Potential-induced degradation of thin-film modules: Prediction of outdoor behaviour

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ABSTRACT

The current standards (IEC 61646 and IEC 61730-2, and IEC 62804 draft for c-Si only) are clearly insufficient to guarantee satisfactory long-term stability and energy yield for thin-film modules, given that reports from the field, as well as from laboratory test results (beyond IEC testing), in some cases show significant degradation of IEC-certified modules. Accordingly, thin-film modules can also exhibit degradation effects, such as TCO corrosion and power degradation, because of potential-induced degradation (PID). This paper presents the results obtained for thin-film modules subjected to bias and damp-heat (BDH) conditions in both indoor and outdoor tests. In order to assess module lifetimes for different thin-film technologies with respect to PID, indoor- and outdoor-determined leakage currents are compared and analysed, taking into account weather data and results from accelerated ageing tests. Finally, on the basis of simulations and investigations for different installation locations, module lifetimes are estimated and discussed.

Introduction

Module producers certify their products in accordance with the established IEC 61646 and 61730-2 standards as minimum requirements. These standards, however, are clearly not sufficient, since field and laboratory test results for conditions exceeding the IEC requirements demonstrate in some cases unacceptable degradation of IEC-certified modules.

Potential-induced degradation (PID) is an effect which can be generated in the laboratory by applying negative or positive bias to the modules in the damp-heat test chamber: this will be referred to as a bias and damp-heat (BDH) procedure. The phenomenon of transparent conductive oxide (TCO) corrosion of silicon thin-film modules has been known for a long time and is well documented [1,2]. Degradation processes for all other thin-film technologies under negative BDH conditions have been identified as well [3,4], but they demonstrate different degradation mechanisms and fault patterns.

In general, the term 'PID' is used for c-Si [5] as well as for thin film (TF). However, TCO corrosion is one specific type of PID for TF and refers to visible delamination of the TCO layer (see Fig. 1). The development of a standard test for PID for c-Si is in progress, but no IEC-standard draft has yet been submitted for PID and thin-film technologies. The work reported in this paper aims to support the development of testing procedures for predicting the outdoor behaviour of thin-film modules and ties in with previous work [1–4,6]. However, the test sequence presented here allows a comparison of thin-film modules from different technologies and designs on the basis of their distinct leakage-current behaviours. Leakage currents are therefore measured and investigated in order to analyse their influence on power degradation and to

