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Long-term degradation rate of crystalline silicon PV modules at commercial PV plants: An 82-MWp assessment over 10 years

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Abstract

Due to high competitiveness in the PV sector, despite the low degradation rate of crystalline silicon PV modules (below 0.5%/year), it is still important for utilities to know its actual value due to its impact on energy yield and hence, profitability, over the lifetime of a PV plant. However, uncertainties related to both the influence of downtime periods due to problems that may appear under normal operation of a commercial PV plant and to the measurement of degradation rates at PV plant level make this a challenging task. In order to obtain a significant value, in this paper, three measuring methods with different uncertainty sources are used for 82 MWp of PV modules on different locations in Spain and Portugal over 10 years. According to the different methods used and PV plants analyzed, excluding PV plants with problems, a range of degradation rates between 0.01 and 0.47%/year has been found. The overall average value observed is 0.27%/year. The findings of this work have also revealed the great importance of good operation and maintenance practices in order to keep overall low degradation rates.

KEYWORDS

crystalline silicon, degradation rate, field testing, PV module, PV plant

1 | INTRODUCTION

The long-term degradation and stability of PV modules has great impact on the economics of PV plants. Financial models usually assume a long-term degradation rate for crystalline silicon, x-Si, modules of around 0.5% per year.[1,2] This is in accordance with the results of an extensive compendium of over 200 studies from the open literature up to 2015, which has found median degradation for x-Si technologies in the 0.5%–0.6% per year range,[3] and in accordance with the guaranties offered by manufactures, most typically in the 0.5–0.7%/year range. However, other studies show degradation rates closer to 0.2%/year.[4–9] The difference between assuming a degradation rate of 0.5%/year or 0.2%/year results in a difference of 3% of the energy yield of the PV plant during 20 years, meaning that it is of great importance to know the actual degradation rate of PV modules.

Measuring degradation rates in commercial PV plants is difficult to achieve experimentally due to the environmental variabilities that arise in consecutive outdoor measurements and due to the small magnitude of the measuring itself. A possibility consists of discrete measurements[10] of I-V curves for deriving the characteristic maximum power at Standard Test Conditions, P_{MPP}^{STC}, at selected modules in consecutive years. Difficulties arise from the high accuracy required, well below 1% of repeatability, and from the extrapolation of results to the whole PV plant. Another possibility consists of continuously observing a performance related parameter such as the Performance Ratio, *PR*.

Now, difficulties arise from the modifications the PV plant or the measuring devices may suffer over the years.

The PV portfolio of Acciona includes 13 PV plants in Spain and Portugal installed between 2004 and 2008, totaling up to 82 MW_p of x-Si modules from four different manufacturers that are being routinely operated and carefully evaluated from this time. As far as we know, this is one of the largest commercial PV fleets in the world with more than 10 years of operation. Degradation rate of these plants is being assessed by both discrete I-V curves measurement separated by some years, and by the analysis of the monthly *PR* evolution. A 2014 publication[11] of the same authors of this paper assessed the degradation rates of four PV plants adding up to 15 MW during 4 years, revealing no apparent degradation during those years. The present paper expands the work presented in previous work[11] in terms of power, timespan, and methodologies. The relevance of our contribution comes from the fact that only 3% of nowadays global PV capacity was built before 2008, and few of those PV systems installed before 2008 have been monitored; moreover, the PV plants analyzed in this work represent around 0.5% of all the PV modules installed globally by the end of 2008. Although the main objective of this paper is to report on midlife normal degradation of x-Si PV modules, also observed failure modes and low P_{MPP}^{STC} at the beginning of life are discussed. The paper is organized as follows: section 2 describes the relevant characteristics of the involved PV plants, Section 3 presents the degradation rate measurement methodology, Section 4 shows the results and discussion and, finally, in Section 5, the main conclusions are explained.

2 | PV PLANT CHARACTERISTICS

All 13 PV plants are made of azimuthal solar trackers with 6 to 18 kWp, with PV modules in the 150- to 250-W range. The first 12 PV plants, up to a total peak power of 36 MW, are in Spain, in a radius of 25 km in the Ebro valley of the province of Navarra. According with the Köppen-Geiger-Photovoltaic climatic classification,[12] this is a DH zone, that is, a temperate zone with high irradiation. In fact, the global horizontal yearly irradiation is around 1,600 kWh/m^2, which translates into global in-plane irradiation around 2500 kWh/m^2. The monthly average of daily ambient temperature ranges from 6°C in January to 25°C in July. This is a strong thermal contrast that leads to a fairly wide cell temperature range of about 45°C (90% chance of a yearly temperature swing from 5°C to 50°C). Annual cumulative precipitation is about 400 mm, with summer rains in the afternoon relatively frequent.

