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Forecasting Photovoltaic Module Remaining Lifetime Using Accelerated Aging Testing and Model-ling on Aged Modules

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Abstract. This work investigates the possibility of predicting the remaining lifetime of a power plant by making accelerated aging testing on monocrystalline silicon cells modules working on a photovoltaic plant for eleven years in France and compares the results with the same testing done on modules from the same batch eleven years ago when they were new. The paper focuses on damp heat results. It is found that the degradation behaviour of the modules exposed outdoor has a similar trend compared to the modules tested eleven years ago when they were new but with a two-to-three-times quicker degradation. Moreover, electroluminescence characterization highlights some degradation differences, especially at the edges of the solar cells. Modelling the lifetime through empirical damp heat model on the used modules predict that degradation may accelerate after 3 to 4 years contrary to what was concluded based on the initial modules testing results eleven years ago: no degradation linked to heat and humidity conditions should have happened before 30 years.

Keywords: Photovoltaic Module, Accelerated Aging, Degradation

1. Context and experimental details

Predicting photovoltaic module lifetime is complex. Accelerated aging testing used in standard like the IEC 61215 can give a first idea of the module reliability but hardly predicts the lifetime of the module due to limited testing time and most of the time individual stress testing [1]. Extended testing like in the technical specification IEC/TS 63209-1 proposes to double or triple the stress from the previous standard [2] but even if the use of this kind of testing combined with empirical modelling can give some time equivalence idea, it cannot be fully representative of the real exposure that will undergo the module in a real power plant during several decades.

Another approach is combined testing like proposed in the technical report IEC/TR 63279 [3]. Multiple stresses are used to be more realistic, but the drawback is the experimental complexity to have climatic chamber with all these stresses. Moreover, lifetime modelling with all these combined stresses is not available and its development will also be complex research to carry out [4].

In this work, we propose a new approach by using accelerated aging testing on modules already working in a PV plant ("exposed" state) and compare the results with the same testing sequence done on modules from the same batch before setting up the power plant ("initial" state).

To test the method, we took some exposed modules from a PV plant localized in France for 11 years and conducted extended damp heat testing. Results have been compared with damp heat testing results performed on modules from the same batch 11 years ago when they were new. Properties, selection of modules and testing protocol are described below.

1.1. Modules properties and usage

The modules have a glass – backsheet architecture and are composed of 72 monocrystalline solar cells (Aluminum back surface field technology) with a 6” format. Their power is labelled at 175 or 180 Wp. They were manufactured in 2011 by a tier 1 manufacturer. 12 modules (180 Wp class) were used in a small plant using a string inverter (capacity of 2.16 kWp) which worked during eleven years from 2011 to 2022. Some spare modules were used for extended damp heat testing in 2011.

1.2. Exposed modules selection

The power degradation of the different modules from the PV plant after 11 years is found to be between 0.6% and 4.5% compared to the datasheet with a degradation average of 1.0% and with fill factor as the main contributor (series resistance increased certainly linked to the presence of cracks in cells and several contact disconnections). Interestingly, 8 modules still have more than 180 Wp power with almost no degradation despite the cited defects.

We selected 4 modules (EXPOSED_1; EXPOSED_2; EXPOSED_3; EXPOSED_4) for damp heat testing with 3 of them having kept their original power. The electrical properties are depicted in the table I.

Table 1. *Modules selection*

Module Reference	Pmax (Wp)	Isc (A)	Voc (V)	Fill Factor (%)
EXPOSED_1	182.0	5.41	45.0	74.9
EXPOSED_2	182.2	5.39	44.9	75.3
EXPOSED_3	182.3	5.43	45.0	74.6
EXPOSED_4	177.7	5.41	44.9	73.1

1.3. Testing protocol

On EXPOSED modules, damp heat testing was performed at 85°C and 85% humidity according to IEC 61215 [2]. Module characterization was done every 250h, the total testing time was 1250h. Electrical characterization (IV) of the PV modules was carried out using a PASAN flash tester SunSim 3b with class AAA equipped with a Dragon Back system. Electroluminescence (EL) measurements were done using a 150 MPixel XT IQ4 Phase One camera with its infrared filter removed and a current injection of Isc in the modules.

