AGEING OF TWO 5 KW PV ARRAYS AT THE IES-UPM AFTER 8 YEARS OF OPERATION

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ABSTRACT: This work analyses the degradation of two 5 kW PV arrays which are located on the roof of the Campus Sur of the Universidad Politécnica de Madrid. These systems were installed in March 2013 and they have been continuously monitored while they have been injecting power into the grid, storing at the same time its DC power and the operation conditions (effective irradiance and cell temperature). These variables allow to calculate their power at Standard Test Conditions over time and, consequently, the degradation rate for each PV array in these 8 years of operation. The linear degradations obtained are similar to the ones presented by other authors, but we have found that there is not apparent degradation in the first years of operation. Besides, it seems that shading could increase the degradation rates. These figures and phenomena can be useful for a better understanding of the actual behavior of PV systems in order to obtain more accurate energy predictions.

Keywords: Ageing, PV array degradation, shading.

1 INTRODUCTION

Year by year the number of installed PV systems all around the world is increasing exponentially thanks to the maturity of PV technology, which makes PV systems more and more competitive. Just 15 years ago, the peak power tolerance of PV modules was typically ±5% [1]. Then, the uncertainty of the yearly energy predictions of PV systems was not so critical because these kind of systems was usually subsidized [2]. Nevertheless, today PV systems compete directly (even unsubsidized) with the traditional energy sources in the framework of call for tenders. Now, modules power tolerance is lower than 2% (and usually positive) and the uncertainty of the energy predictions should be low in order to obtain good conditions to get bank financing for the execution of large photovoltaic projects.

In this scenario, ageing losses begin to play an important role to obtain a more accurate prediction of the energy production. This degradation, which could be almost neglected years ago, now is critical to reduce the uncertainty of these predictions. The problem is that the degradation guaranteed by manufacturer is no more than 20% in 25 years, that is, a linear degradation of -0.8%/year [3][4]. Nowadays this figure has been reduced close to -0.5% because the previous one uses to be conservatives, as shown in several studies about the real degradation rates of PV modules after their exposition outdoors for several years [3][5][6][7]. Therefore, the initial energy reports about the production of a particular PV installation and its performance used to be underestimated.

The Instituto de Energía Solar of the Universidad Politécnica de Madrid (IES-UPM) has two PV installations in operation which have been continuously monitored since their commissioning 8 years ago. This has allowed to study their degradation rate and the actual trend of such power decrease. This will help to better understand the behaviour of these particular modules which were manufactured during the PV boom in the first decade of the 21st century [8][9].

2 THE PV INSTALLATIONS OF IES-UPM.

2.1 Description.

The IES-UPM has two PV installations located on the roof of its headquarters at Campus Sur UPM (latitude: 40.39°; longitude -3.63°) which have been injecting power into the grid from March of 2013. Both systems are made up from modules of the same manufacturer (Siliken SLK60P6L245Wp) which are mounted on a static structure tilted 30º and almost south oriented (-8º). The first one has two strings of 12 modules in series each one (5.8 kWp, Fig. 1) while the second one has three strings of 7 modules in series (5.1 kWp, Fig. 2). Each PV array is connected to an Ingecon Sun Lite 5TL inverter to inject power into the grid.

Figure 1: PV Array 1, with a peak power of 5.8 kWp.

Figure 2: PV Array 2 with a peak power of 5.1 kWp.

2.2 Monthly power at Standard Test Conditions (P^*).

These installations have been continuously monitored, storing periodically their DC power data P_{DC} (every 15 minutes). Simultaneously, the effective irradiance and cell temperature in the plane of the arrays (G_{ef} and T_C respectively) have been also recorded from a modified reference PV module [10] (the PV module on the right side of Array 1, Fig 1). These variables allow to calculate their power at Standard Test Conditions P^* (STC: G^* = 1000W/m^2 and T_C^* = 25ºC) for each single month over the 8 operating years. This can be done if the measured power P_{DC} is corrected in temperature, $P_{DC,25}$

$$P_{DC,25} = \frac{P_{DC}}{1+\frac{\gamma}{100}\cdot(T_C - T_C^*)}$$

and is represented as a function of G_{ef}. In the previous expression, γ is the temperature coefficient of power (%/ºC).

Fig. 3 shows an example of this representation related to Array 2 in March 2020. In this figure we can notice different undesired situations (shadings, inverter saturations and stops) which modify the linear behaviour of the array and, in consequence, the power at STC we are looking for.

