



Review of degradation and failure phenomena in photovoltaic modules



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ABSTRACT

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The degradation of photovoltaic (PV) systems is one of the key factors to address in order to reduce the cost of the electricity produced by increasing the operational lifetime of PV systems. To reduce the degradation, it is imperative to know the degradation and failure phenomena. This review article has been prepared to present an overview of the state-of-the-art knowledge on the reliability of PV modules. Whilst the most common technology today is mono- and multi-crystalline silicon, this article aims to give a generic summary which is relevant for a wider range of photovoltaic technologies including cadmium telluride, copper indium gallium selenide and emerging low-cost high-efficiency technologies. The review consists of three parts: firstly, a brief contextual summary about reliability metrics and how reliability is measured. Secondly, a summary of the main stress factors and how they influence module degradation. Finally, a detailed review of degradation and failure modes, which has been partitioned by the individual component within a PV module. This section connects the degradation phenomena and failure modes to the module component, and its effects on the PV system. Building on this knowledge, strategies to improve the operational lifetime of PV systems and thus, to reduce the electricity cost can be devised. Through extensive testing and failure analysis, researchers now have a much better overview of stressors and their impact on long term stability.

1. Introduction

The economic and societal impact of photovoltaics (PV) is enormous and will continue to grow rapidly. To achieve the 1.5 °C by 2050 scenario, the International Renewable Energy Agency predicts that PV has to increase 15-fold and account for half of all electricity generation (15 TW), increasing from just under 1 TW in 2021 [1]. The quality and commercial attractiveness of a PV system is primarily determined by its performance in the field, cost, and lifetime, to each of which the PV module significantly contributes. During the operational lifetime of a

module, it will be exposed to simultaneous environmental stresses like sunlight, heat and cold, moisture, and mechanical loads. These factors often lead to a gradual decrease of the performance, and in some cases to sudden breakdown and power loss. It is desirable to limit these effects. A recent European Technology and Innovation Platform report [2] highlighted the importance of long-term reliability. Engineers should minimize the degradation as much as possible, and quantitatively predict degradation phenomena that cannot be eliminated. This will enable a more accurate estimation of the expected service lifetime of a module and its electricity yield. Such estimates are required for large-scale investments, since investors, banks, and insurance companies desire to

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Nomenclature

ALT	Accelerated Life Testing
c-Si	Crystalline Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
DSC	Dye-sensitized Solar Cells
EPBT	Energy Pay Back Time
EVA	Ethylene-Vinyl Acetate
IEC	International Electrotechnical Commission
LCOE	Levelized Cost Of Electricity
LETID	Light and Elevated Temperature Induced Degradation
LID	Light-Induced Degradation
NREL	US National Renewable Energy Laboratory
OPV	Organic Photovoltaic(s)
PET	Poly-Ethylene Terephthalate
PID	Potential-Induced Degradation
PV	Photovoltaic(s)
SEMI	Semiconductor Equipment and Materials Institute
TCO	Transparent Conducting Oxide
UV	Ultraviolet

minimize their risks and uncertainties. To optimise reliability and predictability, and to enhance the module lifetime, it is crucial that degradation and failure mechanisms are known and can be easily recognized and contained.

This article aims to give an overview of state-of-the-art knowledge on reliability of PV systems and treats degradation mechanisms that generally affect PV technologies. We intend this article to be a concise and up-to-date introduction to this topic for the general reader and specifically for newcomers into the PV reliability engineering domain. For this review paper, existing literature published during the past 30 years has been explored by a team of experts from various organizations who are members of the working group on “Reliability and Durability of PV” in EU COST Action PEARL PV [3]. In the remainder of this section we will introduce the different photovoltaic technologies that are the dominant focus of industry and academia. Next, Section 2 will define the most important concepts and notions for reliability and degradation, describe the testing standards, and introduce the economic aspects of PV reliability. Section 3 describes the stress factors causing degradation in PV modules; Section 4 subsequently reviews the known degradation effects that arise from these stresses. Finally, the perspective of future research challenges are highlighted in Section 5. A renewable energy technology such as PV will play a key role in the energy transition to a

net-zero emission energy system, however, it is vital for the different PV technologies to continue evolving to allow for further cost reductions, but also to lower environmental impacts and for ease of re-use and recycling. It is clear that new device architectures and materials have to take into consideration scaling effects, ability to exhibit long lifetimes and low environmental impacts. This review paper summarizes the reliability challenges which must be adhered to in order to achieve longer lifetime and ensure these further cost reductions are achieved.

2. Framework for reliability research and metrics n PV modules

2.1. Contemporary photovoltaic technologies

The most common configurations for c-Si and thin-film based PV modules are shown in Fig. 1. Solar cells are one of many components that make up the laminate structure. Other components include the module packaging (glass front cover, encapsulant, backsheet), internal circuit (electrodes, interconnects), bypass diodes, junction boxes, frame, cables, and connectors; all of which may influence or even limit the module's reliability.

Table 1

Comparison of PV technologies in terms of performance, maturity and market share. The market shares were estimated from data supplied by the Fraunhofer ISE [4]. Power conversion efficiencies were obtained from the Green et al. tables [5] and from the National Renewable Energy Laboratories (NREL) Website [6]. Energy payback time values are those reported by and Ludin et al. [7] unless specified otherwise. The review of Ludin et al. covers many studies published since the year 2000; the lower EPBT values in the Table relate to more recent products.

Technology	Year surpassing 10% eff.	2020 Market share (%)	Record cell efficiency (%)	EPBT (y)	Best literature report of outdoor lifetime (y)
Monocrystalline Si	1957 [8]	66.6	26.7	1.4–7.3	>20
Polycrystalline Si	1984	28.4	24.4	0.8–4.2	>20
CdTe	1981	4.1	22.1	0.8–2.7	>20
CIGS	1981	0.8	23.4	1.3–2.8	>20
Amorphous Si:H	1992	0.1	14.0	1.1–3.2	>20
Dye-sensitized Solar Cells	1997	–	12.3	0.6–1.8	<2 [9]
Organic Photovoltaics	2012	–	17.5	0.1–1	~2 [12], [41], [13]
Perovskite Solar Cells	2012	–	25.5	0.2–5.4	<0.5 [14]

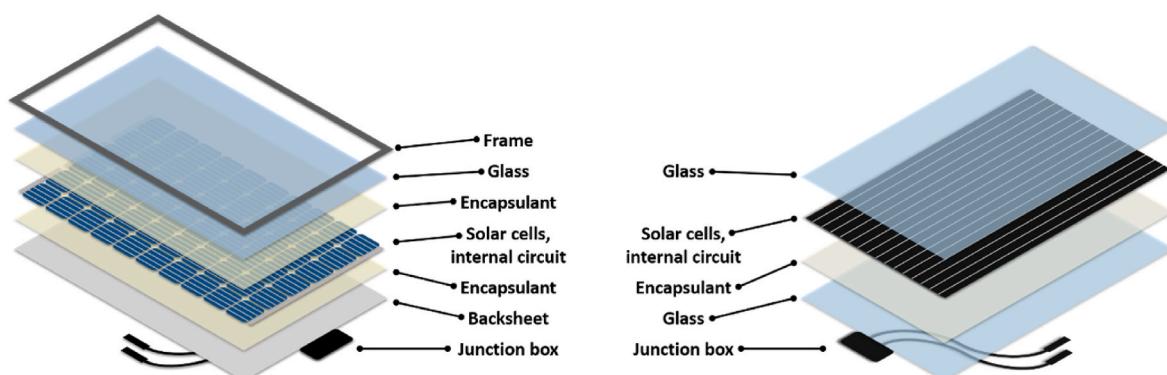


Fig. 1. The most common configurations of PV modules for crystalline silicon (left) and CdTe thin film (right) [15]. Rigid CIGS modules have a similar structure as CdTe modules but with the solar cells under the encapsulant. Besides these two basic configurations, a wide variety of alternative structures exists, e.g. using a polymer frontsheet or containing only flexible components [16].

Table 1 provides a summary of the major PV technologies considered. The table quantifies a trend that one would expect: earlier developed technologies had more time to mature and as a result, they show good efficiency and a good outdoor lifetime. With these properties, in combination with the economy of scale, contemporary photovoltaic systems can generate electricity at a very competitive cost level. The Energy Payback Time (EPBT), further treated in the next section, is of the order of one year for all technologies. Any PV system with a lifetime exceeding the EPBT can be viewed as renewable. The listed PV technologies easily meet this requirement except for the newest emerging ones, where lifetime problems still need to be resolved.

Although it is included in the table for completeness, hydrogenated amorphous silicon has not been reviewed in the remainder of this article as the rather low record efficiency has not improved much since the turn of the Century, indicating a limited potential to contribute to the energy transition. Dye-sensitized solar cells have persistent reliability issues but did lead to the development of the new class of perovskite solar cells. In view of their novelty and promising efficiencies, organic photovoltaics and perovskite solar cells may become serious contenders in the PV market when an affordable solution is found for their stability issues. We may conclude that besides power efficiency, the reliability is decisive for both the economic value and the environmental impact of PV technologies.

