ANALYSIS OF ANNEALING AND DEGRADATION EFFECTS ON A-SI PV MODULES

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ABSTRACT:
This study aims to delve into annealing and degradation mechanisms observed for amorphous silicon modules during outdoor operation. Particular interest is devoted to finding optimum conditions for the annealing process, in terms of temperature level and heating period, leading to high efficiency recovery in degraded amorphous silicon modules.
The interest to thoroughly investigate the characteristics of these two processes comes from the encouraging results obtained with a thermally insulated a-Si PV plant [1]. Findings showed that the better thermal behaviour and annealing processes of a-Si compared to c-Si technologies compensated a significant part of losses due to the nearly horizontal roof integration.
Thus far an analysis on four Riverclack® Elios Deck PV modules has been carried out. Initially the modules have been exposed to outdoor conditions for degradation and subsequently followed different indoor annealing cycles at various temperatures and periods of heating. First results showed important annealing effect already at 80°C and an almost full degradation recovery after heating at 90-100°C for a period of 8-12 hours.
Future works aim to study annealing and degradation effects directly on modules installed and monitored outdoors.
Keywords: Amorphous silicon, Annealing, Temperature

1 INTRODUCTION

The interest to thoroughly investigate the characteristics of the annealing and degradation processes comes from the encouraging results obtained with an a-Si PV plant of 15.36 kWp presented in [1] and [2]. The plant (CPT-plant), composed of flexible triple-junction amorphous silicon modules laminated together with a single-ply roofing system, has been integrated and thermally insulated on a flat roof of a professional school located in the south of Switzerland. Thermal insulation leads to a higher working temperature of CPT-modules improving their performances through annealing mechanisms. Findings revealed that the better thermal behaviour and annealing processes of a-Si compared to c-Si technologies compensated a significant part of losses due to the nearly horizontal roof integration.

In fact the overheating of the amorphous silicon modules above certain values leads to power recovery with respect to initial power degradation typical of this technology. Two reversible mechanisms can adequately represent this phenomenon, presented in [3] and [4]:

1) Slow-degradation mechanisms on the a-Si module performance is related to an high activation energy mechanism requiring high module temperatures (>80°C) to reverse the process.

2) Fast-degradation mechanisms with a lower activation energy that can therefore be easily reversed at lower module temperature (>40°C).

Where the terms of `fast' and `slow' refer to the ease of degradation to be reversed through annealing mechanism.

As observed for the thermally insulated CPT-plant both levels are attained, showing the important influence of annealing effect in practical applications. It is therefore in our interest to deeply investigate on degradation – due to sunlight (Staebler-Wronski effect) – and annealing of a-Si at different temperatures and under real outdoor operating conditions.

This study aims as well to acquire important knowledge for optimization of amorphous silicon plants and particularly in the case of BiPV solutions.

2 EXPERIMENTAL

This study has been carried out on four Riverclack® Elios Deck PV modules. These are triple junction amorphous silicon Unisolar modules (a-Si:H/a-SiGe:H/a-SiGe:H) each of 31Wp. These modules are glued and seamed on aluminium deck, which are snap locked on aluminium roof sheets (Riverclack®) produced by ISCOM (Italy).

The modules have been degraded outdoors in summer time (South Switzerland, latitude 46°N). During the degradation period each module has been kept at its maximum operating power point (MPP). This condition has been obtained connecting each module to a MPPT3000 – device conceived and developed at SUPSI-ISAAC and described in [5] – that allows to monitor the electrical parameters and to choose the module load. The outdoor installation is presented in Fig. 1.

Fig.1: Outdoor installation for monitoring of Riverclack® Elios Deck PV modules during degradation.

Our work has been carried out on 2 different batches of modules. All four modules, named in this paper A, B, C and D, have been degraded outdoors. Afterwards modules A and B followed indoor *test1* and C and D indoor *test2* (both tests are described below), where the annealing process has been investigated at different temperatures. The electrical parameters have been measured before and after the degradation period using a pulsed Sun Simulator (Class: AAA). Through this, IV characteristics were performed where, as irradiance sensor, a filter c-Si reference cell (range 300-1000nm) was used.

