photovoltaic lifetime forecast model based on degradation patterns". In: *Progress in Photovoltaics: Research and Applications* 28.10 (2020), pp. 979–992. ISSN: 1099-159X. DOI: 10.1002/pip.3280.
- [116] Archana Sinha et al. "Prediction of Climate-Specific Degradation Rate for Photovoltaic Encapsulant Discoloration". In: *IEEE Journal of Photovoltaics* 10.4 (2020), pp. 1093– 1101. ISSN: 2156-3403. DOI: 10.1109/JPHOTOV.2020.2989182.
- [117] Jared Tracy et al. "Encapsulation and backsheet adhesion metrology for photovoltaic modules". In: *Progress in Photovoltaics: Research and Applications* (2016). ISSN: 1099-159X. DOI: 10.1002/pip.2817.
- [118] Yuliya Voronko et al. "Correlation of the loss in photovoltaic module performance with the ageing behaviour of the backsheets used". In: *Progress in Photovoltaics: Research and Applications* 23.11 (2015), pp. 1501–1515. ISSN: 1099-159X. DOI: 10.1002/pip.2580.

- [119] Jiang Zhu et al. "Effect of viscoelasticity of ethylene vinyl acetate encapsulants on photovoltaic module solder joint degradation due to thermomechanical fatigue". In: *Japanese Journal of Applied Physics* 57.8S3 (2018), 08RG03. ISSN: 1347-4065. DOI: 10. 7567/JJAP.57.08RG03.
- [120] Archana Sinha et al. "Understanding interfacial chemistry of positive bias high-voltage degradation in photovoltaic modules". In: *Solar Energy Materials and Solar Cells* 223 (2021), p. 110959. ISSN: 0927-0248. DOI: 10.1016/j.solmat.2021.110959.
- [121] Barry Ketola and Ann Norris. "Degradation Mechanism Investigation of Extended Damp Heat Aged PV Modules". In: (2011).
- [122] A. W. Czanderna and F. J. Pern. "Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: A critical review". In: (1996), pp. 101–181.
- [123] Markus Bregulla et al. "Degradation Mechanisms of Ethylen-Vinyl-Acetate Copolymer - New Studies including ultra fast cure foils". In: (2007).
- [124] E. Segal, P. Budrugeac, S. Ciutacu and G. Mares. "On the change of the thermal behaviour of the compound EVA owing to accelerated thermal and radiation-induced ageing". In: (1990).
- J. Jin, S. J. Chen, and J. Zhang. "UV aging behaviour of ethylene-vinyl acetate copolymers (EVA) with different vinyl acetate contents". In: *Polymer Degradation and Stability* 95.5 (2010), pp. 725–732. ISSN: 0141-3910. DOI: 10.1016/j.polymdegradstab.2010.02.020.
- [126] Chiara Barretta et al. "Comparison of Degradation Behavior of Newly Developed Encapsulation Materials for Photovoltaic Applications under Different Artificial Ageing Tests". In: *Polymers* 13.2 (2021). ISSN: 2073-4360. DOI: 10.3390/polym13020271.
- [127] Peter Hacke et al. "Combined and Sequential Accelerated Stress Testing for Derisking Photovoltaic Modules". In: *Advanced micro- and nanomaterials for photovoltaics*. Ed. by D. S. Ginley and Thomas Fix. Micro & nano technologies series. Amsterdam: Elsevier, 2019, pp. 279–313. ISBN: 9780128145012. DOI: 10.1016/B978-0-12-814501-2.00011-6.
- Y. Voronko et al. "Long Term Performance of PV Modules: System Optimization through the Application of Innovative Non-Destructive Characterization Methods: 6 pages / 27th European Photovoltaic Solar Energy Conference and Exhibition; 3530-3535 / 27th European Photovoltaic Solar Energy Conference and Exhibition; 3530-3535". In: (2012). DOI: 10.4229/27THEUPVSEC2012-4BV.3.41.
- [129] Laura Spinella and Nick Bosco. "FTIR Investigation of EVA Chemical Bonding Environment and Its Impact on Debond Energy". In: *IEEE Journal of Photovoltaics* 9.3 (2019), pp. 790–795. ISSN: 2156-3381. DOI: 10.1109/JPHOTOV.2019.2904219.
- [130] C. Peike et al. "Non-destructive determination of the cross-linking degree of EVA by Raman Spectroscopy". In: *Open Journal of Renewable Energy and Sustainable Development* 1 (2014).