2.2. Reliability definitions and quality standards for photovoltaics

In the engineering domain, reliability is quantitatively defined as: *the probability that an item will perform a required function without failure under stated conditions for a stated period of time* [17]. In the context of PV, reliability emerges during the operational lifetime in the field, and thus affects financiers and owners. Quality control on the other hand takes place during fabrication of the modules as a responsibility of the manufacturer. However, reliability and quality are strongly interrelated. Low-quality manufacturing of PV modules will result in a low reliability of PV modules in the field. Conversely, we can assume that high quality materials, module design, and production will yield reliable PV systems. The quality control in present PV manufacturing lines results in an expected life span of PV modules, usually guaranteed to be 25 years, though there are noteworthy systems that have been in operation for over 30 years [18–20].

From a quality engineering point of view, PV modules are assessed against a specification, and ordinarily, a producer will sell a module after it passed design, type approval, and safety qualification standards [21]. PV standards were initiated in 1978 which was supported by the United States Department of Energy and managed by the Jet Propulsion Laboratory. As documented by Verlinden et al. [22], the task of developing standards was taken over by the Institute of Electrical and Electronic Engineers in the 1980s, then by the International Electrotechnical Commission (IEC), the Underwriters Laboratories and, as of 2015, by the Semiconductor Equipment and Materials Institute (SEMI). The original qualification standard for PV modules was called the “Block V Specification” and included a series of qualification tests. There are now a wide range (~170) of PV standards and technical specifications. However, the most well-known and widely used regarding durability are IEC 61215 and IEC 61730. Several countries have their own national PV-related standards, but they are for the most part based on the standards developed by the IEC. The Underwriters Laboratories standards are in general related to the safety of PV components or systems, while the SEMI standards are related to the manufacturing aspects.

However, meeting these standards and specifications provides no measure of the quality, performance, and failure over time, particularly beyond the warranty period. This marks the distinction between quality control and reliability engineering. In reliability engineering, we presume that failures will occur at statistically fluctuating time intervals, often depending on the weather and other stress conditions. So, whilst the PV community has developed standardized tests that assess the time-

zero quality of a PV module, it remains difficult to predict the long-term performance of PV modules installed in PV systems. Such predictions rely on reliability models that may be generic in engineering or specific for a given technology.

An important generic model is the bathtub curve, which describes most product life cycles; see Fig. 2. The bathtub accounts for both *degradation mechanisms* (which result in gradual reduction of performance over time) and *failure* (meaning the inability of components or modules to fulfil their designed function). In the bathtub curve, one distinguishes three stages:

- *Early life* failures are often related to poor design or manufacturing errors that can be reduced by effective process controls or screening. Typically, for PV modules these occur within 1–2 years of use;
- Failures during the *steady-state life* period are often either random or the result of technology limitations;
- *Wear-out* failures, caused by mechanisms that degrade the performance gradually until the device does not function anymore, are related to mechanical, physical or chemical phenomena such as fatigue, electromigration and corrosion. Ideally, wear-out failure only occurs after the warranty period expires.

Work has been conducted to relate failure modes of PV modules to regions in the bathtub curve. Koentges et al. [25] categorized failure modes of crystalline-silicon modules on the basis of data provided by an unnamed commercial distributor. They found that the most common causes of early failure are junction box failure, glass breakage, defective cell interconnect, loose frame, and delamination. A study by DeGraaff [26] on PV modules that had been in the field for at least 8 years estimated that around 2% of PV modules failed after 11–12 years. In this period, there was a much stronger prevalence of defective interconnections in the module, and failures due to PV module glass breakage, burn marks on cells (10%), and encapsulant failure (9%) while failures due to junction-boxes and cables remained high. Whilst these studies are very insightful, it is worth noting that the investigated modules were manufactured some 15–20 years ago. Advances in technology probably reduce known ageing issues, but meanwhile, new degradation phenomena might surface.

2.3. Economic considerations of reliability

A capital investor's decision to invest in photovoltaics is usually based on a financial prognosis and a ranking against other opportunities. Risks include, but are not limited to, module degradation and failure. Clearly, the financial performance indicators cannot be derived from a

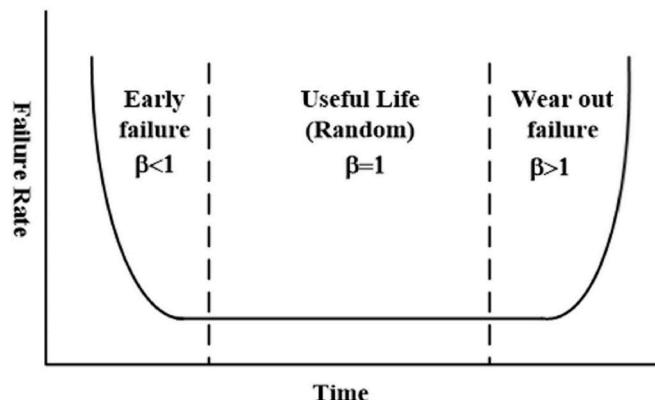


Fig. 2. Bathtub curve [23] showing the typical probability of failures (the failure rate) over the technical lifetime of a product such as a photovoltaic module, where β refers to the ‘shape parameter’ of a probability distribution function (discussed further in Ref. [24]).

solar module's technical performance alone. There are several metrics used for modelling return on investments over time. Quantification of the capital outlay and operating & maintenance expenditure of the PV system and its estimated energy yield are necessary inputs for the stakeholders in an investment.

The leveled cost of electricity is perhaps the most referenced metric of PV system economics. In simple terms, the LCOE gives a leveled (average) cost of electricity generation over the life of the asset. The LCOE could be used to compare the cost of energy generated by a PV power plant with that of a fossil fuel generating unit or another renewable technology [27]. The calculation for the LCOE is the net present value of total life cycle costs of the PV project divided by the quantity of energy produced over the system life.

$$\text{LCOE} = \frac{\text{Total Lifecycle Cost}}{\text{Total Lifetime Energy Production}} \quad (1)$$

The above LCOE equation can be disaggregated for solar generation as follows:

$$\text{LCOE} = \frac{(\text{Initial Investment}) - \left[\sum_{n=1}^N \left(\frac{\text{Depreciation}^n}{(1+D_r)^n} \right) x (\text{Tax rate}) \right] + \left[\sum_{n=1}^N \left(\frac{\text{Annual costs}^n}{(1+D_r)^n} \right) x (1 - \text{Tax rate}) \right] - \left(\frac{\text{Residual value}}{(1+D_r)^n} \right)}{\sum_{n=1}^N \left(\frac{\text{Initial } \frac{kW_h}{kW_p} x (1 - \text{System degradation rate})^n}{(1+D_r)^n} \right)} \quad (2)$$

[28] where N is the system lifetime (in years) and D_r is the discount rate; which is the interest rate used to determine the present value of future cash flows. Clearly LCOE is heavily dependent on the degradation rate and the lifetime as these have a direct impact upon both the produced electric energy and the sum of the running costs (depreciation and

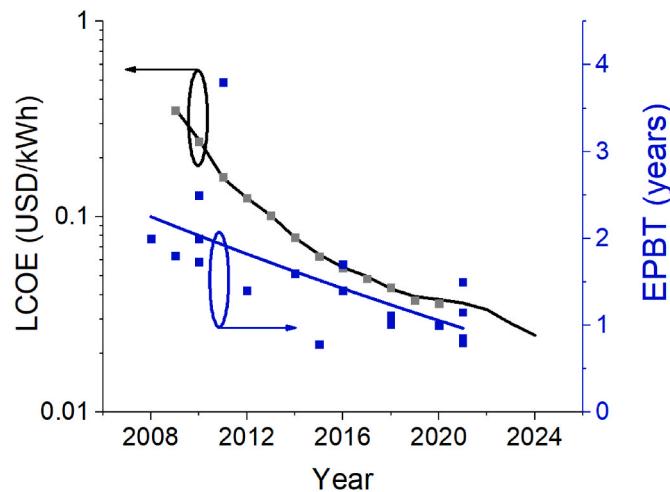


Fig. 3. The historic calculations (grey markers) and future estimates (line) of the leveled cost of electricity (LCOE) for utility scale silicon photovoltaic systems based upon the International Technology Roadmap for Photovoltaic (ITRPV) roadmap from 2020. The historic data estimates are from Ref. [29], prognosis from Ref. [30] assuming an annual irradiation of 1500 kWh(AC)/kW (DC). Note the logarithmic scale of the primary y-axis. Shown on the secondary y-axis is how the calculated Energy payback Time (EPBT) has changed since 2007 based upon work from Ref. [11], with recent reports from Refs. [37–39] using data [30] assuming an annual irradiation of 1600–1800 kWh(AC)/kW (DC). Both metrics have reduced as a result of the falling cost, increase in efficiency and increase in useful life of PV modules.

annual costs). Fig. 3 shows the world averaged LCOE of PV as it developed over time [29], and predictions of its future development [30]. It dropped by an order of magnitude between 2008 and 2020. In most countries, the cost of electricity produced by PV is below that of the grid's spot price, meaning it is economically competitive with conventional electricity sources [31].

