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Predicting moisture-induced degradation of flexible PV modules in the field

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ABSTRACT

Establishing the reliability of PV modules for a typical warranty period of ~25 years is challenging because of several failure mechanisms that can be triggered during outdoor exposure. A critical failure mechanism for PV modules is the degradation in performance as a result of exposure to temperature and humidity. In the case of flexible PV modules, moisture-induced damage becomes a greater concern, since the moisture resistance of barriers and polymer packaging is expected to be lower than that for conventional glass–glass PV products; hence developing a means to assess the field performance of flexible PV modules is essential. The time to failure of a PV module attributable to moisture-induced damage under given field conditions involves multiple factors, including the moisture resistance of the front/back sheets, the encapsulant and edge seal, and the degradation rate of particular solar cells when exposed to moisture. The work presented here is aimed at establishing, through the use of accelerated testing, the field lifetime of flexible PV modules with regard to moisture-induced degradation. A semi-empirical framework for such an assessment is developed using a combination of empirical and analytical models. Testing at different temperature and humidity conditions is carried out for representative flexible copper indium gallium selenide (CIGS) module configurations. The test results highlight the limitations of accelerated testing methodology for high-moisture-barrier systems. In particular, it is shown that for the high-moisture-barrier systems tested, the test times can become prohibitive for establishing humidity dependence through accelerated testing. Through the use of an analytical model, a method is proposed to translate test results to field performance using typical meteorological year (TMY) data.

Introduction

The degradation in performance of PV modules as a result of moisture ingress is a concern that has been raised for c-Si modules as well as for other PV technologies [1]. With the increasing interest in building-integrated photovoltaic (BIPV) products that demand light weight and flexibility, the use of non-glass barriers for PV products is inevitable. Moisture ingress concerns are even more critical in this case than for conventional glass–glass products, since the moisture barrier performance of polymer-based packages is expected to be lower than that of glass products. Some solar cell technologies, in particular copper indium gallium selenide (CIGS), are considered more prone to moisture-induced damage than c-Si, although c-Si modules are not completely free of these concerns.

“The moisture barrier performance of polymer-based packages is expected to be lower than that of glass products.”

The degradation of polymer-encapsulated electronic components is also a concern in the consumer electronics industry, where critical components such as electronic displays and IC metallization may be at risk of performance degradation and failure because of moisture ingress and corrosion [2–3]. One factor that distinguishes degradation concerns and the assessment of field performance for PV modules, as compared with consumer electronics products, is the vast difference in expected product lifetime. While the typical timescale for assessing the performance of consumer electronics products is ~3–5 years, PV modules need to have a field performance assessment covering a typical warranty period of ~25 years. This makes the development of a means of assessing the long-term reliability of flexible PV modules quite critical.

There have been several attempts in the past to develop techniques and models to predict the life of PV modules with moisture ingress as a proposed mechanism leading to failures or degradation in performance [4–8]. For consumer electronics products, a typical approach to characterizing the field performance of encapsulated electronic components, based on accelerated testing with exposure to temperature and humidity, is an empirical approach commonly referred to as the *Hallberg-Peck model* [9–11]. While it may seem conceivable that a similar approach can be taken to assess the field performance of flexible PV modules, this approach is not well established or validated for PV products. The Hallberg-Peck model is an empirical corrosion model, and its successful application to PV products can depend on whether or not the degradation in PV packages can be considered similar to corrosion mechanisms in encapsulated electronic components and metallization. Although there may be similarities which would suggest that such an approach is possible, the details of failure can differ between the two types of system. In particular, the barrier level of the packaging system for a PV module, and the manner in which a particular type of solar cell degrades when exposed to temperature and humidity, may be dramatically different from those of typically packaged electronic components.

In all of these scenarios, predicting the time to failure of the product on the basis of a threshold degradation level due to moisture ingress hinges upon the combination of two factors: the moisture barrier performance and degradation of the encapsulated components when exposed to moisture. A third factor involved in these predictions is the development of schemes to model fluctuations of ambient conditions to which the product is subjected during its lifetime, and relating these variations to the test conditions [5]. The charter of this paper is to explore a methodology based on relationships such as the Hallberg-Peck model for the assessment of the field performance of flexible

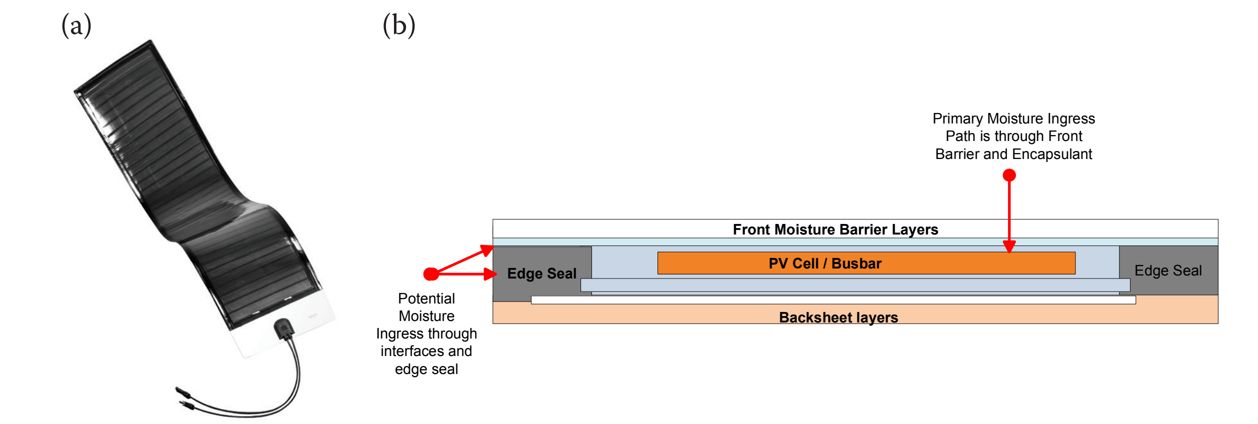

Figure 1. (a) Flexible PV module; (b) potential moisture ingress paths for this type of module.

PV modules with regard to moisture-induced degradation, using the results from accelerated testing. Candidate module configurations chosen for testing are CIGS thin-film flexible modules with different moisture barrier performance levels.

Fig. 1 shows a representative flexible PV module, and illustrates several potential moisture ingress paths that can be present in the system. In order to assess the moisture resistance of the product, it is important to understand the following:

1. The resistance of the edge seal alone to moisture ingress.

2. The resistance of the moisture barrier to moisture ingress.

3. The moisture ingress near the edges of the module, where the ingress through the edge seal may be modulated by the presence of interfaces susceptible to moisture penetration.