- [131] A. P. Patel, A. Sinha, and G. Tamizhmani. "Field-Aged Glass/Backsheet and Glass/Glass PV Modules: Encapsulant Degradation Comparison". In: *IEEE Journal of Photovoltaics* 10.2 (2020), pp. 607–615. ISSN: 2156-3403. DOI: 10.1109/JPHOTOV.2019.2958516.
- [132] C. Motta. "The effect of copolymerization on transition temperatures of polymeric materials". In: (1997).
- [133] Nathaporn Somrang et al. "Non-isothermal melt crystallization kinetics for ethylene– acrylic acid copolymers and ethylene–methyl acrylate–acrylic acid terpolymers". In: *European Polymer Journal* 40.4 (2004), pp. 829–838. ISSN: 0014-3057. DOI: 10.1016/j. eurpolymj.2003.11.021.
- [134] M. D. Kempe, ed. *Rheological and mechanical considerations for photovoltaic encapsulants.* 2005.
- [135] H.-Y. Li et al. "Optical transmission as a fast and non-destructive tool for determination of ethylene-co-vinyl acetate curing state in photovoltaic modules". In: *Progress in Photovoltaics: Research and Applications* 21.2 (2013), pp. 187–194. ISSN: 1099-159X. DOI: 10.1002/pip.1175.
- [136] S. Bistac, P. Kunemann and J. Schultz. "Crystalline modifications of ethylene-vinyl acetate copolymers induced by a tensile drawing: effect of the molecular weight". In: (1998).
- [137] Laila V. Mesquita et al. "Scanning acoustic microscopy analysis of the mechanical properties of polymeric components in photovoltaic modules". In: *Engineering Reports* (2020). ISSN: 2577-8196. DOI: 10.1002/eng2.12222.
- [138] G. Oreski et al., ed. Designing new material for PV: Opportunities for lowering cost and increasing performance through Advanced Material Innovations. Report IEA-PVPS T13-13:2021, 2021. ISBN: 978-3-907281-02-4.
- [139] Christoph Herzog et al. "Differential scanning calorimetry for simulation and optimization of PV module lamination". In: *Proceedings of the 36th European Photovoltaic Solar Energy Conference and Exhibition*. 2019. ISBN: 3-936338-60-4. DOI: 10.4229 / EUPVSEC20192019-4AV.1.15.
- [140] M. Jankovec et al. "Evaluation of different temperature measurement methods of crystalline silicon PV modules". In: *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition/ 5th World Conference on Energy Conversion*. 2010, pp. 4257–4260. ISBN: 3-936338-26-4. DOI: 10.4229/25thEUPVSEC2010-4AV.3.85.
- [141] International Electrotechnical Commission. *Terrestrial photovoltaic (PV) modules Design qualification and type approval Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules*. Geneva, Switzerland, 2016.
- [142] Michael P. Sepe. *Dynamic mechanical analysis for plastics engineering*. PDL Handbook Series. Norwich, N.Y.: Plastics Design Library, 1998. ISBN: 1884207642.

- [143] W. C. Oliver and G. M. Pharr. "An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments". In: *Journal of Materials Research* 7.06 (1992), pp. 1564–1583. DOI: 10.1557/JMR.1992.1564.
- [144] W. C. Oliver and G. M. Pharr. "Measurement of hardness and elastic modulus by instrumented indentation: Advances in understanding and refinements to methodology". In: *Journal of Materials Research* 19.01 (2004), pp. 3–20. DOI: 10.1557/jmr.2004.19.1.3.
- [145] E. G. Herbert, W. C. Oliver, and G. M. Pharr. "Nanoindentation and the dynamic characterization of viscoelastic solids". In: *Journal of Physics D: Applied Physics* 41.7 (2008), p. 074021. ISSN: 0022-3727. DOI: 10.1088/0022-3727/41/7/074021.
- [146] Petra Christöfl et al. "Comprehensive investigation of the viscoelastic properties of PMMA by nanoindentation". In: *Polymer Testing* (2020), p. 106978. ISSN: 0142-9418.
 DOI: 10.1016/j.polymertesting.2020.106978.
- [147] CSM-Instruments for Advanced Mechanical Surface Testing. "Handbook on INSTRU-MENTED INDENTATION: www.csm-instruments.com". In: ().
- [148] J. Woirgard et al. "A new technology for nanohardness measurements: principle and applications". In: *Surface and Coatings Technology* 100-101 (1998), pp. 103–109. ISSN: 0257-8972. DOI: 10.1016/S0257-8972(97)00597-5.
- [149] D. E. Mansour et al. "Nanoindentation Analysis of PV Module Polymeric Components after Accelerated Aging: 4 pages / 35th European Photovoltaic Solar Energy Conference and Exhibition; 1333-1336 / 35th European Photovoltaic Solar Energy Conference and Exhibition; 1333-1336". In: (2018). DOI: 10.4229/35thEUPVSEC20182018-5CV.3.28.
- [150] G. Feng and A. H. W. Ngan. "Effects of Creep and Thermal Drift on Modulus Measurement Using Depth-sensing Indentation". In: *Journal of Materials Research* 17.3 (2002), pp. 660–668. ISSN: 0884-2914. DOI: 10.1557/JMR.2002.0094.
- [151] Jiří Nohava and Jaroslav Menčík. "A contribution to understanding of low-load spherical indentation—Comparison of tests on polymers and fused silica". In: *Journal of Materials Research* 27.1 (2012), pp. 239–244. ISSN: 0884-2914. DOI: 10.1557/jmr.2011.267.
- [152] J. Nohava, N. X. Randall, and N. Conté. "Novel ultra nanoindentation method with extremely low thermal drift: Principle and experimental results". In: *Journal of Materials Research* 24.3 (2009), pp. 873–882. ISSN: 0884-2914. DOI: 10.1557/jmr.2009.0114.
- X. D. Hou and N. M. Jennett. "Defining the limits to long-term nano-indentation creep measurement of viscoelastic materials". In: *Polymer Testing* 70 (2018), pp. 297–309.
 ISSN: 0142-9418. DOI: 10.1016/j.polymertesting.2018.07.022.
- [154] Yuemin Wang et al. "Measurement of viscoelastic properties for polymers by nanoindentation". In: *Polymer Testing* 83 (2020), p. 106353. ISSN: 0142-9418. DOI: 10.1016/j. polymertesting.2020.106353.
- [155] Robert F. Cook and Michelle L. Oyen. "Nanoindentation behavior and mechanical properties measurement of polymeric materials". In: *International Journal of Materials Research* 98.5 (2007), pp. 370–378. ISSN: 1862-5282. DOI: 10.3139/146.101480.