A further decrease of the LCOE is expected as manufacturing volumes grow while both performance and reliability increase. Because of factors such as irradiance, subsidy programs and land price, the leveled cost of electricity depends heavily on the location of the plant. The discount rate, tax rate and degradation rate also strongly influence the LCOE. The steep decline of the overall capital system cost caused by the lowering cell cost is slowing down (on this semilogarithmic scale) as different contributors to the overall expenses now become more prominent. Consequently, this will mean degradation and reliability will have a greater influence over LCOE in the coming years [32]. For example: as estimated in 2017, the LCOE will rise by 6–7% [33], if annual degradation increases by 0.5% abs. assuming a 1 €/Wp investment cost for a

system sited in a high insolation area.

A second important metric for renewable energy systems is their Energy Pay Back Time (EPBT) (see Eq. (3) and Fig. 3), which is defined as the period required for a system to generate the same amount of energy (*in terms of equivalent primary energy*) that was used to produce (and manage at end-of-life) the system itself.

$$\text{EPBT [years]} = \text{CED} / ([E_{\text{Agen}} / \eta_G] - E_{\text{O\&M}}) \quad (3)$$

where CED is the cumulative energy demand [MJ], which includes material and system production energy, transportation and installation energy, and end-of-life management energy. E_{Agen} [MJ_{PE-eq}/yr] is the annual electricity generation, $E_{\text{O\&M}}$ [MJ_{PE-eq}] is the annual primary energy demand for operation and maintenance, η_G is the grid efficiency, i.e. the average life-cycle primary energy to electricity conversion efficiency at the demand side [34]. Contrary to LCOE, EPBT is only moderately sensitive to degradation in mature PV technologies. Depending on the technology and location of the PV system, the EPBT today ranges from 0.4 to 1.5 years and has decreased by around 80% in the past decade due to wafer thinning and more efficient manufacturing (see Fig. 2) [35,36].

2.4. Outdoor reliability testing

The previous sections made clear that the power degradation and the lifetime of a PV technology need to be quantified. In laboratory settings, it is commonplace to undertake stress tests to examine for degradation modes in a systematic approach. However, as modules have improved in reliability, standard accelerated testing has become ineffective. Therefore, a degradation assessment needs to be complemented by outdoor data analysis. Often a combination of indoor accelerated and outdoor tests is used to conduct a failure modes and effects analysis, to assess the relative impact of different failures, in order to proactively improve PV design. In the United States the National Renewable Energy Laboratory (NREL) documented power degradation rates for different PV technologies and discussed the accuracies of different assessment approaches

[40,41]. In particular, NREL evaluated over 2000 modules tested in the field around the world and showed that degradation rates varied from 0.5% to 2% per year depending on the type and vintage. Their report concludes that for modules manufactured after the year 2000, the most stable material systems are polycrystalline Si and CdTe.

Outdoor performance is most commonly monitored by electrical curve tracing or maximum power point tracking, to produce a data set of delivered power (or efficiency) over time. Conventionally such data are then synthesized using a regression model, but data filtering and the selected model can dramatically influence results [42]. Advanced time series modelling can be used to reduce noise and inaccuracy [43–45]. An alternative is the year-on-year approach in which a degradation distribution is determined rather than a single (average) annual degradation rate [46]. Another report [47] has shown that degradation rates can be estimated from yield measurements, although the report adds the caveat that at least 3–4 years of data from at least 10 different PV systems are needed to obtain better than 1%/year accuracy.

The uncertainty on the estimation of the module power affects degradation rate calculations substantially. Temperature and irradiance are normally corrected, but experimental error, drift of sensors and plane of array irradiance still result in some uncertainty. Module shading and module coverage by soiling or snow can be notable yield-reducing factors as well. Also, the location on the system where the measurement has been taken can affect the analysis, for example, if output power is measured from the AC output, the degradation rate includes the inverter degradation as well [48,49]. Another important parameter in yield assessment is PV system availability and clearly the higher the data availability, the more accurate one can be with degradation rate calculation.

2.5. Accelerated testing and relationship to standards

Accelerated life testing (ALT) is an important part of the quality engineering process and uses stress levels higher than normal use conditions to speed up the formation and manifestation of defects. This allows reliability engineers to quickly identify failure modes, assess their relative severity and apply corrective actions. Historically, ALT protocols for reliability assessment of PV modules were developed to address known failures discovered in the field. As discussed in Section 2.1, most manufacturers utilize the international standard IEC 61215. However, failure mechanisms that are undiscovered in ALT are still being found in modules deployed in the field, often resulting in significant financial and energy production losses. Recent examples include backsheets cracking [50], potential-induced degradation (PID) [51], grid finger corrosion [52], light and elevated temperature induced degradation (LETID) [53] and snail trails [7], which are explained and discussed in more detail in Section 4.

Many of these result from a combination of stress factors which were not combined in conventional tests or may require much longer duration testing to be uncovered. Some, such as snail trails, follow from material interactions which were not discovered in component-level tests. As a

result, there has been an increasing interest in extended, sequential, or combined stress factor testing [54,55]. Extended stress testing is described in IEC TS 63209. It takes approximately three times the duration of the module qualification tests laid out in IEC 61215. IEC TR 63279 describes the latest work on sequential and combined stress testing.

Alternatively, DuPont developed the module accelerated sequential testing [56], NREL the combined accelerated sequential testing [37] and Solliance the in-situ degradation method [58]. All three combine multiple stress factors such as light, humidity, temperature, rain, mechanical load and voltage stress. It is worth reminding that stress factors and stress levels in the outdoors are uncontrolled and time-varying, while conventional ALT approaches have a more monotonous character.

Finally, there has been significant effort to develop material and component tests for PV modules, such as the IEC 62788 series of standards. Whilst ALT is key to ongoing reliability programs where it can be used to identify material/supply issues in an early stage, quality engineering is becoming much more important as PV lifetimes extend beyond 30 years. As explained by Kurtz [59], quality assurance is key for identifying manufacturing defects from PV modules that later propagate into failures under operational conditions in the field.

3. Causes of module degradation

During real-world operation, PV modules are exposed to various external and internal stress factors that influence their performance and long-term reliability (see Fig. 4). While external stress factors are related to environmental conditions, internal stress factors are caused by the bill of materials of PV modules and processing related effects. External and internal stress factors are further described in Sections 3.1 and 3.2, respectively.

3.1. Environmental stress factors

3.1.1. Irradiance

The key characteristics of the incident solar irradiance on PV modules are its power, the spectral distribution and the angle of incidence. The global standard (AM 1.5G) solar spectral irradiance [60] covers the wavelength range of 280–4000 nm and corresponds to an integrated solar power of 1000 W/m². Although the UV region (280–400 nm) corresponds to only ~4.6% of this power, its photons are the most detrimental for polymeric materials upon prolonged exposure as the energy of these photons is high enough to cause scission of C–C and C–O bonds, which are typically found in the polymer main chain. These scission reactions lead to embrittlement and discoloration of the polymer [61].

The spectral distribution and intensity level of the incident irradiation depends on a number of factors such as variations in stratospheric ozone with latitude and season, time of the day, season, azimuth (compass angle), tilt angle from the horizontal, cloud cover, surface reflection, altitude, and air pollution [62]. UVB (280–315 nm) is the

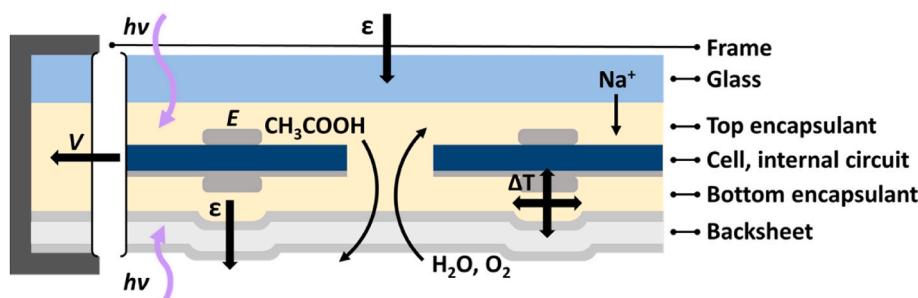


Fig. 4. Some common PV module stressors for a silicon wafer-based PV module, including light ($h\nu$), strain (ϵ), voltage bias (V), chemical diffusion, ingress and egress (CH_3COOH , H_2O , O_2 , Na^+), electric field (E), and thermomechanical strain (ΔT). Dimensions are not to scale.

most damaging part of the UV light, in particular for polymeric materials in PV modules although its power fraction ($\sim 1.5\%$) is small compared to that of UVA (315–400 nm; $\sim 98.5\%$) according to the reference spectrum. This fraction however fluctuates for the incident UV light [63]: it is higher at lower latitudes, during summer, and mid-afternoons, when the sun's rays are strongest, and faster degradation can be expected under such external conditions.