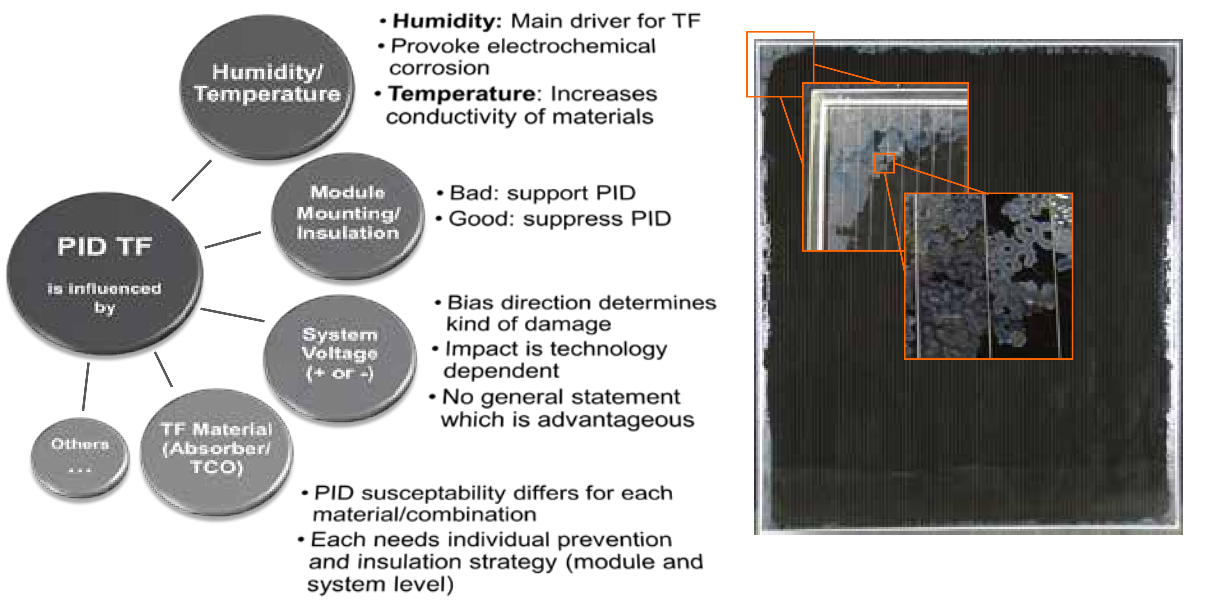

Figure 1. Some of the factors influencing PID of thin-film modules (left). A μc-Si module exhibiting TCO corrosion after a BDH test of duration 1000h and with a bias voltage of –1kV (right).

estimate module lifetimes by means of simulations after an accelerated ageing test. By simulating different weather conditions, it is possible to identify the lifetimes of the tested modules and to draw conclusions with regard to their outdoor behaviour. The main goal of this work can be summarized as the location-dependent prediction of power degradation potential by the determination of individual module leakage currents.

McMahon [7] describes what these failures can look like and presents possible failure mechanisms. Fig. 1 (left) summarizes the main drivers for PID of thin-film modules. Some of these drivers relate to influencing factors such as humidity, temperature and system voltage. Other factors, such as the mounting, have already been investigated [3,8]: it can be stated that a good mounting suppresses PID by keeping leakage currents low and away from sensitive module parts, such as the module edges. Further influencing factors are the choice of material and design – the semiconductor type or the production processes, for example. Fig. 1 (right) shows a µc-Si module that exhibits the well-known TCO corrosion after a 1000h, BDH test with a bias of −1kV; the corrosion begins at the edges of the module and progresses inwards.

Experiment design

In order to investigate in detail the PID effects for thin film and collect the necessary data for the simulation, several thin-film modules were tested in accordance with the test scheme depicted in Fig. 2. Three different thin-film technologies with corresponding industrial modules were investigated: A) CdTe, B) CIGS, and C) µc-Si. All modules were installed in accordance with their specifications in order to simulate 'realistic' leakage-current pathways in the experiment: this entailed the use of a clamp/laminate installation for the CdTe modules, a clamp/frame installation for the CIGS modules, and a back-rail mounting for the µc-Si modules.

The test scheme is divided into a sensitivity test (orange), a degradation analysis (grey) and a simulation (blue); at all stages, the parameters temperature, humidity and voltage were recorded and the distinct module leakage currents measured. Each module type was installed in the prescribed mounting manner and tested under positive and negative system voltages. The outdoor sensitivity test was performed in June 2013 at PI-Berlin's outdoor test site.

The main goal of the sensitivity analysis was to find for each parameter (range) – temperature (T), relative humidity (RH) and voltage (V) – a corresponding leakage current (LC), where $LC_{A,B,C} = f(T,RH,V)$. The I–V curves were recorded before and after each exposure. In contrast to c-Si standard technology, thin-film technologies need special preconditioning procedures, for which commonly agreed procedures and standards for the different technologies do not exist or are still the subject of studies [9,10]. Special preconditioning procedures were conducted, but are not discussed in detail in this paper: further results can be found elsewhere [8].