For the regions of the module near the edges, points (1) and (3) above are critical, whereas in the case of a sufficiently large module, the moisture ingress near the centre of the module is governed by (2).

A methodology for assessing the moisture resistance of the edge seal was developed for a glass–glass module by Hardikar et al. [12]. That method was based on an analytical model that was developed using the solution to a 1D diffusion equation; the model was validated by appropriate test results, and provided a method for assessing the field performance of the edge seal on the basis of the results of accelerated testing.

In the present work, the experience gained from the results in Hardikar et al. [12] is used in conjunction with additional testing to decide upon the preferred dimension of the edge seal. The objective of these initial tests is to ensure that, for the chosen configurations, the dimension of the edge seal is such that the moisture ingress at the edges is sufficiently delayed and that the primary moisture path of concern is through the front barrier. Once this is ensured, further work can be carried out using appropriate edge seal configurations to characterize the performance degradation of a PV device when exposed to controlled temperature and humidity conditions. The results of this testing are then analysed to assess the field performance.

The rest of the paper is organized as follows. First, a candidate empirical model (Hallberg-Peck) and an analytical model are described, which form the basis of the experimental plan. This is followed by a description of the experiments performed, of which there are two sets: 1) measurements of barrier diffusivity, and 2) accelerated testing of flexible module samples, with performance monitoring. Finally, a method is presented for assessing the field performance of the product (on the basis of moisture-induced damage only) using the results of accelerated testing in a manner consistent with the model developed. The limitations of such testing and prediction are discussed, along with recommendations for further work.

Modelling moisture-induced degradation

As stated earlier, the degradation in performance of a PV module attributable to moisture-induced damage depends on several factors. The key factors affecting this degradation are: 1) the moisture resistance of the packaging, and 2) the degradation of a particular solar cell when exposed to temperature and humidity.

The degradation of a particular cell when exposed to moisture will depend on the cell architecture and how moisture reacts with the components of the cell. A separate cell-level study, comprising either a characterization of the materials involved or appropriate modelling of reactions, is required in order to assess this degradation. However, as far as the characterization of product performance is concerned, one may take an empirical approach in which the degradation is measured and empirically modelled, without recourse to a detailed analysis of the mechanisms leading to this degradation. The approach taken in this study is based on a semi-empirical model in which the details of the mechanisms causing cell degradation are not modelled but are instead accounted for through assumptions which need to be verified later. The success of this approach depends on whether or not the implications of these assumptions and subsequent analyses can predict trends that are consistent with experimental results.

Empirical model for time to failure (Hallberg-Peck Model)

In the analysis of failure due to moisture for plastic- or epoxy-packaged electronic devices, it is customary to use an empirical approach for assessing field performance on the basis of the results of accelerated testing. The failures of interest are driven by moisture diffusing through epoxy-type packaging and ultimately driving component failures by corrosion. Typical timescales for which these predictions are desired correspond to the expected warranty period of approximately three years for these products. The approach is based on relationships proposed in the literature [9–11]; the empirical relationship used has the form:

$$TTF = A(RH)^n \exp\left(\frac{\varepsilon_a}{kT}\right) \quad (1)$$

where

TTF = time to failure when exposed to temperature T (K) and relative humidity RH

A = constant, to be obtained empirically

n = humidity exponent, to be obtained empirically (expected to be negative)

ε_a = effective activation energy (eV), to be obtained empirically

k = Boltzmann constant = 8.617×10^{-5}eV/K

It should be noted that Equation 1 can be written in the form of an acceleration factor AF for translating test results to field conditions:

$$AF = \left(\frac{RH_{\text{field}}}{RH_{\text{test}}}\right)^n \exp\left[\frac{\varepsilon_a}{\text{k}}\left(\frac{1}{T_{\text{field}}} - \frac{1}{T_{\text{test}}}\right)\right] \quad (2)$$

Note that in order to exploit Equation 2, the field conditions used need to correspond to equivalent constant temperature and relative humidity conditions. For most indoor applications of consumer products this is not too difficult. It should be noted that this model is based on corrosion failures of encapsulated metallization. The empirical relationship has been demonstrated to correlate to a wide range of data relating to epoxy-based encapsulated metallization [9–11].

It is also worth noting that in Peck [11] this empirical model has been applied to applications involving semiconductor products in a military environment with a timescale of ~10 years. Peck [11] also provides recommended values for the range of effective activation energy and humidity exponents that can be used in such applications; in particular, the relative humidity exponent is expected to be negative, implying that as the relative humidity decreases the time to failure from moisture-induced damage increases.

While the use of this approach is well established for consumer electronics products, this is not the case for PV applications. It is the authors' belief, however, that such an approach may also be reasonable for the assessment of the long-term field performance of PV modules with regard to moisture-induced damage. In order to establish the validity and obtain the model parameters, namely the effective activation energy and humidity exponent, modules of identical construction need to be tested in controlled temperature and humidity conditions (i.e. for different temperatures at a constant relative humidity, and for different relative humidity values at a constant temperature).

Before such a test plan is discussed, a few points are worth noting. First, the degradation of PV cells in the presence of moisture can be thought of as somewhat similar to corrosion failures of encapsulated metallization, since the degradation is expected to be dependent on the reaction between moisture and the materials that constitute the PV cell. In addition, moisture-induced degradation of a PV module involves the diffusion of moisture through packaging materials, as well as the subsequent reaction with the cell in a manner similar to the way in which consumer electronics products might experience moisture-induced failures. It is acknowledged that the details of the reactions and failure mechanisms can differ between applications. Moreover, independently of moisture, for PV cells there can be other failure mechanisms based on temperature alone that can be different in nature from the degradation of electronic components exposed to temperature.

For flexible CIGS PV applications, the moisture barrier used needs to have a low water vapour transmission rate (WVTR) of less than 10^{-4}g/m^2/day. In particular, the moisture resistance of a flexible PV front sheet needs to be very high compared with that of epoxy packaging in semiconductor products, so that the front sheet can withstand the aggressive outdoor environmental exposure over long timescales. The expectation for a PV package is that the amount of moisture reaching the PV cell with such exposure will be very small in order to guarantee a lifetime of ~25 years. As a result, the humidity exponent and effective activation energy values that are recommended in Peck [11] may not work very well for PV packages. Thus, although the similarity in the two applications is compelling enough to consider this approach for a long-term reliability assessment, adequate testing and validation is warranted. In lieu of a full justification for the use of the Hallberg-Peck model in PV applications, an analytical model was first developed to explore the plausibility of an expression such as Equation 2 holding good for flexible PV module degradation attributable to moisture.