- [156] Michelle L. Oyen. "Spherical Indentation Creep Following Ramp Loading". In: *Journal of Materials Research* 20.8 (2005), pp. 2094–2100. ISSN: 0884-2914. DOI: 10.1557/JMR. 2005.0259.
- M. L. Oyen. "Analytical techniques for indentation of viscoelastic materials". In: *Philosophical Magazine* 86.33-35 (2006), pp. 5625–5641. ISSN: 1478-6435. DOI: 10.1080/14786430600740666.
- [158] Yang-Tse Cheng, Wangyang Ni, and Che-Min Cheng. "Nonlinear analysis of oscillatory indentation in elastic and viscoelastic solids". In: *Physical Review Letters* 97.7 (2006), p. 075506. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.97.075506.
- [159] Jennifer Hay and Bryan Crawford. "Measuring substrate-independent modulus of thin films". In: *Journal of Materials Research* 26.6 (2011), pp. 727–738. ISSN: 0884-2914. DOI: 10.1557/jmr.2011.8.
- [160] "Dynamic mechanical analysis by nanoindentation: www.anton-paar.com". In: ().
- [161] D. J. Gardiner, P. R. Graves, and H. J. Bowley. *Practical Raman spectroscopy*. Berlin: Springer-Verlag, 1989. ISBN: 978-0-387-50254-0.
- [162] A.S Nielsen, D.N Batchelder, and R. Pyrz. "Estimation of crystallinity of isotactic polypropylene using Raman spectroscopy". In: *Polymer* 43.9 (2002), pp. 2671–2676.
 ISSN: 0032-3861. DOI: 10.1016/S0032-3861(02)00053-8.
- [163] Neil Everall et al. "Density Mapping in Poly(Ethylene Terephthalate) Using a Fiber-Coupled Raman Microprobe and Partial Least-Squares Calibration". In: *Applied Spectroscopy* 50.3 (1996), pp. 388–393. ISSN: 0003-7028. DOI: 10.1366/0003702963906258.
- [164] F. Adar. "Raman microscopy combined with tensile deformation for understanding changes in polymer morphology". In: *Spectroscopy (Santa Monica)* 32 (Nov. 2017), pp. 14–21.
- [165] Jack L. Koenig. Spectroscopy of polymers. Second edition. New York: Elsevier Science, 1999. ISBN: 9780080541570.
- [166] C. Peike. "Degradation Analysis of the Encapsulation Polymer in Photovoltaic Modules by Raman Spectroscopy". Doctoral Thesis.
- [167] E12 Committee. Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates. West Conshohocken, PA. DOI: 10.1520/E0313-20.
- [168] Donald J. Lovell. "Principles of Colorimetry". In: American Journal of Physics 18.2 (1950), pp. 104–109. DOI: 10.1119/1.1932503.
- [169] Lynda K. Bangtson and Richard J. Goodkind. "The conversion of chromascan designations to CIE tristimulus values". In: *The Journal of Prosthetic Dentistry* 48.5 (1982), pp. 610–617. ISSN: 00223913. DOI: 10.1016/0022-3913(82)90372-9.
- [170] Morteza Sasani Ghamsari, ed. *Quantum-dot Based Light-emitting Diodes*. InTech, 2017. ISBN: 978-953-51-3575-3. DOI: 10.5772/65178.
- [171] In: ().

