# In Field energy performance of solar PV module made of UMG silicon

Moisés Guerra, Íñigo de la Parra, Miguel García and Julio Pascual

***Abstract*— Upgraded Metallurgical Grade Silicon (UMG-Si) PV modules have failed to make their space in the PV market, which was partly to the uncertainty on their in-field performance that brings the wide disparity of results published over the years. The most-recently developed UMG-Si PV modules have demonstrated similar initial degradation and efficiencies under Standard Test Conditions (STC) to those obtained with conventional Solar Grade Silicon (SoG-Si). Nevertheless, their performance under operating conditions other than STC and its impact on the energy production are key aspects that has not yet been properly characterized in the literature. This paper analyses the in-field performance of a PV generator comprised of recently developed UMG-Si modules. This performance was compared to that of another PV generator comprising standard polysilicon modules. The cells and modules of both types of generators were made by the same manufacturer, in the same period and on the same production lines, which guarantees that performance differences encountered are exclusively due to the silicon employed. Contrary to the previous experience, this paper reveals that UMG-Si modules do not necessarily present a better temperature performance than today's conventional modules. The analyzed UMG-Si modules presented 1.6% less efficiency under low irradiance conditions, but this different irradiance performance led to an insignificant difference (less than 0.5%) in their energy production. No significant degradation was measured in both UMG-Si and SoG-Si modules during the two-year analyzed period, being the final energy performance of both types of modules essentially the same. These results can be considered as highly representative of the current state-of-the-art of UMG Silicon technology.**

***Index Terms*—In field performance, SoG-Si, UMG-Si**

## I. INTRODUCTION

Over the last few years, one of the key objectives of photovoltaic technology has been to reduce the levelized cost of energy (LCOE), with the focus on the materials used and also on the production processes employed. With regard to materials, silicon continues to be one of the most expensive raw materials used in the manufacture of solar cells [1]. The vast majority of present-day PV cells are made of polysilicon, obtained either through the well-known Siemens process or, to a lesser extent, through the Fluidized Bed Reactor (FBR) process. However, for some years now, studies have been looking into the possibility of using silicon feedstock that has been purified through metallurgical processes, as a far more energy-efficient way of obtaining silicon than the Siemens or FBR processes [2]–[5]. This alternative method led to what is known as the Upgraded Metallurgical Grade Silicon (UMG-Si) Industry, which experienced a considerable boom in around 2008. At that time, up to 10 different companies were offering this type of material on the market, each with its own specific silicon purification technology.

The main disadvantage of upgraded metallurgical grade silicon is that the impurity content is higher. The Siemens and FBR processes can produce a purity of 9N (99,9999999 %) and 8N (99,999999 %), respectively, while the purity of the silicon produced through metallurgical processes is lower (5N–6N) [6]. This could cause the cells made of this material to have a lower efficiency than those produced using conventional processes. Furthermore, these cells may be subject to increased Light Induced Degradation (LID) and Light and elevated Temperature Induced Degradation (LeTID), etc. [7]–[17], As a result, until a few years ago, the use of UMG-Si silicon was only recommended when mixed with high-purity polysilicon [3]. However, the surprising advances achieved in the purification processes over the years opened the door to the manufacture of monocrystalline and polycrystalline cells using 100% UMG-Si, some of which achieved a peak efficiency of 21.1% using *n*-type Czochralski-grown (Cz) wafers and 2x2 $cm^2$ solar cells [18]–[20]. Some manufacturers took then the decision to market PV modules comprising solar cells made from such material [3], [21], [22]. However, metallurgical Grade Silicon has failed to make much headway in the PV market, partly due to the lack of in-field experience with this technology and to the heterogeneous, and sometimes contradictory, results on the performance of UMG-Si modules published in the available literature including:

Most of the available studies on the in-field performance of UMG-Si modules were published between years 2011 and 2016, while the analytical procedures used, and the conclusions