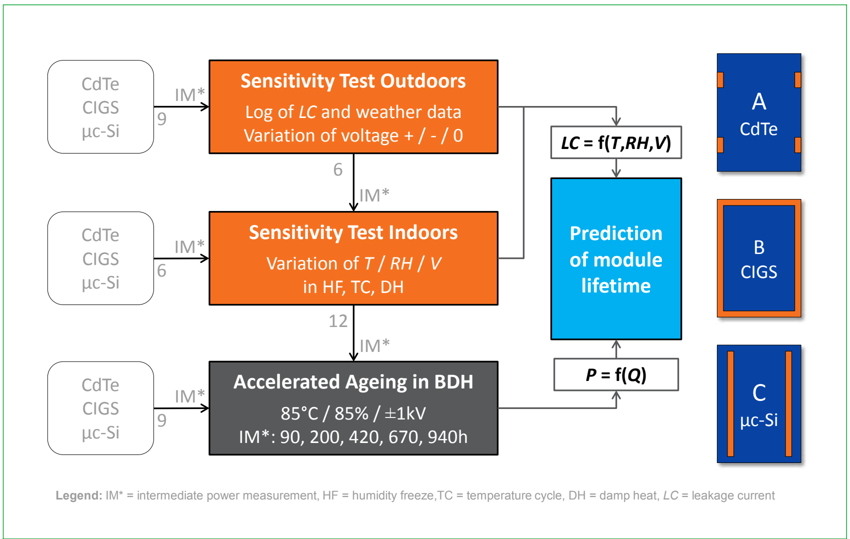

Figure 2. Schematic of the test procedure: sensitivity test (orange), accelerated ageing (grey), and simulation for the prediction of module lifetimes (light blue). Three module technologies (shown far right) were investigated.

Next, the degradation analysis was performed using the results of an accelerated ageing experiment in the damp-heat chamber with applied bias voltages. Intermediate measurements, to determine in particular the power degradations, were conducted after 90, 200, 420, 670 and 940h. The outcome of this experiment is the module degradation determined for a certain charge flow (P), where $P_{A,B,C} = f(Q_{A,B,C})$ with

$$Q_{A,B,C}(t) = \int_0^t I_{A,B,C}(t)\,dt \qquad (1)$$

To obtain comparable results for each module, the charge flow $Q_{A,B,C}(P_{80})$ was determined (partly extrapolated) until the point where 80% of the initial power remained. Finally, all the datasets were fed into a simulation to predict the module lifetimes: this is described in a later section. For further details of the complete test procedure see Weber et al. [8].

Results

All the datasets obtained outdoors were analysed and mean values for the leakage current determined. A data-matrix was created from the results and also incorporated indoor sensitivity test results obtained by LC monitoring in a climate chamber test with varying parameters (outcomes of the orange boxes in Fig. 2). Exemplary values for LC measurements are presented in Fig. 3(b) for a CIGS module of type B biased at −1kV. Fig. 3(a) shows the total number of hours for which a parameter lies within typical ranges during one year in Berlin (for details see the simulation section below). The charge flow for each temperature range is calculated by multiplying LC and time (Equation 1), and can be seen in Fig. 3(c). By summing up all these values for a module, one obtains the specific annual charge flow, which will play an important role in the simulation of module lifetimes.

From an analysis of the daily leakage-current behaviours (not presented here), it was obvious that the highest leakage currents did not occur when the ambient conditions were highest, in other words when absolute humidity was high. The highest leakage currents were measured at times of low absolute humidity (mostly low temperatures with high relative humidity in morning-dew or rain situations). The impact of module-type design or mounting differences, however, cannot be extracted from such results. In general, leakage currents vary significantly, depending on polarity, ambient conditions and module design. (The last of these was not studied here – see Osterwald et al. [2], Gossla et al. [3] and Weber et al. [8]).

Module Temperature [°C]

Relative humidity *RH* [%]

(a) Time *t* [hours]

RH (a)	< –10	–10-0	0-10	10-20	20-30	30-40	40-50	50-60	60-70	> 70
> 75	4	174	704	694	203	4	-	Hours in each parameter range		
65-75	-	7	155	274	237	29	-			
50-65	-	-	65	257	406	159	7	-	-	-
40-50	-	-	1	64	217	193	31	-	-	-
30-40	-	-	-	8	81	127	48	2	-	-
< 30	-	-	-	-	3	8	9	-	-	-

×

(b) Current *LC* [µA]