- [172] Z. Xia, D. W. Cunningham, and J. H. Wohlgemuth. "A new method for measuring cross-link density in ethylene vinyl acetate-based encapsulant". In: *Photovoltaics International* 5 (2009), p. 150.
- [173] Arno Hendrikus Marie Smets et al. Solar energy: The physics and engineering of photovoltaic conversion, technologies and systems. First published in 2016. Cambridge, England: UIT Cambridge, 2016. ISBN: 9781906860752.
- [174] Sergiu Deitsch et al. "Automatic classification of defective photovoltaic module cells in electroluminescence images". In: *Progress in Solar Energy 1* 185 (2019), pp. 455–468.
 ISSN: 0038-092X. DOI: 10.1016/j.solener.2019.02.067.
- [175] Jan. "EDFAAugust2009". In: ().
- K. Ramspeck et al. "Recombination current and series resistance imaging of solar cells by combined luminescence and lock-in thermography". In: *Applied Physics Letters* 90.15 (2007), p. 153502. ISSN: 0003-6951. DOI: 10.1063/1.2721138.
- [177] Jan. "EDFAAugust2009". In: (). URL: https://www.researchgate.net/profile/Jan-Martin-Wagner/publication/228666193_Lock-in_Thermography_A_Versatile_Tool_ for_Failure_Analysis_of_Solar_Cells/links/55d339e008ae7fb244f58334/Lock-in-Thermography-A-Versatile-Tool-for-Failure-Analysis-of-Solar-Cells.pdf?origin= publication_detail.
- O. Breitenstein et al. "Luminescence Imaging versus Lock-in Thermography on Solar Cells and Wafers: 8 pages / 26th European Photovoltaic Solar Energy Conference and Exhibition; 1031-1038 / 26th European Photovoltaic Solar Energy Conference and Exhibition; 1031-1038". In: (2011). DOI: 10.4229/26thEUPVSEC2011-2CO.13.5.
- [179] Viktor Wesselak, ed. RET. Con 2018: Tagungsband : 1. Regenerative Energietechnik-Konferenz in Nordhausen 8.-9. Februar 2018. Nordhausen: Hochschule Nordhausen, 2018. ISBN: 978-3-940820-13-6.
- [180] Max Henrik Siegloch. Failure analysis of thin film solar modules using lock-in thermography. Vol. Band 258. Schriften des Forschungszentrums Jülich : [...], Reihe Energie & Umwelt. Jülich: Forschungszentrum Jülich, 2015. ISBN: 978-3-95806-047-0.
- [181] Laila Verissimo Mesquita. "Albert-Ludwig-University Freiburg". In: ().
- [182] Moitreyee Sinha and Donald J. Buckley. "Acoustic Properties of Polymers". In: *Physical properties of polymers handbook*. Ed. by James E. Mark. New York, NY: Springer Science+Business Media LLC, 2007, pp. 1021–1031. ISBN: 978-0-387-31235-4. DOI: 10.1007/978-0-387-69002-5{\textunderscore}60.
- [183] Peter H. Mott, C. Michael Roland, and Robert D. Corsaro. "Acoustic and dynamic mechanical properties of a polyurethane rubber". In: *The Journal of the Acoustical Society of America* 111.4 (2002), pp. 1782–1790. DOI: 10.1121/1.1459465.
- [184] N. G. Parker et al. "Longitudinal acoustic properties of poly(lactic acid) and poly(lacticco-glycolic acid)". In: *Biomedical materials (Bristol, England)* (2010), p. 055004. DOI: 10.1088/1748-6041/5/5/055004.

- [185] Toru Tuziuti et al. "Measurement of speed of sound in poly(lactic acid)-clay composite". In: *Ultrasonics* (2014), pp. 1010–1014. DOI: 10.1016/j.ultras.2013.11.014.
- [186] Jarlath Mc Hugh. *Ultrasound Technique for the Dynamic Mechanical Analysis (DMA) of Polymers*. 2007. DOI: 10.14279/depositonce-1706.
- [187] Dirk Lellinger, Sascha Tadjbach, and Ingo Alig. "Determination of the elastic moduli of polymer films by a new ultrasonic reflection method". In: *Macromolecular Symposia* 184 (2002), pp. 203–213. ISSN: 1022-1360.
- [188] W. Mühleisen, M. Biebl-Rydlo, and M. Spielberger. "Determining the Degree of EVA Cross-Linking in Assembled PV Modules Acoustically and In-situ: 4 pages / 26th European Photovoltaic Solar Energy Conference and Exhibition; 3480-3483 / 26th European Photovoltaic Solar Energy Conference and Exhibition; 3480-3483". In: (2011). DOI: 10.4229/26thEUPVSEC2011-4AV.1.59.
- [189] James E. Mark, ed. Physical properties of polymers handbook. 2. ed. New York, NY: Springer Science+Business Media LLC, 2007. ISBN: 978-0-387-31235-4. DOI: 10.1007/ 978-0-387-69002-5.
- [190] Dirk Lellinger, Sascha Tadjbach, and Ingo Alig. "Determination of the elastic moduli of polymer films by a new ultrasonic reflection method". In: *Macromolecular Symposia* 184.1 (2002), pp. 203–214. ISSN: 1022-1360. DOI: 10.1002/1521-3900(200208)184: 1{\textless}203::AID-MASY203{\textgreater}3.0.CO;2-8.
- [191] A. Briggs. "Acoustic microscopy-a summary". In: *Reports on Progress in Physics* 55.7 (1992), pp. 851–909. ISSN: 0034-4885. DOI: 10.1088/0034-4885/55/7/001.
- [192] J. T. Seitz. "The estimation of mechanical properties of polymers from molecular structure". In: *Journal of Applied Polymer Science* 49.8 (1993), pp. 1331–1351. ISSN: 1097-4628. DOI: 10.1002/app.1993.070490802.
- [193] Jan C. Schlothauer et al. "Correlation of spatially resolved photoluminescence and viscoelastic mechanical properties of encapsulating EVA in differently aged PV modules". In: *Progress in Photovoltaics: Research and Applications* 24.6 (2016), pp. 855–870. ISSN: 1099-159X. DOI: 10.1002/pip.2734. URL: https://onlinelibrary.wiley.com/doi/pdf/10. 1002/pip.2734.
- [194] Michael Owen-Bellini et al. "Influence of Viscoelastic Properties of Encapsulation Materials on the Thermomechanical Behavior of Photovoltaic Modules". In: *IEEE Journal of Photovoltaics* 8.1 (2018), pp. 183–188. ISSN: 2156-3381. DOI: 10.1109/JPHOTOV.2017. 2762583.
- [195] A. P. Valerga et al. "On the Relationship between Mechanical Properties and Crystallisation of Chemically Post-Processed Additive Manufactured Polylactic Acid Pieces". In: *Polymers* 12.4 (2020). ISSN: 2073-4360. DOI: 10.3390/polym12040941.