Because the Spanish feed-in tariffs until 2004 specially promoted small individual systems (the feed-in tariff declined from 0.40 to 0.22 €/kWh when the rated AC power became larger than 5 kW) and due to market conditions before 2008 in Spain, which encouraged small investors to own small PV systems, those PV plants, which were called *solar farms*, were mostly constituted by the aggregation in AC of individual systems of 5 or 11 kW, each associated with an individual selling contract, hence, each with its own inverter and energy meter for billing purposes. As such, the readings of these power meters have been registered monthly without fail. Moreover, thanks to this modularity, the systems have been monitored very closely by the maintenance team, which has detected, recorded, and solved every problem promptly, attaining very short downtime periods and providing us with very valuable information. These plants do not have other specific means of monitoring. Hence, we have used irradiation, data from nearby state-owned weather stations, whose data is accessible at Gobierno de Navarra.[13] As a representative example, Figure 1A shows the PV plant P1, constituted by 153 individual systems, and Figure 1B one of the trackers. Operational experience with these plants has led to publications about energy performance,[14] hot spots[15,16] power degradation during the first 4 years of operation[11] and power fluctuations.[17–19]

The 13th PV plant is 45.8 MWp in Amareleja, Southern Portugal. The climatic conditions are somewhat more extreme that in Spain. Global horizontal and in-plane yearly irradiations are 1800 and 2700 kWh/m^2, respectively. The monthly average of daily ambient temperature ranges from in 9°C in January to 25°C in July; and the yearly cumulative precipitation is about 500 mm. The Portuguese feed-in tariffs regulations allowed individual contracts with large plants. In fact when this PV plant was built it was the largest in the world. Hence, PV plant P13 looks more like a modern standard PV plant (see Figure 2), grouping PV modules in larger inverters (500 kW) and having only one power meter for billing purposes. This lower modularity is highly compensated by the extensive supervisory control and data acquisition (SCADA) system that continuously monitors this PV plant recording generated power of every quarter of inverter (inverters are internally divided in four 125-kW units) and PV modules' temperature and in-plane irradiance in nine different locations within the PV plant. Operational data from this plant has been used in already published studies regarding irradiation distribution,[20] module temperature[21] and PV power fluctuations.[22,23]

Finally note that all modules are composed by a glass-EVA-Tedlar structure but different types of x-Si cells exist in different plants. Cell technology and relevant parameters of all PV plants including the P_{MPP}^{STC} measurements calendar and the *PR* evaluation periods are shown in Table 1, grouped by cell technology.

3 | DEGRADATION RATES ESTIMATION

Several methods have been proposed for assessing PV degradation. Traditionally, long-term performance is expressed as a constant rate, in percentage per year, resulting in a gradual and homogeneous decline in annual performance. Implicit is the assumption of linear performance loss. More recently, methods for considered nonlinearities[24,25] and for reducing estimation uncertainties[26] have been proposed. However, these new methods require of continuous monitoring of irradiation, temperature, and energy production data. This is not available for the Spanish "solar farms." As mentioned above, monthly energy production is the only routinely monitored variable. That lead us to assess the degradation of the here concerned PV