Analytical model and functional form for the acceleration factor

The diffusion of moisture through a barrier material is a process which involves the adsorption of moisture on the exposed surface, followed by the diffusion of moisture through the barrier. The primary driving force for any diffusion process is the concentration gradient of the diffusing species (Fick's Law). Typically, the maximum concentration of moisture at the exposed surface is a function of the solubility of the material. The propagation of moisture through the barrier is a function of the diffusivity of the material.

As discussed earlier, once the configuration of the edge seal has been judiciously chosen, the primary moisture ingress path for a PV module is through the front barrier. This moisture ingress can be modelled using a 1D diffusion equation. For the high-barrier system used in PV modules, the moisture emerging near the solar cell after passing through the barrier and encapsulant is assumed to be consumed through a reaction with the materials constituting the PV cell, such as transparent conductive oxide (TCO) or CIGS material. This leads to a candidate model described by the following initial boundary value problem (see Fig. 2):

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \quad (3)$$

$$C(x,0) = 0; C(x=0,t) = C_1; C(x=l,t) = 0 \quad (4)$$

where

x = distance from the exposed surface

t = time

$C(x,t)$ = moisture concentration at position x at time t

D = diffusivity of the material between the exposed surface and the PV cell

l = effective thickness of the medium through which moisture diffuses between the exposed surface and the PV cell

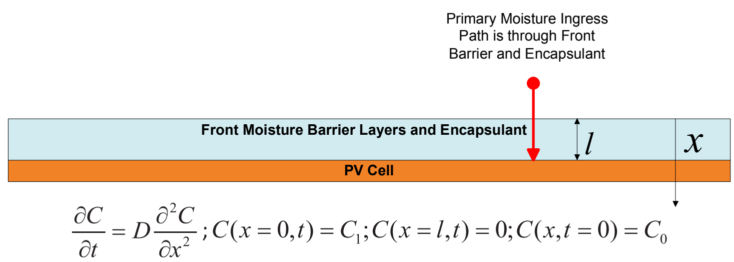

Figure 2. Illustration of the boundary value problem used in developing the analytical model.

It should be noted that the boundary condition at $x = l$ is based on the assumption that the moisture arriving at this location is consumed through the reaction with PV cell, whereas the boundary condition at $x = 0$ is governed by ambient conditions. It can be shown [13] that this initial boundary value problem can be solved analytically, and the solution is given by:

$$C(x,t) = C_1\left(1-\frac{x}{l}\right) - \frac{2}{\pi}\sum_{1}^{\infty} C_1 \frac{\sin\left(\frac{n\pi x}{l}\right)}{n} \exp\left(-\frac{Dn^2\pi^2 t}{l^2}\right) \quad (5)$$

From this solution, the flux of the moisture reaching the PV cell can be evaluated analytically using $\left.\frac{\partial C}{\partial x}\right|_{x=l}$. The expression for the amount of moisture Q_t reaching the cell in time t can be obtained by integrating the flux up to time t. The resulting expression is available in Crank [13] and is given by:

$$\frac{Q}{lC_1} = \frac{Dt}{l^2} - \frac{1}{6} - \frac{2}{\pi^2}\sum_{1}^{\infty}\frac{(-1)^n}{n^2}\exp\left(-\frac{Dn^2\pi^2 t}{l^2}\right) \quad (6)$$

Fig. 3 shows the variation of the quantity of moisture Q_t reaching the PV cell over time t (non-dimensional quantities are used on the two axes). Now, it may be assumed that the degradation in performance of the PV cell up to time t due to reaction with moisture is proportional to the quantity of moisture that has reached the cell through the diffusion process. This assumption, however, needs to be validated by some means. One possible way is to provide a mechanistic understanding of the reaction between moisture and the PV cell, and the subsequent relationship of this reaction to the performance degradation. Another approach is to examine the implication of this assumption, namely study the trends it implies and then validate those trends by means of experimental data. In the study reported here, the latter approach is preferred, since the primary purpose is to provide a model for the assessment of product performance.

On the basis of the assumption that the degradation in performance of a PV module up to time t due to moisture ingress is proportional to the amount of moisture reaching the PV cell up to time t, and using the result in Equation 6, the following dependencies can be inferred:

1. The series in the solution given by Equation 6 converges rapidly. In fact, one can see that even a one-term approximation of the infinite series can be satisfactory for practical considerations with $t \sim l^2/D$. For the representative values $l \sim$ 1mm = 0.1cm and $D \sim 10^{-9}\text{cm}^2/\text{s}$, the characteristic time is 2780 hours. From Equation 6 and the plot in Fig. 3, the performance degradation of the PV module, as characterized by the percentage change in power (equivalently, the amount of moisture consumed at the cell surface), can be expected to be linear in time, i.e. $\Delta P/P \propto t$.

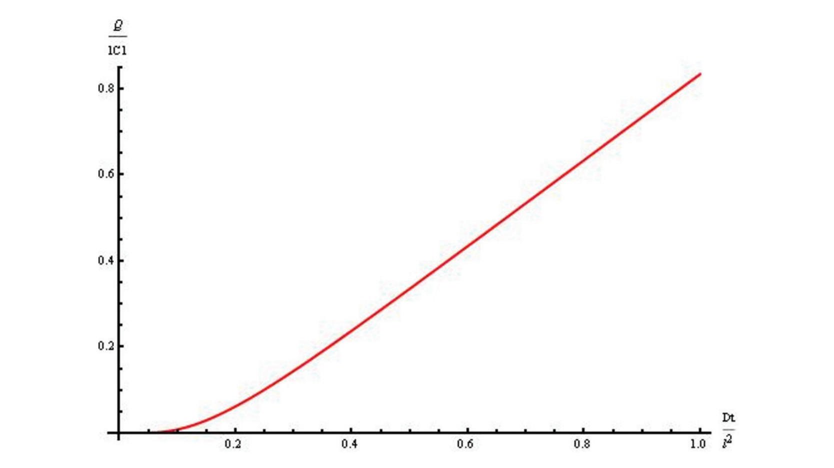

Figure 3. Quantity of moisture reaching the PV cell as a function of time.