- [196] David C. Miller, Michael Owen-Bellini, and Peter L. Hacke. "Use of indentation to study the degradation of photovoltaic backsheets: Solar Energy Materials and Solar Cells, 201, 110082". In: Solar Energy Materials and Solar Cells, 201, 110082 (2019). DOI: 10.1016/J.SOLMAT.2019.110082.
- [197] Michelle L. Oyen. "Sensitivity of polymer nanoindentation creep measurements to experimental variables". In: *Acta Materialia* 55.11 (2007), pp. 3633–3639. ISSN: 1359-6454. DOI: 10.1016/j.actamat.2006.12.031.
- [198] Michelle L. Oyen and Robert F. Cook. "A practical guide for analysis of nanoindentation data". In: *Journal of the mechanical behavior of biomedical materials* 2.4 (2009), pp. 396–407. DOI: 10.1016/j.jmbbm.2008.10.002.
- [199] Jaroslav Menčík, Li Hong He, and Jiří Němeček. "Characterization of viscoelastic-plastic properties of solid polymers by instrumented indentation". In: *Polymer Testing* 30.1 (2011), pp. 101–109. ISSN: 0142-9418. DOI: 10.1016/j.polymertesting.2010.11.006.
- [200] Proceedings of Conference on Electrical Insulation and Dielectric Phenomena CEIDP '96. IEEE, 20-23 Oct. 1996. ISBN: 0-7803-3580-5.
- [201] L. Verissimo Mesquita et al. "Scanning Acoustic Microscopy as a Non-Destructive Method for the Investigation of PV Module Components: 5 pages / 35th European Photovoltaic Solar Energy Conference and Exhibition; 1318-1322". In: (2018). DOI: 10.4229/35THEUPVSEC20182018-5CV.3.23.
- [202] Sebastian Brand, Peter Czuratis, and Kay Raum. "Signal analysis in acoustic microscopy for nondestructive inspection of varnish layers on metal substrates". In: *The Journal of the Acoustical Society of America* 123.5 (2008), p. 3081. DOI: 10.1121/1.2932892.
- [203] R. G. Maev et al. "Imaging of Deep Internal Layers in Layered Polymer Systems Using the Ultra-Short Pulse Acoustic Microscope". In: *Review of Progress in Quantitative Nondestructive Evaluation*. Ed. by Donald O. Thompson and Dale E. Chimenti. Boston, MA: Springer US, 1997, pp. 1845–1851. ISBN: 978-1-4613-7725-2. DOI: 10.1007/978-1-4615-5947-4{\textunderscore}241.
- [204] Stéphane Blouin et al. "Mapping dynamical mechanical properties of osteonal bone by scanning acoustic microscopy in time-of-flight mode". In: *Microscopy and microanalysis : the official journal of Microscopy Society of America, Microbeam Analysis Society, Microscopical Society of Canada* (2014), pp. 924–936. DOI: 10.1017/S1431927614000646.
- [205] Yuriy Shmaliy. *Continuous-time signals*. Signals and communication technology. Dordrecht: Springer, 2006. ISBN: 978-1-4020-4818-0.
- [206] Andrea Pfreundt et al. "Post-processing thickness variation of PV module materials and its impact on temperature, mechanical stress and power". In: *Proceedings of the 36th European Photovoltaic Solar Energy Conference and Exhibition*. 2019. ISBN: 3-936338-60-4. DOI: 10.4229/EUPVSEC20192019-4CO.4.3.

