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Moisture ingress in photovoltaic modules: A review

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ABSTRACT

Moisture ingress in photovoltaic (PV) modules is the core of most degradation mechanisms that lead to PV module power degradation. Moisture in EVA encapsulant can lead to metal grids corrosion, delamination and discolouration of encapsulants, potential induced degradation, optical and adhesion losses. The present work is a review of literature on the causes, effects, detection, and mitigation techniques of moisture ingress in PV modules. Literature highlights on determining the diffusivity, solubility, and permeability of polymeric components of PV modules via water vapour transmission rate tests, gravimetric, and immersion methods, have been presented. Electroluminescence, photoluminescence, and ultraviolet fluorescence spectroscopy, as well as dark lock-in thermography are some techniques used to detect moisture ingress in modules. Encapsulants with excellent moisture barrier and adhesion characteristics, desiccant-stacked polyisobutylene sealants, imbedded moisture sensors, and PV designs with/without breathable backsheets are ways of preventing/detecting moisture ingression in PV modules. Areas of focus for future research activities have also been discussed.

1. Introduction

Durability and reliability of field installed photovoltaic (PV) modules over their useful lifetime of ca. 25 years (35 years proposed) with optimal energy output of not less than 80% of their rated capacity is one of the foremost concerns for all parties in the photovoltaic business (Köntges et al., 2014; Wohlgemuth et al., 2015). The long-term reliability of PV modules can be studied more accurately from the degradation mechanisms and the fault modes associated with PV modules in natural field operating conditions (Halwachs et al., 2019; Santhakumari and Sagar, 2019). This is because performance degradation of modules during real operating conditions are directly related to the environmental and climatic factors of the geographical area within which modules are deployed (Lyu et al., 2020). These degradation and reliability issues are in the form of solar cell metal grids corrosion (Asadpour et al., 2019; Peike et al., 2012), glass/antireflection coating

Abbreviations: A, preexponential factor; AES, Auger Electron Spectroscopy; AFM, atomic force microscopy; AR, antireflection coating; C Sensor, capacitance embedded sensor; C, carbon; Ca, calcium; CIGS, copper indium gallium selenide; c-Si, crystalline silicon; D, diffusivity; D_0, diffusion coefficient at infinity time; DH, damp heat; DLIT, dark lock-in thermography; DMA, dynamic mechanical analysis; DSC, differential scanning calorimetry; DVS, dynamic vapor sorption; E, Young's modulus; E_a, activation energy; E_D, activation energy for diffusivity; EDS, energy dispersive spectroscopy; EDX, energy-dispersive X-ray spectroscopy; EL, electroluminescence spectroscopy; E_p, activation energy for permeability; E_s, activation energy for solubility; ETFE, Ethylene tetrafluoroethylene; EVA, ethylene vinyl acetate; F, diffusion flux; FEM, finite element methods; FTIR, Fourier transform infrared spectroscopy; FTIR, fourier transform infrared spectroscopy; GC/MS, thermal desorption gas chromatography/mass spectrometry; GWFID, gas chromatography/flame ionization detection; HF, humidity freeze; IEC, International Electrotechnical Commission; I_{sc}, short circuit current; I-V, current-voltage; k, Boltzmann constant; *l*, layer thickness; LIT, lock-in thermography; mc, multicrystalline; MI, moisture ingress; N, nitrogen; n, number of samples; NIR, near infrared; NREL, National Renewable Energy Laboratory; O, oxygen; OTR, oxygen transmission rate; P, permeability; P_0, permeability constant; PA, polyamide; PCTFE, polychlorotrifluoroethylene; PDMS, polydimethylsiloxane; PET, polyethylene terephthalate; PIB, polyisobutylene; PID, potential induced degradation; PL, photoluminescence spectroscopy; POE, polyolefin elastomer; PPE, PVDF/PET/EVA; PV, photovoltaics; PVB, polyvinyl butyral; PVDF, polyvinylidene fluoride; PVF, polyvinyl fluoride; R, gas constant; RFID, radio-frequency identification; RH, relative humidity; S, solubility; S_0, solubility constant; SC, solar cell; SEM, scanning electron microscopy; SEM-EDS/EDX, scanning electron microscopy-energy dispersive (X-ray) spectroscopy; SOCT, spectroscopic optical coherence tomography; T, temperature; TC, temperature cycling; T_g, glass transition temperature; TGA, thermo-gravimetric analysis; TM, melting temperature; TPO, thermoplastic polyolefin elastomer; TPSE, thermoplastic silicone elastomer; TPT, Tedlar®/PET/Tedlar®; T_{TTF}, test-to-failure; UV, ultraviolet; UV-F, ultraviolet fluorescence spectroscopy; VA, vinyl acetate; V_{oc}, open circuit voltage; W_p, peak watt; WVTR, water vapour transmission rate; XPS, X-ray photoelectron spectroscopy.

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(AR) degradation (Kudriavtsev et al., 2019), delamination (Kempe et al., 2014) and discolouration (La Mantia et al., 2016; Oreski and Wallner, 2005; Tracy et al., 2018) of encapsulants, solar cell degradation (Adams et al., 2015; Peike et al., 2012), potential induced degradation (PID) (Hacke et al., 2016; Mon et al., 1985; Virtuani et al., 2019a), interface adhesion losses (Bosco et al., 2019; Tracy et al., 2018), optical losses (McIntosh et al., 2011), and solder bond degradation (Asadpour et al., 2019; Kim et al., 2013). An overview of these failure mechanisms is shown in Fig. 1.

One of the major factors than links climatic conditions to module degradation is moisture ingress (Hülsmann and Weiss, 2015; Jankovec et al., 2016; KEMPE, 2006; Mon et al., 1985). This is true for environments with high humidity and temperature (Hülsmann et al., 2014; Schlothauer et al., 2012). According to Mon et al. (1985), moisture ingress together with ambient temperature play a vital role in determining the rate of many life-limiting processes such as corrosion and majority of materials deterioration in solar cells and modules. In addition to environmental and climatic factors, the properties of the polymeric materials and the module technology influence moisture ingress (KEMPE, 2006).

Usually, moisture ingress takes place through the polymeric materials, edges of the modules, and voids created by manufacturing, handling, and climatic stressors (Bosco et al., 2019; Crank, 1953; Han, 2020; Jankovec et al., 2018; Marais et al., 2001; Novoa et al., 2014). Once water comes into the PV module, the accumulated moisture within the module in the presence of other climatic stressors can lead to all forms of degradation modes in PV module's components and other packaging materials (Ballif et al., 2014; Kudriavtsev et al., 2019; Wohlgemuth and Kempe, 2013). The most common of these defects and failure modes are shown in Fig. 1. Fig. 2 shows an example of a PV module affected by moisture ingress.

The Fickian laws of diffusion are good model that forecasts moisture diffusion into encapsulation materials, and based on the water vapour transmission rate (WVTR) parameters determined experimentally, the moisture or gaseous barrier quality of a polymeric material could be predicted (Dadaniya and Datla, 2019; Oreski et al., 2017). Polymeric material here does not refer to organic or polymer-based PV devices. WVTR is the amount of water molecules that penetrates a given strip of encapsulant in a given time frame. This concept will be explained further in Section 4.1.

When it comes to testing moisture ingress reliability of PV modules, the common tests are damp heat test (DH), humidity freeze test (HF), and thermal cycling test (TC). These tests at times have negative impact on the test modules (Bosco et al., 2019; Eder et al., 2019; Lyu et al., 2020). Damp heat and humidity freeze tests sometimes predispose the polymeric components of the module to moisture ingress at elevated temperatures, reduces the optical properties of the module, and leads to the formation of acetic acid within the ethylene–vinyl acetate (EVA) encapsulant. Acetic acid accumulation in PV modules is a major precursor for interconnect corrosion in solar cells and modules (Eder et al., 2019; Kempe et al., 2007; Kim et al., 2013; Oreski et al., 2019). TC can induce thermomechanical stresses that can promote loss of adhesion at the encapsulant/PV-cell interfaces, cracks in solar cells, and other material induced degradations which also influence moisture ingress (Annigoni et al., 2015; Bosco et al., 2019; Tracy et al., 2018).

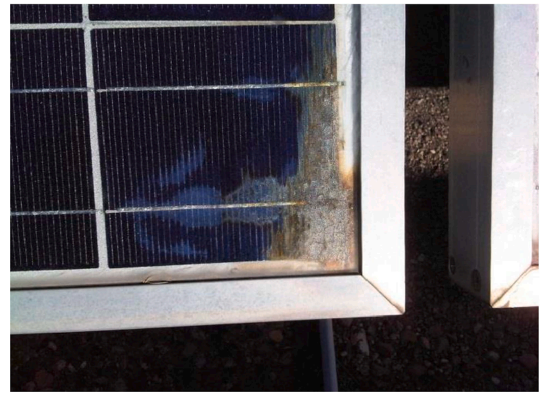


Fig. 2. A typical moisture ingressed PV module showing signs of corroded metal grids, delamination and discolouration of encapsulants. .
Adapted from Wohlgemuth et al. (2015)

To this effect, several research groups across the globe in the field of photovoltaics are focused on PV reliability and durability studies (Halwachs et al., 2019; Köntges et al., 2014). Most of these investigations are focused on the performance monitoring, operation, and maintenance of PV plants (Annigoni et al., 2015; Eder et al., 2019). Even though there is yet to be any formal working documents on moisture ingress reliability of PV modules (Lyu et al., 2020), there have been a lot of work that have been done in this respect over the past decades (Dadaniya and Datla, 2019; KEMPE, 2006; Kumar et al., 2019; Mitterhofer et al., 2020; Annigoni et al., 2015; Jankovec et al., 2018). A collection of these works is represented in Fig. 3.

In 1953, Crank (1953) published an article on the diffusion in

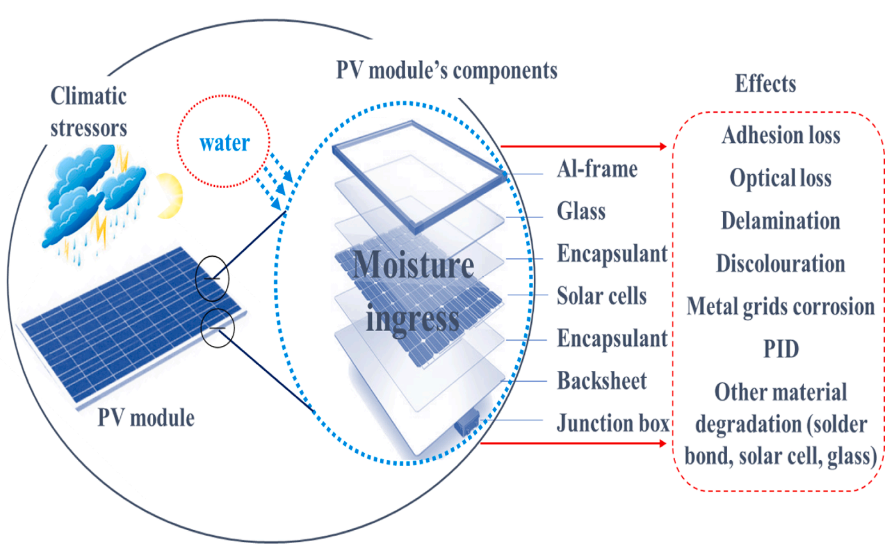


Fig. 1. Defects and failure modes associated with moisture ingress in PV devices. Under environmental and/or climatic stressors (e.g., high humidity, temperature, and UV radiation), PV modules can suffer from moisture ingress which can lead to PV module degradation.