For the modules tested in 2011, damp heat measurements were done in a similar manner on 3 modules (INITIAL_1; INITIAL_2; INITIAL_3). The duration was 4000h with control at 2000, 3000, 3500 and 4000h of testing. IV measurements were carried out with the same PASAN flash tester (but without dragon back system) and EL were performed with a Yamamatsu infrared camera and a current injection of Isc in the modules.

2. Results

2.1. Damp Heat

The Figure 1 presents the power variation results during damp heat testing with a comparison with the original measurements performed in 2011.

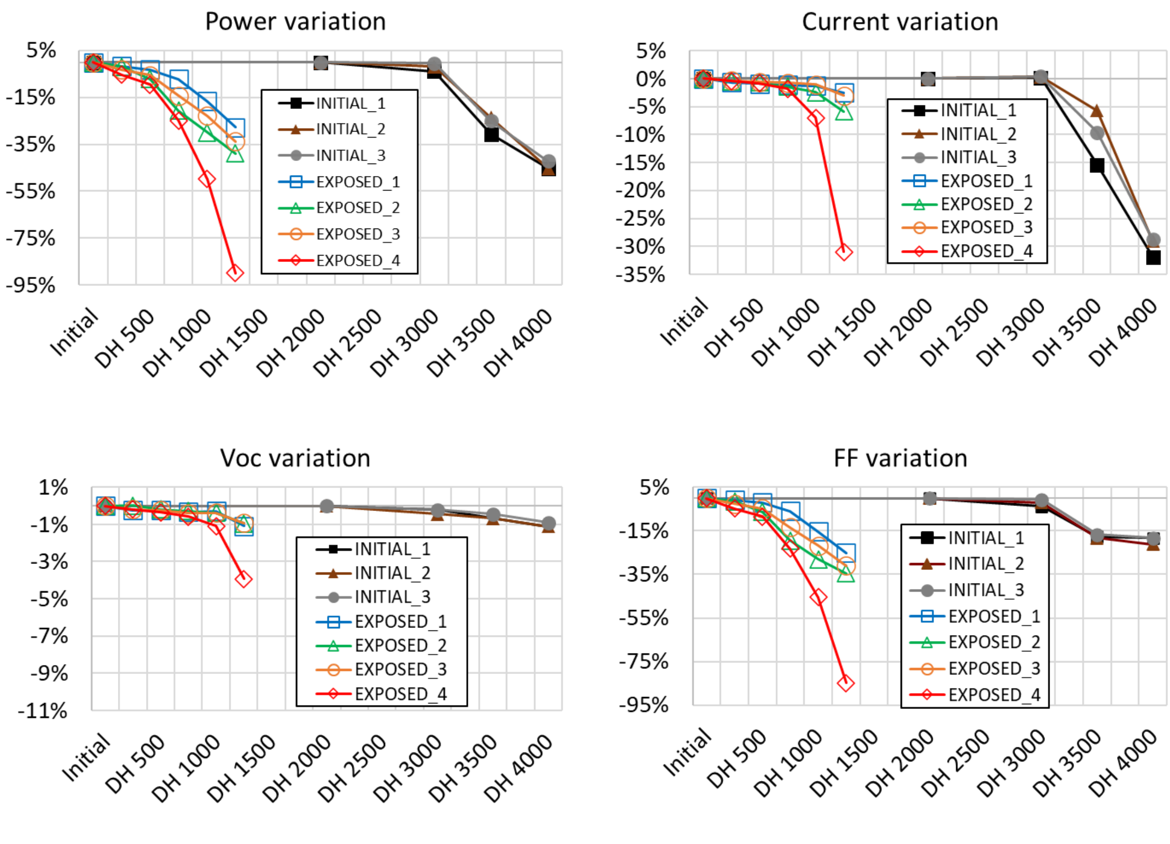

Figure 1. *Modules' power relative evolution after damp heat testing.*

On the EXPOSED modules, the degradation is happening two to three times quicker compared to the INITIAL modules. For instance, the degradation after 1250h on EXPOSED modules is like the degradation after 3500h for the INITIAL modules. EL images (shown in Figure 2) indicate different degradation behaviors for the two batches. For the INITIAL modules, the edge of the cells are darkening and this darkening is slowly progressing toward the cells' center with the increase of damp heat duration whereas on EXPOSED modules, the same behavior is visible, but the cell perimeter remains bright.