- [207] E. Malguth, B. Buhl, and T. Schenk. "Fast and Non-Destructive Determination of the EVA Cross-Linking Degree for In-Line and Off-Line Application: 4 pages / 28th European Photovoltaic Solar Energy Conference and Exhibition; 472-475 / 28th European Photovoltaic Solar Energy Conference and Exhibition; 472-475". In: *in Proceedings of the 28th European Photovoltaic Solar Energy Conference and Exhibition; 472* (2013). DOI: 10.4229/28THEUPVSEC2013-1CV.2.9.
- [208] C. Lux et al. "Variations in Cross-Link Properties of EVA of Un-Aged and Aged PV-Modules: 5 pages / 29th European Photovoltaic Solar Energy Conference and Exhibition; 2462-2466 / 29th European Photovoltaic Solar Energy Conference and Exhibition; 2462-2466". In: *in Proceedings of the 29th European Photovoltaic Solar Energy Conference and Exhibition; 2462-2466* (2014). DOI: 10.4229/EUPVSEC20142014-5DO.10.3.
- [209] S. Kunath et al. "Evaluation of Gel Content-Measurement-Method for Mass Production of Glass-Foil Based Crystalline Silicon PV Modules: 4 pages / 31st European Photovoltaic Solar Energy Conference and Exhibition; 2461-2464 / 31st European Photovoltaic Solar Energy Conference and Exhibition; 2461-2464". In: *in Proceedings of the 31st European Photovoltaic Solar Energy Conference* (2015). DOI: 10.4229/ EUPVSEC20152015-5CV.2.1.
- [210] John Lloyd et al. "NON-DESTRUCTIVE MEASUREMENT OF THE DEGREE OF CROSS-LINKING OF EVA SOLAR MODULE ENCAPSULATION". In: *37th IEEE Photovoltaic Specialists Conference (PVSC)* (2011), pp. 2273–2278.
- [211] P. Schenk et al. "Correlation of Peel Forces to EVA Degree of Cross Linking and Accelerated Weathering: 6 pages / 37th European Photovoltaic Solar Energy Conference and Exhibition; 834-839 / 37th European Photovoltaic Solar Energy Conference and Exhibition; 834-839". In: (2020). DOI: 10.4229/EUPVSEC20202020-4BO.14.5.
- [212] G. Oreski et al. "Crosslinking and post-crosslinking of ethylene vinyl acetate in photovoltaic modules". In: *Journal of Applied Polymer Science* 134.23 (2017), p. 101. ISSN: 0021-8995. DOI: 10.1002/app.44912.
- [213] A. Morlier et al. "Influence of the Curing State of Ethylene-Vinyl Acetate on Photovoltaic Modules Aging: 28th European Photovoltaic Solar Energy Conference and Exhibition; 2832-2837 / 28th European Photovoltaic Solar Energy Conference and Exhibition; 2832-2837". In: (2013). DOI: 10.4229/28THEUPVSEC2013-4CO.9.5.
- [214] Sachiko Jonai et al. "Relationship between cross-linking conditions of ethylene vinyl acetate and potential induced degradation for crystalline silicon photovoltaic modules". In: *Japanese Journal of Applied Physics* 54.8S1 (2015), 08KG01. ISSN: 0021-4922. DOI: 10.7567/JJAP.54.08KG01.
- [215] J. Zhu et al. "Correlation of Degree of EVA Crosslinking with Formation and Discharge of Acetic Acid in PV Modules: 4 pages / 33rd European Photovoltaic Solar Energy Conference and Exhibition; 1795-1798". In: (2017). DOI: 10.4229/EUPVSEC20172017-5DV.3.21.
- [216] Jiang Zhu, Daniel Montiel-Chicharro, and Michael Owen-Bellini. "The role of EVA encapsulation in the degradation of wafer based PV modules". In: *IN: Hutchins, M., Treharne, R. and Cole, A. (eds.) 12th Photovoltaic Science, Application and Technology Conference C98 (PVSAT-12), University of Liverpool, 6-8th April* (2016).
- [217] P. Klemchuk et al. "Investigation of the degradation and stabilization of EVA-based encapsulant in field-aged solar energy modules". In: *Polymer Degradation and Stability* 55.3 (1997), pp. 347–365. ISSN: 0141-3910.
- [218] K. Agroui, G. Collins, G. Oreski, M. Boehning, A. Hadj Arab and D. Ouadjaout. "Effect of crosslinking on EVA-based encapsulant properties during photovoltaic module fabrication process". In: *Revue des Energies Renouvelables Vol. 18 N°2 (2015) 303 314* ().
- [219] Nicholas X. Randall, Matthieu Vandamme, and Franz-Josef Ulm. "Nanoindentation analysis as a two-dimensional tool for mapping the mechanical properties of complex surfaces". In: *Journal of Materials Research* 24.3 (2009), pp. 679–690. ISSN: 0884-2914. DOI: 10.1557/jmr.2009.0149.
- [220] ASTM International. *Standard test methods for determination of gel content and swell ratio of crosslinked ethylene plastic.* 2011.
- [221] Matthias Jaunich et al. "Investigation of the curing state of ethylene/vinyl acetate copolymer (EVA) for photovoltaic applications by gel content determination, rheology, DSC and FTIR". In: *Polymer Testing* 52 (2016), pp. 133–140. ISSN: 0142-9418. DOI: 10.1016/j.polymertesting.2016.03.013.
- [222] Atsushi Masuda, Naomi Uchiyama, and Yukiko Hara. "Degradation by acetic acid for crystalline Si photovoltaic modules". In: *Japanese Journal of Applied Physics Part 1-Regular Papers Brief Communications & Review Papers* 54.4S (2015), 04DR04. ISSN: 0021-4922. DOI: 10.7567/JJAP.54.04DR04.
- [223] P. Huelsmann, M. Heck, and M. Koehl. "Simulation of water vapor ingress into PVmodules under different climatic conditions". In: *Journal of Materials* 2013 (2013), 7 pages (1–7?)
- [224] S. Mitterhofer, M. Jankovec, and M. Topic. "One- and two-dimensional finite element analysis of humidity ingress in polymeric materials". In: *in Proc. 54th Int. Conf. Micro-electron., Devices Mater.,* 2018, pp. 93–98 ().
- [225] Stefan Mitterhofer et al. "A Dual-Transport Model of Moisture Diffusion in PV Encapsulants for Finite-Element Simulations". In: *IEEE Journal of Photovoltaics* 10.1 (), pp. 94–102. ISSN: 2156-3381. DOI: 10.1109/JPHOTOV.2019.2955182.
- [226] F. G.-M. Marko Jankovec. In-Situ Monitoring of Moisture Ingress in PV Modules Using Digital Humidity Sensors. Vol. VOL. 6. Ieee-Inst Electrical Electronics Engineers Inc (Piscataway), 2016.