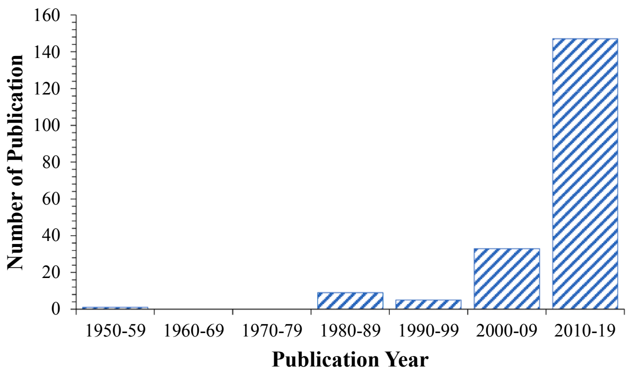


Fig. 3. Histogram of 195 published articles related to moisture ingress in PV devices. Data grouped into clusters based on the years of publication. The figure shows an exponential rise in the number of published articles related to moisture ingress in PV modules from the 1950s to 2019.

polymers due to their structure and stresses they are exposed to. Though it was not directly related to PV applications, it served as a foundation for investigating this phenomenon in PV devices as they are also made with polymeric materials. Since then, it took three decades for Mon et al. (1985) to publish an article on the "effect of temperature and moisture on module leakage currents" which marked the beginning of well-tailored research into the effect of moisture ingress in PV modules. However, for the past three decades more research attention is attached to this phenomenon, as illustrated in Fig. 3. The articles used for this review are obtain via the Scopus Document Download Manager using the word string: (*"moisture ingress" OR moisture AND photovoltaic OR solar AND module OR panel*) together with Google Scholar searches by using the phrase "*moisture ingress in photovoltaic modules*". The search flowchart is illustrated in Fig. 4. Articles published after 2019 are excluded from Fig. 3 to minimize challenge of benchmarking associated with new article publication process (Haustein et al., 2015). The results were further refined using research subject area, themes, and keywords, and a combination of analytical techniques to arrive at the most relevant articles for the purpose of this review. This was done with reference to the guideline proposed by Moher et al. (2009).

In literature, there are reviews on the general degradation mechanisms of PV devices (Halwachs et al., 2019; Jordan and Kurtz, 2013; Köntges et al., 2014; Santhakumari and Sagar, 2019), PV polymeric materials (de Oliveira et al., 2018; Omazic et al., 2019), and moisture ingress into polymeric films and coatings (Han and Kim, 2017; Van der Wel and Adan, 1999). However, to the best of our knowledge, there is yet to be a dedicated review article on moisture ingress in PV modules to guide further research work in this area.

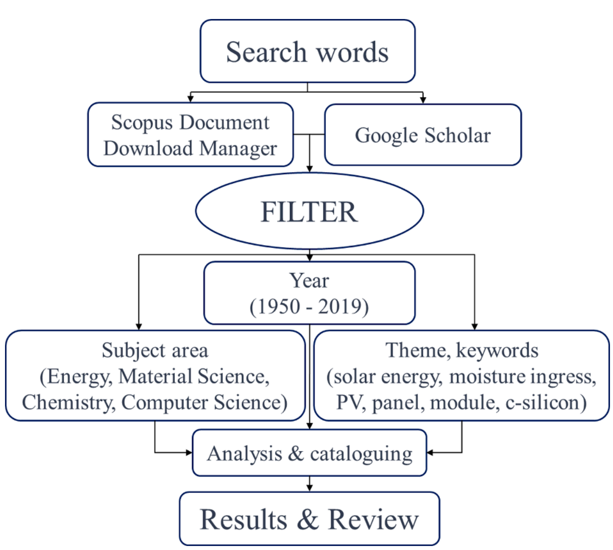


Fig. 4. Search flowchart for collecting relevant articles for this review.

The aim of this work is to reconcile the literature on moisture ingress regarding crystalline silicon (c-Si) PV modules. The effects, mechanism, and the predisposing factors of moisture ingress are presented and discussed, in that order. Test methods for assessing the moisture barrier propensity of PV encapsulants and diagnosing moisture ingressed PV modules are also examined. Finally, the mitigation techniques for moisture ingress in PV modules are discussed. It is anticipated that the present work thoroughly organizes the existing knowledge across the reported literature cogently and in an accessible way to serve as a guide for future work on moisture ingress in PV modules.

2. Components of crystalline silicon photovoltaic modules

Crystalline silicon (c-Si) PV modules usually consist of a superstrate solar glass covering, a polymeric encapsulating layer, silicon solar cells, a substrate polymeric backsheet material, aluminum frame, junction boxes, and other materials such as solder bonds, edge sealants and dielectric coating (de Oliveira et al., 2018; Omazic et al., 2019), see Fig. 1. These components, especially the polymeric elements of PV modules play vital roles in the durability and reliability of these devices (Peike et al., 2013b). Polymeric materials among other functions ensure optical coupling, electrical and physical insulation, give mechanical support and cohesion, serve as ancillary electrical connectors, and offer protection against climatic and environmental weathering (Peike et al., 2013b; Yang et al., 2020; Yang, 2019).

In order to perform these functions optimally, encapsulants are required to have high transparency, high resistance to UV degradation, and high adhesion characteristics (Cheacharoen et al., 2018; Lyu et al., 2020; Pern, 2008). In addition, encapsulants are expected to be cost-effective and environmentally benign (Lyu et al., 2020; Pern, 2008). For that matter, there are several material indicators that are evaluated when considering encapsulating materials for PV modules' applications (Peike et al., 2013b; Yang, 2019), some are listed in Table 1. Some of the methods that can be used to determine or characterize each encapsulant parameter (including differential scanning calorimetry- DSC, dynamic mechanical analysis- DMA, and dynamic multimode spectroscopy- DMS) are also highlighted in Table 1.

In addition to the optical transparency and glass transition temperature of the polymeric encapsulant under consideration, the electrical and mechanical properties are equally vital to ensure electrical insulation and resilience to mechanical and climatic stressors (Yang, 2019). Usually, a common limiting factor for modules' reliability and durability is the diffusion properties of PV encapsulation materials (Kempe et al., 2014; Lyu et al., 2020; Pern, 2008; Yang et al., 2020).

Encapsulation polymeric materials can either be thermoplastic or elastomeric in nature. The thermoplastics do not form cross-linked chemical bonds upon melting during processing, while the elastomers

Table 1
Some properties of PV module encapsulation materials and their means of evaluation.

Parameter	Technique	Importance
Diffusivity (WVTR/OTR) (D)	Permeation, gravimetry	Moisture or gaseous barrier quality
Refractive index (η)	Refractometry	Optimizes optical efficiency
Volume resistivity (ρ_v)	Resistivity test	Electrical insulation
Glass transition temperature (T_g)	DSC, DMA, etc.	Reliability over the temperature range of application
Young's modulus (E)	DMA, tensile testing, etc.	Minimize mechanical stress on cells
Melting temperature (T_M)	DSC, DMS, etc.	Processing feasibility
Absorptivity (α)	FTIR spectroscopy	Optimizes optical efficiency

form cross-linked covalent bonds under high temperature, UV, or chemical processing conditions (Peike et al., 2013b). The cross-linking process improves on the mechanical, chemical, and electrical properties of these materials (Berghold et al., 2014).

Some of the popular encapsulation materials that are used for PV applications are listed in Table 2. Among these encapsulation materials are ethylene vinyl acetate (EVA), ionomer, polyvinyl butyral (PVB), silicone rubber (e.g. polydimethylsiloxane, PDMS), thermoplastic silicone elastomer (TPSE), polyolefin elastomer (POE), thermoplastic polyolefin elastomer (TPO), polyethylene terephthalate (PET), polyamide (PA), polyvinyl fluoride (PVF) or Tedlar®, polyvinylidene fluoride (PVDF) or Kynar®, ethylene tetrafluoroethylene (ETFE) or Halar®, and polychlorotrifluoroethylene (PCTFE) or Xylan® (Peike et al., 2013b; Yang, 2019).

The first encapsulation material used in the early days of PV industry was polydimethylsiloxane (PDMS) (Yang, 2019). However, the search for cost-effective encapsulants with optimal properties to meet the new dynamics of the PV applications has opened up the market for other encapsulants such as EVA, a dominant material in the PV market for decades (Peike et al., 2013b; Yang et al., 2020). This is because the choice of encapsulants are mostly based on trade-offs between material properties and cost (Yang, 2019). EVA encapsulants are cost-effective, and in addition, have high optical efficiency, good adhesion properties, high glass transition temperature, and optimal resistance to other climatic stressors (Novoa et al., 2016; Pern, 2008).

Backsheets are typically comprised of three main layers: a weathering resistant outer layer, an electrically insulating inner core layer, and an adhesion promoting cell side layer and can be used together with any suitable front encapsulation (Lyu et al., 2020), see Table 3. Fluoropolymer based backsheets are more common and takes up to 80% of the market base (Oreski, 2019). However, the non-fluoro-polymer based ones are slowly making their way into the market space. PET based backsheets have been mostly used for commercial PV module production over the years. These multilayered backsheets are thought to be cost-effective and have superior inter-layer adhesion properties, which are most suitable for outdoor PV applications (Oreski et al., 2019).

However, some commercial PA-based backsheets are susceptible to unexpected degradation (e.g. cracking) after a few years of outdoor exposure (Eder et al., 2019). These physico-chemical degradation processes largely depend on temperature, moisture (humidity), and UV irradiation (Han, 2020). This is because during field operation, PV modules under these climatic and environmental stressors are exposed to moisture and vaporous ingress, a precursor for most degradation mechanisms (KEMPE, 2006; Annigoni et al., 2015; Jankovec et al., 2018).

Table 2
. Properties of some PV module front encapsulation materials (Berghold et al., 2014; Peike et al., 2013b).

Polymer	Polymer class	Parameter			
		D [g/ m^2/d]	η	T_g [°C]	ρ_v @ 23 °C [Ωcm]
EVA	Elastomer	8.38	1.48 to	−40 to	10^{14} to
Silicone		9 to 68	1.49	−34	10^{15}
rubber (eg.			1.38 to	−120 to	10^{14} to
PDMS)			1.58	−50	10^{15}
PVB	Thermoplastic	19.26	1.48	+12 to	10^{10} to
Ionomer		0.31	1.49	+ 20	10^{12}
				+40 to	10^{16}
				+ 50	
TPSE	Thermoplastic	38.50	1.42	−100 to	10^{16} to
TPO	elastomer	0.89	1.48	−5	10^{17}
				−60 to	10^{14} to
				−40	10^{18}

Table 3
Some commercially available backsheet designs. PVF is Tedlar®, PVDF is Kynar®, coating (C) is fluoro-polymer coating (e.g., Kynar, Xylan coatings). New backsheet designs substitute cell side EVA layer with olefins such as POE and TPO. The choice of a backsheet is independent of the front encapsulant chosen, and a backsheet could be a polymer or a combination of polymers.

Backsheet Design	TPT	TPE	KPK	KPE	PPE	KPC	PPC
Outer Layer (~100 μm)	PVF	PVF	PVDF	PVDF	PET	PVDF	PET
Inner core layer (~125 μm)	PET	PET	PET	PET	PET	PET	PET
Cell side layer (~30 μm)	PVF	EVA	PVDF	EVA	EVA	coating	coating

3. Moisture ingress in photovoltaic modules

Polymeric encapsulants and backsheets are important in PV modules because of the various functions they perform (Czanderna and Pern, 1996; Omazic et al., 2019; Peike et al., 2013b; de Oliveira et al., 2018; Pern, 2008; Yang, 2019). However, these polymeric components (as shown in Fig. 1) are not perfectly air-/water- tight, and are prone to permeation of gases, including moisture, oxygen, and other gaseous species from the ambient surrounding (KEMPE, 2006; Yang et al., 2020). Some of the predisposing factors are the climatic conditions, the age of the modules, the materials used for the PV module (especially the polymeric materials), and the solar cell and module technology (Mitterhofer et al., 2020; Peike et al., 2013b; Tracy et al., 2018).

Moisture within the EVA layer in the presence of other climatic stressors (temperature and UV radiation) leads to the formation of acetic acid and its related degradation products which lead to corrosion of metal contacts, delamination and discolouration of encapsulants (La Mantia et al., 2016; Omazic et al., 2019; Oreski et al., 2017). It has been observed that delamination and discolouration at the edges of the PV module is most critical to power degradation and also a catalyst for other failure modes, including moisture ingress (Bosco et al., 2019; Kempe et al., 2014; Tracy et al., 2018). Moisture ingress can also affect the optical efficiency of the module (Hoffmann and Koehl, 2014; Kim et al., 2013; Kudriavtsev et al., 2019; Peshek et al., 2019; Yang, 2019).

Water vapour transmission rate, WVTR tests (the most popular) (KEMPE, 2006), gravimetric (Dadaniya and Datla, 2019), capacitance (Miyashita et al., 2012; Reese et al., 2011), and water immersion methods (Nagayama et al., 2020) are usually employed to determine the moisture barrier characteristics of PV encapsulants. Usually, parameters for these material properties are used together with climatic data to predict moisture ingress into PV modules using finite element methods (Jankovec et al., 2018; Wisniewski et al., 2019). Mitigation methods use encapsulants with low diffusivity and good adhesion properties, desiccant-stacked polyisobutylene sealants, and PV designs with/without breathable backsheets to prevent or delay moisture ingress into PV modules (Hardikar et al., 2014b; Kempe et al., 2018; Miyashita et al., 2012; Morita et al., 2015; Reese et al., 2011).