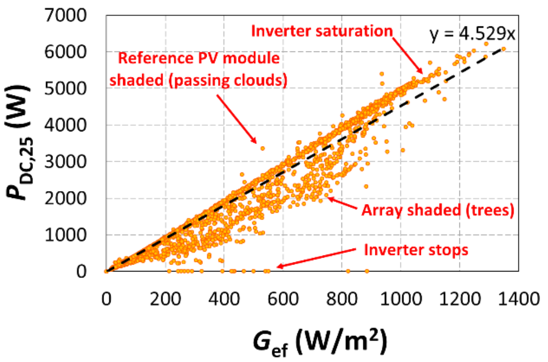

Figure 3: $P_{DC,25}$ as a function of G_{ef} (Array 2, March 2020).

When all the data related to these undesired situations (outliers) are removed, we can observe the linear relationship between $P_{DC,25}$ and G_{ef}. It allows to calculate P^*, which is obtained when $G_{ef} = G^*$ in linear fit equation. Fig. 4 shows the result for March 2020: in this month the power at STC of Array 2 is 4906 W.

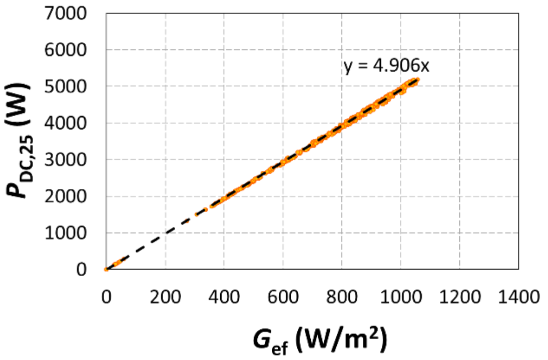

Figure 4: $P_{DC,25}$ as a function G_{ef} once outliers have been removed (Array 2, March 2020).

3 DEGRADATION OF THE ARRAYS POWER.

3.1 Linear model.

Once P^* is calculated for every single month, the degradation rate for each PV array can be analysed. Fig. 5 shows the evolution of P^* for Array 1 and Fig. 6 shows the one for Array 2. As can be seen, both arrays present some kind of oscillation along the year (it is clearer on Array 1), maybe related to spectral issues as suggested by other authors [11]. Dashed lines represent the linear least squares fit for all data for each array (excluding outliers, dark points), where the slope indicates the degradation rates: Array 1 degrades with a rate of -0.25%/year while Array 2 doubles this figure, -051%/year. Probably this difference between the arrays degradation explains why the seasonal behaviour is more evident in Array 1: the higher degradation rate of Array 2 hides the spectral phenomena. Despite the difference, the figures are in agreement with other representative studies [7].

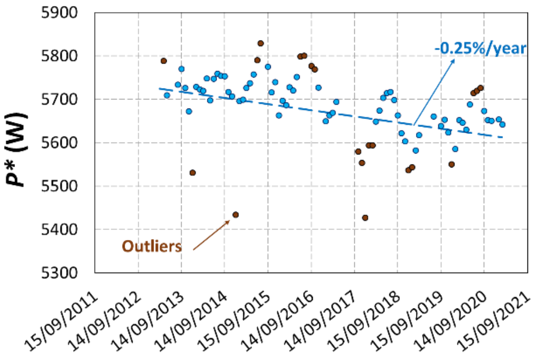

Figure 5: Linear behaviour of P^* for Array 1 from March 2013 to February 2021.

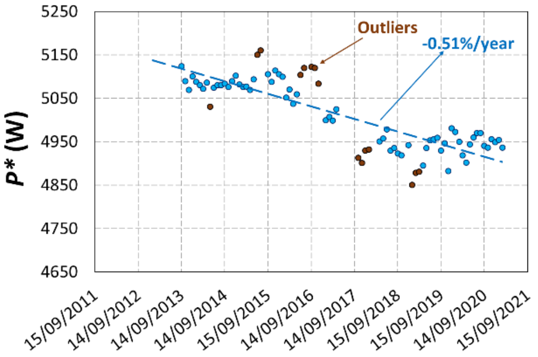

Figure 6: Linear behaviour of P^* for Array 2 from March 2013 to February 2021.

As the arrays are constituted by the same PV modules and the same inverters, they have similar interconnection configuration and they are located at the same location, we have found that this difference could be associated to their particular shading profile: the PV array which is more affected by shading from surroundings is also the PV array which has developed a higher ageing. While Array 1 is almost free of shading, the shadows from two nearby trees (one in the east, Fig. 7, another in the west, Fig. 8) reach Array 2 in the morning and in the afternoon (in the last case, shortly after solar noon with high levels of irradiance). This situation is repeated every single day and can contribute to accelerate the degradation of the modules; however although it does not have immediate harmful effects or threaten the integrity of the modules (in thermographic inspections, transient hot spots have not been detected, at least with relatively large shadows).