RH (b)	< –10	–10-0	0-10	10-20	20-30	30-40	40-50	50-60	60-70	> 70
> 75	*0.018*	*0.036*	0.057	0.117	0.084	*1.600*	-	Leakage current [µA], CIGS -1kV		
65-75	-	*0.036*	0.032	0.048	0.069	0.064	-			
50-65	-	-	0.014	0.021	0.034	0.032	0.047	-	-	-
40-50	-	-	0.007	0.009	0.016	0.017	0.021	-	-	-
30-40	-	-	-	0.004	0.008	0.011	0.012	0.017	-	-
< 30	-	-	-	-	0.004	0.005	*0.006*	-	-	-

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(c) Charge *Q* [As]

RH (c)	< –10	–10-0	0-10	10-20	20-30	30-40	40-50	50-60	60-70	> 70
> 75	0.000	0.023	0.143	0.292	0.062	0.023	-	Transferred charge [As]		
65-75	-	0.001	0.018	0.047	0.059	0.007	-			
50-65	-	-	0.003	0.019	0.050	0.019	0.001	-	-	-
40-50	-	-	0.000	0.002	0.013	0.011	0.002	-	-	-
30-40	-	-	-	0.000	0.002	0.005	0.002	0.000	-	-
< 30	-	-	-	-	0.000	0.000	0.000	-	-	-

Figure 3. Illustration of charge calculation: (a) number of hours for which each temperature vs. relative humidity parameter range prevails for a statistical year in Berlin; (b) measured leakage currents (from sensitivity tests) representative of a CIGS module, indicated as mean values for each parameter range; (c) charge for each parameter range, calculated by multiplying time in (a) and current in (b).

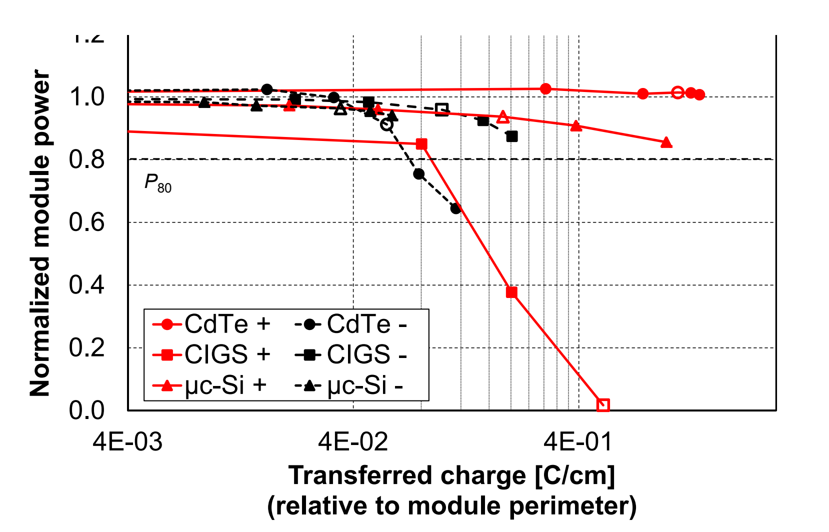

Figure 4. Degradation behaviour of the CdTe, CIGS and µc-Si modules tested in BDH conditions, as a function of the transferred charge relative to the module perimeter. One set of modules was tested under positive bias (red), the other under negative bias (black). Empty symbols indicate measurements after 420h.

The next step in the procedure was the determination of the degradation behaviour in an accelerated ageing test (see grey box in Fig. 2). The results are presented in Fig. 4 for modules tested in BDH only, and the power measurement was performed with no preconditioning. The graph shows the power drop as a function of the transferred charge flow.

Also indicated is the P_{80} line, which represents a relative power of 80% of the initial value. Modules tested under positive voltages are labelled in red, and negative ones in black. Table 1 summarizes the power drops for each module after each resolved intermediate measurement time.

It is obvious that CdTe modules of type A with a positive bias (circles) remain unaffected, despite a high charge transfer; the same type under a negative bias degrades by 25% after 680h. CIGS modules of type B (squares) degrade slowly under a negative bias (13% after 940h), but very quickly under a positive bias (15% after 90h). The µc-Si modules of type C (triangles) are the most stable ones under both conditions: these modules degrade 14% after 940h under a positive bias, and 6% after 940h under a negative bias.