3.1.2. Temperature

Temperature is a key environmental stress factor as it may affect the electric performance of a PV module directly, accelerate permeation and reaction rates in materials, and induce mechanical stress due to differences in thermal expansion coefficients of module parts. The temperature within the cell or module may differ from the ambient temperature, particularly because of incident irradiance. The flow of heat out of the cells depends on the geometry and thermal conductivity of the surrounding materials, wind speed and the installation configuration of the PV module.

Temperature has an accelerating effect on many module degradation mechanisms particularly those related to chemical reactions and diffusion. The temperature dependence of such effects is often modelled using the Arrhenius equation with a mechanism-dependent activation energy [24,64]. The degradation of the encapsulant and backsheet films, and corrosion of the metallization elements follow Arrhenius behaviour.

Due to thermal expansion coefficient mismatches, module materials expand and contract at varying rates as temperature changes. This mismatch can induce thermo-mechanical stresses within the module construction. The mechanical stability of the active electrical elements, such as cells, solder joints, and interconnect ribbons, is particularly affected by such stresses. Deformation, delamination at the module interfaces and even cell cracking can result [65]. Variations in diurnal and seasonal temperatures produce cyclic thermo-mechanical stresses and this can lead to fatigue induced failures in the various module components.

3.1.3. Moisture

Moisture is also an important stress factor for PV modules as moisture ingress can deteriorate adhesive bonds at the interfaces between module components, resulting in delamination, causing loss of passivation and degrading anti-reflection coatings; and it leads to corrosion of metallization elements. In outdoor conditions, moisture appears in many forms such as water vapor (or humidity), condensation (or dew), rain, snow, and ice.

Since water vapor is in the gas form, it can permeate through polymeric packaging materials, accumulate within the module construction, and induce degradation of module components. Liquid water, mostly condensed humidity, dew, or rain, can be absorbed or desorbed as well [13]. Water ingress in larger quantities can induce mechanical stresses because of the hydro-dynamic volume expansion and contraction. It can also erode low molecular weight species and additives away from the polymeric materials. It can further dissolve ions, deteriorate the electrical insulation of dielectrics, and cause leakage current [66]. In the solid form as ice, it can experience volume change during freeze-thaw cycles and produce mechanical stresses on the outer side of the PV module that lead to delamination of the front glass or frame damage.

When the module is saturated with moisture, a drop in temperature can cause the moisture level to exceed its saturation limit leading to condensation in the form of water droplets especially at the interfaces, on cell surfaces, and at metallization elements. While weakened interfaces can delaminate and produce further paths for moisture ingress, shorting and corrosion of metallization can cause significant performance loss due to increased resistance. Modules hardly contain water after production, but internal moisture concentrations will rise over time in the field. The time to achieve the equilibrium moisture concentration level is one of the key parameters for the service lifetime of PV modules. It was estimated to be few days to a week in a breathable construction

(glass/backsheet module), but up to a few years in an unbreathable construction (glass/glass module) [67].

3.1.4. Mechanical load

Various mechanical stresses can arise in PV modules due to manufacturing processes, transportation, handling during installation, wind, hail, snow, and thermo-mechanical loads. Since solar cells and metallization elements are thin and brittle, they are susceptible to such stress conditions and must be protected against cracking or fracture. Embrittled backsheets are also susceptible to mechanical loads. The front glass and the frame can also be damaged by mechanical loads which can lead to failure of the PV module. For polymeric packaging materials, mechanical stresses can create or extend cracks, in particular when the mechanical strength of a polymer is already weakened by other environmental stress factors such as UV light or humidity.

Depending on the orientation, modules often experience mechanical stresses on the front side during operation. Snow load is a static stress factor and long-term accumulation on the front side can exert significant force on the module which can cause cell cracks. If the module is tilted, snow accumulation and formation of ice on the module edge can induce bending forces and damage the rigidity of the frame. Even detachment of the frame from the module can occur [25]. In this case, modules lose their environmental and electrical protection. Wind, on the other hand, is a dynamic stress factor and can apply force on the front and the back depending on its direction. Mechanical loads due to wind can be significant as its direction and speed can change suddenly in gusty weather conditions. Prolonged exposure to cyclic gusty winds can cause cell micro-cracks to grow, and may induce fatigue failures of metallization elements [68]. Modules in the mounting structure should therefore be allowed some degree of twisting to withstand wind-induced vibrations.

3.1.5. Soiling

Soiling can arise from dust accumulation, air pollution, microbial algae growth, or bird droppings on the module surface. Uniform dust or biological soiling does not affect the long-term reliability of PV modules as opposed to other failure mechanisms such as corrosion, delamination, and cell cracks, but it can influence the power performance and this needs to be considered when measuring degradation outdoors. The degree of soiling can depend on the module surface properties, the location of the installation, and the mounting configuration of the modules such as tilt angle and height from ground. Dew formation or drying-out cycles can cause cementation of dust particles making them hard to remove by natural cleaning [49]. Dust soiling can be significant especially in desert climates [69]. On the other hand, in tropical climates with high humidity and frequent dew formation, biological soiling can also hinder the light transmission into the solar cell.

Bird dropping can be considered as a form of biological soiling, but its effect is different from dust and biological soiling. Because of their larger size and non-uniform formation on the front surface, they can block the light transmittance locally and thus can significantly affect the module performance and reliability [70]. This way they can act like partial shading of the module and lead to cell mismatch phenomena which would eventually result in hotspot formation unless cleaned. Hotspots are localized areas of elevated temperature, sometimes exceeding several hundreds of degrees. These are potentially one of the most severe types of module degradation because they can be dangerous and cause significant damage the solar cell and module packaging [71]. Hotspots form in areas where large currents pass through a small, resistive area, and can be caused by shading, soiling, and damaged cells or connections (metallization, interconnects) [72–75]. Whilst soiling can cause hotspots, there are a variety of other potential causes, and these are discussed further in section 4.

3.1.6. Chemicals (natural and industrial pollutants)

Some naturally occurring, or industrially produced, chemical species can cause corrosion of PV modules. The most common are salt mist in

offshore areas (especially harmful in tropical climates), ammonia in agricultural rural areas, and sulfuric and nitric acid in industrial areas. These stress factors can degrade various components of the PV modules such as backsheets, adhesive edge sealants, junction boxes, wiring, and connectors. Besides performance degradation, they may cause safety issues due to impaired insulation of the modules.

3.2. Internal stress factors: processing and material incompatibility

In addition to environmental stress factors described before, internal factors like module design, bill of materials and processing related effects can also cause or influence module degradation. The lamination process has a big impact not only on quality, but also on reliability and long-term behaviour of PV modules [49,76,77]. Even though there are no substantial publications quantifying the relationship between quality and reliability of PV modules, qualitative descriptions on the effect of encapsulation quality on module reliability are available.

3.2.1. Processing

Poor processing, either in component or module manufacturing, is often identified as the root cause of PV module failures in the field. Some examples: thermal stressing during stringing and lamination can cause microcracks in solar cells [25,77]. Excessive thermal expansion of ethylene vinyl acetate (EVA) [78] during lamination may dislocate solar cells, increase the cell gaps and induce additional stress into the PV ribbon and the solder bonds [77]. Residual stress can be induced when the laminate is cooled down from the curing temperature of the encapsulant polymer to room temperature, and this can lead to warpage of the laminate [79]. One major reported issue is poor crosslinking of EVA, typically due to too low temperatures or too short crosslinking times [80–83]. Once installed, modules with a poor degree of crosslinking will eventually fully cure under operating conditions [83]. However, the availability of non-consumed peroxides has adverse effects on module reliability. Several studies reported higher susceptibility of modules with poorly crosslinked EVA towards PID and corrosion [61,80, 81,83]. Poorly crosslinked EVA was also found to be more prone to delamination, as it leads to insufficient adhesion strength between EVA and its adjacent module components (glass, cells and backsheets) [84–86].