The annealing has been performed by means of an air-heating oven at different temperature levels: 80, 90, 100 and 120°C. For each temperature an annealing cycle has been performed consisting in subsequent heating steps - 4h+4h+4h+4h+14h for a total of 30 hours - in order to verify the performances recovery during the time. As previously announced the modules A and B followed *test1* which consisted in 4 complete annealing cycles at 80, 90, 100 and 120°C (one cycle per temperature). Whereas modules C and D performed *test2* with 2 complete annealing cycles at 100°C and 120°C. The electrical parameters (IV curves) have been measured after every step, whereas after some temperature cycles the analysis performed on the modules involved also the measurement of the temperature's coefficients (α, β and γ) and the I-V curves at different irradiance levels.

3 RESULTS

After an outdoor exposure of 10 days during August (total irradiation received was 65.6 kWh/m^2) A and B modules then followed *test1*, analyzing annealing behavior at different temperatures. In Fig. 2 the four electrical parameters variations of Pm, FF, Voc and Isc with respect to initial values (before outdoor exposure) are compared.

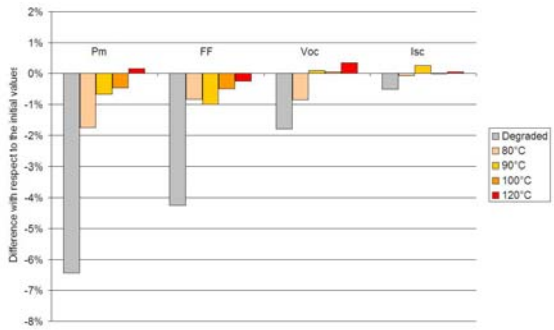

Fig.2: Electrical parameters variations of Pm, FF, Voc and Isc produced with indoor heating (annealing effect).

For each temperature the electrical characteristics are those measured after 30 hours of heating (end of each temperature cycle). Average values between A and B modules are plotted. As shown the average Pm degradation after outdoor exposure amounted to 6.5%, representing a partial degradation as a consequence of the short period of outdoor exposure. Nevertheless the annealing performed in *test1* showed an important recovery already at 80°C for both A and B modules. As a matter of fact Pm after 30 hours of heating resulted less than 2% below initial value. This performance increase corresponds to more than 70% of the outdoor degradation occurred during 10 days. For the cycle at 90°C the annealing effect led to further maximum power increase with an average level less than 1% lower with respect to initial value. Subsequently the cycle at 100°C did not show important changes with respect to previous one at 90°C. Whereas at 120°C annealing still appeared allowing a full maximum power recovery. The fact that the initial maximum power was reached let understand that the modules were already exposed to light before reaching SUPSI-ISAAC institute. Their previous light history is unfortunately not exactly known. This conclusion is based on results presented in [6] where for same conditions efficiency recovery was around 80%.

Besides it is clear from Fig. 2 that the main changes in electrical parameters during the annealing process occur mostly in FF (and hence in Pm) and Voc. The same aspect is clearly pointed out in Fig.3 where IV characteristics before and after annealing (end of *test2*) are presented for module D.

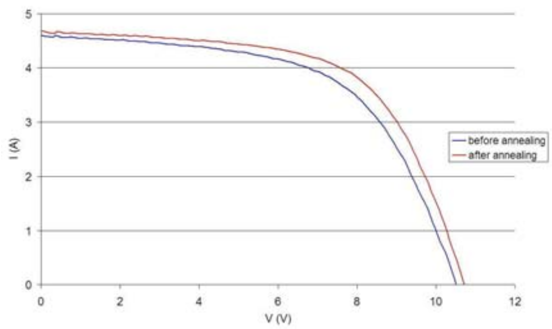

Fig.3: IV curves before and after annealing.