Comparing the results of one module type with another is difficult when the actual field degradation and leakage-current behaviour are excluded. As a consequence, it is not possible to derive the actual impact in the field for degraded modules. To do that, it is suggested to simulate the results of $P(Q)$ from Fig. 4 with the actual leakage currents measured in the field, as described in the next section. A particular value is therefore necessary – one which correlates the outdoor leakage currents (sensitivity tests: orange boxes in Fig. 2) with the leakage currents of the accelerated test (BDH test: grey box in Fig. 2). The interpolated and extrapolated $Q(P_{80})$ values representing the amount of charge up to the point where 80% of initial power remains were determined from the graph in Fig. 4 and are listed in Table 2.

	90	200	430	670	940
CdTe +	3%	1%	1%	1%	1%
CIGS +	–15%	–62%	–98%	–	–
µc-Si +	–3%	–4%	–6%	–9%	–14%
CdTe –	2%	0%	–9%	–25%	–36%
CIGS –	–1%	–2%	–4%	–7%	–13%
µc-Si –	–2%	–3%	–4%	–5%	–6%

Table1. BDH degradation in % after *x* hours.

Type	CdTe +	CdTe –	CIGS +	CIGS –	µc-Si +	µc-Si –
$Q(P_{80})$ [C/cm]	2.147	0.071	0.093	0.255	1.410	0.155

Table 2. Interpolated and extrapolated $Q(P_{80})$ values representing the amount of charge up to the point where 80% of initial power remains.

Among other factors, the results are influenced by the preconditioning before a power determination. Fig. 5 shows the results for the investigation of the influence of performing a preconditioning (PC) procedure. The results are shown for the case of CIGS modules of type B differing in two parameters. The first parameter is the use of a PC procedure, for which a combined light-soaking and pre-current-soaking method was used. The solid line in Fig. 5 indicates a PC was performed, whereas the dashed line means there was no PC (i.e. the module was fresh from the production line). The second parameter is the bias voltage of the accelerated ageing experiment. The results show that the preconditioning improves the power measurement by up to 12% (CIGS –: black line) and 40% (CIGS +: red line) for degraded modules. For the positive-biased module, the improvement increases with the level of degradation.

Simulation of module lifetimes

Simulations were carried out using a simple model. The assumption is that the PID and individual leakage-current behaviour of a thin-film module are correlated with its degradation in outdoor and indoor tests. Other degradation mechanisms, such as material degradation, are neglected.

The outdoor and indoor leakage currents determined under certain conditions were referenced to different parameter ranges in order to simulate the leakage currents over a whole year at different locations (for illustration of this step see Fig. 3). Weather data for Tokyo (Japan), Kuala Lumpur (Malaysia), Tucson (USA) and Berlin (Germany) were analysed for the parameter ranges shown in Figs. 3 and 6. The graphs in Fig. 6 show a relative distribution of the temperature and relative humidity; they were generated from the Meteonorm database and based on monthly values (station data), which were calculated for hourly values of all parameters using a stochastic model [11]. To obtain the module temperature T_{Module} from the outdoor temperature T_{Outdoor}, the following linear dependence was used:

$$T_{\text{Module}} = T_{\text{Outdoor}} + k * \frac{Irradiance}{Irradiance_{\text{STC}}} \tag{2}$$

where the irradiance at standard test conditions (STC) is 1000W/m^2, and k is a constant factor, which depends on the module installation set-up (k = 20°C for free standing, k = 30°C for roof integration with ventilation, k = 45°C for roof integration without ventilation). In this case, a free-standing