3.2.2. Module architecture and bill of materials

Also, the module architecture and the bill of materials (BOM) affect degradation pathways and kinetics [49,87,88]. Availability of oxygen and water vapor, which play an important role in many degradation modes, strongly depends on the transport properties of the module packaging materials [89–92]. Physical properties of the packaging materials like water vapor transmission rates, oxygen transmission rates, acetic acid transmission rates, water solubilities, and film thicknesses are the key parameters for phenomena such as moisture ingress, acetic acid evaporation and oxidation [92]. In a breathable module construction with a backsheets film with a high water vapor transmission rate, moisture can move in and out of the module because of concentration gradients depending on the ambient relative humidity level and temperature during diurnal (and seasonal) cycles. Moisture in this case penetrates during the night when the temperature is low (and the relative humidity is high) and is released during the day when the temperature is high (and the relative humidity is low). A backsheets layer with a low (or zero) water vapor transmission rate, in an unbreathable construction as in glass/glass modules, can help prevent moisture ingress to some degree (since moisture can still penetrate from the sides), but it also keeps water vapor and other gaseous degradation by-products trapped inside the module which may cause further problems.

3.2.3. BOM incompatability

Design matching of relevant PV components, especially of the

encapsulant and backsheets with the rest of the module components, is therefore important for the durability and reliability of the module. Degradation modes influenced by the encapsulant and backsheets include discoloration, delamination, PID, snail trails and corrosion of metallization [49]. Also, the thermo-mechanical properties of the encapsulant (like the coefficient of thermal expansion, softening and damping behaviour) play an important role and must be balanced for a proper module design [49,61,93].

The first very prominent case of material incompatibility was yellowing of EVA, observed for PV modules which were installed in California in the early 1980s [93,94]. The discoloration has been found to be due to interactions between cross-linking peroxide and some stabilizing additives. A reformulation of the encapsulant with compatible additives has dramatically reduced this type of discoloration [94].

However, in recent years more cases of material incompatibilities have appeared, mostly due to the introduction of new materials into PV modules. Until 2010 most PV modules combined an EVA encapsulant and a fluoropolymer based backsheets with polyvinyl fluoride as outer layers, where the individual components were modified to enable proper adhesion. New encapsulant – backsheets combinations therefore require special attention. Many backsheets are optimized towards good adhesion to EVA. With new encapsulation films, e.g., based on polyolefins [95], common surface modifications may not have the intended effect. Also, certain combinations like polyethylene based encapsulants and polypropylene based backsheets may have adhesion issues [96,97]. Another example is the use of UV transparent encapsulants, which requires backsheets with UV stabilized inner layers in order to avoid backsheets degradation [98]. In relation to this, the influence of new encapsulant formulations on the corrosion of PV ribbons or the silver grid is poorly investigated so far, as well as the long-term behaviour of new solder materials on ribbons.

A special case with high impact has been the use of co-extruded backsheets based on polyamide. In recent years PV module failures with cracked polyamide backsheets occur more and more. The cracks appeared after several years of field aging but have never been observed after accelerated testing in the laboratory [99–102]. Two main types of polyamide backsheets-cracking were observed: tile-shaped, square cracks (along the intercellular spacings) and longitudinal cracks (beneath the busbars of the cells) [99]. The longitudinal cracks could be explained by deterioration of mechanical properties due to chemical and physical aging effects in combinations with thermo-mechanical stresses as the main driver for crack propagation [99,101]. For the squared cracks, however, a material incompatibility has been identified as the main root cause. The cracks are exclusively forming in conjunction with certain

Table 2

Common degradation and failure modes of PV module components and their effects. The delineation between degradation and failure is not always well defined.

Component	Degradation modes	Failure Modes	Effects
Frame	Corrosion	Warpage	Increased risk of module damage
Glass	Glass corrosion	Breakage, soiling, abrasion	Reduced current, hotspot formation
Encapsulant	Photo-oxidation	Discoloration, delamination	Reduced current, increased corrosion
Internal circuit (interconnects, TCO)	Corrosion	Fatigue, cracks	Reduced current, cell isolation, hotspot formation
Solar cells	PID, LID, LETID	Cracks, cell isolation (cracks)	Reduced power, hotspot formation
Backsheet	Photo-oxidation, hydrolysis	Discoloration, delamination, cracks	Increased corrosion, isolation failure
Junction box	–	Arcs, delamination	Electrical fault, detachment

EVA types which are prone to show degradation accompanied by significant acetic acid formation. A high concentration of acetic acid as well as the presence of a phosphate additive in the EVA correlated to stress cracking [99].

4. Degradation and failure modes

From the existing literature on PV reliability, degradation and failure modes can be identified that generally occur in photovoltaic technologies. In spite of the diversity of solar cell technologies, many of the module materials and components are identical or very similar. These elements include the module packaging, internal electrical circuit, bypass diodes, junction boxes, wiring and connectors, and frames. Table 2 connects the degradation phenomena and failure modes to the module component on one hand, and their effects on the PV system on the other. The upcoming subsections will treat each part of a PV module and its main degradation and failure problems.

4.1. Module packaging

Solar cells form just a small part of a PV module, as illustrated in Fig. 1; most of a module consists of packaging materials, including front and rear covers (glass, frontsheets, backsheets) and encapsulants. These fulfil several functions in a module, most importantly mechanical support, an optical couple, electrical insulation, and environmental protection. The role of packaging in photovoltaic energy generation is generally underestimated, as it does not play an active role in the power generation itself. However, the durability of module packaging is essential for long-term operation, and the choice of materials has a distinct impact on PV module attributes such as:

- Efficiency, as the optical properties of the module package determine the amount of light arriving at the solar cells;
- Quality, as the main early failures are caused by poor design and processing parameters, which are partly determined by the properties of the packaging components and material incompatibilities [25, 49, 61, 78, 83, 103];
- Reliability, as many PV module degradation modes are directly linked to packaging degradation and material interactions with it [49, 61, 104].

Module packaging degradation does not always lead to immediate performance losses, though many are suspected to have an impact on long-term performance, and therefore module lifetime. Besides performance losses, packaging failures may give rise to safety hazards, especially if the electrically insulating layers are compromised [105].

4.1.1. Glass

Low-iron soda-lime float glass is the most common superstrate or substrate material in PV modules because of its high transparency, good mechanical robustness, and low cost. Moreover, it is an excellent electrical insulator and impermeable to moisture and gases. It is most commonly used as a module front cover, and is also found increasingly for use as a back cover, especially in bifacial modules. The standard thickness is 3.2 mm, though other thicknesses may be used in particular applications such as bifacial and building-integrated PV.

4.1.1.1. Breakage. PV glass is commonly tempered or annealed to increase its strength, but nonetheless, the most common failure mode is breakage [25, 49, 106, 107]. It has been found to account for up to a third of module field failures [26], though other reports mention a much lower occurrence [20, 104, 108]. Glass breakage can already happen during transportation or installation. It can also occur during operation because of thermal or mechanical stresses, such as from hotspots and static or dynamic loads. Frameless modules are additionally susceptible

to damage from edge impacts and improper clamping.

For c-Si modules, broken glass does not always have an immediate impact on performance and safety, because the cells, encapsulation and wiring can still be intact. Thin-film modules use a superstrate or substrate configuration with the solar cells deposited onto the glass, so broken glass is a more direct concern. In all cases, broken glass may cause cell or circuit damage that may generate hotspots, and it can also no longer act as an impermeable barrier to moisture or as an electrical insulator. Because of this it may accelerate degradation of the encapsulant and other components [109].

4.1.1.2. Coating erosion. PV glass is sometimes coated with anti-reflection or anti-soiling layers to improve overall module performance. Reflections off the surface of glass result in an optical loss of about 4% of incoming light, while soiling can cause optical losses of over 50% in some locations [108, 110–112]. Anti-reflection and anti-soiling coatings are intended to minimize these losses, but they are subject to erosion over time, and thus lose their efficacy. This will reduce the output of a module, but it does not cause any safety hazards by itself.

4.1.2. Encapsulants

Solar cells are in direct contact with elastomeric materials called encapsulants. The most common encapsulation material today is a copolymer of ethylene and vinyl acetate (EVA). Historically, silicones (e.g. polydimethylsiloxane) and polyvinyl butyral were also used [19, 93, 113]. However, the combination of low cost and decent properties – even if not the best – long made EVA the first choice in the PV market. Limitations of EVA and ever increasing demands on module performance and lifetime have led to the introduction of alternative encapsulation materials, most notably polyolefin elastomers, thermoplastic polyolefins, and ionomers [92, 113].

The main degradation and failure modes of PV encapsulants include discolouration and delamination, such as in Fig. 5. Additionally, encapsulants are often partly responsible for degradation of other module components by facilitating or mediating degradation modes such as corrosion or potential induced degradation (PID) [25, 61, 104, 114, 115].

4.1.2.1. Discoloration and delamination. Discoloration is directly related to the polymer films [18, 80, 93, 116–120], and leads to light absorption in front of the cell, and therefore power losses. In most cases discolouration of the encapsulant is not attributed to photo-oxidation of the polymer chains themselves, but to the degradation of additives in the encapsulant. Discolouration was once a very common degradation mode, but in recent years encapsulants have been formulated with fewer or more stable additives, so its occurrence is much lower. Delamination is another relevant failure mode, and can occur at any interface within the laminate structure. Several factors affect adhesion strength, and physical and chemical aging processes of the encapsulants can promote delamination [86, 121–123]. Though less common than discolouration, this failure mode can accelerate cell and internal circuit degradation by facilitating accumulation of moisture and degradation products.