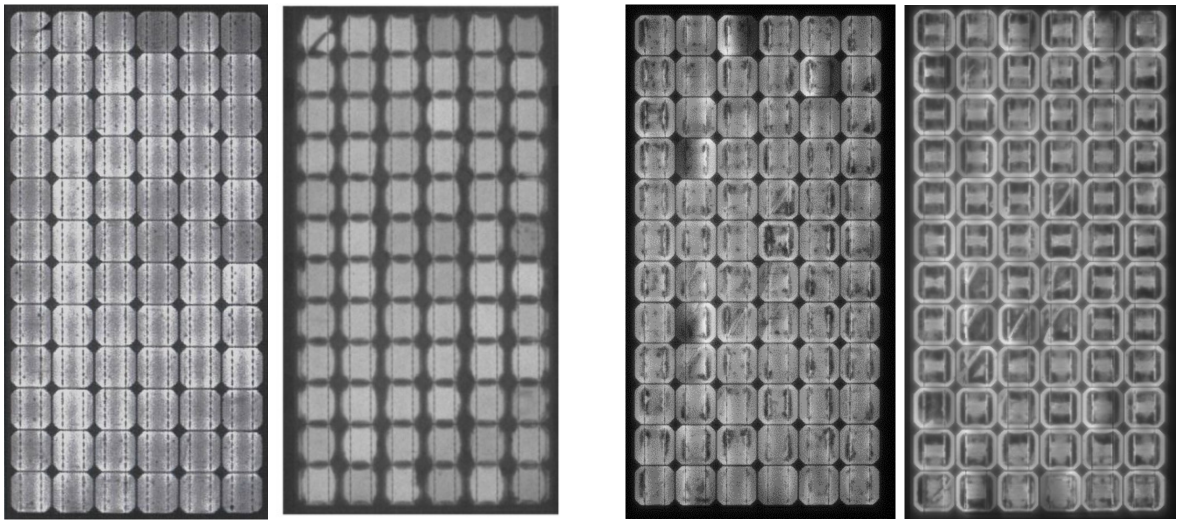

Figure 2. *From left to right, electroluminescence images of INITIAL_1 after 2000 and 3500 h of DH; electroluminescence pictures of EXPOSED_3 after 500 and 1250h of DH.*

Several hypotheses can be given on the behavior difference. It is possible that the module bill of materials is not the same even on similar batches (manufacturers have most of the time at least two suppliers for each module component). We cannot also exclude process variations as the modules may not have been manufactured in the same exact line. Another possibility is the impact of the environmental outdoor stresses on the modules during eleven years. In INITIAL modules, the darkening is usually explained by the humidity ingress from the edge of the cell to the center entailing encapsulant degradation which can cause corrosion [3]. The same may happen on the EXPOSED modules but as they were also exposed to UV, heat, thermal cycling… it is possible that the encapsulant has been significantly aged, especially at the cells' center (more heat and difficulty for the water to be expelled through the backsheet) contrary to the edge of the cells. The darkening of the edges might happen in the end but probably after a longer time as observed on INITIAL modules after 3000h of testing.