3.1. Effects of moisture ingress

3.1.1. Material degradation

The degradation of all PV components into various forms can be classified as material degradation. In EVA encapsulation, the adhesion promoter is the least stable additive and hence limits the longevity of EVA encapsulants (Köntges et al., 2014). The loss of adhesion between the solar cells, encapsulants, glass, and other active layers due to environmental, climatic, and/or artificial mechanical stressors results in delamination (Bosco et al., 2019; Tracy et al., 2018; Yang, 2019). This can occur prior and/or after moisture ingress and can account for ≤4% loss in power output at a localized polymer/cell interface. However, the presence of delamination with its by-standing defects and failure modes can lead to greater power losses in PV plants (Köntges et al., 2014).

Discolouration can also be a result of moisture ingress in PV modules (Han, 2020). Usually, the chemical reaction between moisture or gaseous species and encapsulation additives (including adhesion, UV, and thermal stabilizers) can lead to undesirable degradation products (Oreski et al., 2019; Tracy et al., 2018). In the field, these degradation products can take varying colouring forms depending on several complex reactions with moisture or gaseous species and UV radiation (Pern and Glick, 2000). Usually, discolouration can be detected with visual inspection, and can account for ca. 0.5% of the 0.8% power degradation per year for PV plants (Jordan and Kurtz, 2013). This loss is largely attributed to short circuit degradation (Jordan and Kurtz, 2013; Köntges et al., 2014). Fig. 5 shows some moisture ingress induced defects and fault modes of field-aged PV modules.

Delamination and discolouration cause optical performance losses (La Mantia et al., 2016), but of a greater concern is that they create voids within the module which serve as a suitable reservoir for moisture and gas accumulation (Yang, 2019). This can enhance the chances of corrosion of metal interconnects in modules and therefore may result in power loss (Peike et al., 2013a; Yang et al., 2020; Peike et al., 2012). Usually, these forms of material degradation are observed to occur around the cell interconnect ribbons and cell metallization (Hu and French, 2019), as in Fig. 5.

Particulate water trapped within encapsulants behaves as an optical barrier increasing absorption losses which has significant effect on the modules' quantum efficiency (Hoffmann and Koehl, 2014; Hülsmann et al., 2014; Peshek et al., 2019). For instance, Kudriavtsev et al. (2019) found a significant deterioration in the transmittance of a soda-lime glass sample after they were exposed to high humidity at 88 °C for two months. This optical loss can result in significant reduction in the quantum efficiency and therefore power output of the PV module. Using identical PV modules, McIntosh et al. (2011) investigated the effect of damp heat and UV ageing tests on the optical efficiency of EVA and silicone encapsulants by monitoring their absorption coefficients. After the damp heat test, they observed tiny absorption peaks within the 250–500 nm wavelength range which correlates to a drop in the PV module's efficiency of 0.39% and 0.14% for EVA and silicone encapsulants, respectively. In addition to the drop in the PV module's efficiency, the UV dose had insignificant effect on the absorption coefficients of both encapsulants.

In an earlier study, Vandyk et al. (2005) studied delamination induced degradation in a PV module over 30 months. They found that there was a small reversal in degradation during dryer periods of the year during their experiment. Hence, they concluded that the degradation in power was due to the presence of moisture in the delaminated regions of the module, as observed by increased series resistance with time. Also, Adams et al. (2015) believed that the presence of ingressed water at the hole extraction/active layer interface is the major denominator for PV device degradation.

The formation of acetic acid and its co-degradation products (such as lead acetate) in EVA encapsulants after prolonged damp heat tests have been observed and reported (Eder et al., 2019; Han, 2020; Kempe et al., 2007; Oreski et al., 2017, 2019). It is believed that the formation of these moisture assisted degradation products (and subsequent PV module material degradation) have direct correlation with extended exposure to high humidity, temperature and UV doses (Czanderna and Pern, 1996; de Oliveira et al., 2018; Omazic et al., 2019; Tracy et al., 2018; Wohlgemuth and Kempe, 2013).

3.1.2. Corrosion

Corrosion is the deterioration of materials due to reactions (chemical, electrochemical, physical, or physicochemical) with the environment. Traditionally, corrosion of metals occurs when there is an exchange of electrons between a metal and its environment. In the presence of oxygen and moisture, metals can experience electrochemical corrosion (Mon et al., 1985; Peshek et al., 2019; Tracy et al., 2018). Moreover, it is known that EVA produces acetic acid in the presence of moisture and other environmental stressors, which can lead to corrosion of metal grids and other components of PV modules (KEMPE, 2006; Kim et al., 2013; Oreski et al., 2017). Additionally, moisture ingress induces adhesion loss and creates voids in encapsulants and backsheets and therefore predisposes all components of the PV module to corrosion (Mon et al., 1985; Oreski and Wallner, 2005; Yang et al., 2020; Yang, 2019), see Fig. 5c.

Solar cell metal interconnect corrosion is known as a major cause for the overall module performance degradation (Annigoni et al., 2019; Bosco et al., 2019; Eder et al., 2019; Klemchuk et al., 1997; Virtuani et al., 2019b; Yang et al., 2020). Kim et al. (2013) studied three crystalline silicon PV modules under accelerated ageing conditions using I-V measurements, SEM-EDX, and Auger Electron Spectroscopy (AES) and found that the major effect of moisture ingress in PV modules is metal contact corrosion. Also, (Kraft et al., 2015) studied the corrosion of the screen-printed silver front-side contacts of silicon solar cells after damp heat test. They observed that the presence of acetic acid, a decomposition product of moisture ingressed EVA encapsulants, was responsible for the corrosion of the metal grids.

According to Peshek et al. (2019), the routes to corrosion are dominated by moisture ingress from the perimeter to the interior of the module. Earlier on, Jorgensen et al. (2006) studied the properties of module packaging materials, including moisture ingression, corrosion, and interfacial adhesion characteristics, under damp heat ageing conditions. They deposited an 80-nm-thick aluminum veneers onto a 100-cm^2 glass substrate and observed that the designs with the imbedded Al-glass laminates were effective in trapping deleterious species that catalyze moisture driven corrosion. These species they believed are low molecular weight PET fragments of carbonyl, carboxylic, and phenolic origins. Also, Wohlgemuth and Kempe (2013) performed series of damp heat tests on BP Solar modules to evaluate the effect of temperature and humidity on solar module degradation. They discovered that corrosion was the dominant degradation mechanism identified with the test

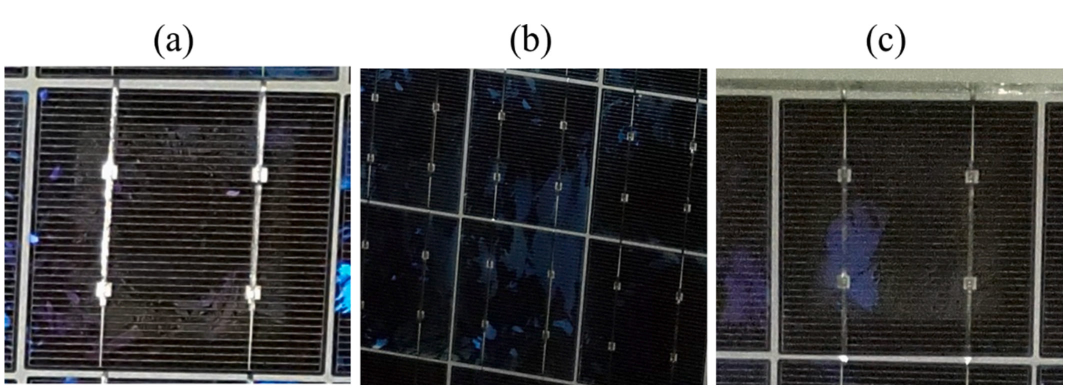


Fig. 5. (a) Delamination around solar cell edges, (b) discolouration of encapsulants, and (c) oxidation of metal grids as a result of moisture ingress.

modules. Later, Peike et al. (2013a) explored the origin of damp-heat induced cell degradation in c-Si PV modules under (80% / 80 °C and 80% / 90 °C RH) damp heat conditions using EL imaging and EDX. They concluded that the corrosion of the grids is the underlying cause for the degradation.

3.1.3. Potential induced degradation (PID)

PV modules are usually connected serially in grid-connected systems to increase voltage output and for safety purposes, modules frames are grounded. However, several factors can induce high potential difference between solar cells and the PV module frame due to electrochemical interactions (Carolus et al., 2019; Kwembur et al., 2020; Luo et al., 2017; Yamaguchi et al., 2020). Some of these factors include module encapsulation and design, solar cell's anti-reflection coating, PV system electrical topology and inverter type, environmental/climatic factors (such as humidity, temperature, UV radiation, soiling, etc.), and grounding conditions of the front glass (Carolus et al., 2019; Luo et al., 2017; Naumann et al., 2019). According to ongoing investigations, migration of sodium cations (Na^+) from the soda lime glass and/or the solar cell is responsible for the observed increased potential between the solar cell and module frame (Carolus et al., 2019; Kwembur et al., 2020). Fig. 6a shows the accumulation of Na^+ at the antireflection-silicon cell interfaces using time of flight (ToF) and secondary-ion mass spectrometry (SIMS). In a conventional multicrystalline silicon PV module, the possible conduits for leakage current from the module frame to the solar cells (or vice versa) are via the surface and bulk of the front glass and encapsulation (Luo et al., 2017; Yamaguchi et al., 2020). The electric potential difference lead to increased electrical conductivity and leakage currents from the solar cells to the module frame (or vice versa, depending on the state of the module in the string), which can lead to PID, and hence, power degradation (Carolus et al., 2019; Hacke et al., 2015; Hoffmann and Koehl, 2014; Luo et al., 2017; Mon et al., 1985; Naumann et al., 2019; Virtuani et al., 2019a).

It has been observed that humidity and temperature are the two most common environmental stressors that underpin PID which results in significant power degradation in PV modules (Kwembur et al., 2020; Luo et al., 2017; Naumann et al., 2019). High humidity and temperature drive moisture into PV modules and may lead to PID due to the electrochemical reactions of the antireflection coating and/or reduced bulk resistivity of the encapsulants (Fig. 6b and 5c) (Hacke et al., 2015; Luo et al., 2017; Pingel et al., 2010).

For instance, Hoffmann and Koehl (2014) in their experiment to explore the influence of temperature and humidity on the onset of PID using both indoor and outdoor exposures observed that humidity is the major denominator for the observed leakage current which causes PID. In another investigation, Hacke et al. (2015) employed accelerated degradation models (the Peck Equation and exponential models) to model temperature and humidity induced degradation in crystalline silicon solar modules. Their model was based on a semi-continuous statistical power degradation and leakage current data obtained via in-situ monitoring of modules undergoing PID in a climatic chamber. They found that the quantum of power transferred from the active cell circuit to the ground during the stress test has a linear correlation with time and the stress factors. Furthermore, Hacke et al. (2016) observed PID in cadmium telluride, CdTe PV modules after the modules were subjected to multiple stress factors. They concluded that the onset of the PID was as a result of moisture ingress.

Also, Virtuani et al. (2019a) in their investigation using sandwich structures with higher moisture barrier properties, found that limiting moisture ingress into the encapsulants helps in mitigating the incidence and impact of PID. In another work, Naumann et al. (2019) using damp heat test conditions (85 °C, 85% RH), found that moisture and soiling was the underlying cause for PID in test mini PV modules. According to Barth et al. (2019), moisture ingress is the major cause of PID, delamination and discolouration of encapsulants in PV modules.

In order to reduce the LCOE of PV projects, there are reports of PV plants operating at absolute voltages with at least 1000 V between the module frame and the solar cell, with a target of reaching maximum system voltage of ca. 1500 V (Carolus et al., 2019; Luo et al., 2017). This only indicates that the problem of PV module PID will be quite challenging with such high voltages going into the future. A critical review of PID in PV modules is given by Luo et al. (2017). Although mitigation techniques for the PID phenomenon at cell, module, and system levels have been proposed and demonstrated, these techniques are yet to be implemented commercially largely due to the complexity of PID (Carolus et al., 2019; Luo et al., 2017; Pingel et al., 2010). Also, the so-called PID-free modules may be susceptible to PID after long-term exposure to repeated mechanical stress and outdoor weathering which can cause microcracks and pinholes in the encapsulation. The increasing installations of floating PV power plants represent a challenge even for PID-free modules, as leakage currents increases with increasing localized humidity (Luo et al., 2017). This emphases the need for early-stage diagnostics of moisture ingress in PV plants.