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reached differ widely. For example, in 2014 Yang et al. [23] published a study on two PV plants of 330 kW and 10 MW respectively, whose modules were entirely made from UMG silicon with a purity of 99.9997 %. Based on a comparison between the observed and estimated performance, they concluded that the yield obtained over the first year was 30% less than the expected one and with an initial degradation of around 10% and an annual degradation rate of 1.6%/year. But these findings differ considerably from those obtained on other UMG-Si modules, which showed very similar initial degradation and performance to that of standard polysilicon-based modules [21], [24]. In fact, Odden et al.[25], in a study made on a number of low-power plants in Asia and Oceania, indicated that the energy performance of the UMG silicon modules analyzed even appeared to be higher than that of conventional silicon modules during those period of the year with higher irradiance levels. As a potential cause, they pointed to their better performance in the elevated temperatures occurring during these periods. However, the methods of analysis used in this study did not allow to quantify what part of these differences was due to performance in relation to temperature and what part was due to other phenomena such as the response to the irradiance received.

The better performance of UMG silicon modules with temperature has been reported in most of the available publications [24]–[28]. However, contradictory results has been found on their performance as a function of the incident irradiance level. Thus, in 2014, Chengquan Xiao et al. [28], tried to analyze the impact of both irradiance and temperature on the performance of single UMG-Si solar cells. This study concluded that the performance of the UMG silicon cells was slightly higher than that of solar grade silicon cells at high temperatures although it was slightly lower at low irradiance levels. On the contrary, Ounadjela et al [29], in his study carried out two years earlier on the comparison of the same technologies reported a better performance of the UMG silicon module at low irradiance levels. It is worth noting that those studies analyze single PV cells or compare UMG-Si modules with conventional SoG-Si modules made by a different manufacturer or even composed of a different cell technology. However, the design, the manufacturing process and the materials used in the manufacture of the module may also affect to the module performance (cell to module losses). Besides, in all those studies the energy performances of UMG-Si and SoG-Si modules were compared in terms of Performance Ratio (PR). This index does not allow to evaluate how much of the differences in that performance are due to the technology and how much are due to the fact that modules are not usually operating exactly in the same temperature conditions. Furthermore, the use of PR also does not allow to quantify separately the influence of irradiance level and the operating temperature on the energy production, something that becomes necessary in order to extrapolate their performance to any other location.

In the recent years, further improvements and optimizations in the silicon purification methods have been achieved and new results are now available. In 2019, a study was published showing the results of a mass production test of solar cells and modules made of 100% UMG-Si manufactured on conventional production lines [22]. This UMG-Si had a purity of 99.9999 %. A considerable number of the wafers produced during this test were sent to an independent AL-BSF cell and module manufacturer. Their performance was compared to that obtained with standard polysilicon wafers produced in the same lines and periods. The test results at a cell level showed very similar parameter and efficiency values to those obtained with the polysilicon. At a module level, only the initial degradation of both types of material were thoroughly studied, showing that the initial degradation in the modules made with UMG-Si was similar to that of those made with polysilicon [30], [31]. Yet again, the separate effect of operating temperature and irradiance level on their efficiency and energy production were not analyzed.

The proper characterization of the energy that current UMG-Si modules can deliver, compared to conventional SoG-Si modules, requires clarifying all those above-mentioned aspects that have not yet been fully addressed in the available literature. For this reason, this paper shows a detailed analysis on the in-field performance of two PV generators, one comprising modules made from recently developed UMG-Si and the other comprising standard polysilicon modules. The same manufacturer from the top five main producers in the world, made the cells and modules of both materials, in the same period and on the same commercial production lines. Thanks to the analysis methodology here proposed, this article depicts the main differences in performance observed in both generators in terms of power and energy delivered in the course of a two-year study, quantifying both the influence of temperature and irradiance conditions on the said differences. Their initial degradation over those two first years of in-field operation has also been determined.