4.1.2.2. Material interactions. More often, material interactions with the encapsulant are a root cause for PV module degradation. For example, acetic acid, which is a degradation product of EVA not only causes corrosion of the solar cell metallization and interconnects [25, 49, 91, 93, 124–128], but also promotes PID and delamination [51, 81, 129–131]. Furthermore it accelerates the oxidation process of EVA itself. In addition to acetic acid, which increases ion mobility, the PID effect is strongly affected by encapsulant properties like polarity, volume resistivity, and water vapor transmittance rate [51, 61, 114, 132]. The permeation behaviour of encapsulant films also plays a significant role in corrosion processes, which are accelerated by the presence of water [133, 134]. These problems with EVA are major limitations for

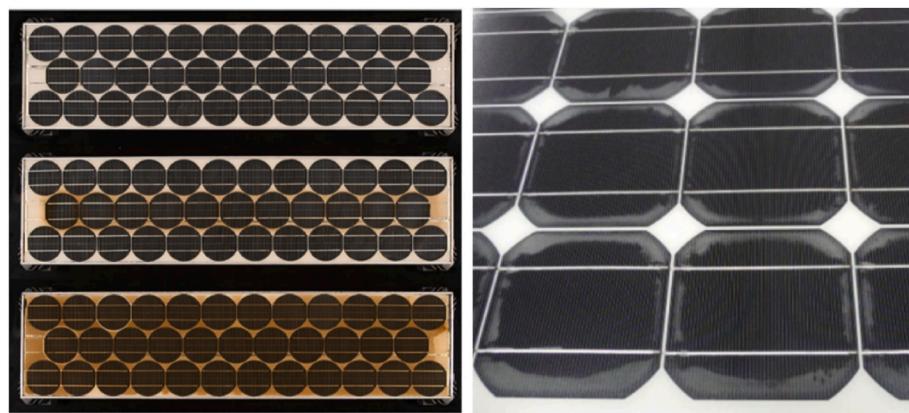


Fig. 5. Examples of encapsulant degradation and failure: discolouration (left; brownish haze) and delamination (right; lighter grey areas at the cell edges). Reproduced with permission from Refs. [18,25].

further improvements in module lifetime, and have motivated the development of alternative encapsulants [92,113,135,136].

4.1.3. Backsheets

The backside of a PV module is most often covered by a polymeric backsheets to provide electrical insulation and environmental protection. Alternatively, another layer of glass can be used to protect the backside, and there is ongoing discourse about the best architecture. Backsheets usually consist of a multilayer structure which is either laminated or coextruded, including an outer layer with good resistance to environmental stresses, an electrically insulating layer, and an inner layer with good adhesive properties. The outer layer (air-side) is commonly a fluoropolymer material, which is resistant to environmental degradation due to the strong carbon-fluorine bonds. Non-fluoropolymer alternatives are also in use, but they require stabilization, especially against UV light. The core layer is most often polyethylene terephthalate (PET) which has a high dielectric breakdown strength and mechanical stability. The inner layer (cell-side) is usually an EVA film, or another polymer with modified properties to improve adhesion. Typical fluoropolymers used in backsheets outer and inner layers include polyvinyl fluoride, polyvinylidene fluoride, and fluoroethylene vinyl ether. Non-fluoropolymer alternatives for outer layers include materials such as PET, polyamide, and polyolefin, but there is a trade-off between the environmental stability and cost [63,137–139].

Degradation mechanisms and hence durability of the backsheets films differ depending on the specific backsheets structure and material formulations [63,137,140–146]. The most common degradation and failure modes observed during outdoor service are discolouration, chalking, delamination, and cracking, illustrated in Fig. 6. Several reports exist on

the frequency of backsheets defects and failures, and while the reported ranges vary widely, they consistently appear as one of the most common PV module degradation modes [20,25,26,49,108,110].

4.1.3.1. Discoloration. Discolouration is mostly caused by photo-oxidative reactions during operation due to the formation of chemical degradation by-products called chromophores which give a yellow appearance [50,88,147–150]. White pigments such as TiO₂ and BaSO₄ are often added to polymer formulations because of their light absorbing properties which can increase the backsheets UV stability. However, degradation of the polymer surface on the air-side can cause these pigments to accumulate, which leads to gloss-loss and a chalky appearance [151–153]. Although both backsheets yellowing and chalking are not directly linked to module performance loss, their occurrence indicates chemical and morphological changes in the polymer structures and are early indicators of more serious forms of degradation such as embrittlement, cracking, and delamination.

4.1.3.2. Cracking. Backsheet cracking is a major problem found with increasing frequency [20,99–101,137,154,155]. Cracking impairs the electrical insulation and causes safety issues such as ground faults, current leakage, and reduced wet insulation resistance. It also opens new conduits for penetration of moisture and other chemicals into the module and thus facilitates degradation of other module components. After weathering, polymers have reduced molecular weight and increased crystallinity, which leads to embrittlement [99,104]. Cracks usually initiate at these weakened polymer chains and propagate in the presence of mechanical stresses. Therefore, in particular backsheets cracks that align with the gap between the cells and with metallization



Fig. 6. Examples of backsheets degradation and failure: discolouration (left), cracking (center), and delamination (right). Reproduced with permission from Refs. [25,99].

are critical. Cracking can be observed both on the cell-side and air-side, and crack patterns can vary depending on the material processing and exposure conditions [156].

4.1.3.3. Delamination. Delamination can occur at the backsheet/encapsulant interface as well as between the layers of backsheet itself due to poor adhesion and lamination processes, or weather-induced degradation [86,109,157–162]. Delamination can be a cause for immediate concern for both performance and safety if it occurs at the module edge or near the junction box because it can result in current leakage or cause the box to detach. If delamination occurs at the module's center, it can elevate the thermal resistance and lead to a higher operating temperature for the cells in that area and act as a point for water condensation [163–165].

4.1.4. Frontsheets

As a frontside cover, polymeric sheets are sometimes used to replace glass, though they are less common than backsheets. Nonetheless, they are increasingly being used, especially in applications requiring lightweight and flexible module structures [166–168]. The materials for frontsheets are similar to those for backsheets, but they are not pigmented with mineral fillers for broadband light absorption because they must have high transparency. Instead, they are stabilized with chemical additives, including UV absorbers. The degradation modes described for backsheets are generally similar for frontsheets, however, in contrast with backsheets, discolouration and delamination will lead to immediate optical losses because of reduced light transmittance.

4.1.5. Edge seals

Both encapsulants and backsheets have some degree of permeability to moisture, so a PV module will become saturated with water after several months or years in the field [89,169]. Technologies which are especially sensitive to water (e.g. thin-film solar cells) sometimes have glass sheets both at the front and the back to ensure a long module lifetime. The weakest link for moisture ingress then becomes the edge sealant. Most edge sealants are based on desiccant-filled polyisobutylene [170–173].

In spite of their advantages, there are challenges in manufacturing modules with edge seals which has limited their adoption, and as such there is a lack of reports on their long-term performance. Edge sealing requires an additional process step prior to lamination. Moreover, edge seals are sensitive to glass edge pinching and they may prevent excess encapsulant from escaping a module during processing, leading to quality issues. Polyisobutylene edge seals are pigmented black for UV protection, and the material by itself is resistant to environmental degradation [170,172,173]. However, delamination can cause failure of the edge seal, especially in the presence of an external stress such as edge pinch.

4.2. Module internal circuitry

Solar cell metallization and interconnect wiring constitute the internal electrical circuit of a module laminate. Many failures or weaknesses in the circuit can occur because of design or processing factors, such as improper sizing or poor soldering quality [174–176]. Excluding such issues, the degradation of metallization and wiring is usually gradual and thus tends to have a delayed effect on performance. If the resistance of these components becomes too high, for example due to corrosion, hotspots and arcs may form which could pose safety concerns [25,26,49,109].

For crystalline silicon modules the front contact metallization layers (fingers and busbars) are usually made of a screen printed Ag-glass frit. Some emerging and high efficiency cell concepts utilize plating and additional metal layers for seeding, passivation, or improved contact resistance [177,178]. Rear contact metallization varies by cell

architecture, with Al, Ag, Ni, and Cu in use. For CIGS and CdTe front contact metallization is not common in commercial modules, and instead a transparent conducting oxide (TCO) serves as front contact. Some have suggested a TCO plus metal grid structures to improve module efficiencies, in which case Ni/Al, Al, and Cu are used [179,180]. For the back contact in CIGS solar cells, Mo is the industry standard, whereas for CdTe cells, ZnTe and Cu/Au, and Cu/C are common [181–183].