2.2. Modelling

To have an estimation of the equivalent temperature and humidity stress in the power plant during 30 years near Paris in France, we used a modified Peck model integrating temperature and humidity mechanisms taken from [5] to forecast how should behave the module based on the accelerated damp heat testing results.

$$R_D = A.(MM_{RH})^n.\exp(-\frac{E_a}{k_B T}) \qquad (1)$$

Where:

- R_D: The degradation rate
- MM_{RH}: The average relative humidity
- E_a: The activation energy (1.32 eV)
- t: The time in hours
- T: The module's temperature (K)
- K_B: Boltzmann constant (8.62x10^{-5} eV/K)
- A: Parameter allowing to adjust the curve to previously tested experimental data
- n: Parameter varying between 2 and 3

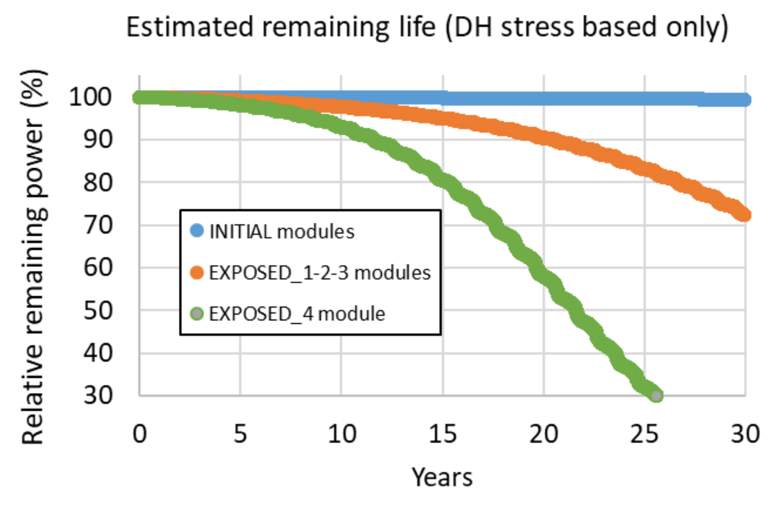

Figure 3. *Results of the forecast remaining lifetime of the modules tested through damp heat stress testing using Paris climate. Reference time is the date before the testing, i.e. 2011 for INITIAL modules and 2022 for EXPOSED modules.*

The Figure 3 presents the results of the modelling. INITIAL and EXPOSED_1-2-3 module groups were modelled together as the degradation trend is similar. EXPOSED_4 module is modelled separately to highlight its quicker degradation. The main important result is the risk for the EXPOSED modules to significantly degrade in the next years to come, especially for the EXPOSED_4 module which has already shown a slightly lower power before the testing compared to the others modules. This degradation risk is not in accordance with the prediction for the INITIAL modules results where degradation was not planned to occur before thirty years with Paris climate. Like what has been discussed previously, the obtained trend for EXPOSED modules is probably underestimated as only temperature and humidity impacts are considered and through a quite simple model.

Nevertheless, this experiment confirms the relevance of the approach to forecast potential issues with the module degradation in an existing power plant: the re-evaluation of the power plant degradation clearly shows a risk of having some degradation appearing in the next years contrary to what was concluded 11 years ago.

3. Conclusion

This study has highlighted the relevance of making accelerated aging testing during the PV plant life by comparing initial and current photovoltaic module behaviors toward environment stresses. Damp heat study has shown a significant lower tolerance for module exposed for eleven years in outdoor environment compared to modules from the same batch tested eleven years ago when they were new. The lifetime evaluation using a quite simple Peck model was found to be significantly different with a degradation acceleration caused by temperature and humidity which should happen in the next five to ten years for modules in outdoor environment and not after more than thirty years based on what was concluded with the initial characterization.

In summary, this approach allows to re-evaluate the forecasted power plant degradation in the next years, even with simple models. The testing was done only using damp heat stress but it needs to be extended and combined with other stresses (thermal cycling, UV,…) that occur in a power plant. Moreover, due to the limited accuracy of the models used, it is recommended to re-evaluate regularly the remaining life of the power plant, every 5 to 10 years for instance with this method or to use more accurate models.

Underlying and related material

All relevant raw data were submitted with the article and can be asked directly to the authors.

Author contributions

Julien Dupuis: Conceptualization, Investigation and Writing (original draft)

Christine Abdel-Nour: Formal Analysis and Writing (review).

Competing interests

The authors declare no competing interests.

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