## II. EXPERIMENTAL SETUP

### *A. Description of installation.*

The experimental setup is comprised by two 2275 Wp photovoltaic generators located at a PV plant in the north of Spain and the experimental period was from March 2019 to February 2021. Both generators are composed by 7 polycrystalline glass-backsheet PV modules, all manufactured identically with the only exception of the material employed in the cells manufacture (SoG-Si for one generator an UMG-Si for the other). The purity of the UMG-Si feedstock is 99.9999% (6N), while the SoG-Si purity can be considered 9N. The cells are P-type multi-crystalline Al-BSF. Both generators are mounted on a stationary structure with a 30° tilt in relation to the horizontal plane, south-oriented and completely shadow-free, as shown in figure 1. Finally, given that each generator is connected to the grid via a 2.5 kW inverter, the generators are always able to operate at their maximum power point (MPP).

Table (1) shows the rated characteristics of the generators based on the datasheet provided by the manufacturer for both SoG-Si and UMG-Si modules, where $P_N^{STC}$ is the nameplate power of PV modules and γ, β, α are, respectively, their temperature coefficients of power, voltage and current. The rated values of both types of module are the same.

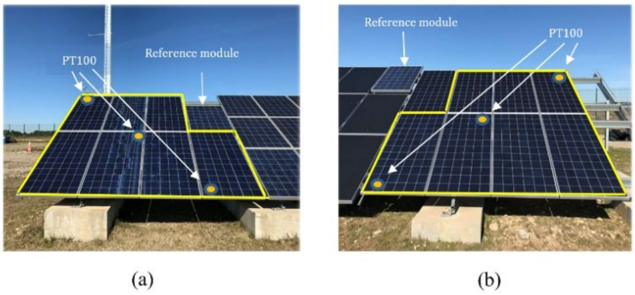


**Fig. 1.** Experimental generators, Spain, latitude 42.104667, longitude -1.640611. a) SoG-Si modules and b) UMG-Si modules.

TABLE 1.
RATED CHARACTERISTIC OF PV GENERATORS

| Type of Module | Module nameplate STC power, $P_N^{STC}$ [W] | Module nameplate efficiency, $\eta_N$ [%] | Total modules | Total generator power [W] | γ (%/K) | β (%/K) | α (%/K) |
|---|---|---|---|---|---|---|---|
| UMG-Si | 325 | 16.7 | 7 | 2275 | -0.40 | -0.33 | -0.058 |
| SoG-Si | 325 | 16.7 | 7 | 2275 | -0.40 | -0.33 | -0.058 |

The generators were equipped with a monitoring system to measure the DC power at the inverter input, the global irradiance on the plane of the generators, $G^{ef}$, and their operating temperature, $T_C$. This data was stored in a database in the form of ten-minute averages. The incident irradiance was measured using two crystalline silicon reference modules, which were calibrated by an independent organization and the generators were mounted on the same structure, the incident irradiance can be considered the same [32]. Thus, the two calibrated modules provides redundant measurements and the average of such measurements is considered a better reference of the incident irradiance on both generators than the single value provided by each reference module. The use of reference modules instead of pyranometers allows to minimize the influence of soiling in the performance characterization, assuming that soiling in the reference modules is similar to that of the PV generators.

The measurement of the generator operating temperature is subjected to the dispersion that appears on the generator surface. This dispersion may be as high as 1°C per meter, depending on the existing wind conditions [33]. Thus, in order to obtain this operating temperature in an accurate way, three Pt100 sensors were mounted on the back of each generator, as shown in figure 1. Table 2 shows the accuracy of the equipment used.