3.2. Mechanism of moisture ingress

Moisture ingress refers to the diffusion of water molecules and other gaseous species (e.g., oxygen, nitrogen, carbon dioxide, etc.) into the interior of a PV module. Diffusion is initiated when water or gaseous molecules are adsorbed onto the surface of an encapsulant, and with an appropriate concentration gradient, are transported through and desorbed onto other components of the PV module (Kempe et al., 2014; Kim

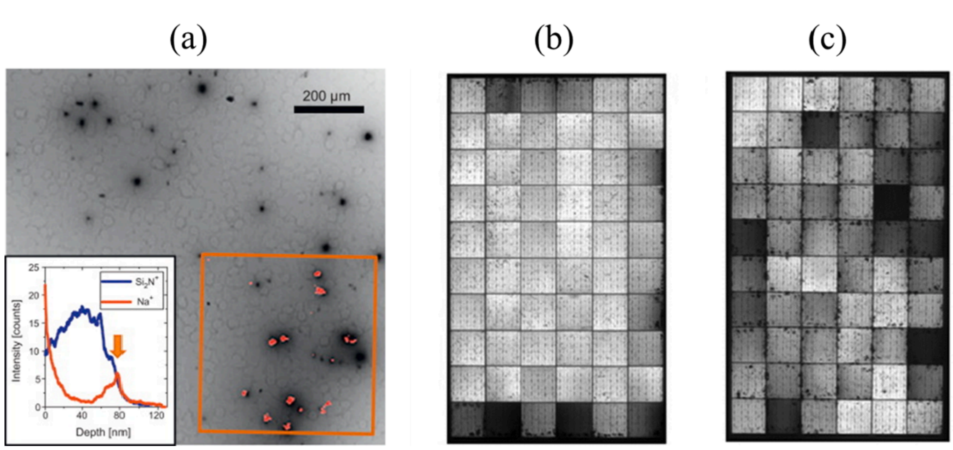


Fig. 6. (a) An EBIC image of a monocrystalline silicon solar cell acquired at an acceleration voltage of 30 kV showing a population of PID shunts. The insert is a ToF-SIMS image showing the distribution of Na^+ at the SiN_x-Si interface. Adapted from Naumann et al. (2014). (b)-(c) EL images of crystalline silicon PV modules after a high humidity and temperature (85 °C / 85% RH) PID tests. PID shunted solar cells turned dark. Adapted from Luo et al. (2017).

and Han, 2013). The process continues until equilibrium is established with the ambient humidity conditions as postulated by the Fickian laws (KEMPE, 2006), Eqs. (1)–(3). Fig. 7 is a scheme of moisture ingress phenomenon in PV modules. It illustrates the formation of photoproducts under the action of photons and formation of carboxylic acids in the presence of moisture in PV module. The diffused carboxylic acids and moisture initiate different degradation processes in the PV module (Grossetête et al., 2000; Kumar et al., 2019; Oreski et al., 2017).

Diffusion mechanisms could either be classified as Fickian or non-Fickian. Fickian diffusion models are those that obey the Fick's laws: Eqs. (1)–(3), otherwise, they are known as non-Fickian diffusion models (Kempe et al., 2018; Mitterhofer et al., 2020; Slapsak et al., 2019; Jankovec et al., 2018). According to Mitterhofer et al. (2020), the Fickian diffusion models can accurately model the behaviour of moisture or gaseous species across the interface, in channels and bulk of the polymeric material. However, in some special cases where the diffusion process is largely influenced by the channels within the polymeric material rather than the polymer bulk, the non-Fickian models such as dual transport models are more representative in modelling the profiles of the actual diffusion process (Slapsak et al., 2019; Jankovec et al., 2018).

The amount of moisture absorbed by a polymeric material depends on the temperature, concentration gradient, and also the material properties (Mitterhofer et al., 2020; Van der Wel and Adan, 1999). Some of the material properties that influence diffusion are polymer crystallinity, chemical morphology, polarity, free volume, voids in material, degree of cross-linking, ageing, and chemical additives (Mitterhofer et al., 2020).

It is believed that using materials of excellent moisture barrier properties is the best way to manage the challenge of moisture ingression into PV modules (KEMPE, 2006; Kempe et al., 2018). To this end, the diffusivity, permeability, and solubility properties of polymeric materials that are used for encapsulating PV modules are of greatest importance (Hülsmann and Weiss, 2015; Wisniewski et al., 2019). Hence, the majority of research work in understanding and preventing moisture ingress in PV modules are dedicated to investigating these material properties via experimental and theoretical methods (Hülsmann and Weiss, 2015; Jankovec et al., 2018; Kempe et al., 2018; Wisniewski et al., 2019).

3.3. Factors that influence moisture ingress

3.3.1. Module technology

PV modules can be fabricated in two configurations: modules with permeable and impermeable encapsulants, as illustrated in Fig. 8. With the impermeable encapsulants, usually referred to as glass-to-glass configuration, moisture and gases can diffuse in from the edges of the modules. This is the universal configuration for thin film PV and other emerging (e.g. organic PV) technologies (KEMPE, 2006), see Fig. 8a. This is because, thin films such as cadmium telluride (CdTe), amorphous silicon (a-Si), copper indium gallium selenide (CIGS) modules are highly vulnerable to moisture, which can lead to corrosion of metal grids, especially when these technologies are deployed in hot and humid environments (Han, 2020; Theelen et al., 2017). Similarly, low stability and moisture induced degradation in organic PVs makes the glass-to-glass encapsulation the most suitable for organic PVs and their related emerging technologies. Recent developments have also led to substantial growth in the bifacial market, where glass-glass based crystalline silicon modules are projected to become a leading technology (Liang et al., 2019).

The permeable configuration, known as "breathable" or glass-to-polymer configurations are universally associated with the traditional silicon crystalline technologies. Permeable designs are more prone to moisture ingress. According to Kempe et al. (2007), a typical EVA encapsulated module with permeable and impermeable backsheets can quickly equilibrate to pH values of 4.76–7.0 and <4.76, respectively under similar conditions (KEMPE, 2006). A scheme of this design is illustrated in Fig. 8b. Hence, this design is said to facilitate the acetic acid diffusion rate. Thus, it reduces acetic acid accumulation within the PV module (Oreski et al., 2017), which in turns prevents metal contacts corrosion.

In the same way, due to the relatively high moisture diffusivity in EVA encapsulants, it is largely challenging to completely prevent moisture ingress into modules (KEMPE, 2006). Even those with perfect hematic configurations are liable to moisture ingress through voids created (either via manufacturing, mechanical or climatic stressors) at the perimeter of the module (Jankovec et al., 2016; Wisniewski et al., 2019). Table 4 shows the major PV technologies available commercially.

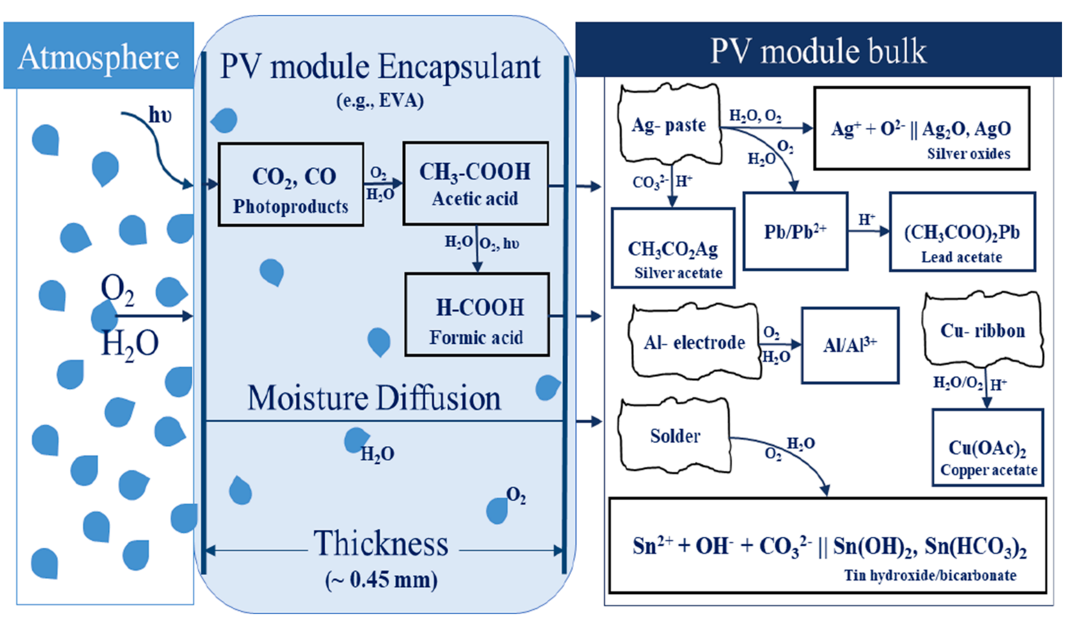


Fig. 7. Moisture ingress in PV devices. In the presence of sunlight (hυ), the encapsulant produces photoproducts (Grossetête et al., 2000), and interaction of the photoproducts with moisture can lead to the formation of carboxylic acids (Oreski et al., 2017). Moisture and the carboxylic acids diffuse into the PV module and initiate various degradation processes (Kumar et al., 2019). Silver (Ag) and lead (Pb) comes from the silver paste, and the solder and rear Al- electrode are the sources of tin (Sn) and aluminum (Al), respectively. Moisture is the electrolyte which sustains the degradation reactions in Fig. 7 (Kumar et al., 2019).

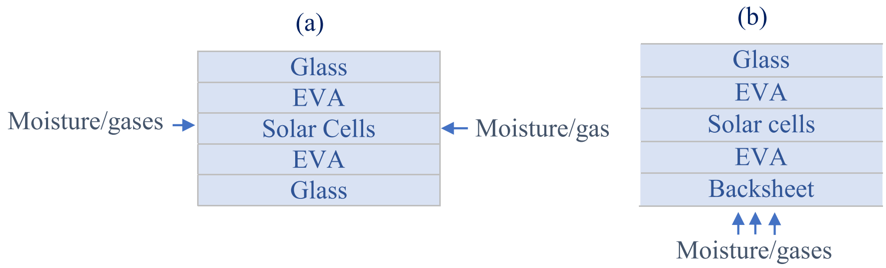


Fig. 8. PV module configurations: (a) impermeable and (b) permeable encapsulants.

Table 4
Types of commercial PV modules (Liang et al., 2019; Lopez-Garcia et al., 2018; Philipps and Warmuth, 2019).

PV module type	Characteristics	Encapsulation type
Monocrystalline (pure silicon)	- ca. 20% efficiency - relatively expensive - temperature coefficient: −0.3 to −0.5%/°C - blue in colour	Permeable (glass-to-polymer)
Polycrystalline or multicrystalline (fragments of molten Si crystals)	- ca. 15% – 17% efficiency - relatively low cost - temperature coefficient: −0.3 to −0.5%/°C - black in colour	Permeable (glass-to-polymer)
Thin film (CdTe, a-Si, CIGS, etc.)	- ca. 7% – 18% efficiency - lower cost - temperature coefficient: −0.1 to −0.4%/°C - blue/black in colour	Impermeable (glass-to-glass)
Crystalline silicon bifacial PV modules	- ca. 17% – 24% efficiency (front), 16% – 19% efficiency (rear), 0.70–0.9 bifaciality factor - lower LCOE - temperature coefficient: −0.3 to −0.4%/°C	Impermeable (glass-to-glass)
Emerging PV (e.g., Organic PV, Perovskites, etc.)	- relatively low efficiency - flexible, lightweight, and inexpensive - positive temperature coefficient - poor stability	Impermeable (glass-to-glass)

The effect of moisture ingress on thin film and organic PV devices is well documented in literature (Bag et al., 2016; Cheacharoen et al., 2018; Han, 2020; Morlier et al., 2013; Tanenbaum et al., 2012; Theelen et al., 2017; Weerasinghe et al., 2015a). The presence of moisture or gaseous species within the bulk of these modules result in photochemical reactions at the interfaces which leads to ultimate device degradation (Weerasinghe et al., 2015a, 2015b). However, there are efforts within the PV scientific community to develop suitable designs that will ensure the stability and reliability of these devices against moisture and gaseous ingress (Bag et al., 2016; Cheacharoen et al., 2018; Morlier et al., 2013; Tanenbaum et al., 2012). For the purpose of this review, we will focus on crystalline silicon PV module technologies, which are usually made with polymeric encapsulants. These technologies are not to be confused with emerging polymer-based PV modules which have the active materials of the solar cells made from polymeric materials or their blends: donor and hole transport materials (Tanenbaum et al., 2012).