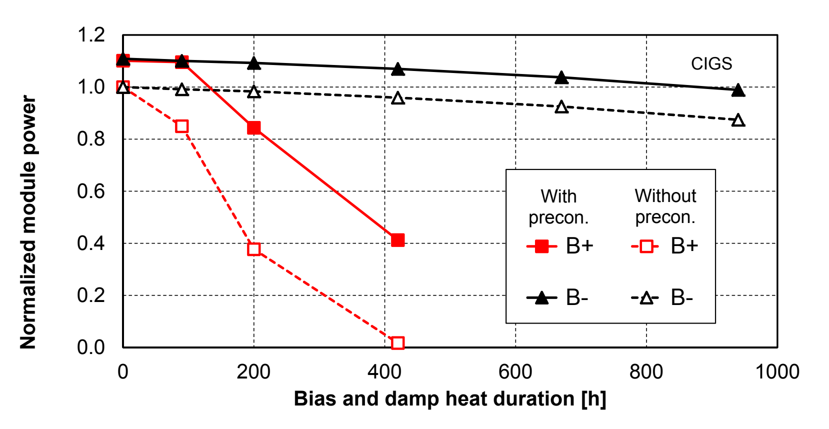

Figure 5. Power measurements for CIGS modules of type B with positive and negative PID-bias voltages, showing that module power can be influenced by preconditioning.

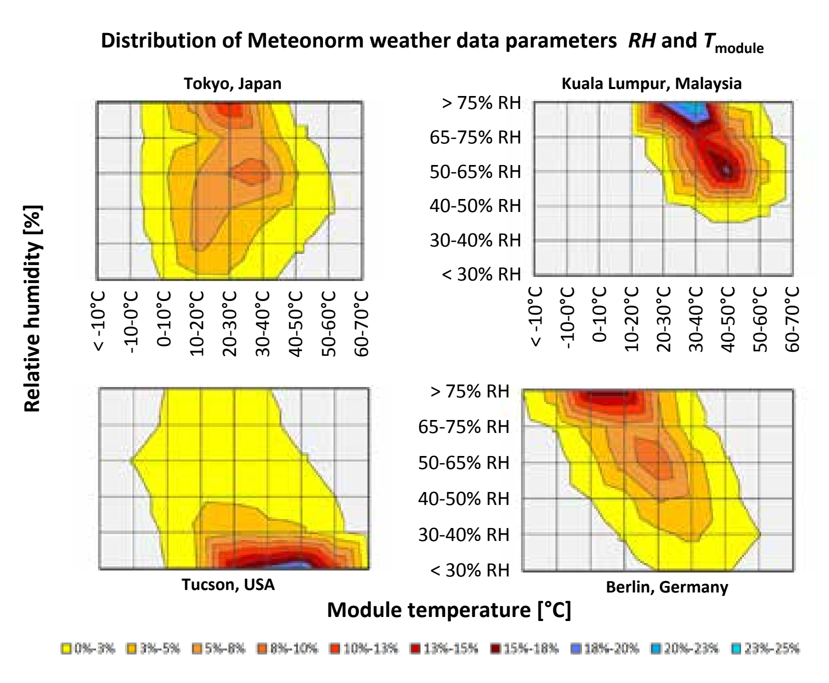

Figure 6. Meteonorm weather data analysed for Tokyo (Japan), Kuala Lumpur (Malaysia), Tucson (USA) and Berlin (Germany), showing the relative distribution of the temperature vs. humidity parameter ranges of interest.

plant was simulated [12]. It is only during the daytime that the modules operate under voltage and that leakage currents arise; therefore, only values with global irradiances above $5W/m^2$ can be chosen, and the corresponding frequencies of occurrence allocated to the different parameter ranges.

To obtain the module lifetime (*LT*), the charge flows under +/– BDH conditions are divided by the annual charge flow Q_{annual} calculated from the weather and leakage-current data:

$$LT = \frac{Q(P_{80})}{Q_{annual}} \qquad (3)$$

where Q_{annual} is determined from the outdoor-measured leakage currents, complemented by indoor-measured leakage currents under damp-heat, humidity–freeze and thermal-cycling conditions.