2. The approximation for the expression in Equation 6 and the observed approximate linear behaviour in Fig. 3 imply that the degradation in performance may be expected to be approximately linear in diffusivity D. It is known that the diffusivity varies with temperature following an Arrhenius relationship:

$$D = D_0 \exp\left(-\frac{\varepsilon_a'}{kT}\right) \quad (7)$$

This implies that the degradation in performance can be expected to have an Arrhenius dependence on temperature (using an effective activation energy ε_a, which in principle can differ from the activation energy ε_a' for the diffusion coefficient):

$$\frac{\Delta P}{P} \propto \exp\left(-\frac{\varepsilon_a}{kT}\right) \Rightarrow TTF \propto \exp\left(\frac{\varepsilon_a}{kT}\right) \quad (8)$$

3. From Fig. 3, one can infer that the quantity of moisture Q_t reaching the PV cell is linear in external concentration C_1. If the reaction between moisture and PV cell material is assumed to be first order, and the degradation in performance of the PV cell is assumed to be proportional to the extent of the reaction, it would be concluded that the degradation in performance of the PV cell due to moisture is proportional to the external concentration. On the basis of the discussion in Klinger [14], if the concentration of moisture on the surface is expressed in terms of a single variable independent of temperature, then there is reason to believe that the variable chosen should be relative humidity. If the temperature dependence is accounted for through an Arrhenius relationship, such as in Equation 8, the concentration dependence must be accounted for through relative humidity. Hence it may be conjectured that:

$$\frac{\Delta P}{P} \propto (RH) \Rightarrow TTF \propto (RH)^{-1} \quad (9)$$

Note that the exponent '–1' can change depending upon the assumption regarding the order of the reaction of moisture with the cell material.

4. When the above dependencies are combined, the functional form obtained for the time to failure of a flexible PV module based on this semi-analytical model is:

$$TTF = \mathrm{A}(RH)^{-1}\exp\left(\frac{\varepsilon_a}{kT}\right) \quad (10)$$

The corresponding form for the acceleration factor is:

$$AF = \left(\frac{RH_{\text{field}}}{RH_{\text{test}}}\right)^{-1}\exp\left[\frac{\varepsilon_a}{k}\left(\frac{1}{T_{\text{field}}} - \frac{1}{T_{\text{test}}}\right)\right] \quad (11)$$

In summary, the semi-analytical model presented here provides a plausible approach to establishing a Hallberg-Peck type of relationship for the acceleration factor in analysing moisture-induced damage in flexible PV modules. The key point of the above discussion is that the test plan for analysing moisture-induced failures in flexible PV modules should be geared towards examining temperature and humidity dependence, by testing identical module constructions in different temperatures at the same relative humidity, and for different humidity values at the same temperature in order to obtain the effective activation energy and RH exponent.

> "The analytical model provides a means of assessing the expected values of activation energy and humidity exponent."

While one must resort to extracting effective activation energy values and humidity exponent from experimental data, the analytical model provides a means of assessing the expected values of activation energy and humidity exponent; in other words, the activation energy is expected to be similar to the activation energy for the diffusion coefficient of the barrier material, whereas the relative humidity exponent is expected to be –1 on the basis of an assumed first-order reaction between moisture and the PV material. The relative humidity exponent could be different from –1, but will be a negative value, depending on the details of the reaction. The activation energy will be dominated by the barrier diffusion if that is the rate-limiting step in the degradation process. In theory, the activation energy associated with degradation can be different from that for the barrier diffusion and needs to be verified by appropriate experimental data.

Experimental set-up, results and analysis

Two sets of experiments were performed in this study. First, the barrier material permittivity, diffusivity and solubility were measured at different temperatures through tests carried out at MOCON. The second set of experiments involved testing sample PV modules of identical construction at different temperature and humidity conditions. As stated earlier, a set of experiments was initially undertaken to establish the width of edge seal required to ensure that the primary path of moisture ingress for the samples (and for the corresponding product) was through the front barrier and not through the edges. The work in Hardikar et al. [12] indicates that (for their desiccated butyl edge seal, which is identical to that used in this study) the edge seal width of ~10mm or greater is sufficient to delay moisture ingress beyond a typical warranty period of 25 years for a glass–glass product, even in aggressive field conditions such as in Bangkok. Extending that work further determined that an edge seal width greater than 14mm ensures that the moisture breakthrough from the edge does not influence the test for a flexible product, since in that particular assembly the primary moisture ingress path is through the front barrier.

Measurement of barrier properties

In order to characterize the moisture resistance of barrier materials, it is customary to measure their WVTR; typically, this characterization begins with measurements of permittivity (P), diffusivity (D) and solubility (S). For this study, A4-sized sheet samples of a barrier were sent to the MOCON testing service [15]; the barrier, referred to as *barrier-1*, was a 0.0254cm-thick weatherable superstrate barrier system, with a nominal WVTR of 0.002g/m^2/d at 40°C/90% RH. The barrier-1 sample was tested on a MOCON AQUATRAN Model 2, using a remote cell to determine P, D and S. These tests were carried out at 37°C, 65°C and 85°C, with 100% RH; nitrogen was used as the carrier gas.

The goal of measuring diffusivity at different temperatures was to estimate the activation energy for the barrier diffusion from an expected Arrhenius relationship. Fig. 4 shows an Arrhenius fit for measured diffusivity values for barrier-1; in this case the activation energy is estimated to be 0.58eV. In principle, the estimation of lifetime can proceed using this estimated activation energy along with the acceleration factor derived from the analytical model in Equation 11. Before undertaking such a calculation, it is necessary to examine how this compares with the actual flexible module performance when exposed to different temperature and humidity conditions in a controlled manner. In this study it was also intended to examine the performance of another barrier, with a WVTR < 5.0e-4g/m^2/d at 50°C/100% RH. However, this barrier, referred to as *barrier-2*, was not amenable to MOCON testing, since the associated WVTR was below the detection level for the MOCON apparatus.

Accelerated testing of flexible module samples for field performance assessment

Accelerated testing was carried out on two representative module constructions: one configuration used barrier-1 (WVTR of 0.002g/m^2/d at 40°C/90% RH), whereas the second set of modules were constructed using barrier-2 (WVTR < 5.0e-4g/m^2/d at 50°C/100% RH). The test modules consisting of eight cells in series were constructed for current–voltage–luminance (IVL) measurements using the same techniques as for the production process. Fig. 5 shows a schematic of module construction used in this study.