This aspect confirms results of previous presented studies [7].

As explained *test1* is composed of four test cycles in the range from 80°C to 120°C which have been done in a row. In order to verify the annealing behaviour starting from a higher temperature than 80°C, C and D modules have followed *test2* with first heating cycle at 100°C. In Fig. 4 the maximum power recoveries of the four modules after 30 hours of heating for 3 temperature cycles, namely at 80, 90 and 100°C, are compared.

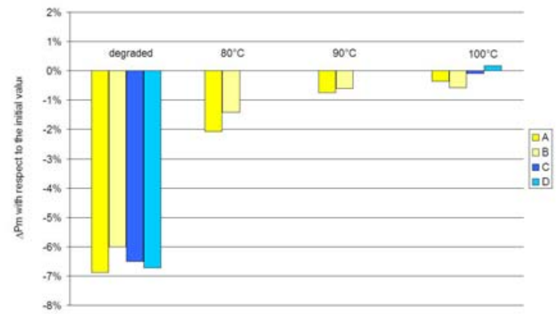

Fig.4: Pm degradation and recoveries at 80, 90 and 100°C.

Degradation levels are also included in Fig. 4. As shown modules C and D started annealing at 100°C and reached practically same level as modules A and B which had already followed two complete cycles of 30 hours at 80°C and 90°C. Actually a comparable level between the two batches of modules - A, B and C, D - was even reached before, after an heating period of only 10 hours. This result clearly showed that the annealing effect on efficiency recovery depends mostly on temperature level. In fact, recovery for an enough long period of heating seems to be independent to previous annealing at lower temperature.

Comparing the cycles at 80°C (for modules A and B) and 100°C (for modules C and D) permitted to study the performance recovery evolution with heating time and its temperature level dependency. This result is presented in Fig. 5 where the maximum power levels, expressed as a percentage with respect to initial values, are presented for each heating step.

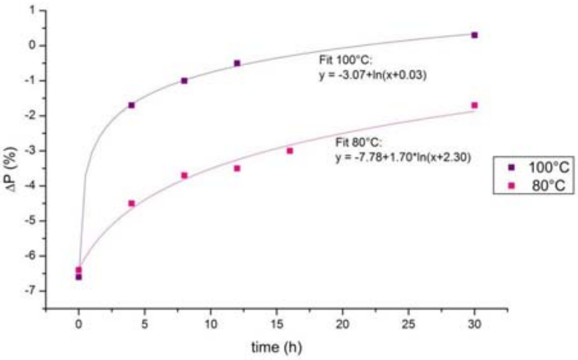

Fig.5: Pm levels during annealing cycles at 80°C and 100°C.

This comparison mainly shows that the performance recovery speed trough annealing increases with temperature, as similarly observed and presented in [6]. As a matter of fact average value of maximum power levels of modules C and D reached more than 80% after only 8 hours of heating at 100°C whereas around 20 hours were required to reach same maximum power recovery for modules A and B heated at 80°C. This aspect led to an average maximum power recovery for modules C and D after only 4 hours of heating at 100°C equal to the one reached for modules A and B after 30 hours at 80°C. Results obtained with *test2* on modules C and D revealed also that 8 hours at 100°C were sufficient to increase maximum power from a partially degraded level of 6.6% to a level of 1% both below and referred to initial value before outdoor exposure.

Within *test1* and *test2*, measurements of IV characteristics at different irradiance and temperature levels were investigated. The main results in both cases consist of unimportant changes related to annealing effect. For instance in Fig. 6 are presented maximum power temperature dependencies after outdoor degradation and at the end of annealing cycle performed at 120°C for module C.