Figure 7: Shadow cast every day on Array 2 by a tree located at its east.

Figure 8: Shadow cast every day on Array 2 by a tree located at its west.

3.2 Two-step model.

On the other hand, once the initial light-induced degradation is overcome, we have observed that ageing is not really linear from the beginning: it could be considered that in the first years of operation there is not apparent degradation, as stated by some manufacturers [12] and as proposed by other studies [13] [14]. Later the power begins to decrease at a higher rate than the measured in the single linear model (below the manufacturer warranty) but achieving the same final power value at the end of the considered period.

In this case, it is clear that a two-step degradation profile fits much better to the actual data, as can be seen in Fig. 9 and Fig. 10: in the first 3 years the power varies in a narrow range lower than 2% (points in yellow background). Later, the degradation can be considered as linear, but now of about -0.39%/year (Array 1) and -0.81%/year (Array 2). This rates are almost double the single linear ones obtained previously.

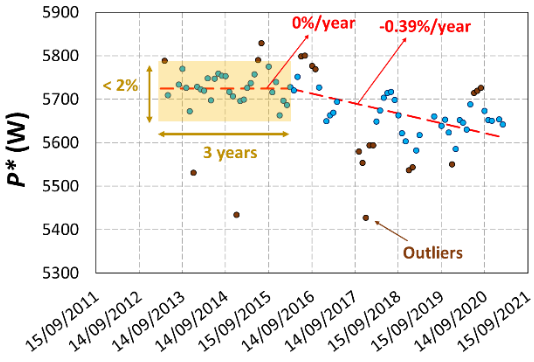

Figure 9: Two-step P^* degradation profile of Array 1.

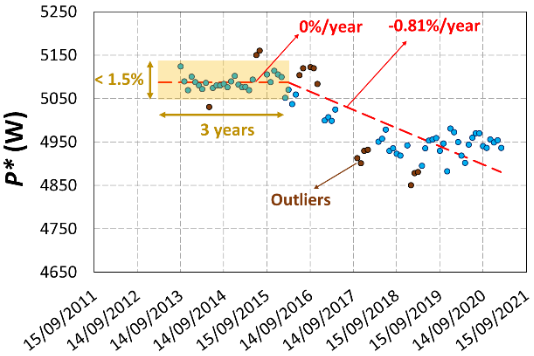

Figure 10: Two-step P^* degradation profile of Array 2.

The assumption of these models, or the linear with a reduced ageing, instead the conventional one based on the warrantied degradation (usually -0.8%/year) has a not negligible impact on the energy yield simulations of the systems.

4 IMPACT OF THE SELECTED AGEING MODEL ON THE ENERGETIC SIMULATIONS.

In order to evaluate the energetic impact of the different models of ageing we have simulated in SISIFO [15] the production of the two PV arrays under study. Our objective is to compare the energetic production for each ageing model: so we have performed these simulations assuming that the PV arrays are free of shadows.

First, we have defined the initial power for each PV array as the average power calculated in their first 3 years of operation (those inside the yellow rectangles, disregarding the outliers). So, the initial power is 5725 W for Array 1 and 5087 W for Array 2. If the linear model with the warrantied rate is used, the arrays final powers are 5358 W and 4762W respectively after 8 years. These figures turn into 5612 W and 4881 W if we consider the actual degradation measured. That is, the real power degradation of the modules in this period is between 4.7% and 2.5% lower than the warrantied.

So, as the PV modules have a better ageing, the real energy production during this period will be higher than the one obtained based on warrantied rate. Table I shows the results of the energy yield estimation for the first 8 years of operation of Array 1 for each degradation model considered:

- Manufacturer warranty degradation: linear rate of -0.8%/year.
- Actual degradation (measured): linear rate of -0.25%/year.
- Two-step degradation: without any power degradation in the first 3 years followed by a linear rate of -0.39%/year.

When a degradation rate closer to reality is used, the energy production increase is higher than 2% (2.3% just in 8 years; we must keep in mind that the warrantied lifetime of a PV installation is 25 years or higher). Moreover, if a two step model is selected, there is an additional improvement of 0.3%. Fig. 11 shows this graphically: the energy obtained from the classical model with the warrantied degradation is represented by the black area ($E_{linear\_warranty}$, the total area covers until the “x” axis), which is lower than the area covered by the actual linear degradation (the energy increase is indicated in blue, ΔE_{linear_actual}). An additional energy gain is obtained when using a two-stage model (red area, ΔE_{2_step}).