All cells were power matched (within 0.5% abs.) before the construction of the modules. A gap was included between the last cell of the string and the edge seal to allow the inclusion of $CoCl_2$ paper as an independent indicator of moisture penetration. One piece of indicator paper was centred in a segment of edge seal to serve as a reference. Five samples were made for each test condition for each barrier being evaluated; two glass–glass control samples were also constructed for each test condition. Samples were removed from the test chamber at one-week intervals and allowed to cool to ambient conditions before taking IVL measurements using a SPIRE flash tester at 1000W/m^2. The drop in P_{max} was used to determine the degradation in performance. Fig. 6 shows the test conditions chosen for testing. (At the time of writing of this paper, data from barrier-1 were available for further analysis, whereas the testing of barrier-2 samples was still in progress.)

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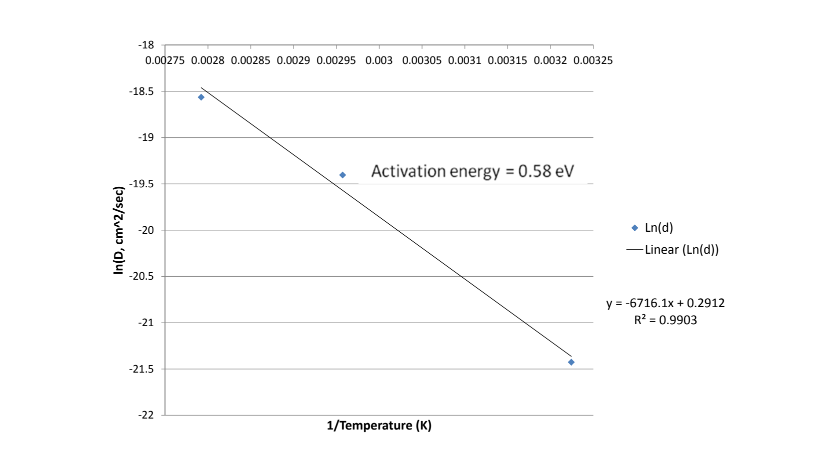

Figure 4. Arrhenius fit for the measured diffusivity values for barrier-1.

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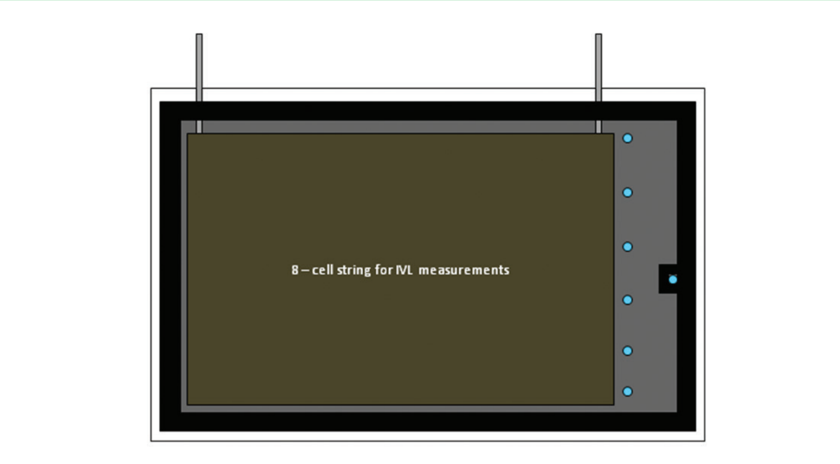

Figure 5. Module configuration for accelerated testing.

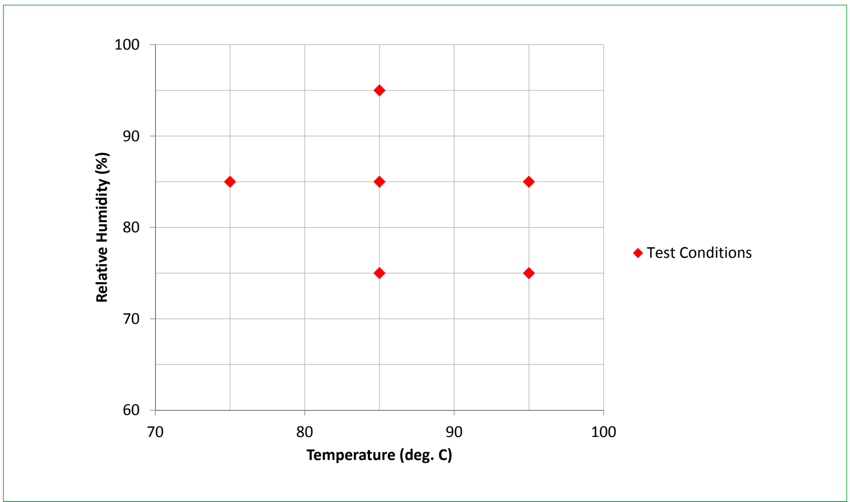

Figure 6. Test conditions chosen for accelerated testing. Five samples per barrier were used for each test condition.

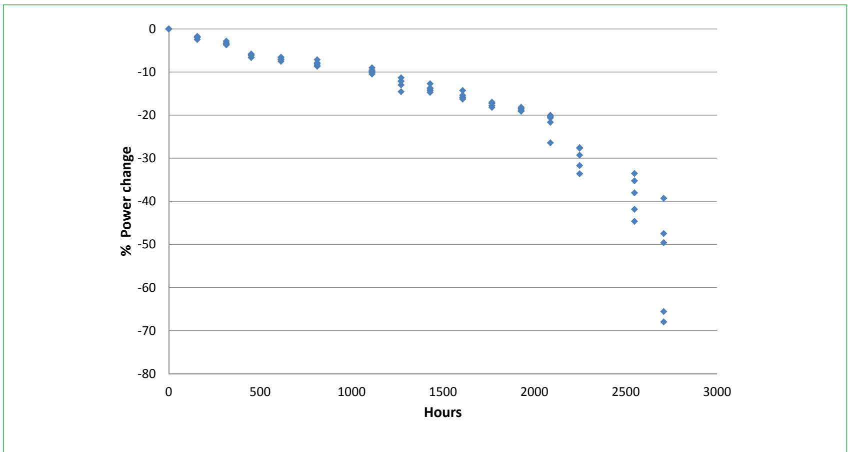

Figure 7. Degradation in P_{max} for modules with barrier-1, tested at 85°C/85% RH.

barrier-1 samples there are two aspects of measured degradation that merit discussion here. On the basis of the analytical model discussed earlier, it is of interest to see if observed degradation is indeed linear in time; it is also of interest to obtain the effective activation energy and relative humidity exponent from these measurements. Both of these aspects are discussed next and apply to barrier-1 samples only. Follow-up work is planned as and when data for barrier-2 samples become available.