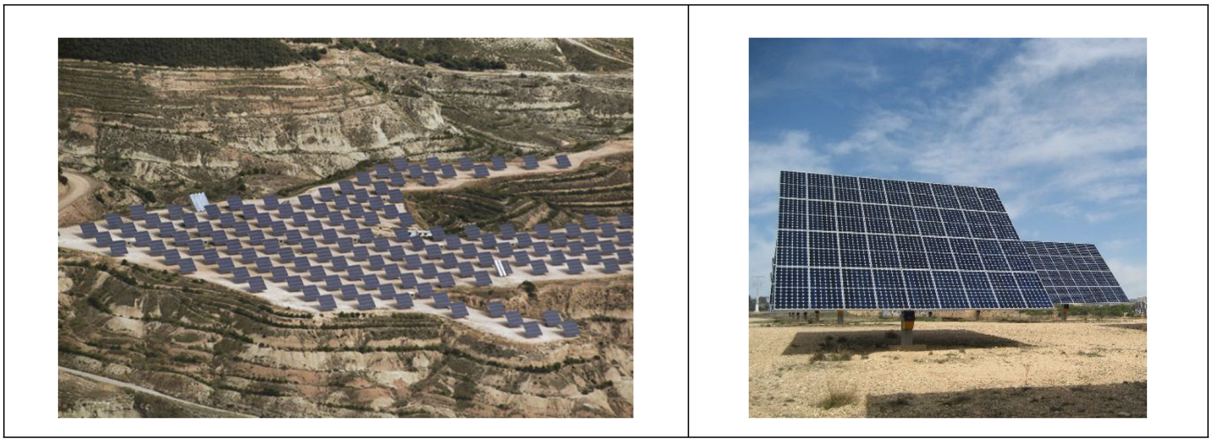

FIGURE 1 PV plant P1, with 1 MW, was installed in 2004. It is composed by 159 45.3 m^2 trackers, each associated with a different sales contract and with the corresponding billing energy meter

FIGURE 2 PV plant P13, with 46 MWp, was installed in 2008. It is composed by 134 m^2 trackers. Each group of 36 trackers is connected to a 500- kW power station, having one only selling contract for the whole plant

TABLE 1 Relevant information of the PV plants

PV plant	Rated P_{MPP}^{STC} [MWp]	*Year instal.*	*Module manufacturer and cell technology*	*Trackers*	*Power meters*	*Years of peak power measurement*	*Period of PR evaluation*
P1	0.98	2004	M1: mono-Si, Laser groove buried grid (LGBG)	159	153	2006–2009,2016	2006–2016
P2	1.19	2004		191	205	2006–2009,2016	2006–2016
P3	1.44	2005		231	154	2006–2009,2016	2006–2016
P4	2.10	2005		336	233	2006–2009,2016	2006–2016
P5	2.64	2006		400	279	2006–2009,2016	2006–2016
P6	3.17	2007		230	120	2008, 2009,2016	2008–2016
P7	1.78	2005	M2: mono-Si	280	200	2006–2009,2016	2006–2016
P8	2.49	2008		376	165	2016	2012–2016
P9	1.17	2007	M3: mono-Si, HIT	79	54	2008, 2009,2016	2008–2016
P10	3.78	2007	M4: poly-Si	556	554	2008, 2009,2016	2008–2016
P11	7.47	2008		1,098	858	2016	2012–2016
P12	7.81	2008		556	162	2016	2012–2016
P13	45.78	2008		2,520	70	2011–2016[a]	2013-2016

[a]Continuous monitoring.

plants in terms of the conventional linear degradation rate. This is still a rather good representation of the degradation of x-Si modules.[27] We have proceeded with two different methodologies.

3.1 | Discrete peak power measurements

The P_{MPP}^{STC} of about 10 PV arrays of every plant is determined by recording their I-V curves and translating the maximum power point to STC assuming linear dependence against irradiance and constant power temperature coefficient.[28] To minimize uncertainty, the in-plane irradiance, G is measured by means of the short-circuit current of a reference module, and solar cell operation temperature, T_C, is measured using an infrared camera, always on clear days with very low wind speed. These few arrays are selected from among those with no operation anomalies in the year before the measurement, and the results are used to stablish a relation between P_{MPP}^{STC} and yearly energy production, which is then extended to calculate the P_{MPP}^{STC} of the rest of the arrays from the respective yearly energy productions, after discounting the differences due to other than degradation causes: on the one hand, the position of the corresponding tracker, which affects to shading and, on the other hand, possible operation anomalies (inverter shut-off, module change, etc.), as listed in maintenance records. More details are given in Llaria et al.[29] Finally, the degradation rate is determined from the results corresponding to several years by the conventional standard least square regression, SLS, approach. As a representative example, Figure 3A shows the P_{MPP}^{STC} measured in PV plant P5 and the derived degradation rate. The first value, in 2006, was measured 3 months after the plant's installation, which assures LID stabilization. We carried out two P_{MPP}^{STC} measurements campaigns. One between 2006 and 2009 was devoted to study the plants installed before 2007. The other in 2016 covered all the plants. Because of that, we lack of initial P_{MPP}^{STC} values for the plants installed in 2008.

3.2 | *PR* evolution

The yearly *PR* of the plant is, first, determined. For that, the yearly in-plane irradiation is calculated from the corresponding monthly values of horizontal irradiation recorded at close meteorological stations and free available in the web[13]; and the energy production recorded at all the energy meters of the plant is corrected for discounting losses due to possible operation anomalies. Figure 3B shows the evolution of the yearly *PR* in PV plant P5 from 2006 to 2016.