- [227] Djamel Eddine Mansour, Stefan Mitterhofer, Christoph Herzog, Esther Fokuhl, Marko Jankovec, Paul Gebhardt, Daniel Philipp, ed. *Correlation between EVA degree of crosslinking and moisture ingress into PV laminates*. 37th European Photovoltaic Solar Energy Conference and Exhibition 1009 - 1013. 2020. ISBN: 3-936338-73-6. URL: https: //www.eupvsec-proceedings.com/proceedings?fulltext=Mansour&paper=49323.
- Bernt-Åke Sultan and Erling Sörvik. "Thermal degradation of EVA and EBA—A comparison. I. Volatile decomposition products". In: *Journal of Applied Polymer Science* 43.9 (1991), pp. 1737–1745. ISSN: 0021-8995. DOI: 10.1002/app.1991.070430917.
- Bernt-Åke Sultan and Erling Sörvik. "Thermal degradation of EVA and EBA—A comparison. II. Changes in unsaturation and side group structure". In: *Journal of Applied Polymer Science* 43.9 (1991), pp. 1747–1759. ISSN: 0021-8995. DOI: 10.1002/app.1991. 070430918.
- [230] Bernt-Åke Sultan and Erling Sörvik. "Thermal degradation of EVA and EBA—A comparison. III. Molecular weight changes". In: *Journal of Applied Polymer Science* 43.9 (1991), pp. 1761–1771. ISSN: 0021-8995. DOI: 10.1002/app.1991.070430919.
- [231] Michael Owen-Bellini, Peter Hacke, Sergiu Spataru, David C. Miller, Michael Kempe.
 "Combined-accelerated stress testing for advanced reliability assessment of photovoltaic modules". In: *in Proceedings of the 35th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC); Brussels, Belgium* (2018). DOI: 10.4229/35thEUPVSEC20182018-5DO.7.6.
- [232] Edwin P. Plueddemann. *Silane Coupling Agents*. Boston, MA: Springer US, 1991. ISBN: 978-1-4899-2072-0. DOI: 10.1007/978-1-4899-2070-6.
- [233] B. Arkles. "Silane Coupling Agents". In: (2014).
- [234] D. R. Coulter, E. F. Cuddihy, and E. P. Plueddeman. Chemical bonding technology for terrestrial photovoltaic modules (Technical Report) | OSTI.GOV. URL: https://www. osti.gov/biblio/6601157-chemical-bonding-technology-terrestrial-photovoltaicmodules.
- [235] Lawrence Dunn, Michael Gostein and Bill Stueve. *Literature Review of the Effects of UV Exposure on PV Modules.*
- M. A. Munoz et al. "Early degradation of silicon PV modules and guaranty conditions". In: *Progress in Solar Energy 1* 85.9 (2011), pp. 2264–2274. ISSN: 0038-092X. DOI: 10.1016/j.solener.2011.06.011.
- [237] Sascha Lindig et al. "Review of Statistical and Analytical Degradation Models for Photovoltaic Modules and Systems as Well as Related Improvements". In: *IEEE Journal of Photovoltaics* 8.6 (2018), pp. 1773–1786. ISSN: 2156-3403. DOI: 10.1109/JPHOTOV.2018. 2870532.
- [238] Trang Ngo et al. "Effects of UV on power degradation of photovoltaic modules in combined acceleration tests". In: *Japanese Journal of Applied Physics* 55.5 (2016), p. 052301.
 ISSN: 0021-4922. DOI: 10.7567/JJAP.55.052301.

- [239] Norman S. Allen et al. "Physicochemical aspects of the environmental degradation of poly(ethylene terephthalate)". In: *Polymer Degradation and Stability* 43.2 (1994), pp. 229–237. ISSN: 0141-3910. DOI: 10.1016/0141-3910(94)90074-4.
- [240] E. M. Abdel-Bary et al. "Stability of Polypropylene Blends Under the Effect of Thermal and UV Degradation". In: *Polymer-Plastics Technology and Engineering* 44.5 (2005), pp. 847–862. ISSN: 0360-2559. DOI: 10.1081/PTE-200060842.
- [241] Norman S. Allen and Michele Edge. "Perspectives on additives for polymers. 1. Aspects of stabilization". In: *Journal of Vinyl and Additive Technology* 27.1 (2021), pp. 5–27. ISSN: 1083-5601. DOI: 10.1002/vnl.21807.
- [242] Gabriele C. Eder et al. "Climate specific accelerated ageing tests and evaluation of ageing induced electrical, physical, and chemical changes". In: *Progress in Photovoltaics: Research and Applications* 27.11 (2019), pp. 934–949. ISSN: 1099-159X. DOI: 10.1002/pip.3090.
- [243] I. L. Repins et al. "Stabilization of light-induced effects in Si modules for IEC 61215 design qualification". In: *Progress in Solar Energy 1* 208 (2020), pp. 894–904. ISSN: 0038-092X.
- [244] Friederike Kersten et al. "Stability investigations of Cz-PERC modules during damp heat testing and transport: The impact of the boron-oxygen defect". In: 15th International Conference on Concentrator Photovoltaic Systems (CPV-15). Ed. by AIP Conference Proceedings. AIP Conference Proceedings. AIP Publishing, 2019, p. 090001.