Linear degradation and criterion for time to failure

Fig. 7 shows a representative degradation curve for modules tested at 85°C/85% RH: it is seen that the degradation appears to be close to linear up to a ~20% loss of P_{max}, beyond which a 'crash behaviour' is seen. The scatter in the data also increases in the 'crash' region. At the outset it is not clear that the degradation can be considered consistent with a 'linear behaviour' predicted by the analytical model.

"Degradation appears to be close to linear up to a ~20% loss of P_{max}, beyond which a 'crash behaviour' is seen."

The data can be analysed on a log–log scale to identify if the crash behaviour is significantly different from the initial degradation, or if the entire degradation is indeed a power-law type of degradation. On the log–log scale two different regimes were seen: the 'pre-crash' behaviour was different from the 'post-crash' behaviour. On the basis of the examination of the data, it was determined that the linear degradation model was appropriate and acceptable for a degradation of up to 20%.

It is also possible that measurement errors can lead to deviations from linearity. The sample size can be improved and the measurement techniques refined in order to address possible sources of error and allow an improved statistical representation of the configurations tested. In one case, sample measurements were seen to deviate from others in the same group because of corrosion of the electrical contacts as a result of exposure to high-temperature and high-RH conditions. These deviations had to be addressed by repeating the measurements with another set of newly constructed samples. It was noted that for highly accelerated conditions using 95°C, the deviations and scatter were the most significant; this included an initiation of the crash behaviour before 20% degradation.

The onset of the crash behaviour was not quantified in this study because of the small sample size and the scatter in the data. A larger sample size and conducting tests under additional conditions would be required in order to fully understand this behaviour. It should be noted that these tests are resource intensive as a result of the test times involved for high-barrier systems. Additionally, increasing the sample sizes can be challenging because of chamber occupancy and associated costs.

In the authors' opinion, the assumption of linear degradation is acceptable for moderate field conditions where the temperatures do not reach these extremes (~95°C) over extended periods of time. It seems possible that some temperatures used in highly accelerated test conditions (such as 95°C) over extended test times trigger other failure mechanisms that may not be representative of field failures attributable to moisture ingress; this requires further investigation. Nevertheless, for an initial assessment as undertaken in this study, the rest of the analysis is carried out directly using the results for time to failure as defined by a 20% degradation in power and using the models described earlier.

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Analysis of time to failure using a 20% power loss as a criterion for obtaining model parameters

It is desirable to validate the model developed earlier using the data from accelerated testing; in particular, the objective is to obtain the activation energy and relative humidity exponent from the experimental data. Fig. 8 shows an Arrhenius plot for the time to failure as defined by a 20% power degradation for different temperature conditions at 85% RH. The activation energy derived from these results is $\varepsilon_a = 0.63$eV.

It is interesting to note that the quality of regression is not as good as that for the diffusivity measurements, but the value of the activation energy calculated from module-level tests is consistent with the activation energy measured for barrier-1 using MOCON testing. It is also interesting to note that the activation energy estimated using just the mean time to failure at each condition is somewhat lower in value, namely $\varepsilon_a = 0.6$eV, and the quality of regression is better.

It should be pointed out that the module-level tests, in principle, account for other degradation processes associated with the module construction when exposed to temperature and humidity, whereas the MOCON testing includes only the barrier material; hence, in theory, the two values can differ. For further analysis, the accepted value for the activation energy is 0.63eV.

Fig. 9 shows the log–log plot that is intended for the extraction of the humidity exponent; on the basis of this data, the relative humidity exponent is calculated to be $n = -3.41$. It is interesting to compare the values of activation energy and relative humidity exponents obtained in this study with those reported in Peck [11]: representative values given in Peck are $\varepsilon_a = 0.79$eV and $n = -2.66$ for encapsulated electronic components, whereas the current data set suggests $\varepsilon_a = 0.63$eV and $n = -3.41$ for the tested PV modules. While the consistency between the two sets of values is promising, further considerations are necessary in order to assess the field life on the basis of the parameter values obtained from accelerated testing.

Prediction of field performance

Predicting field performance for flexible modules with regard to moisture ingress using the results of accelerated testing requires reconciliation with available meteorological data. The module performance is expected to be location dependent because of variations in local temperature and relative humidity. With that in mind, two aspects need to be examined:

1. A model based on given typical meteorological year (TMY) data for predicting cell and module temperatures.

2. An analysis framework for translating the results of accelerated testing and acceleration factor relationship, such as Equation 11, to field conditions. It is desired that the analysis of TMY data be consistent with the framework used for Equations 2 or 11.

Modelling cell temperature using meteorological data

A well-known empirical model for cell temperature based on typical meteorological data is the Sandia model [16]. The expression for cell temperature is given by:

$$T_c = T_{amb} + I\exp(a + bv_{wind}) + \frac{1000}{I}T_{offset} \quad (12)$$

where

T_c = cell temperature at 1000W/m^2 irradiance
T_{amb} = ambient temperature
I = irradiance (W/m^2)
a = irradiance coefficient
b = wind speed coefficient
v_{wind} = wind speed
T_{offset} = offset ΔT between the back-side and cell temperatures

The coefficients for a variety of module constructions and mounting

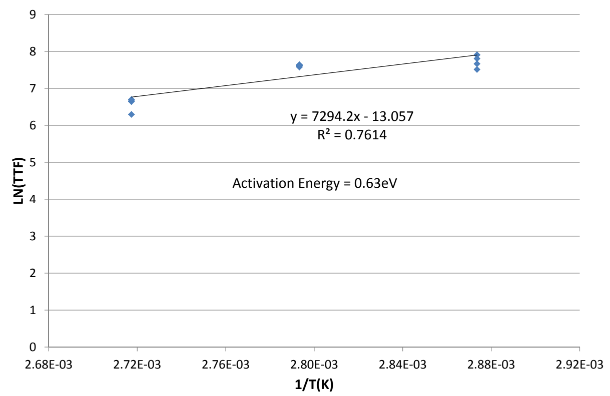

Figure 8. Arrhenius plot for time to failure (as defined by a 20% degradation in power) for samples subjected to different temperatures at 85% RH (activation energy = 0.63eV).