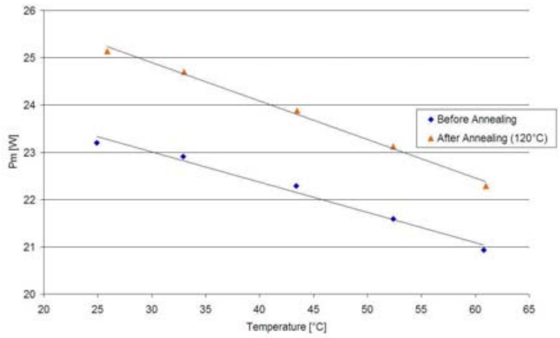

Fig.6: Pm temperature dependencies after outdoor degradation and at the end of annealing cycle performed at 120°C .

As pointed out in Fig. 6 and summarized in Table 1 the resulting temperature coefficients for Isc(α), Voc(β) and Pm(γ) – referred to values of Isc, Voc and Pm at $800W/m^2$ and 25°C - remain constant within the associated errors.

	γ [%/°C]	β [%/°C]	α [%/°C]
Before Annealing	-0.27	-0.39	0.09
After Annealing	-0.30	-0.38	0.08

Table 1: Temperature coefficients before and after annealing performed at 120°C during 30 hours. Values are referred to Pm, Voc and Isc at $800W/m^2$ and 25°C.

Modules didn't show any visual damages after *test1* and *test2* where last cycle was performed at 120°C for a period of 30 hours.

Finally the four modules have been recently exposed outdoors ready for a new and longer degradation cycle (2-3 months). The outdoor monitoring allowed investigation of real outdoor performances before and after annealing test cycles. An example is reported in Fig. 7 where the performance ratio behaviours for one day at the end of the first outdoor exposure and first day after indoor annealing tests are represented.

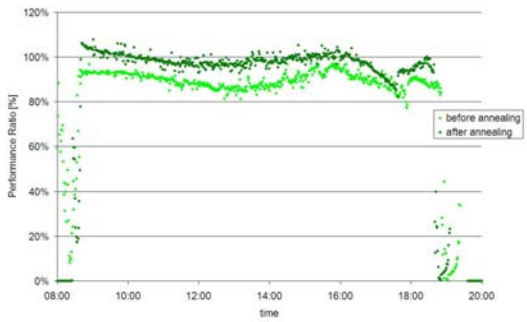

Fig.7: Outdoor Performance Ratios (1 min scan frequency) of module D before and after annealing cycles.

Both days correspond to nice weather conditions (about 6 kWh/m^2 per day). Performance ratio is referred to nominal power of PVL31T, namely 31W. From the comparison it is clear that the performances after indoor annealing are improved. For instance for the two days presented in Fig. 7 the difference on average PR values for irradiances on module D higher than 400 W/m^2 and wind speed less than 1 m/s is about 11%. This result exceeds the power increase measured indoor after annealing cycles. In fact the power level after *test2* for module D resulted 9.4% higher than power after outdoor exposure. Besides, given that from indoor tests unimportant changes were observed on irradiance and temperature behaviours with respect to annealing, reveals that some others effects could arise with annealing mechanism as, for instance, spectral changes. This aspect is foreseen to be investigated within the future planned works.

4 CONCLUSIONS

This study has been focused on the analysis of annealing and degradation processes occurring in amorphous silicon triple junction modules. Main effort has been devoted to characterize annealing effect on electrical PV performances by heating the modules indoor - after outdoor degradation during summer – in the range of 80-120°C and for different periods of time.

Annealing effect showed an important recovery already at 80°C (more than 70% of degradation), confirming the results of high performances observed for thermal isolated a-Si plants. The most relevant parameter for annealing is temperature, which characterises the degree of performance recovery and its evolution with time. Annealing at 90-100°C for a period of 8-12 hours - after outdoor degradation around 7% - allowed an almost full power recovery in a-Si triple junction modules (remaining however below power level at the exit of production line).

Future planned works foreseen to analyse annealing and degradation effects directly for modules in real operating conditions. Ideal conditions for annealing as well as stability and reversibility of annealing-degradation cycles will be investigated.

This study aims as well to acquire important knowledge for optimization of amorphous silicon plants and particularly in the case of BiPV solutions.

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