3.3.2. *The material factor*

Material properties have been known to be the key factor to every device optimization, and this is not an exception in PV devices (Van der Wel and Adan, 1999). The material properties of the polymeric materials used as PV components are understood to be the limiting factor which predisposes PV modules to all forms of degradation and failure modes (Mitterhofer et al., 2020; Omazic et al., 2019), including moisture ingress (Kempe et al., 2014). Therefore, polymeric materials used as the component of the module have to be of desirable characteristic, especially as regards diffusivity, permeability, and solubility of gaseous species taking into consideration the economic and environmental concerns (Wisniewski et al., 2019). The most common parameter that is used is the diffusion coefficient which relies on both the permeability and solubility of moisture in a given polymeric material. Fig. 9 highlights some of the works in literature on the diffusion of moisture in different encapsulants and backsheets.

A close inspection of Fig. 9 shows that ionomer as an encapsulation material outperforms all other encapsulants including EVA, especially when it comes to resilience to moisture ingress. In contrast, PA is highly vulnerable to temperature changes. Similarly, it has been observed that the solubility and permeability of encapsulation materials follows the same trend. That is, the solubility and permeability of polymeric encapsulants increase significantly with increasing temperature (Hülsmann et al., 2014; Kim and Han, 2013; Köhl, 2013; Wisniewski et al., 2019).

Currently, EVA is the most preferred encapsulant material in crystalline silicon solar modules largely because of its cost effectiveness. However, EVA has a relatively high water diffusion coefficient and is liable to acetic acid production in the presence of moisture (Kempe et al., 2007). This and other factors open up the market for other encapsulation materials (Peike et al., 2013b). Even though these new polymeric encapsulants have their individual advantages, they all have some limitations in one way or the other, especially when it comes to PV applications (Peike et al., 2013b). Table 5 highlights some of the advantages and limitations of the most common PV encapsulants. Ionomer encapsulants, the most promising among the emerging PV encapsulants has a higher resilience to discolouration and PID, lower diffusivity, and higher optical transmittance among other properties. However, they are limited by higher costs, lower adhesion characteristics, and field data on their usage is limited (Tracy et al., 2020). The most vital parameter that is considered for the selection of an encapsulation material for PV module

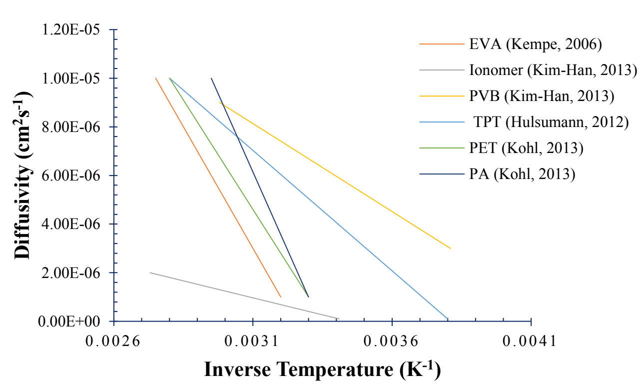


Fig. 9. Diffusion in different encapsulant materials. Data extracted from Kempe (2006), Kim and Han (2013), Hülsmann et al. (2014), and Köhl (2013).

Table 5
Advantages and limitations of some PV module's encapsulation materials.

Encapsulant	Advantages	Limitations
EVA	Cost-effective High adhesion	Acetic acid production UV instability High diffusivity
Ionomer	High volume resistivity High UV stability Low diffusivity High optical transparency High resilience to PID	High cost Poor adhesion Limited data High glass transition temperature
Silicone	High optical transparency High thermo-chemical stability Low thermal modulus High UV stability Low diffusivity	High cost High diffusivity High technical expertise
PVB	High UV stability and transparency Good adhesion	High diffusivity High cost High glass transition temperature
TPSE	High water repellent High thermo optic stability Easier recycling High volume resistivity	High cost
TPO	High volume resistivity Cost-effective High thermo-chemical stability Good resistance to hydrolysis	High diffusivity

application is cost (Peike et al., 2013b; Tracy et al., 2020; de Oliveira et al., 2018).

Czyzewicz and Smith (2011) carried out an investigation with several commercial grades of PVB, EVA and ionomer-based materials under repetitive 1000 hr damp heat ageing tests. Their findings, in part, led to the development of the commercially available cost-effective DuPont™ PV5300 and PV5400 ionomer-based encapsulants which exhibit superior moisture barrier quality as compared to EVA-based encapsulants.

Also, Kim and Han (2013) studied the amount of permeated moisture through an ionomer and PVB encapsulants and compared them with that of EVA encapsulants. They found that EVA has relatively lower diffusivity whilst ionomer encapsulants have relatively lower moisture retention capacity. Another study by Köhl (2013) using experimental and 2-dimensional finite element methods (FEM) in four different microclimates found that different encapsulants and backsheets behave differently under different climatic conditions. In a related work, Hülsmann et al. (2014) studied the behaviour of different encapsulants in different climates via simulation. They observed that in the same climatic condition, the solubility and permeability which account for the equilibrium moisture concentration is significantly influenced by the material composition. That is, additives, chemical structure, and morphology of the encapsulants affect moisture ingress reliability (Mitterhofer et al., 2020; Van der Wel and Adan, 1999).

In that respect, in order to protect the PV module over its useful lifetime against ingress of gaseous species, polymeric materials for making PV modules need to have good adhesion and lower diffusivity, solubility, and permeability characteristics to serve as good moisture or gaseous barrier materials (KEMPE, 2006; Miyashita and Masuda, 2013; Annigoni et al., 2015).

3.3.3. Environmental and climatic factors

In hot and humid climates, corrosion, delamination and discolouration of encapsulants as a result of ingress of moisture and gaseous species dominated old field deployed photovoltaic modules (Hülsmann and Weiss, 2015; Hülsmann et al., 2014; Schlothauer et al., 2012). Moisture ingress is also influenced by pressure and concentration gradients of diffusants, which are also functions of humidity and temperature. (Mitterhofer et al., 2020). In an investigation, Kempe et al. (2007) found that the ingress of water and oxygen into PV modules is highly influenced by temperature as compared to phase transitions (glass transition temperature, Tg or melting temperature, Tm) of the investigated materials. In addition, Koehl et al. (2012) investigated the impact of humidity on PV modules based on monitored climatic data at specific locations. Using phenomenological models, they estimated the moisture concentration at the surfaces of photovoltaic modules and concluded that degradation kinetics strongly depend on climatic locations.

In another study, Hülsmann et al. (2014) using a FEM simulation, studied the moisture ingress into wafer-based photovoltaic modules under extended periods of exposure in four different climatic conditions (namely *moderate climate* - Freiburg, Germany, *arid climate* - Negev desert, Israel, *alpine climate* - Zugspitze, Germany and *tropic climate* - Serpong, Indonesia), using polyethylene-terephthalate- (PET-) based and polyamide- (PA-) based backsheets and EVA as the encapsulating material. They observed a faster moisture ingress for warmer regions and higher moisture concentrations for moderate climate test sites. In a related report, Hülsmann and Weiss (2015) compared a simulated moisture uptake by PV modules under the standard IEC 61215 type approval ageing tests and moisture ingress into PV modules based on measured data sets from four different climatic zones using ethylene vinyl acetate, EVA as an encapsulant and polyvinyl fluoride/polyethylene terephthalate/polyvinyl fluoride (Tedlar®/PET/Tedlar®), TPT stack as a backsheet. They found that the standard IEC 61215 ageing tests causes twice as much moisture content in encapsulants than 20 years field exposure of modules. This is due to the dependency of diffusion (and solubility) on temperature and humidity and also the type of encapsulants, a trend highlighted in Fig. 9. They also compared their results to prior results in literature and found a good agreement among the results. Wisniewski et al. (2019) used a finite element model based on experimental data from WVTR tests to comprehend the moisture ingress into double glass modules and concluded that moisture ingress increases with increasing temperature. They also argued that the moisture content of the EVA can affect the diffusivity factor up to two folds.

According to Kempe et al. (2007) moisture ingress, acetic acid (due to ingressed moisture), and UV irradiation can lead to significant loss of adhesion of EVA encapsulants. Also, Novoa et al. (2014) developed a fracture kinetics model based on a quantitative characterization technique to study the effects of moisture, temperature, and mechanical stress on the adhesion characteristics of backsheets using ageing tests. They found that the delamination rate increased with test duration, temperature, and relative humidity. In another related study, the same group with the same model investigated the influence of humidity and temperature on the debonding kinetics of EVA and polyvinyl butyral (PVB) encapsulants and reported the same trend as observed with backsheets (Novoa et al., 2016). Similarly, Bosco et al. (2019) also investigated the influence of humidity and temperature on the delamination kinetics of the EVA/Si–PV cell boundary and concluded that electrochemical reactions dominated at higher humidity levels.

Kempe and Jordan (2017) investigated the possible influence of a manufacturing anomaly on the long-term reliability of a utility scale photovoltaic (PV) project. They subjected test modules to varying humidity and temperature conditions with periodic monitoring. They found that the degradation mechanism was dependent on the moisture content within the module due to damp heat test, and extrapolation to field scenarios forecasted minimal deviation for the project location. They also acknowledged the uncertainties in forecasting performance from damp heat tests. Thus, high humidity, temperature, and UV irradiation contribute significantly to loss of adhesion, solder bond and other material degradation which can lead to moisture ingress in PV devices.

Beside environmental and climatic factors in the field, the IEC 61215 type approval tests also have consequences of creating favourable routes for moisture ingress into PV modules. Humidity as an important stress factor for PV modules achieved through the Damp Heat test, as specified by IEC 61215 type approval testing under a 1000 hr at 85 °C and 85%

RH condition, can result in significant failures and damages to modules when not done according to standard specifications. These tests can serve as a precursor for other material degradation and fault modes. In one investigation, (Oreski and Wallner, 2005) observed chemical degradations in polyethylene terephthalate, polyvinylidene fluoride, and polyvinyl fluoride encapsulants after 85% / 85 °C damp heat tests.

Furthermore, Hoffmann and Koehl (2014) studied the effect of physical conditions (namely humidity, temperature, accelerated ageing scheme, and extreme voltage stress exposure in two different climatic zones) on the degradation mechanism of PV modules and found that accelerated ageing tests cause degradation in some orders of magnitude as compared with outdoor exposure. Later, Hülsmann and Weiss (2015) compared the simulated moisture ingress results of photovoltaic modules during accelerated ageing tests contained in the type approval standard IEC 61215 protocol and moisture ingress under real ambient outdoor conditions. They observed that the damp heat, thermal cycling, and humidity freeze tests as per the IEC 61215 standard resulted in twice as much moisture concentration in the encapsulant between the cell and glass than outdoor weathering over 20 years.

Recently, Tracy et al. (2020) investigated the resilience of ionomer and EVA encapsulants using both indoor and outdoor tests. Under 5000 h of accelerated aging at 65 °C/30% RH and 340 nm UV exposure, they observed significant discolouration in the EVA encapsulants and only a hazy discolouration in the ionomer encapsulants. They noted that the field-aged test samples did not experience any form of discolouration even under the same voltage exposure conditions of $\sim 8.0 \times 10^{-4}$ W•hr/m^2. Their result is shown in Fig. 10.

They also observed that EVA outperformed the ionomers as regards adhesion characteristics. They attributed these degradation processes partly to environmental and climatic factors which led to undesirable chemical reactions within the encapsulants.

Ultimately, all encapsulation materials are prone to moisture ingress at higher humidity, temperatures, and UV radiation conditions. These climatic or environmental stressors together with the encapsulants' properties (such as diffusivity, solubility, and permeability) and the PV module's design (permeable or impermeable) play a major role in the insurgence of moisture ingress. Optimization of these material properties and the module design to be resilient in all climatic conditions will be a key to achieving PV modules' durability and reliability.

4. Test methods for moisture ingress susceptibility

Moisture ingress is a tricky phenomenon that connects most material degradations in PV modules (Mon et al., 1985), and is a threat to module reliability. Hence, more effort must be put in place to address the incidence of moisture into PV modules. Unfortunately, we cannot control environmental factors but for the material properties and technology we can, especially when the failure mechanisms are well understood. To understand the role moisture plays in modules' failure mechanisms, all predisposing elements including the materials, the kinetics and the conditions in which modules operate must be well understood. The luminescence and fluorescence signals from moisture induced degradation products of PV modules are measured using electroluminescence (EL), photoluminescence (PL), and ultraviolent fluorescence (UV-F) spectroscopy, respectively. Dark lock-in thermography (DLIT) is based on the thermal signatures from degraded products from moisture ingress whilst scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and fourier transform infra-red spectroscopy (FTIR) measure the chemical products (based on functional groups) associated with moisture ingress (Kim et al., 2013; Kumar et al., 2019).