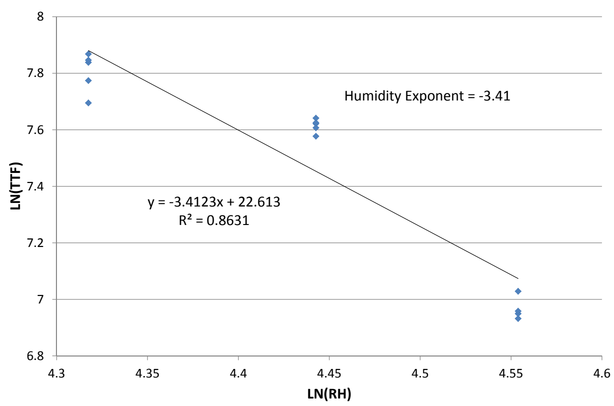

Figure 9. Log–log plot for the relative humidity exponent (n = –3.41).

configurations can be found in King, Boyson and Kratochvil [17].

For the flexible module construction used in this study, the coefficients were expected to be similar to an insulated back glass/cell/polymer sheet configuration (a = −2.81, b = −0.0455, T_{offset} = 0), as a polymer/cell/polymer sheet configuration with an insulated back was being tested. To obtain these coefficients by regression, module temperatures were measured with cell-level embedded thermocouples in outdoor testing for a year under variable atmospheric conditions at a location in Santa Clara, California, USA. The parameters derived using available data to date are a = −2.96, b = −0.0178, T_{offset} = 0. It should be noted that since the temperature offset for the flexible module is T_{offset} = 0, Equation 12 can be used to predict 'module temperature'. These values have been obtained using data at the California site, with further testing in progress at other sites. The data collected to date have shown strong consistency with these model parameters, but the parameter refinement will continue as more data become available.

A comparison of the model fit and measured temperatures at Santa Clara is shown in Fig. 10. The period chosen for the comparison corresponds to the week in which some of the highest average error values between the model prediction and measured data occurred. It is noted that this period also corresponds to the time when some of the highest module temperatures were reached. It is seen that there is good agreement between measured and predicted temperatures at midday, while the agreement is not so good during the evening and night time. The module temperatures at night time tend to be overestimated by the model, compared with the actual measured night-time temperatures (at the time when RH is expected to be high). This is a limitation of the model and is attributed to radiation losses that are not accounted for in Equation 12.

For the calculation of moisture-induced degradation, the Arrhenius variation with temperature would imply that matching the module temperatures at the high-temperature end is more important, and hence this fit is accepted. With this model, the module temperature can be predicted at different locations using available TMY data. Such a prediction using parameters obtained from data in California is used in this work for the field performance assessment of the barrier under consideration. The methodology for performance prediction is discussed in detail next.

Prediction of field performance with regard to moisture-induced damage

The prediction of field performance needs to be based on the acceleration factor relationship from Equation 2 or Equation 10; however, the variations in field temperature and humidity conditions need to be accounted for in this relationship. To this end, the assumption is made that the variations in field conditions (T, RH) are sufficiently slow that the ambient conditions may be assumed to be constant for the analysis of TMY *hourly* data (i.e. the conditions are approximately constant over each hourly interval). It should be noted that the temperature and humidity conditions for the module can change within an hour as a result of sudden changes in ambient conditions (e.g. rain); however, it is assumed that appropriate averaging will account for such deviations. On the basis of this consideration, a proposed averaged acceleration factor relationship is:

$$\langle AF \rangle = \frac{1}{t_{1yr}} \int_{1TMY} \left(\frac{RH_{field}(t)}{RH_{test}} \right)^n \exp\left[\frac{\varepsilon_a}{k} \left(\frac{1}{T_{field}(t)} - \frac{1}{T_{test}} \right) \right] dt \quad (13)$$

where $\langle AF \rangle$ represents expected yearly averaged value of the acceleration factor.

Once the acceleration factor has been computed for a given location, reference test results can be scaled to field conditions using:

$$TTF(\text{field}) = \langle AF \rangle \times TTF(\text{test}) \quad (14)$$

The reference condition used in this calculation is the well-accepted high-acceleration condition of 85°C/85% RH.

Three features of the acceleration factor relationship to be used in Equations 13 and 14 merit attention:

1. For typical applications in the consumer electronics industry, the use of average temperature and average RH conditions in the operating environments may suffice for a prediction over shorter product lifetimes, since the conditions typically do not vary significantly in such usage environments. However, using *yearly* average values of temperature and RH for PV applications would be inappropriate, since such averages do not correctly reflect the conditions that correspond to maximum damage. Outdoor fluctuations of temperature and RH values need to be accounted for in PV applications in a consistent manner: hence the consideration of the integral representation of the acceleration factor relationship proposed in Equations 13 and 14. In addition, this relationship is typically evaluated using hourly TMY data, implying that the conditions are assumed to be constant over an hour in these calculations.

2. The prediction of the field life using this relationship is based on scaling a result obtained under a particular test condition. The prediction can in principle vary, depending on the test condition chosen as the reference. If the fit to experimental data is good for all conditions, this should not be a concern; however, the quality of fit under different conditions will alter the quality of prediction. To obtain a good predictive model, it is essential that the model parameters be derived from tests that are performed under many different conditions and that use statistically significant sample sizes. For this study, the limitation imposed by the available test resources was accepted, and the condition chosen as a reference was 85°C/85% RH.

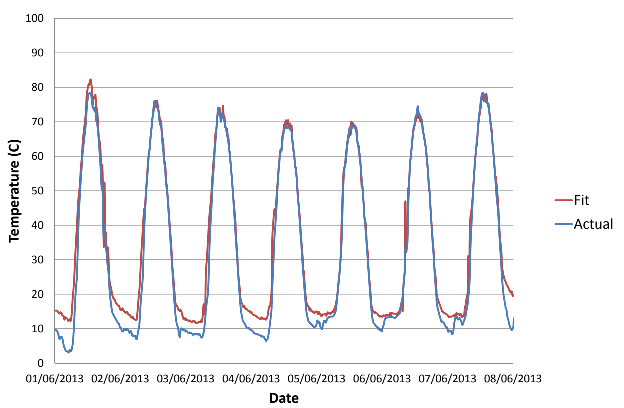

Figure 10. Comparison of predicted and measured module temperatures at Santa Clara.