The purpose of solar cell and string interconnects is to connect cells or strings of cells in series. For crystalline silicon modules these are usually made from solder-coated copper ribbons, which are soldered onto the silver busbars. Pb-Sb and Pb-Sn-Ag solders are the most commonly used, though there is a push towards lead-free solders [184–186]. In thin-film module architectures a laser-based monolithic interconnection is standard, in which the various layers are patterned by laser ablation and the TCO acts as the interconnect [187,188]. Less commonly, ribbons or deposited metals are used as the interconnect material for thin-film solar cells, in a so-called grid assisted interconnection.

4.2.1. Corrosion, cracking, and contact failure

For all technologies, the metallization is susceptible to corrosion, cracking, and contact failure, shown in Fig. 7, and degradation of metallization appears as one of the most common field module failure modes [20,25,26,49,108,189–192]. The presence of moisture accelerates corrosion, and when an EVA encapsulant is used acetic acid is produced as it degrades, which poses an additional risk [91,93,125,126,128]. For soldered and glued interconnects the joint is a weak point, because solders coarsen and phase separate over time, while adhesives become brittle [193,194]. This, in combination with corrosion and thermal cycling can cause fatigue failure [109,128,184,186,190,195–197]. The impact of internal circuitry failure is severe because it reduces module performance and has a high risk of causing safety issues.

4.3. Solar cells

While the physics of failure for each PV absorber material (e.g. silicon, CIGS, CdTe, CdS) is unique, there are some general degradation modes which can affect all of them, including cell cracking, hotspots, light induced degradation (LID), and potential induced degradation (PID). Cell defects and degradation are among the most commonly reported module defects in the field, but are not always readily detected by simple inspection.

4.3.1. Cell cracking

Many semiconductors are brittle, so cell cracking is a concern for PV modules [198,199]. Cell cracks can be initiated during manufacturing due to residual stresses from thermal processing, soldering, and lamination [200–203]. They can also arise during transportation and installation, and from static or cyclic mechanical loads during operation [106,107,204]. Depending on the number and size of cracks, module power may be only slightly affected, or hotspots and dead areas may form. However, once present their severity is likely to increase over time due to mechanical or thermomechanical stresses, which would open and propagate cracks [201,205–208]. Thin-film solar cells are less susceptible to cracking, because strain levels are comparatively lower than for silicon solar cells. Nonetheless, damage to the glass superstrate or substrate may cause cell cracks.

4.3.2. Hotspots

As discussed, hotspots are cell areas of elevated temperatures, which can potentially cause severe module degradation and accelerate the formation and propagation of other failure mechanisms [71]. Hotspots form in areas where large currents pass through resistive areas, and can be caused by shading, soiling, and damaged cells or connections (metallization, interconnects) [71,209,210].

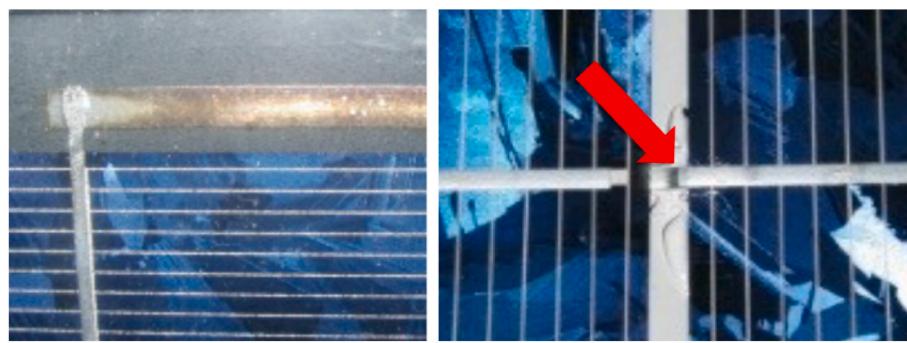


Fig. 7. Examples of degradation and failure of the internal electrical circuit, including corrosion (left: discoloration visible on the string interconnect ribbon) and fatigue cracking (right: broken interconnect ribbon between cells). Reproduced with permission from Ref. [49].

4.3.3. Light induced degradation (LID)

Light induced degradation (LID) is a power degradation effect which occurs during the initial stabilization of a PV module when exposed to light. It affects practically all module technologies, though the effect is typically small, resulting in a loss of up to 5% of module power. Because of its ubiquity and predictability the name-plate power ratings of modules already take these losses into account [25]. The mechanism of LID involves metastabilities in the semiconductor layers present from high temperature processing or diffusion between layers [211,212].

4.3.4. Potential induced degradation (PID)

In recent years potential induced degradation (PID) has been identified as a major concern in field modules [25,49,108,115]. This occurs when there is a high electrical potential between the module frame and solar cells, which generates leakage currents through the module packaging and drives cations (notably sodium) from the glass into the solar cell, TCO, or anti-reflective coatings [51,81,115,129–132]. PID leads to enhanced recombination and shunt formation, and in thin-film modules it can also lead to TCO corrosion and p-n junction damage. The PID effect can lead to significant power losses, and is more severe on the negative pole of a string. PID can be mitigated by use of modified anti-reflective coatings, high volume resistivity encapsulants, Na-free glass or Na diffusion barriers, or alternative inverter configurations [51,114,115,132,213–215].

4.4. Other components

4.4.1. Bypass diodes

Bypass diodes are protective components intended to minimize module losses during reverse bias operation by providing a path for the current of good cells to bypass bad cells. When there is a large mismatch in short-circuit current between several cells, the cell or cells with lowest current may become reverse biased and then overheat. This can occur temporarily during shading or permanently when a cell or the internal electric circuit is compromised.

Bypass diodes are usually integrated into the junction box, and are a somewhat common source of issues in underperforming or failed modules [25,108,110,216–220]. Catastrophic failure modes of bypass diodes include arcing, electrostatic discharge, and thermal runaway, and can lead to severe performance losses as well as safety problems [25,108, 221–226]. Electrostatic discharge occurs when a large current passes through the diode over a short period of time, which can occur due to a lightning strike or during manufacturing if there are inadequate electrostatic discharge protections in place. Thermal runaway happens when there is insufficient heat dissipation, which results in more current passing through the diode, and consequently higher temperatures. This runaway process continues until the temperature is high enough to destroy the diode. Aside from these catastrophic failures, gradual degradation of bypass diodes can occur due to continuous high temperature operation or thermal cycling. In both cases excessive

temperatures and temperature excursions degrade the semiconductor junction and contacts, ultimately resulting in their failure [223].

4.4.2. Junction box

The junction box is typically located on the backside of a PV module, and less commonly on the edge. It protects the connections of the strings, external wiring, and often the bypass diodes. The box is typically made from polycarbonate, and adhered to the backside of the module. In documented module field failures the junction box is a fairly common problem [25,26,49,108,110,227–229]. The main failure modes for junction boxes include detachment (from the module backsheets), poorly sealed or closed boxes, corrosion, and arcing due to bad or degraded wiring. Degradation and failure of junction box components can lead to major performance losses and safety hazards because of the high current levels passing through [25,26,108].

4.4.3. Frame

The majority of commercial modules are framed to protect the edges of the glass and provide module mounting points. Anodised aluminum is the most common frame material, because of its high strength, low weight, and low cost. Frames can become loosened, deformed, or corroded over time [25,192]. These can be caused or accelerated either by poor manufacturing quality or mechanical loading. Degradation of the frame is less common than most of the other failure modes described in this section [108,110]. Nonetheless, because it serves as a mounting point for modules, its weakness or failure can increase the likelihood of cell damage or module failure, especially in conditions of strong mechanical loading (e.g. wind or hurricane) [230].

4.5. Overview of complexity

The interplay of stressors on component and resultant failure mechanisms and their effects on module functioning is complex. The same stressor can act upon multiple components, leading to multiple failure modes. Also, some failure modes also result in new stressors (e.g. a failure that allows water to ingress will result in a new stressor of corrosion). Fig. 8 serves as an aid so as to obtain a clear view of this complex interplay.