Table I: Yearly energy production of Array 1 (SISIFO simulation).

Array 1 (kWh)	Warranty	Actual	Two-step
Year 1	9797	9797	9797
Year 2	9707	9770	9797
Year 3	9617	9743	9797
Year 4	9528	9715	9758
Year 5	9437	9686	9720
Year 6	9348	9659	9681
Year 7	9259	9631	9643
Year 8	9168	9604	9604
Total	75863	77605	77799
Difference (%)	0	2.3	2.6

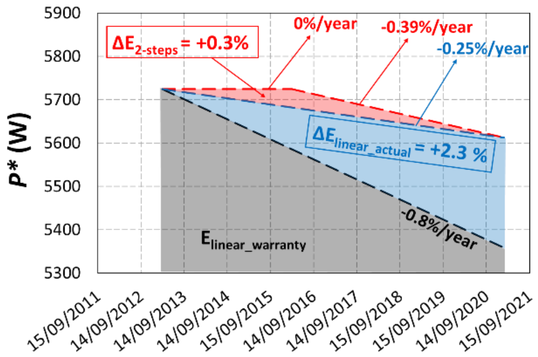

Figure 11: Energy production of Array 1 for each degradation model.

Table II shows the results obtained for Array 2. In this case the degradation models considered are:

- Manufacturer warranty degradation: linear rate of -0.8%/year.
- Actual degradation (measured): linear rate of -0.51%/year.
- Two-step degradation: without any power degradation in the first 3 years followed by a linear rate of -0.81%/year.

Table II: Yearly energy production of Array 2 (SISIFO simulation).

Array 1 (kWh)	Warranty	Actual	Two-step
Year 1	8703	8703	8703
Year 2	8624	8653	8703
Year 3	8543	8601	8703
Year 4	8464	8552	8632
Year 5	8383	8500	8562
Year 6	8304	8450	8490
Year 7	8223	8399	8419
Year 8	8144	8349	8349
Total	67388	68206	68560
Difference (%)	0	1.2	1.7

Now, the selection of a degradation rate closer to reality leads to an increase of energy production higher than 1% (again, just in 8 years). And if a two step model is selected, there is an additional improvement of 0.5%. In this case, as the actual degradation rate of Array 2 is closer to the warrantied by manufacturer, the energetic improvement with a linear model is reduced (compared to Array 1) but now the additional improvement achieved with a two-step model is almost doubled: it increases from 0.3% to 0.5%. Fig. 12 shows this graphically.

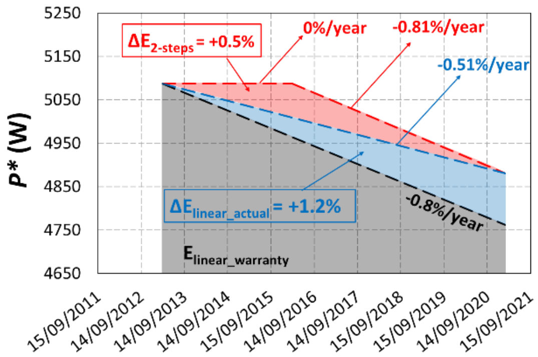

Figure 12: Energy production of Array 2 for each degradation model.

So, it is very important to select a model which best fits reality: this not only leads to more accurate predictions, but also can help to the bankability of the PV system. A higher productivity translates into in a shorter payback time and, consequently, more advantageous financing conditions. This advantages are much smaller if the strictly warrantied degradation rates are used. As we have shown, these figures used to be quite conservative at least 10 years ago. In fact, warrantied degradation rates of currently PV module are around -0.5%, figure which is closer to the actual results obtained.

5 SUMMARY

This paper reports about the actual degradation rates obtained from two PV installations of 5.8 kWp and 5.1 kWp which are operating in Madrid since 2013. Their rates have been calculated from the actual peak power measured monthly thanks to the continuous monitoring of power and operating conditions (G_{ef} and T_C) from a reference PV module.

We have observed that the manufacturer ageing warranty is too conservative: the actual degradation rates measured are lower. Besides, an ageing model which is based on a two-step degradation instead of a single linear one seems to be more appropriate to simulate the real behavior of PV modules. Energy production gains about 1%-2% are achieved in 8 years if the proper ageing model is selected. So, this increase could reach 2%-3% when the whole lifetime of the PV installation in considered (25 years).

On the other hand, we have noticed that shading over PV arrays could accelerate natural ageing. We have obtained that prolonged shading conditions throughout the whole year could lead to double the degradation rates.

6 ACKNOWLEDGEMENTS

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