Most often, the moisture diffusion characteristics of encapsulants such as EVA and backsheets is estimated using permeation-based techniques. The most common among these techniques is the water vapour transmission rate (WVTR) experiments, which can be derived from either the flux density (F), Equation (2) or permeability (P), Equation (3) in a polymeric material. Using the water transmission rates from the permeation tests, the overall mass transfer of water through the encapsulant can be determined. Normally, finite element models are used together with parameters from the gravimetric and permeation techniques in order to estimate the moisture absorption, retention, and transmission characteristics of the polymeric materials (Hülsmann and Wallner, 2017; Hülsmann and Weiss, 2015; Kim and Han, 2013; Meitzner and Schulze, 2016; Oreski et al., 2017; Wisniewski et al., 2019).

4.1. Predicting moisture ingress in polymeric materials

EVA is the most common encapsulant used in crystalline silicon solar modules currently, and several methods have been employed in order to understand and predict the moisture barrier characteristics of PV module encapsulants and backsheets. It is noteworthy that, determining the moisture concentration and mass transport characteristics of encapsulants (such as EVA) and backsheets under multiple moisture absorption and desorption conditions as in the case of real field operation is complex and challenging (Dadaniya and Datla, 2019; KEMPE, 2006; Novoa et al., 2016; Peike et al., 2013a). An overview of some of the methods that have been reported in literature are illustrated in Fig. 11. In Fig. 11, all the methods show a good agreement: diffusivity increases with increasing temperature. It has been shown that diffusion is more sensitive to temperature changes as compared to other environmental stressors and hence, influences the moisture barrier characteristics of materials the most (Dadaniya and Datla, 2019; KEMPE, 2006; Wisniewski et al., 2019).

According to Wisniewski et al. (2019), the material properties that determine the suitability of a polymeric material for encapsulants for PV applications are the permeability, mass concentration, solubility, and

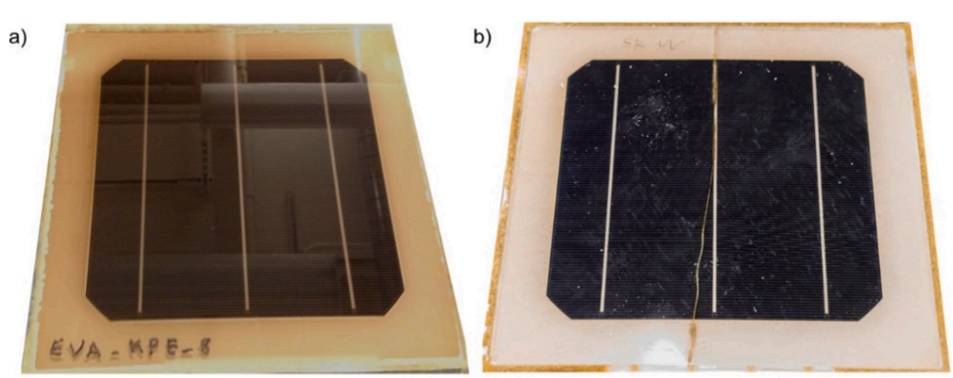


Fig. 10. Discoloration in (a) EVA and (b) ionomers encapsulants after 5000 h of accelerated aging (65 °C/30% RH, 340 nm UV) exposure. Ionomers showing greater resilience to discolouration as compared to EVA. .
Adapted from Tracy et al. (2020)

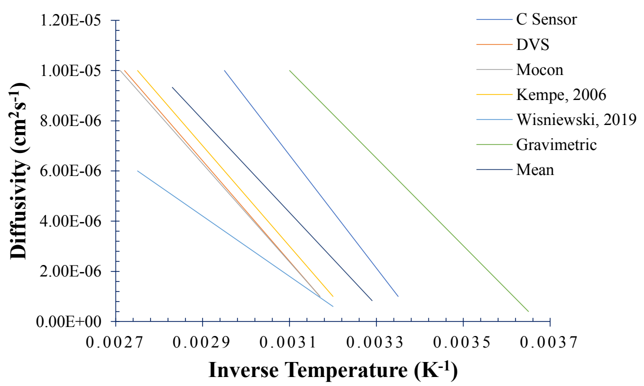


Fig. 11. Different approaches for determining the diffusion coefficient of EVA-water system. Data extracted from KEMPE (2006), Ballif et al. (2014), and Wisniewski et al. (2019), Dadaniya and Datla (2019) and the mean of these data points.

diffusivity of water through and within the EVA. In their work, they determined these parameters using a two-dimensional finite element model based on experimental data obtained via WVTR from Miami and Mumbai to forecast moisture ingress into solar modules during long-term outdoor exposure and laboratory accelerated tests. They argued that their model could be used to study specific regions on the module for degradation behaviour. More importantly, they concluded that the duration required for equilibrium could be much enhanced by controlling the initial moisture content of EVA.

Usually, the diffusion, permeability, solubility, and moisture concentration characteristics of encapsulants and backsheets are determined experimentally, and from these parameters, moisture or gaseous ingress profiles of these polymeric materials could be predicted with the Fickian laws, Equations (1) – (3), (Hülsmann and Weiss, 2015; KEMPE, 2006; Mitterhofer et al., 2020; Wisniewski et al., 2019; Jankovec et al., 2018). For an ideal thin film of polymeric material in the presence of moisture or gaseous species (assuming an ideal environment), the process dynamics could be represented with:

$$\frac{\partial C}{\partial t} = \nabla\cdot(D\nabla C), \tag{1}$$

where t is diffusion time, D is the diffusivity and C is the concentration of the species within the host material.

For isotropic diffusion (1-dimensional diffusion), that is, if the concentration gradient is assumed to be along the x-axis only, Equation (1) is the differential equation of the rate of flow of permeants per unit area, known as diffusion flux (F), and is given by

$$F = -D\cdot\frac{\partial C}{\partial x}, \tag{2}$$

where x is the space coordinate measured normal to the section, $-\partial C/\partial x$ is the driving force for the diffusion. The experimental measured value of F from Equation (2) could be taken as the *WVTR* of the material (Kim and Han, 2013; Wisniewski et al., 2019). For an ideal barrier material without voids, the behaviour of easily condensable permeating species could be represented by

$$P = S\cdot D, \tag{3}$$

where P is the permeability coefficient and S is the solubility (concentration proportionality constant). The solubility, S is usually known as the “Henry’s coefficient”, because it is based on the famous Henry’s law (Sander, 2015), which describes the partial pressure of a solute-absorbent system. So, for the equilibrium between saturated moisture concentration, C_{sat} and ambient vapor pressure, p_v for a moisture–polymer system, the Henry’s law could be expressed as $C_{sat} = S\cdot p_v$. For moisture and other gases, such as oxygen, that condense or interact with polymeric materials easily, permeability could be expressed in terms of flux density and solubility by comparing Equations (2) and (3) as

$$P = -\frac{F}{v/\partial x}\cdot S. \tag{4}$$

Thus, the *WVTR* of encapsulants or backsheets could be estimated from the experimental measured value of P (Hülsmann et al., 2014; KEMPE, 2006).

Assuming an ideal Fickian diffusion process, the transient $WVTR_{(t)}$ as a function of time, also known as the fractional mass of water, can be represented as (Crank, 1975)

$$WVTR_{(t)} = \frac{D\cdot C_{sat}}{l}\left[1+2\sum_{n=1}^{\infty}(-1)^n exp^{\left(\frac{-Dn^2\cdot\pi^2\cdot t}{l^2}\right)}\right], \tag{5}$$

where n is the number of points in space, t is the time, and l is encapsulant film thickness. n takes values 0, 1, 2, … Usually, experimental results fit well with $n = 10$, but is best predicted with a real model with acceptable error values (Yang et al., 2020).

Using the permeability tests is often preferred when dealing with easily condensable fluids such as moisture and oxygen. This is because for these fluids, permeant flux is limited by the solubility of permeants in the polymeric material, which is due to the high degree of interaction of permeants with the polymeric material. This can result in alteration in the chemical morphology of the encapsulant (Luo et al. (2017). Moreover, the diffusion, solubility, and permeation processes are strongly influenced by temperature and are reliably described in a homogenous material with the Arrhenius equation as

$$X = X_0 exp^{\left(-\frac{E_X}{R\cdot T}\right)}, \tag{6}$$

where X, X_0, and E_X is the coefficient, the constant, and the activation energy of parameter X respectively (X = diffusivity, solubility, and permeability). R is the universal gas constant, and T is the absolute temperature (in kelvins). X_0 is also called the preexponential factor, which describes the relationship between temperature and the reaction rates. Using the definition of solubility, together with the *WVTR* fitted data derived from Equations (2), (4) and (5), the constants (D, S, and P) could be determined. The activation energy, E_a (E_X in Equation (6)) could be determined graphically and be used to evaluate the properties (diffusivity, permeability, and solubility) of the polymeric material at varying temperature conditions. For instance, using Equation (7), which is a linearized version of Equation (6) (KEMPE, 2006),

$$lnD = InD_0 - \frac{E_D}{R}\cdot\frac{1}{T}. \tag{7}$$

The diffusivity could be estimated for a given polymeric material at different operating temperatures. Assuming that the diffusion process is only influenced by a perfect linearized experimental temperature distribution in the polymeric encapsulant, D_0 and E_a (E_D) could be extracted from a fitted graph of (ln D) against ($1/T$). However, the Arrhenius equation assumes that the activation energy of the water diffusion process is independent of temperature and that water diffusion has insignificant influence on the physical properties of the polymeric material (Yang et al., 2020). In contrast, material properties such as chemical structure and morphology together with other additives can also influence the diffusion properties of polymeric materials (Van der Wel and Adan, 1999). So, at times, E_a (E_D in Equation (7)) is affected by unexpected chemical interactions due to temperature variations, and therefore a perfect linear relation between (ln D) and ($1/T$), in these cases, becomes largely unrealistic (Yang et al., 2020). In such circumstances, E_a could be determined using the difference in the diffusivity (D_1 and D_2) at two different temperatures (T_1 and T_2) respectively as (Yang et al., 2020)

$$ln\frac{D_1}{D_2} = \frac{E_a}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad (8)$$

It is noteworthy that the equation above depends on the experimental methods and the error functions associated with these methods. According to Kimball et al. (2016), based on the Fickian and Arrhenius laws, the lifetime (t_{TTF}: test-to-failure in hours) of field deployed PV modules could be estimated based on the relative humidity (RH) in %, the humidity exponent (n), and the preexponential factor, A as

$$t_{TTF} = A \bullet exp^{\left(\frac{E_a}{R \cdot T}\right)} \bullet RH^{(n)}. \quad (9)$$

However, a few research findings have observed that the irreversible interactions between moisture or gaseous species and polymeric materials during real field operations may occur at higher humidity and temperature conditions (Mitterhofer et al., 2020). This can result in hydrothermal degradation due to some unforeseen chemical reactions which demonstrates some non-Fickian behaviours of these polymeric materials. Indeed, some researchers have shown that the Fickian models have not predicted the diffusion process in some encapsulants perfectly as compared to non-Fickian models. It is believed that moisture ingress could lead to the introduction of N-CO-N and C-O functional groups into the polymer chemical morphology or dehydration in some polymeric materials with significant additives, which can lead to many forms of degradation (Yang et al., 2020). These and other factors limit the reliability of the Fickian models. This has led to a search for a more reliable way of profiling the diffusion behaviours of PV module encapsulants.

Mitterhofer et al. (2020) developed a new non-Fickian 2-dimensional finite-element model using four different encapsulants based on in-situ humidity measurements after the encapsulants were exposed to transient humidity conditions. The scheme of their experiment by using humidity sensors is shown in Fig. 12. They argued that the simulation parameters from their experiment could be used to precisely define moisture ingress (20–80% RH) and egress (40–20% RH) profiles for PV devices. However, they also observed a deviation of the egress curves under higher humidity conditions. Immersion techniques have also been explored by a few researchers for the same purpose (Nagayama et al., 2020).

According to Ballif et al. (2014), apart from the permeation techniques, the capacitance embedded sensor measurements, FTIR, dynamic vapor sorption (DVS), and calcium (Ca) spot oxidation experiment could be used to determine the moisture ingress into PV modules. Nonetheless, they were quick to point out that all of these methods have their specific limitations. Capacitance embedded sensor methods are limited by long time drifts and lower operational temperatures (typically below 70℃) as the sensor needs to be imbedded in the encapsulant.