TABLE 2.
MEASURING EQUIPMENT AND DATA ACCUCARY

| Parameter | Equipment | Manufacturer | Maximum Uncertainty |
|---|---|---|---|
| DC voltage | Datalogger | Yokogawa | ± (0.2% of reading +0.2% of range) |
| DC current | Datalogger | Yokogawa | ± (0.2% of reading +0.2% of range) |
| DC active power | Datalogger | Yokogawa | ± (0.2% of reading +0.2% of range) |
| Temperature | Pt100 | Omega | B Class = ±0.3°C at nom. resistance (0°C)<br>B Class = ±0.8°C at nom. resistance (100°C) |
| Global irradiance | mc-Si Module | Yingli Solar | ±2% (Calibrated by CIEMAT*) |

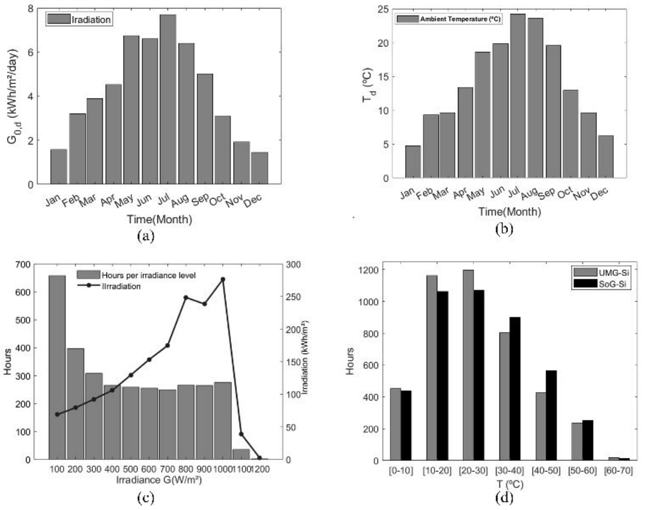
### B. Environmental and operating conditions

According with the Köppen-Geiger-Photovoltaic climatic classification [34], the modules are in a DH zone, i.e., a temperate zone with high irradiation. Table 3 summarizes the environmental conditions observed during the two-years experiment: daily horizontal irradiation measured with a pyranometer, $G_{0,d}$ and mean daily ambient temperature, $(T_A)$. The table also includes the operating conditions observed in the generators in terms of effective daily in-plane irradiation, $G_d^{ef}$ and equivalent operating temperature, $T_{C,EQ}$. The latter is defined as the daily irradiance-weighted average of the modules' temperature.

TABLE 3
AMBIENT AND OPERATING CONDITIONS

|  | Ambient conditions |  | Module operating conditions |  |  |  |
|---|---|---|---|---|---|---|
|  |  |  |  | $T_{C,EQ}$ (°C) |  |  |
|  | $G_d^{BB}(0)$ $(kWh/m^2)$ | $T_A$ (°C) | $G_d^{ef}$ $(kWh/m^2)$ | UMG-Si | SoG-Si | Difference (UMG-Si vs SoG-Si) |
| **Yearly average** | 4.4 | 12.1 | 4.5 | 32.1 | 31.1 | 1.0 |
| Lowest $G_d^{BB}(0)$ **month** | 1.5 | 3.9 | 2.1 | 19.8 | 17.5 | 2.3 |
| Highest $G_d^{BB}(0)$ **month** | 7.7 | 21.2 | 6.9 | 44.4 | 43.3 | 1.1 |

Figure 2 shows the mean daily values in each month of temperature $(T_d)$ and irradiation $(G_{0,d})$ for the two years analyzed. It should be pointed out that the operating temperature of both generators was not exactly the same. This is due to the fact that each generator was subject to different cooling conditions as a result of their different exposures to the wind. The generator located further to the west (comprising the SoG-Si modules) was more exposed to the predominant winds in the area, giving temperature differences of up to 8°C lower compared to the UMG-Si generator at certain specific instants in time. Some authors [33] already found similar temperature differences between the modules of a 12-meter-wide array. The different generator operating conditions must be taken into account when comparing their performance. Finally, it is also worth noting that, during the summer months, the generators were exposed to high irradiance levels and temperatures, thereby providing sufficient conditions to check for the possible appearance of Light and elevated Temperature Induced Degradation (LeTID) [35] in the modules.