Fig. 7 summarizes the results of the simulation of lifetimes for the A, B and C module types under positive and negative bias conditions. In Fig. 7 (right) a classification of the results for evaluation purposes is suggested. For locations with a dry climate, such as Tucson, all investigated module types are very stable (LT >> 25 years), as Fig. 7 (left) demonstrates. CdTe + and µc-Si + are stable in all simulated locations, but short lifetimes (LT < 25 years) are indicated for CdTe – and µc-Si –. A humid and warm place, such as Kuala Lumpur, does not appear to be a suitable place to install the CIGS +/–, CdTe – and µc-Si – module types, whereas warm and dry climates seem to be very suitable for thin films from the PID point of view.

If the degradation results from the accelerated ageing test are compared with the simulated lifetimes, interesting results are obtained. Although the investigated CIGS module type degrades considerably and rapidly under a positive

Module	PID Module Lifetime (LT) [years] (module LT may be limited by other mechanisms)			
	Kuala Lumpur	Berlin	Tokyo	Tucson
CdTe +	83	166	183	362
CIGS +	9	41	37	127
µc-Si +	51	135	157	1659
CdTe –	3	8	10	31
CIGS –	13	141	77	637
µc-Si –	20	21	39	294

Classification of the Results [years]
LT < 25 → PID critical
25 < LT < 40 → PID likely uncritical
LT > 40 → no PID likely

Figure 7. Simulated module lifetimes with regard to PID for all investigated locations and module types (left), and suggested classification scheme for evaluation purposes (right).

bias, the module lifetime is significantly affected only in Kuala Lumpur, a hot and humid place; the other simulated locations result in long lifetimes. The same scenario can be seen for the µc-Si module type under a positive bias. The µc-Si – module exhibits no perceptible degradation in the accelerated BDH ageing test, although the lifetime simulation results in a 20% degradation in Berlin (after 21 years) and in Kuala Lumpur (after 20 years). If one takes other degradation effects into account this might become critical.

No degradation could be found with CdTe under a positive bias, which correlates to long lifetimes; the same was found for others.

To dramatically improve the effectiveness and reliability of accelerated ageing experiments and/or this simulation, it is necessary to correlate the degradation behaviour $P = f(Q)$ with the actual leakage currents occurring during realistic conditions in the field.

Given the actual problems associated with some TF module types in the field, it is suggested by some technology providers to install off-set boxes (for the application of a positive potential overnight) as a short-term solution in the case of identified PID issues in a solar installation. However, the results presented here might call into question the implementation of such an approach as a 'standard' solution, because it has been shown that not only can PID occur in negative bias conditions but it can also occur in positive bias conditions in certain cases.

"The leakage-current analysis and simulation results revealed a high humidity to be the main driver for PID of thin-film modules."

Conclusion

The results obtained for thin-film modules under BDH conditions in indoor and outdoor tests have been presented. The development of a standard test for PID for c-Si is in progress; however, for thin-film technologies an IEC-standard draft has not yet been submitted.

Leakage currents were measured and investigated in order to analyse their influence on power degradation and to estimate module lifetimes after an accelerated ageing test and simulation. A simple simulation model was presented and enabled the deduction of lifetimes by conducting an accelerated stress test. It is therefore important to determine outdoor leakage currents that are adjusted using results from indoor sensitivity tests for the simulation. Moreover, the simulation allowed lifetimes for different climate conditions to be distinguished. The leakage-current analysis and simulation results revealed a high humidity to be the main driver for PID of thin-film modules. On the other hand, warm and dry climates seem to be less critical for thin films in terms of PID.

The results of accelerated PID tests do not necessarily reflect the PID risk at a certain location (expressed by the module lifetime). For example, although module type C (µc-Si) exhibits negligible degradation under a negative bias in a BDH test, the simulated lifetime for Berlin – corresponding to a 20% power drop in 20 years – could become critical when other degradation mechanisms are taken into account. In contrast, the same module type under a positive bias exhibits heavy degradation in the PID test, but the simulated lifetimes are quite acceptable for moderate latitudes.

To sum up in one sentence, the simulation model developed for a worst-case analysis enables benchmarking, the identification of PID-sensitive modules, the determination of a location-specific suitability of a technology, and a statement to be made regarding the distinct advantage of a positive or negative system voltage.

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