FTIR gives optimal results with only optically transparent samples and are ideal for PVB encapsulants. DVS is best for measuring moisture ingress in bulk materials and not in multilayered materials such as backsheets. Ca spot technique is best suited for materials with low WVTR such as ionomer encapsulants and as such excellent for qualitative, but not quantitative tests.

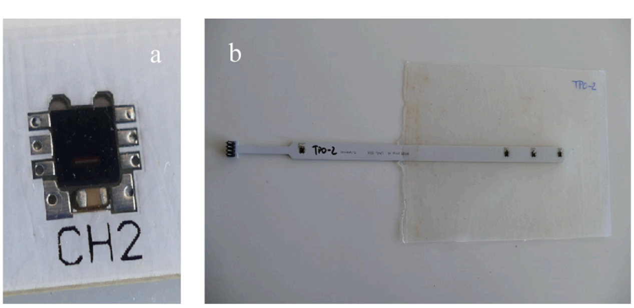


Fig. 12. A prototype in situ humidity sensor with (a) miniature sensor and (b) sensor strip in the encapsulant. .
Adapted from Mitterhofer et al. (2020)

4.1.1. Permeation based techniques

The water vapour transmission rate depends on the material properties (diffusivity, permeability, and solubility), thickness, temperature, and saturated water vapor pressure (Hu and French, 2019; Hülsmann and Wallner, 2017; Wisniewski et al., 2019).

KEMPE (2006) used water vapor transmission rate technique to measure several 12 cm diameter EVA films between 0.46 mm and 2.84 mm thickness. He used the data he obtained from these measurements together with meteorological data to perform a one-dimensional finite element analysis to determine the transient moisture concentration within a breathable backsheet and a double glass laminated PV module. He concluded that due to the high diffusivity of EVA, modules with EVA encapsulants are limited in preventing moisture ingress from the perimeter for the 20 – 30-year warranty lifetime of PV modules. He also argued that prevention of moisture ingress could only be achieved significantly by using encapsulants with very low diffusivity or perfect desiccant filled sealants. In another study, Hülsmann et al. (Köhl, 2013) employed a simulation based on parameters from WVTR tests to predict the moisture ingress into wafer-based PV modules under extended periods of exposure in four different climates. Their test modules were made from PET- based and PA- based backsheets and EVA as the encapsulating material. They observed a common similarity between their results and the results from already published articles (Jorgensen et al., 2006; KEMPE, 2006; Kim and Han, 2013).

In a related work, Hülsmann and Wallner (2017) using the WVTR tests studied the moisture permeability characteristics of different encapsulant and backsheet materials as a function of temperature. They found that WVTR tests are suitable for predicting moisture ingress in different encapsulants and under varying temperature conditions. Similarly, Wisniewski et al. (2019) also used the WVTR technique to determine the diffusivity, moisture concentration, solubility, and permeability of a 510 μm EVA film and concluded that moisture ingress depends on temperature and the moisture content of the EVA layer.

In addition, Meitzner and Schulze (2016) employed a gravimetric technique and the WVTR tests to investigate moisture barrier capability of polyvinyl butyral, PVB encapsulant. The parameters they obtained can be used for numerical simulation of the moisture ingress into PV modules when meteorological data is available.

4.1.2. Gravimetric methods

Gravimetry is when a sample is placed in a climate chamber and is intermittently taken out of the chamber to study the weight changes of the sample. Traditionally, gravimetric methods were used to determine the solubility and diffusivity of any encapsulant, for instance EVA. Then the moisture concentration within the encapsulant together with the moisture transmission rate can be determined directly from the measured solubility and diffusivity values (Dadaniya and Datla, 2019; Oreski et al., 2017). However, the moisture diffusion characteristics of polymeric materials, e.g., EVA is complex and cannot be determined reliably especially with the conventional gravimetric techniques without making considerations and adjustments. In one study, Swonke and Auer (2009) investigated the moisture barrier quality of different PV encapsulants, namely EVA, PVB, an ionomer, and thermoplastic polyurethane and silicone under varied climatic conditions. They observed that the water storage capacity of the silicone and the ionomer as compared to the other encapsulation materials is negligible.

In another work by Oreski et al. (2017), they employed an isostatic gravimetric method to investigate the influence of acetic acid transmission rates on laminates and single layers of backsheets (PET, PA, PVF, PVDF, and aluminum). They concluded that the acetic acid transmission rate strongly depends on temperature, layer thickness, and film composition. They also found that the acetic acid permeation rate of PET-core-backsheets is determined by the PET core layer, whilst an additional aluminum layer within the backsheet has insignificant barrier effect. In addition, they observed that acetic acid retention by EVA layers in a PV module is insignificant due to the high acetic acid transmission rate of EVA. Finally, they argued that "breathable" backsheets enhance the diffusion of acetic acid out of a module, thereby enabling guarantee performance and reliability of PV modules of this design type over a longer time span.

More recently, Dadaniya and Datla (2019) employed a finite element method based on an in-situ gravimetric measurement technique to study the effects of temperature on the moisture ingress into PV modules. They demonstrated (using Delhi outdoor and accelerated environments) that moisture concentration at the edges of the modules depends strongly on the period and index of exposure. They also argued that, using their method, at a location 50 mm from the perimeter of the module, 1000 h of damp heat ageing can be equated to 339 days of outdoor exposure.

4.2. Detection methods based on degradation products

Permeation and gravimetric methods are used to predict the moisture and gaseous absorption characteristics of encapsulants and backsheets. However, these parameters are only used for material engineering purposes. More of a concern is the environmental and climatic conditions which are highly unpredictable and are almost impossible to control in real conditions. As a result, modules with even perfect hermetic designs are limited in preventing moisture ingress effectively (KEMPE, 2006; La Mantia et al., 2016; Hu and French, 2019). Therefore, diagnosis prior to degradation in electrical performance of the module is very important for predicting module durability and reliability (Köntges et al., 2020). As such, there have been efforts within the photovoltaic community towards early detection of moisture ingress into PV modules in order to put in place effective mitigation plans to avert the phenomenon and its effects (Kim et al., 2013; Klemchuk et al., 1997; Kumar et al., 2019; Schlothauer et al., 2012; Sinha et al., 2017).

Analytical methods for analyzing moisture ingress associated degradation (especially encapsulants, solar cells and other PV components degradation) on a molecular level are based on chemical degradation products (Köntges et al., 2014). These methods can be destructive or non-destructive in nature. Table 6 highlights some techniques for detecting moisture ingress in PV modules and their advantages.

Usually, visual inspection and I-V characterization are employed together with EL spectroscopy, PL spectroscopy, dark lock-in thermography (DLIT), ultraviolet fluorescence (UV-F) spectroscopy, and a variety of spectroscopic methods to investigate degradation mechanisms associated with moisture ingress and their effects (Kumar et al., 2019).

In the 1990s, Klemchuk et al. (1997) investigated the discolouration of several EVA based encapsulated field-aged modules and concluded that discolouration of encapsulants was due to chemical reactions between cross-linking peroxides and stabilizers and possible photobleaching of the encapsulants. They employed TGA, FTIR, Raman spectroscopy, GC/MS, GWFID, XPS, and SEM-EDX for their investigation.

In another study, Peike et al. (2011) studied the degradation behaviour of two EVA encapsulated c-Si PV modules after damp heat and combined humidity-UV tests using Raman spectroscopy. They observed lateral non-uniform fluorescence and C-H stretching vibration intensities of the EVA, and indication of additive degradation products of moisture. They concluded that their observation could be an indication of moisture diffusion into the encapsulant. Rashtchi et al. (2012) studied the practicability of using a combination of FTIR and spectroscopic optical coherence tomography (SOCT) to measure water concentration of the EVA layer within PV modules. They argued that absorbed water within different layers in the PV module could be quantified using SOCT which provides in-depth resolved spectral information on the state of the module. Furthermore, Kim and Han (2013) investigated the moisture-induced degradation mechanisms in multicrystalline silicon modules under accelerated test conditions using EL imaging, Dark I-V, Suns V_{oc} measurements, SEM-EDX and AES. They observed a power drop due to corrosion of the solder joints due to moisture ingress, and an increment in the oxide concentration on the metal electrodes after the accelerated ageing tests.

Recently, Kumar et al. (2019) explored the effects of moisture induced degradation in c-Si PV modules under damp heat ageing tests using electroluminescence, dark lock-in-thermography, and scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDS) imaging techniques. They observed moisture induced conditions such as tin migration at the finger-wafer interface and formation of silver oxide at cell cracks and edges as the dominant chemical mechanisms, and loss in interfacial adhesion between wafer, encapsulant and fingers. They also argued that the ribbon interconnects served as an active site for deposition of oxides from the solder material, and the aluminum electrode served as an electrolyte in the presence of moisture. They concluded that increase in series resistance is the main parameter that characterizes all forms of chemical degradation. Fig. 13 shows some of their SEM-EDS results.

Meyer and Van Dyk (2004) believe cell degradation may manifest itself in the form of high series resistance, shunting, and deterioration of the antireflection coating. EL and PL techniques are reliable for spatially resolved determination of the series resistance as both techniques rely on luminescence signals emitted from degradation products from polymeric components (Trupke et al., 2012). Fig. 14 shows an EL image from a test material after exposure to varying damp heat conditions illustrating corresponding dark regions due to solar cell and electrode degradation (Kim et al., 2013). This is because the degraded areas conduct little or no electrons.

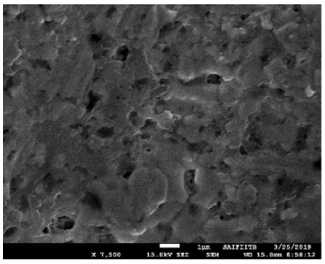
In another study, Sinha et al. (2017) utilized a spatially resolved infrared thermography to investigate delamination, corroded interconnects and other electrical losses in a PV module. In the same work, they also used the EL imaging to estimate the severity of encapsulant discolouration, finger, and cell cracks. Similarly, Roy and Gupta (2019) employed EL and DLIT techniques to study the severity of shunts in commercial c-Si PV modules and argued that these techniques could be used to investigate the state of shunts in PV modules.

Most often, EL imaging requires an alteration in the system circuit layout, can only be done effectively in the night or at twilight, and applications in outdoor test facilities are still under investigation (Köntges et al., 2020; Trupke et al., 2012). Hence, PL imaging which is also based on the detection of degradation products of the polymeric encapsulant, usually EVA, is preferred (Morlier et al., 2017). However, it is highly reliant on the excitation source and can give unwanted luminescence contribution from spurious sources such as the antireflection coating (Paduthol et al., 2018). For the detection of defects and fault modes, including cracks and moisture ingress, the ultraviolet UV-F is very promising (Köntges et al., 2013; Morlier et al., 2018; Köntges et al., 2020).

In PV modules, the polymeric materials such as EVA can degrade into fluorescent species when exposed to environmental stressors and chemical species, see Fig. 15. In the presence of ingressed moisture and other gaseous species such as oxygen, the fluorescent degraded species

Table 6
Some techniques for detecting moisture ingress in PV modules.