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3. A critical aspect of the relationship expressed in Equation 13 is that the implied time to failure for low-humidity conditions (low RH) is high. For smaller values of relative humidity exponent *n*, the singular behaviour at lower RH values will dominate the prediction. For instance, see Fig. 11 for the Hallberg-Peck acceleration factor for a constant field temperature of 50°C with the test conditions of 85°C for different RH values; in this case, below around 40% RH the acceleration factor starts to exceed 100. For reference, an acceleration factor of 100 would imply that 3000 hours at 85°C/85% RH is equivalent to ~34 years at 50°C/40% RH. The basis for this large time to failure prediction is that according to this model, the failure induced by moisture is significantly delayed, since the availability of moisture to drive the damaging reactions is affected. This does not, however, imply that the actual failure time of the module in the field is large. Fig. 11 illustrates that in hot and dry environments, Equations 13 and 14 will predict very large times to failure, while in reality other mechanisms, such as thermal degradation, can dominate module failure. The prediction from Equations 13 and 14 would be appropriate only with regard to *moisture-induced damage*.

With the above considerations, the mean times to failure calculated using TMY data for Bangkok and San Jose are given in Table 1. It should be noted that these predictions are intended to be the best assessment of the field performance of barrier-1 *for moisture-induced degradation only*; other potential modes of degradation, such as UV-induced degradation or delamination within the barrier layers, are not taken into account. It is noted that the results imply that the barrier-1 product may not meet typical warranty requirements for aggressive environments, such as those in Bangkok, while it may marginally survive in other locations.

In comparison, from the available data gathered to date (tests are ongoing), the barrier-2 product was seen to dramatically outperform the barrier-1 product with regard to moisture-induced degradation, showing a power degradation of less than 20%, even after ~7000h exposure to 85°C and 85% RH. Similar differences were also seen under other test conditions, indicating that barrier-2 performance is superior to barrier-1 performance.

On the basis of these results, the barrier-1 product may not meet typical warranty requirements in aggressive environments, such as in Bangkok, and is seen to only marginally meet the requirements in environments such as San Jose, California. On the other hand, barrier-2 is expected to be adequate in resisting moisture ingress over a typical PV module lifetime of 25 years. To enhance this method for predicting field performance in different locations, including those which have low RH values, it is essential to carry out tests under low RH conditions. It seems possible that the singular behaviour at low relative humidity, as dictated by Hallberg-Peck-type relationships, may not hold because of failure modes driven by thermal effects alone. This merits further work and is currently under investigation.

There is another aspect of these results that is not obvious from the data presented so far. As mentioned earlier, the prediction methods based on Equations 13 and 14 will over-predict the time to failure of the module with regard to moisture ingress because of the singular behaviour implied by the negative RH exponent. It is also noted that in order to capture appropriate behaviour at low RH values, test data at low RH values is crucial. In principle, to obtain a power-law exponent from the log–log plot, data over a wide range of RH values would be desirable.

The singular behaviour in a relationship such as Equation 2 implies that it may be overly challenging to capture the behaviour at low RH values using accelerated testing. There is practical difficulty in testing at low RH values, because the associated test times will be large. This concern is exacerbated for systems such as the module construction using very high barrier systems (e.g. barrier-2). As the barrier level increases, the fluctuations in external moisture content (ambient RH conditions) are even less detectable through its effect on cell performance. In the limiting case where the barrier level tends to be infinitely high, the primary degradation mode will switch to the one purely activated by thermally induced mechanisms or by the moisture ingress from the edge seal. The model based on a relationship such as Equation 2 will fail to capture such transitions. Furthermore, extensive testing will be necessary in order to identify threshold barrier levels (i.e. critical values of WVTR) below which the effects of ambient RH fluctuations are not detected in cell performance. Such a threshold level, of course, depends on the particular cell structure and composition as well as on the barrier WVTR.

On the basis of these considerations, the plan for future work is to explore similar tests at lower RH values in order to obtain a better estimate of RH dependence; in addition, lower barriers as well as very high barrier systems, such as a module construction using barrier-2, will be investigated further. At the time of writing this paper, testing is in progress for barrier-2 systems.

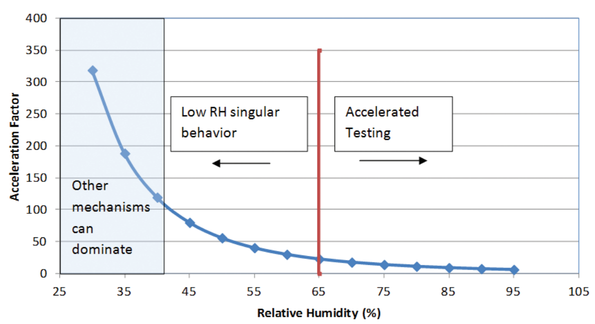

Figure 11. Hallberg-Peck acceleration factor for a constant field temperature of 50°C, with the test conditions of 85°C for different RH values. This highlights the limitations of accelerated testing with regard to conditions of low relative humidity (RH exponent n = –3.41).

Location	Power change at failure	Years to failure (RH exponent = –3.41)	Years to failure (RH exponent = –1)
Bangkok	20%	13.1	10.1
San Jose	20%	71.5	33.1

Table 1. Predicted field performance for barrier-1, considering moisture-induced degradation only.

Conclusion

A methodology based on accelerated testing has been presented for the assessment of the field performance of flexible PV modules with regard to moisture-induced damage. A framework based on an empirical relationship (the Hallberg-Peck model) used in consumer electronics industry has been proposed as a candidate for relating performance in accelerated testing to degradation in the field. An analytical model has been developed to justify the use of a Hallberg-Peck-type relationship in the testing and analysis of the performance of a PV module when exposed to temperature and humidity.

"In order to correctly capture relative humidity dependence, testing needs to be carried out under conditions that cover a wide range of relative humidity values."

It was shown that, while Arrhenius temperature dependence can be demonstrated in the testing of the barrier alone, as well as through module-level tests, obtaining relative humidity dependence is challenging. In particular, it has been learnt that in order to correctly capture relative humidity dependence, testing needs to be carried out under conditions that cover a wide range of relative humidity values.

For high-barrier configurations used in PV modules, the associated test times can be prohibitive because of resource constraints. A framework, which uses a combination of test results and an analytical model, has been provided for predicting field performance from accelerated testing. For the configurations tested, and the limited data available, it has been shown that the barrier-1 product (WVTR = $0.002g/m^2/d$ at 40°C/90% RH) considered in the study may not meet the typical warranty requirement of 25 years for PV modules in aggressive environments, such as in Bangkok; the barrier-2 product (WVTR < $1.0e\text{-}5g/m^2/d$ at 40°C/90% RH), on the other hand, is likely to be adequate for resisting moisture ingress over the intended service life of the PV module. Further experimental work is necessary in order to establish a threshold value of WVTR for ensuring a product life of ~25 years for flexible PV modules.

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