Djamel Eddine Mansour

mansourdjameleddine@gmail.com @dmansour_djamel
 https://solar-train.eu/fellowships/fellows/djamel
 https://www.linkedin.com/in/djamel-eddine-mansour-269b9199/
line +49 1520 7980879 Ludwigstraße 2, 79104 Freiburg, Germany



Educational path

2017 – 2021	Ph.D., Doctoral school of Energy , Solar Energy and Building Physics Laboratory Topic: <i>Photovoltaic material and module parameters and their resistance to accelerated aging</i> Ecole Polytechnic Federal de Lausanne (EPFL), Lausanne, Switzerland Based in Fraunhofer ISE, Freiburg, Germany
2015 - 2016	M.Sc. Chemistry, Nanoscience and Energy University of Paris 7 Diderot, Paris Sorbonne city, France
2013 - 2015	M.Sc. Chemical Engineering University of Pierre et Marie Curie Paris 6 centre consortium, Paris Sorbonne, France
2010 - 2013	B.Sc. Material sciences University of Oran, Algeria

Training and research experience

2020 –	Project Leader at Fraunhofer Institute of Solar Energy Systems (ISE), at Module Characterization Reliability (MCR) Group. Freiburg, Germany
2017 – 2020	Early stage researcher (ESR) at Fraunhofer ISE, "Solar-Train" project under the Marie Sklodowska- Curie Horizon 2020. Freiburg, Germany
01–03 2019	Visiting research #3 at Polymer Competence Center Leoben (PCCL), Leoben, Austria
07–08 2018	Visiting research #2 "Industrial secondment" at Anton Paar Germany GmbH, Stuttgart, Germany
02–03 2018	Visiting research #1 at el Centro Nacional de Energías Renovables (CENER), Pamplona, Spain
04–08 2016	Master Thesis at Ecole Polytechnic Federal de Lausanne (EPFL), "Development of novel elec- trochromic material deposited by magnetron sputtering for advanced windows". Lausanne, Switzerland
03–08 2015	Internship at Institut d'Electronique Fondamentale (clean room experience), "Evaporated zr-v, zr-ti and zr-co getter thin films for vacuum packaging of MEMS". Paris, France
04–07 2014	Internship at Chimie ParisTech – Ecole Nationale Supérieure de Chimie de Paris, "Electrochemical impedance spectroscopy (EIS) on Composite materials for high temperature fuel cells". Paris, France

Skills

Languages	Mother tongue for Arabic and Bilingual for French Strong reading, writing and speaking competencies for English Good reading, writing and speaking competencies for German Basic reading, writing and speaking competencies for Spanish	155
IT — Skills	MS-Office, Origin, Aspen HYSYS,	155
Coding	MAT-LAB, Python, R, LATEX,	

Miscellaneous Experience

Fellowship Honors and scholarship

2017 **Initial Training Networks (ITN) - Marie Sklodowska Curie Actions**, European Commision

2013 **Erasmus Mundus exchange of excellence (EMMAG)**, European Commision

Summer schools and awards

#4: Industrial Soft Skills and Entrepreneurship (Agile methods). PCCL Leoben, in coop. with EDF, Austria
#3: Career Development Session. Eurac Bolzano, in coop. with BayWa r.e. Italy
#2: PV Module Lifetime and Reliability (advanced course). University of Ljubljana, Slovenia
#1: State-of-the-art in PV module technology. Loughborough University, UK
Engineer without border: Humanitarian and educational projects. Awarded by three French grants (2018, 2019 and 2020) for schools building. Bidi-bidi in northwestern Uganda

Research Publications

Journal Articles

- Mansour, D. E., Barretta, C., Pitta Bauermann, L., Oreski, G., Schueler, A., Philipp, D., & Gebhardt, P. (2020). Effect of backsheet properties on pv encapsulant degradation during combined accelerated aging tests. *Sustainability*, 12(12), 5208. Ø doi:10.3390/su12125208
- Mesquita, L. V., Mansour, D. E., Gebhardt, P., & Pitta Bauermann, L. (2020). Scanning acoustic microscopy analysis of the mechanical properties of polymeric components in photovoltaic modules. *Engineering Reports*.
 doi:10.1002/eng2.12222
- Mansour, D. E., Bouvard, O., & Schüler, A. (2017). Development and characterization of electrochromic oxide and ion conductor deposited by reactive magnetron sputtering. *Energy Procedia*, 122, 787–792.
 doi:10.1016/j.egypro.2017.07.397

Conference Proceedings

- Mansour, D. E., Kotterer, S., Philipp, D., & Gebhardt, P. (2020). Pv backsheet failure analysis by scanning acoustic microscopy. 37th eupvsec; 1014-1018. & doi:10.4229/EUPVSEC2020202-4AV.1.29
- Mansour, D. E., Mitterhofer, Herzog, C., Fokuhl, E., Jankovec, M., Gebhardt, P., & Philipp, D. (2020). Correlation between eva degree of crosslinking and moisture ingress into pv laminates. 37th eupvsec; 1009-1013.
 doi:10.4229/EUPVSEC2020202-4AV.1.27
- 3 Mansour, D. E., Swientek, F., Kaaya, I., Philipp, D., & Pitta Bauermann, L. (2018). Nanoindentation analysis of pv module polymeric components after accelerated aging. 35th eupvsec; 1333-1336. *J* doi:10.4229/35thEUPVSEC20182018-5CV.3.28
- Mesquita, L. V., Mansour, D. E., Philipp, D., & Pitta Bauermann, L. (2018). Scanning acoustic microscopy as a non-destructive method for the investigation of pv module components. 35th eupvsec; 1318-1322.
 doi:10.4229/35THEUPVSEC20182018-5CV.3.23
- ⁵ Wu, M., Lemettre, S., **Mansour, D. E.**, Plante, M.-P., Bosseboeuf, A., Seok, S., & Moulin, J. (2016). Evaporated zr-v, zr-ti and zr-co getter thin films: Activation temperature and microstructure. In *Symposium on design, test, integration and packaging of mems/moems.* & doi:10.1109/DTIP.2016.7514851

References

156

Available on Request