5. Summary of reliability challenges and future perspective

As shown in section 3, PV modules are exposed to various external (environmental conditions) and internal stress factors (processing, module architecture, bill of materials) that influence their performance and long-term reliability. In the rarest cases PV module failures are related to just one single stress but usually an effect occurs due to multiple combined stresses [25,231]. This complex stress situation however is usually not reflected in accelerated indoor aging testing, where samples are exposed to single stresses. Especially failure modes that include thermo-mechanical stresses or electrical potentials were not

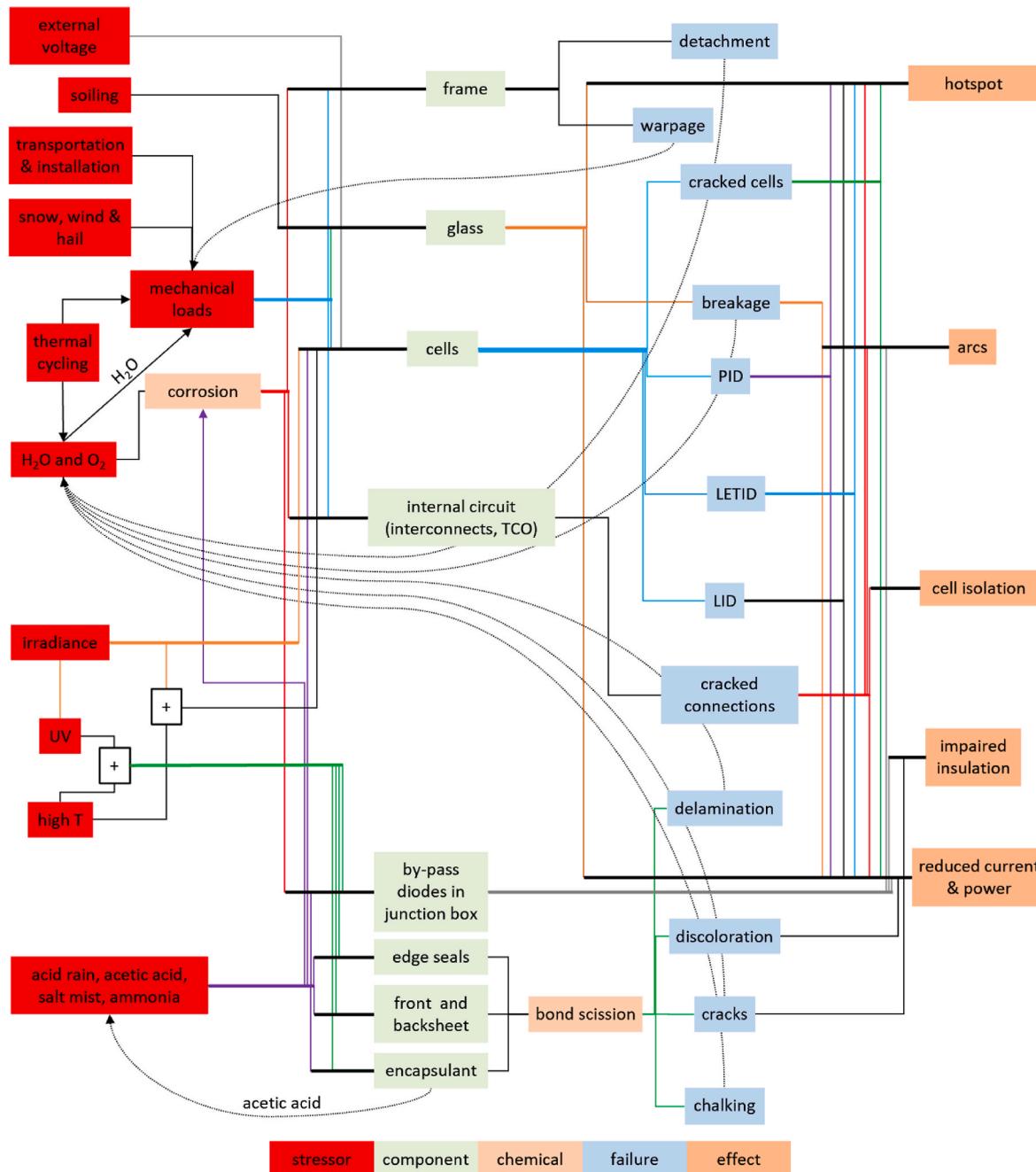


Fig. 8. Flow diagram representing the relationships between stressor, component, failure and effect. Lines are coloured to discern line crossings. Thick black lines to the left of the “component” and “effect” are there to indicate the termination of the connector from the previous point in the flow diagram. Thick coloured lines to the right indicate branching. Dotted lines indicate when failure results in a new stressor.

induced by traditionally used single stress tests. In the past this has led to unexpected degradation mechanisms several years after field deployment of PV modules, which were not previously foreseen in laboratory accelerated testing, such as PID [51] LeTID [53,232] and backsheet cracking [99,100,233]. In all cases, after a first description of the failure modes an analysis was executed, trying to identify the main stress factors, as well as the chemical and physical degradation mechanisms leading to the failure modes. Consequently, new accelerated test setups have been developed in order to trigger these specific failure modes, such as, for instance, PID tests on cell and modules level or the solder bump test developed for backsheet cracking [234].

A more recent approach is the development and implementation of so-called agnostic stress tests that try to replicate the complex stress

situation as well as possible. These tests either rely on the sequential or combined exposure to multiple stresses [56,57,235,236]. In both cases failure modes like backsheet cracking [237] have successfully been triggered. To summarize this review, Fig. 8 shows potential relationships between stressors, components, failures and effects on the basis of our findings. The body of experimental data and field studies shows that there are a number of stressors that impact upon multiple parts of a PV module. A key effort to support future reliability work would be to understand which degradation mechanisms have the greatest impact in the field. Challenges exist with this as the dominant failure mechanism is likely to be influenced by the specific situation on location, manufacturing control, module type, vintage and bill of materials. Such studies will be a complex piece of work however utterly useful for the PV

research community and essential for the development of reliable PV modules for various markets.

So, what is the main lesson for deployment of future PV technologies, and where are the research gaps? The current PV market shows an extremely high-cost pressure, which is also the driving factor for the development and implementation of new module designs and the use of new materials and components. New technologies, which promise either higher efficiency for the same cost or cost reduction at same efficiency, are very often quickly introduced to the market [30,238]. Moreover, the process of material innovation for PV is further complicated by the complex interactions within a PV module. The advantage of one material may be outweighed by its interaction with another component. For example, EVA is inexpensive and highly effective for encapsulation, however it degrades to form acetic acid which can cause corrosion of the metallization if it is not allowed to escape the module package due to use of an impermeable backsheet. New materials must work within the whole module package and in concert with the other materials present [238]. With current production capacities, many Gigawatts of modules with new technologies and materials can be produced and installed without having sufficient experience about long term reliability. This presents a technology risk for the industry.

However, proper material selection and comprehensive knowledge of material properties combined with suitable qualification and reliability testing exceeding current test protocols or IEC standards can help to minimize these risks. It is clear that future research is needed on new materials and module design changes as they are introduced. The bottom line is that each module design or material combination has to be tested and qualified individually. Moreover, agnostic combined stress tests need to be used, so that also unknown, new failure modes related specific designs or BOMS may be triggered during the development phase. Standardization of such agnostic stress tests will be instrumental in the further development of long-lifetime modules and the necessary market acceptance and appreciation of long-lifetime claims.

A future research gap is to consider the impact of performance, cost and reliability on the PV module sustainability. Greater research in this direction is needed as sustainability has long been an afterthought in PV research driven by cost reduction. As we have surpassed the point of grid parity and the module price is only a smaller fraction of the overall system cost, price differentiation becomes an option for longer-lifetime modules. It is worth stressing that through increased reliability and higher lifetime of PV modules, a significant impact on sustainability and economics is achieved. A recent study showed that module stability becomes more important for economic evaluation and that inferior stability cannot be compensated by lower module prizes but only by much higher efficiency [239]. Longer lifetimes would also reduce the environmental impact of photovoltaics, as they reduce the number of modules that need to be produced for replacement and consequently also PV waste. To give a rough estimation, improving the service life of a PV module from 25 to 40 years saves about 130 GW/year of new modules, that do not need to be produced and 7 million tons/year of PV panel waste, that does not require recycling. In addition, 'Design for Recycling, Repair or Reuse' might become a greater research area and design challenge. However, as designs and materials are changed, a strong understanding of module reliability will still be needed and many of the testing/failure modes.

6. Conclusions

This review article has presented an overview of the state-of-the-art knowledge on the reliability of PV modules and their degradation mechanisms. The most common technology today is mono- and multi-crystalline silicon, but this article aims to give a generic summary which is relevant for a wider range of photovoltaic technologies including thin-film devices. Initially definitions for reliability and quality and testing standards were reviewed. Subsequently the primary stress factors that affect module degradation were summarised; this

includes irradiance, temperature, moisture, mechanical stress, soiling and chemicals. Finally, common degradation and failure modes were identified that occur generically in photovoltaic technologies were reviewed. Many PV technologies consist of similar architectures in terms of the module materials and components. These elements include the module packaging, internal electrical circuit, bypass diodes, junction boxes, wiring and connectors, and frames. The dominant degradation phenomena and failure modes in all module components were summarised. Quality and reliability testing has come to a stage where the durability of each component under a single stress can be predicted well, but accurate reliability estimations for a combination of materials under a combination of time-varying stresses remain challenging. Building on this knowledge, strategies to improve the operational lifetime of PV systems and thus, to reduce the electricity cost and improve the sustainability can be devised and lifetimes of PV modules can be extended.

Declaration of competing interest

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

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