It is worth commenting that the *PR* depends not only on P_{MPP}^{STC} of the modules but also on temperature and on the performance of the other PV system components: inverters, wiring, etc., that can also suffer degradation. That suggests that the degradation rate obtained with this method may represent, in general, an upper bound for the degradation rate of silicon cells. However, we have observed that yearly temperature is practically constant, and that energy loss due to equipment failure is very low and constant in well maintained PV plants. This is the general case for these PV plants, and, moreover, data from periods with performance issues (e.g., underproduction due to damaged modules, inverters, or structures) is not used for the degradation rate estimation in this study. Hence, the annual trend of *PR* may well be assumed to be only caused by P_{MPP}^{STC} derating during this period, and the difference between degradation rates resulting from both methods can be understood as a general uncertainty indication.

The P_{MPP}^{STC} of the 48-MW PV plant, P13, has been directly determined from operational data provided by the SCADA (DC power, in-plane irradiance, and solar cell temperature) in selected clear days. Note that with this method, there is no need of measuring I–V curves in order to estimate the degradation rates. However, whenever the SCADA finds a performance issue, I–V curves, thermal images, visual inspection and other common diagnosis tasks are carried out in order to find the cause of the problem. Analogously, the *PR* evolution of this plant has been directly determined using the energy production and in-plane irradiation records registered by the SCADA. More

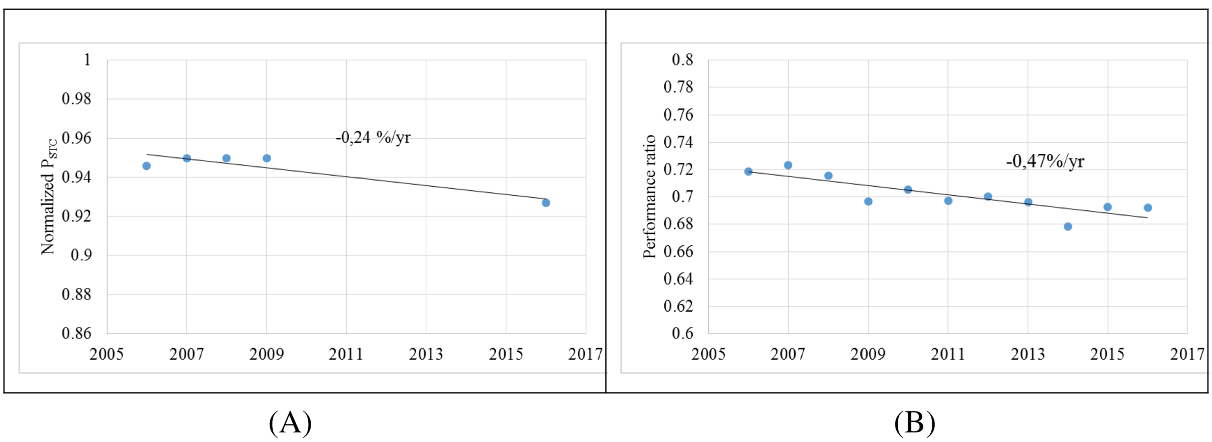

FIGURE 3 Degradation rate estimates in PV plant P5. (A) Peak power values measured in 2006–2009 and 2016. Values are normalized to the nominal power (2.64 MW). Corresponding linear regression leads to a degradation rate of 0.24%/year. (B) Yearly *PR* data and linear regression leading to a 0.47%/year degradation rate

information on the SCADA system and the methods for obtaining P_{MPP}^{STC} and *PR* can be found in Muñoz.[30]

4 | RESULTS

According to the circumstances arising during operation, four main groups of PV plants have been identified:

Group 1: no significant problems

These PV plants have had negligible PV module defects, inverter faults or any other setbacks that may have caused a drop in energy yield. As such, the *PR* values fit linearly when plotted against time as the example in Section 3. This was the case for 7 out of 13 PV plants analyzed, as shown Table 2.