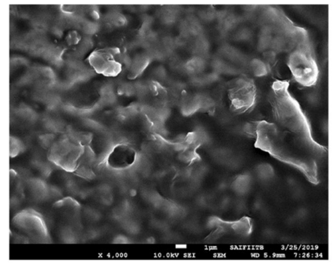
Testing type	Testing techniques	Advantages of test type
Destructive	FTIR, Raman, XPS, SEM-EDX, AES, AFM, TGA, and SOCT spectroscopy	Well established Detailed investigation Assesses the effects of different testing methods on test coupons
Non-destructive (based on degradation products)	Visual inspection, I-V imaging, (EL, PL, UV-F) spectroscopy, DLIT	Equipment is easy to operate Defects can be detected without damaging test coupons Quick and accurate



(a)

Element	Atomic%
Oxygen	41.83
Carbon	21.34
Silicon	4.41
Silver	28.04
Tin	0.00
Lead	0.11

(b)

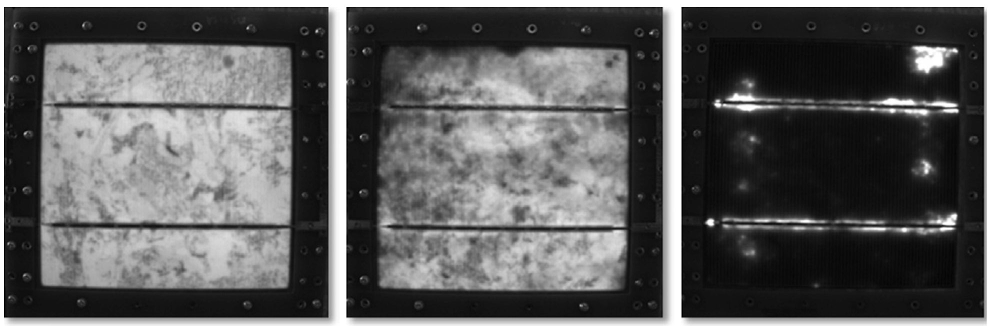


(c)

Element	Atomic%
Oxygen	20.80
Carbon	53.80
Silicon	3.29
Silver	20.46
Tin	0.00
Lead	1.43

(d)

Fig. 13. SEM-EDS results of DH testing of fingers on cell edge: (a) SEM image and (b) EDS results; and cracked regions on cell: (c) SEM image and (d) EDS results. Ingress of moisture and gases might have accounted for higher fractions of oxygen, silver, and carbon as shown in (b) and (d). .
Adapted from Kumar et al. (2019)



(a) 45 °C, 85% RH (b) 65 °C, 85% RH (c) 85 °C, 85% RH

Fig. 14. An EL image of a test PV module after 3500 h damp heat tests. Darker areas indicate degradation, possibly due to moisture ingress, and cracks. .
Adapted from Kim et al. (2013)

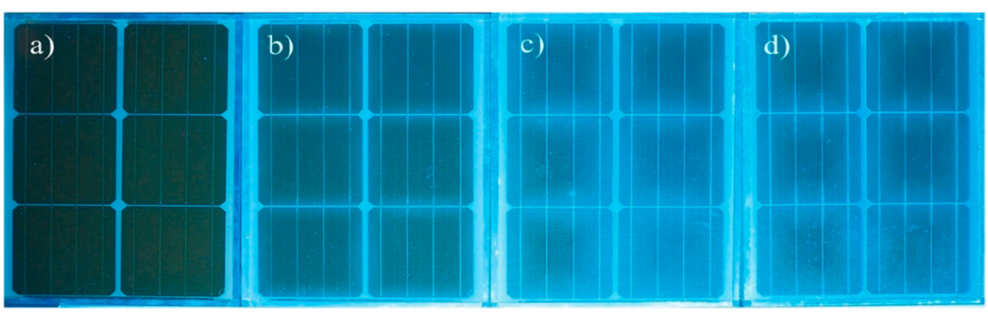


Fig. 15. UV-F signatures of a test PV encapsulants at 85℃ / 85% RH after: (a) original state, (b) 1000 h, (c) 2000 h, and (d) 3000 h tests. The increasing brightness of samples from left to right corresponds with increasing degraded fluorescent species with exposure time. .
Adapted from Eder et al. (2019)

undergo metamorphoses to nonfluorescent species, that is photobleaching (Morlier et al., 2018). These nonfluorescent species from the photobleaching marks areas around and within the module show darker traces when exposed to UV-F (Köntges et al., 2013; Morlier et al., 2017; Köntges et al., 2020).

This makes UV-F one of the most powerful tools that can be used to investigate defects and fault modes such as solar cell cracks, moisture ingress and its effects in PV modules based on the degraded products induced by the presence of moisture or gaseous species in the module.

5. Mitigation techniques

Controlling moisture ingression into PV modules will ensure the durability and reliability and therefore boost the marketability of PV devices substantially (KEMPE, 2006). There has been significant work within the scientific community to understand and develop possible mitigation strategies for preventing or delaying moisture ingress in PV modules. Investigations on the material properties of the major encapsulants (Kempe et al., 2014; Oreski and Wallner, 2005), the use of edge sealants (Bag et al., 2016; Kempe et al., 2018) and humidity sensors (Jankovec et al., 2016; Mitterhofer et al., 2020; Miyashita et al., 2012; Reese et al., 2011), developing intricate PV configurations with breathable backsheets (KEMPE, 2006), and making PV devices with high substrate adhesion and super hydrophobic materials on the surfaces have been explored and are still under serious investigation (Bosco et al., 2019; Novoa et al., 2016). A collection of some literature on barrier materials is illustrated in Fig. 16. The figure indicates that ionomer possesses the best moisture barrier potential has better prospects for PV applications.

In addition, the moisture barrier properties of encapsulants could be improved significantly when they are used together with edge seals such PIB sealants (Kempe et al., 2018), On the other hand, PA, PET, and TPT

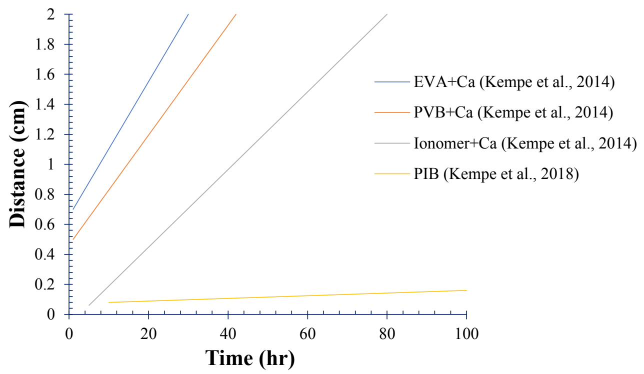


Fig. 16. Moisture barrier resilience of some edge sealants. Data extracted from Kempe et al. (2014) and Kempe et al. (2018).

encapsulants and backsheet have better moisture barrier properties than even a desiccant stacked edge sealed EVA (Hülsmann et al., 2014; Köhl, 2013). Marais et al. (2001) investigated the effect of moisture and gas (oxygen and carbon dioxide) transport through various blends of EVA with varying vinyl acetate (VA) contents. They found that, in the case of water, permeation rates increase with higher VA content whilst the gas permeation rate is unaffected even with varying contents of VA. As such, EVA with lower VA contents can limit the ingression of moisture into PV modules. In another study, Czyzewicz and Smith (2011) developed ionomer-based encapsulants with superior electrical, mechanical and moisture barrier properties with a possibility of making modules without supplementary edge seals. They argued that their developed ionomer-based encapsulant, with superior moisture barrier properties can be a solution to the problem of moisture ingression into PV modules.

Kim and Han (2013) studied the permeation rates in various encapsulants and observed that ionomer encapsulants are the best when considering only their lower moisture diffusivity, but EVA comes top when all characteristics and requirements of a good encapsulant is considered. In Fig. 16, the best moisture barrier material is the PIB base edge sealants proposed by Kempe et al. (2018), which can perform optimally over a vast temperature range. Additionally, Wisniewski et al. (2019) believe that PV modules with EVA films with lower initial water content can delay the time taken by the EVA to reach equilibrium with the ambient environment by two folds.

In an earlier work, Kempe (2005) evaluated the performance of desiccant edge-seal materials in a PV module. They employed an optical method where the reaction of water with calcium was used to quantify and compare moisture ingress into a PV module by exposing different test samples to humidity and heat. They concluded that desiccant filled PIB sealants have the potential to slow down moisture ingress in PV modules. In a related work by the same group, Reese et al. (2011) proposed a method of determining the moisture barrier properties of encapsulants based on the resistivity of Ca films when they undergo hydrolysis. In this process, the conductive Ca film changes to an insulator in the presence of moisture, and hence, the resistivity. Also, Miyashita et al. (2012) used colour changes in cobalt chloride, $CoCl_2$ paper to investigate moisture ingress into PV modules and found out that moisture ingress occurs from the back to the core of the module, but also depends on the WVTR of the backsheet.

Furthermore, Kempe et al. (2014) used a thin film of Ca between two laminated glass pieces for a variety of encapsulant and edge-seal materials to evaluate the ability of these configuration to prevent moisture ingress into PV modules. They found that the Ca-embedded structures are capable of preventing moisture ingress just like desiccant-stacked PIB sealants. They argued that since the best encapsulants are still permeable to moisture, low diffusivity encapsulants are reliable in preventing moisture ingress, in case edge sealants fail. In a related work by the same group, they developed permeation models that could be useful for field applications. They also concluded that molecular sieve desiccants can serve as a good moisture barrier materials when used in PIB based edge seals (Kempe et al., 2018). The synopsis of these results and other related reports in literature are illustrated in Fig. 16. Further, Hardikar et al. (2016, 2014a); (2014b;) using a theoretical framework, studied the moisture barrier performance of edge seals in PV modules based on accelerated testing and historical meteorological data. They concluded that edge sealants are capable of securing modules, even in aggressive environments.

In a related work, Morita et al. (2015) investigated the moisture barrier reliability of organic PV modules using the Ca method proposed by Kempe et al. (2014) and Reese et al. (2011). Test samples were connected to a data acquisition system via signal cables in order to test under varying environmental conditions. An edge card connector (with Ca film) was used to connect samples to the barrier material enabling easy switching of samples in and out of test. They observed a high moisture barrier resilience under conditions of 85 °C / 85% RH. However, they noticed a degradation (which was thought to be due to products from the encapsulant) of the modules, a condition which they believe could be improved by incorporating a vacuum process into the sample preparation procedure.

In other investigations, Jankovec et al. (2018, 2016) proposed an in-situ moisture measuring technique for PV modules using miniature digital humidity and temperature sensors embedded in encapsulants. They were able to test different encapsulants, backsheets, and edge sealants in different PV modules. They believed that using their monitoring technique, module's reliability and durability analysis could be done based on extracting the diffusion coefficients of encapsulants and backsheets after exposure to high humidity and temperature. In another study, Slapsak et al. (2019) developed an in-situ miniature digital relative humidity (RH) sensor based on a wireless radio-frequency identification (RFID) technology which could be used for monitoring moisture concentration in PV modules under indoor and outdoor conditions. They believe that the size of the sensors makes it possible to integrate them into any module design conveniently for reliable extraction of required data.

Most materials used for edge seals are limited by low fracture strength, and therefore are prone to mechanical failure (Han and Kim, 2017; Van der Wel and Adan, 1999; Yang et al., 2020). Hence, delamination or ripping can occur when edge seal environment of the module is subjected to even the slightest stress or strain (Bosco et al., 2019; Marais et al., 2001; Tracy et al., 2018). Kempe et al. (2016) investigated the adhesion characteristics of edge seals with a developed wedge test using glass substrates and PV encapsulants or edge-seal materials under accelerated ageing conditions. They concluded that edge seals barely provide mechanical integrity. Therefore, testing in the final product is necessary in selecting encapsulation materials with optimum barrier characteristics (Kempe et al., 2019; Novoa et al., 2016).

6. Conclusion

The effect of moisture ingress on PV modules has been reviewed. The major environmental and climatic factors such as temperature, humidity, and UV radiation influence moisture ingress into PV modules. In addition, the PV module design and the properties of the polymeric materials also determine how fast a material will equilibrate with ambient humidity conditions during operation. Usually, moisture can enter the module from the perimeter and through cracks and voids created either by manufacturing, transportation, or environmental/climatic stressors. The presence of moisture (inside or outside the PV module) together with high temperature and UV radiation can lead to delamination and discolouration of encapsulants, PID, corrosion of metal contacts, optical loss, solar cell degradation, adhesion loss, and other related material degradation culminating into PV module degradation and loss in power output.

WVTR tests, gravimetric, and immersion methods are used to determine the diffusivity, solubility, permeability, and moisture concentration of polymeric components of PV modules. These parameters together with climatic data can be used in FEM models to predict the moisture barrier properties of PV encapsulation materials. Visual inspection, I-V characterization, (EL, PL, and UV-F) spectroscopy, and DLIT are some of the techniques that can be used to detect moisture ingress in PV devices. In addition, analytical tools such as SEM-EDS, Raman and FTIR spectroscopy have also been explored but are considered destructive techniques.

The use of encapsulant materials with excellent moisture barrier and adhesion characteristics, desiccant-stacked edge seals, and the use of permeable and impermeable PV designs are some of the proposed ways of preventing moisture ingress into PV modules. Embedded moisture sensors, calcium films (based on resistivity), and cobalt chloride paper strips (based on colour changes) could also be used for detecting moisture ingress in PV devices. Unfortunately, the complexity of the moisture ingress phenomenon itself, especially in real field operations under transient multiple factors, means there is yet to be an established reliable way to predict, detect, and prevent moisture and gaseous ingress into PV devices.

A solution to moisture ingress into PV devices will be a solution to most PV module degradation mechanisms. In this regard, focused research into encapsulant materials with optimal moisture barrier properties and desiccant-stacked edge seals for PV applications will be promising. When this is achieved, more power over the lifetime of PV modules can be expected, and hence, lower cost per peak watt (W_p) for electricity from PV devices.

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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