Group 2: defective modules with substitution

PV plants in this group have had an initial accelerated degradation due to the existence of defective modules. Due to the evident degradation problem, these PV plants had their defective modules replaced and degradation rate could be calculated by means of *PR* analysis of the following years. In particular, these PV plants have had significant problems regarding hot spots related to defective soldering between cells and contact ribbons, which was studied and published in previous works.[15,16] This failure resulted in a resistive point in the current path releasing enough heat so as to burn the local area of the PV cell. Therefore, this problem led to a very rapid degradation of the PV plant, resulting, in PV plant P1 for example, in a 4.3%/year drop in the *PR* during the first 2 years of operation as shown in Figure 4. The percentage of PV modules replaced per year is also shown in this figure next to every data point, revealing the extensive replacement campaign that took place in 2009. Moreover, during the following years, some PV modules had to be replaced as hot spots kept appearing in the originally installed PV modules. As shown in Figure 4, removing data points of years 2007 to 2010, results in an estimated yearly degradation of 0.38%/year. PV plants P4 and P2 also fall into this group.

Group 3: defective modules without substitution

PV plants in this group have had a faster than usual degradation process due to defective modules, however, unlike those in Group 2, modules in these PV plants have not been replaced. This is due to an observed degradation not as evident as that in Group 2 but still higher than in healthy modules. Two PV plants fall into this group: P3 and P10.

The PV modules in P3 had the same hot spot problems that in the previous group. However, the problem appeared later, and PV modules were not replaced until 2016–2017. As a result, the average degradation rate of this PV plant during the years of study is 0.94%/year, as shown in Figure 5A. On the other hand, PV plant P10 had a very widespread problem of cracked cells although this problem does not reduce the energy yield as much as what could be seen in PV plants with hot spots, since cracks do not lead to power reduction if the cracked part of the cell is still connected to the busbar via the fingers, that is, if the cracked part is not electrically isolated. As energy yield, apparently, did not drop significantly, practically no PV modules were replaced in this PV plant. However, after some years, the evolution of *PR* over time revealed that degradation was happening faster than in other plants, at a rate of 0.71%/year as shown in Figure 5B, showing that, although most cracks observed did not cause an isolation of a part of the cell, some of them finally do. A more in-depth analysis of this phenomenon was carried out in García et al.[16]

Group 4: catastrophic events

Finally, PV plant P12 is presented, which had good overall performance, but had about 50% of the structures and tracking systems broken and even some of them were partly blown away or

TABLE 2 Main results of P_{MPP}^{STC}, *PR*, degradation rate and number of PV modules substituted since installation

PV plant	$P_{STC,rated}$ [MWp]	*Group*	$\frac{P_{MPP,2016}^{STC}}{P_{MPP,rated}^{STC}}$	*PR 2016*	ΔP_{STC} (%/year)	ΔPR (%/year)	*Average degradation (%/year)*	*PV modules substituted (%)*
P13	45.78	1	0.947	0.753	−0.20	−0.17	−0.27	4.8
P9	1.17		0.931	0.741	−0.31	−0.33		0.0
P6	3.17		0.934	0.729	−0.01	−0.47		3.1
P8	2.49		0.931	0.730	–	−0.32		0.3
P11	7.47		0.935	0.712	–	−0.07		0.1
P5	2.64		0.927	0.692	−0.24	−0.47		2.9
P7	1.78		0.875	0.658	−0.41	−0.19		1.6
P4	2.10	2	0.925	0.691	−0.12	−0.43	−0.30	24.8
P1	0.98		0.900	0.680	−0.36	−0.38		29.7
P2	1.19		0.911	0.713	−0.20	−0.33		28.4
P10	3.78	3	0.900	0.692	−0.52	−0.71	−0.63	0.1
P3	1.44		0.929	0.691	−0.34	−0.94		14.4
P12	7.81	4	0.918	0.730	–	−0.24	−0.24	0.0

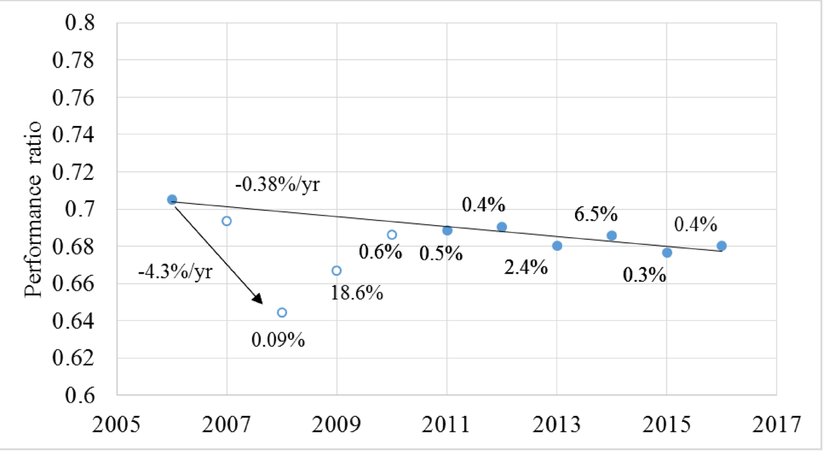

FIGURE 4 *PR* of PV plant P1 over the years of study. Hot spots at the beginning resulted in a 4.3%/year drop in the *PR*. Numbers show percentage of PV modules replaced per year. Hollow data points are removed for linear regression that results in a degradation rate of 0.38%/year

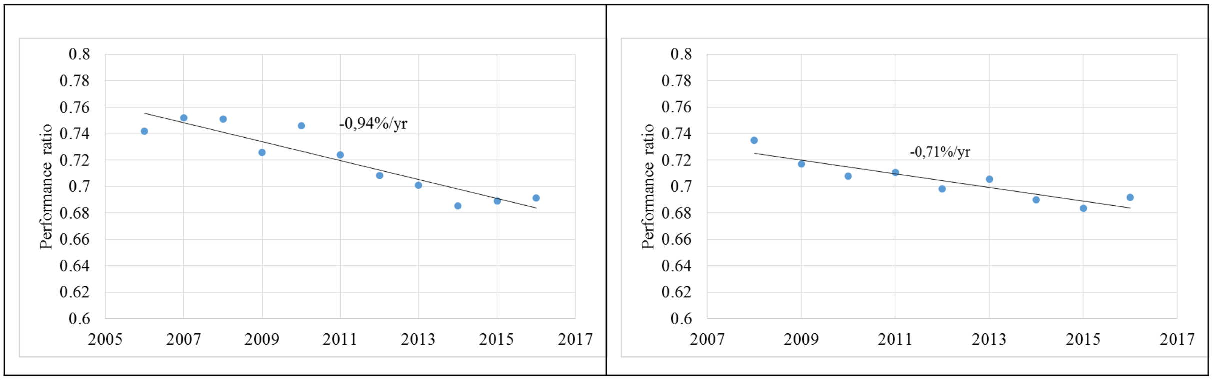

FIGURE 5 *PR* of PV plant (A) P3 and (B) P10. A faster than usual degradation is observed

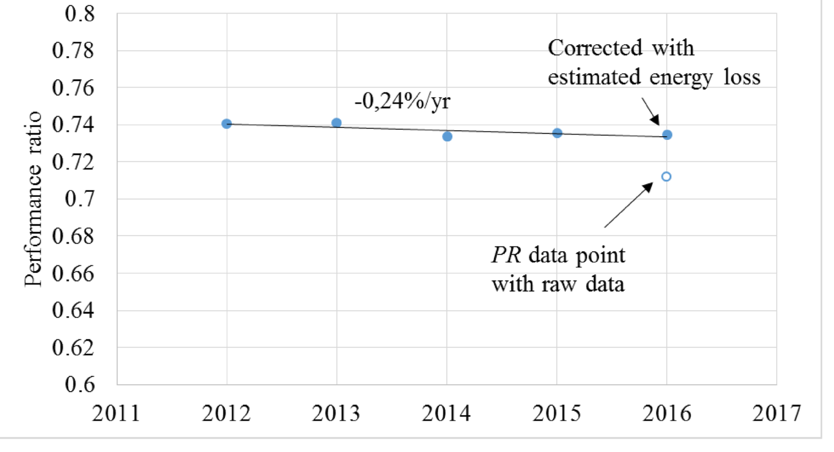

FIGURE 6 *PR* of PV plant P12 over the years of study. Year 2016 presents the *PR* calculated with both raw data (hollow dot) and corrected with the energy lost calculated by the owner in accordance with the insurance company (solid dot)

bent by unusual strong local winds in July 2016, which even led to the falling of several trees in the vicinity of the PV plant. It took a few months to repair all generators hence about 3% of the annual energy yield was lost. Figure 6 shows the raw *PR* data for 2016 as a hollow dot, which can obviously not be used to compute the degradation rate of the PV modules. However, the energy lost caused by this event was calculated by the owner in accordance with the insurance company and an estimated *PR* could be calculated, which is shown as a solid dot. According to data in years 2012–2015 and corrected data of 2016, degradation rate in this PV plant is 0.24%/year.

Table 2 presents the degradation rates resulting from both peak power measurements and *PR* evolution, ordered by group. Figures of the substituted PV modules and of the peak power and *PR* observed in 2016 are also given. In order to visualize the results in Table 2, in Figure 7, it is depicted the hypothetical normalized energy yield of the PV plants, assuming constant yearly irradiation, during the first 10 years of operation using the obtained degradation rates (calculated as the average of the degradation rate obtained with the evolution of *PR* and the evolution of peak power). As it can be seen, PV plants in Groups 1, 2, and 4, that is, PV plants that either had no significant problems or had problems that were corrected timely, present similar degradation rates, in particular, 0.27%/year, 0.30%/year, and 0.24%/year, respectively, well below the maximum limit guaranteed by the module manufactures, typically of 0.5%/year. On the other hand, PV plants in Group 3, that is, plants with defective modules that have not been substituted, have an average degradation rate of 0.63%/year, which shows the importance of good maintenance in a PV plant.

Note that PV plants without significant problems, which have an average degradation rate of 0.27%/year, represent 79% of the total involved power. Figure 8 shows an example of the impact on 20 years energy production of different degradation rates, assuming constant yearly irradiation. Considered cases are as follows: (a) 20 years at −0.5%/year, (b) 20 years at −0.27%/year, and (c) first 10 years at −0.27%/year followed by 10 years at −0.73%/year, which still match the long-term warranty. Corresponding total energy losses by respect to the hypothetical absence of degradation are 5%, 2.7%, and 3.8%. In other words, the degradation path observed in this work implies a production surplus by respect to the warranty ranging from 1.2% to 2.3%, which is certainly relevant in financial terms.

Finally, note that, although no significant differences have been found among different manufacturers regarding degradation rates, PV modules' faults have appeared mostly for two of the manufacturers and rarely among the rest. As a result, three PV plants have had around one quarter of their PV modules substituted due to hot spots as seen on Table 2. The one still affected with hot spots, has already had 14.4% of its PV modules substituted and more are to be replaced.

Regarding differences between degradation rates estimated via P_{MPP}^{STC} and via *PR* evolution, in most cases, it is greater when estimated with the *PR* method, which includes other degradation factors than cell degradation, than with P_{MPP}^{STC}, which may notably increase the

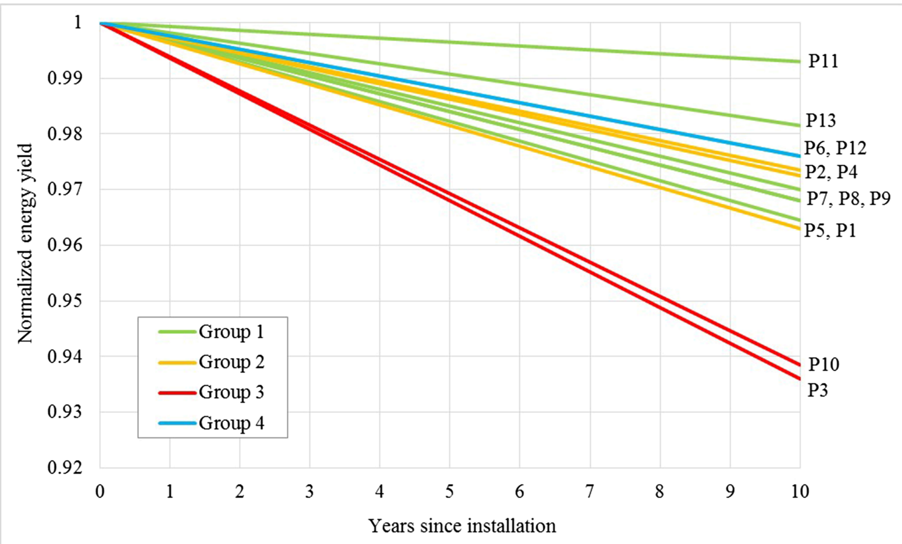

FIGURE 7 Normalized energy yield of PV plants during the first 10 years using their average degradation rate, colored by group: Green for Group 1, orange for Group 2, red for Group 3, and blue for Group 4

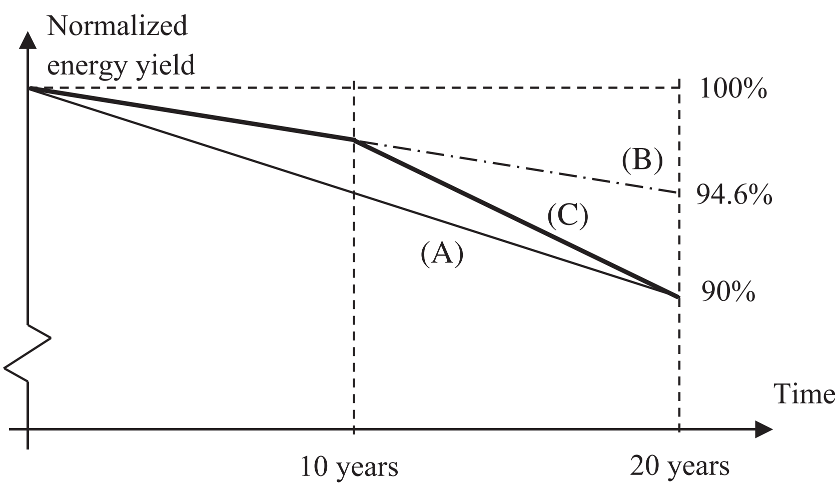

FIGURE 8 Impact on 20 years energy production of different degradation rates, assuming constant yearly irradiation. (A) 20 years at −0.5%/year, (B) 20 years at −0.27%/year, and (C) first 10 years at −0.27%/year followed by 10 years at −0.73%/year

degradation rate of a PV plant as seen in Bolinger et al.[31] Nonetheless, the difference in these PV plants is, in general, quite low, which can be partly explained by good operation and maintenance practices. On the other hand, two PV plants present higher degradation rates when estimated with P_{MPP}^{STC}, which can only be due to uncertainty. While in P13 the difference is very low, in the case of PV plant P7, this deviation is more notable. This is most probably due to the measurement of P_{MPP}^{STC} in 2016. An extra measurement of P_{MPP}^{STC} was carried out in 2017 for this PV plant which showed the same value as in 2016, hence, a lower degradation rate estimation, -0.36%/year. This value is still above that calculated with the *PR* but lies closer. Nevertheless, the differences seen are very low in absolute terms; having used different methods of measurement with different sources of uncertainty in addition to the methods and precautions taken in the data processing and considering the size of the sample in terms of both timespan and power, makes the overall values representative of the degradation rate of x-Si PV modules.

5 | CONCLUSIONS

The degradation rate of 82 MWp of crystalline silicon PV modules over 10 years (from 2006 to 2016) has been assessed by several methods. In the case of the PV plants in Spain, which account for 36 MWp, two independent methods have been used: discrete peak power measurements separated in time and observation of the yearly *PR* evolution. On the other hand, for the PV plant in Portugal, the degradation has been directly determined from operational data. The modules are from four different manufacturers and operate in commercial PV plants in high irradiation regions of Spain and Portugal. Because they are installed over vertical axis trackers, they are subjected to high in-plane irradiation conditions, around 2600 kWh/m^2 per year. Spanish feed-in tariffs regulations before 2004 and market conditions until 2008 especially favored small individual systems in the PV plants in Spain, which represent half the total power here involved, and are hence constituted by the aggregation in AC of individual systems of 5 or 11 kW, each associated with an individual selling contract, and energy meter for billing purposes. As such, the readings of these power meters have been registered monthly without fail and constitute a key information for our work. Moreover, peak power measurements have been carried out in the frame of two different testing campaigns: one covering the years between 2006 and 2009 and the other in 2016, and irradiation data has been obtained from nearby state-owned meteorological stations. The plant in Portugal is more like a modern standard PV plant, grouping PV modules in larger inverters and having a complete SCADA that carefully monitors all the variables describing the operation conditions (irradiance, temperature, etc.) and the power response of the plant (DC and AC powers).

Non defective modules represent about 80% of the total modules population and degrade at about 0.27%/year in average. That is well below the limit guaranteed by the manufacturers. That means the energy production along 20 years is between 1.2% and 2.3% larger than estimated on the base of the guaranteed degradation. Two plants, representing 6.4% of the total involved power, have shown degradation rates above 0.5%/year due to cracked cells and hot spots.

Last but not least, degradations of up to 4.3%/year have been observed in short periods of time due to PV modules' failure or destructive weather events for example. In these particular cases, thanks to appropriate monitoring tools and supervisory protocols, the maintenance team was fast enough in detecting and correcting these problems in time which, otherwise, would have caused significant and permanent degradation of the PV plant and, hence, great economic losses to the owners. These events have shown that good operation and maintenance practices are essential for the correct performance of PV plants.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study is property of a third party. It may be available from the corresponding author upon reasonable request to him and to the third party.

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