(a) (b) (c) (d)

**Fig. 2.** Ambient and operating conditions in generators (March 2019-February 2021) a) Monthly horizontal irradiation b) Monthly average ambient temperature c) Incident irradiance distribution and d) Daytime modules' operating temperature distribution for UMG-Si and SoG-Si.

## III. EXPERIMENTAL RESULTS

The comparison of the performance of the two types of material used in the generators is made by means of three main aspects: *power* (or efficiency) initially delivered as a function of the operating conditions; *degradation in power* observed over study period and *total energy production* in the course of this period.

### A. *Initial power delivered as a function of the operating conditions*

1) **Power under Standard Test Conditions (STC)** Once the modules were installed on the structure, the STC power of the whole generators, $P_{Exp}^{STC}$, were in field measured according to the wattmeter procedure described in [36]. Likewise, the results of the flash-test performed by the manufacturer over the PV modules were also available. From those flash-test results, the STC power of the whole PV generators, $P_{\sum Flash}^{STC}$, were obtained as the sum of the flash measurements of each module. Table 4 shows the results of the initial characterization made on the generators. Differences of around 0.8% between flash and in-field measurements are observed, which can be due to mismatch losses, wire losses and to the unavoidable uncertainty associated to the measurements. It can be seen that the difference between measured and nameplate STC power values is less than 1% in both generators. The experimental STC power measured in the UMG-Si generator was around a 0.3% higher than the STC power of the SoG-Si generator and coincides with the difference in their $P_{\sum Flash}^{STC}$ values. Such a small difference in STC power measurements is of very little significance.

TABLE 4
CHARACTERISTICS MEASURED

| Generator | **Flash Characterization** | | **In-Field Characterization** | | $\gamma_{exp}$ (%/K) | $\gamma_N$ (%/K) |
|---|---|---|---|---|---|---|
| | $P_{\sum Flash}^{STC}$ (W) | ∑ Flash vs Nameplate (%) | $P_{Exp}^{STC}$ (W) | Experimental vs Nameplate (%) | | |
| SoG-Si | 2281 | +0.3 | 2263 | -0.5 | -0.41<br>(±0.02) | -0.4 |
| UMG-Si | 2290 | +0.6 | 2270 | -0.2 | -0.41<br>(±0.02) | -0.4 |
| Difference (UMG vs SoG) | | **+0.3** | | **+0.3** | **0** | **0** |

2) **Power at different operating temperatures** Two PV modules of each type was sent to two independent laboratories, which determined their experimental power temperature coefficients, $\gamma_{exp}$. The mean values obtained and the estimated uncertainty are included in table 4 together with the nameplate value, $\gamma_N$, of the conventional SoG-Si modules. It can be seen how the mean value of this coefficient is practically the same for both types of modules. This appears to differ from what is shown by most of the studies currently available in scientific literature. Those studies affirm that the temperature coefficient of the UMG-Si modules is lower than that of the conventional SoG-Si ones, basically as a consequence of the lower resistivity of the UMG-Si wafers due to the higher doping level. However, Ponce-Alcántara et. al., in a study published in 2014 [37], showed that, depending on the supplier, the resistivity of the wafers of both types of material can vary within a similar range and that it is possible to find PV cells made from SoG-Si with a small temperature coefficient, similar to that of cells made from UMG-Si. This appears to be the case of the SoG-Si modules analyzed here. Indeed, the temperature coefficient of the SoG-Si modules here analyzed can be considered as representative of today´s SoG-Si modules. Therefore, the change in performance of the two generators in other operating temperature than standard temperature conditions is also essentially the same.

3) **Power at different irradiance levels** Figure 3 shows the relative efficiency (in relation to the nameplate value, $\eta_N$) measured for each generator as a function of the incident irradiance. To eliminate the effect of the operating temperature, this efficiency was extrapolated to 25°C using temperature coefficients $\gamma_{exp}$, showed in table 4. The points on the graph correspond to different moments in a sunny and windless day. The operating temperature was extremely similar in both PV generators along the whole day. The average values obtained for each irradiance interval can be found in table 5.

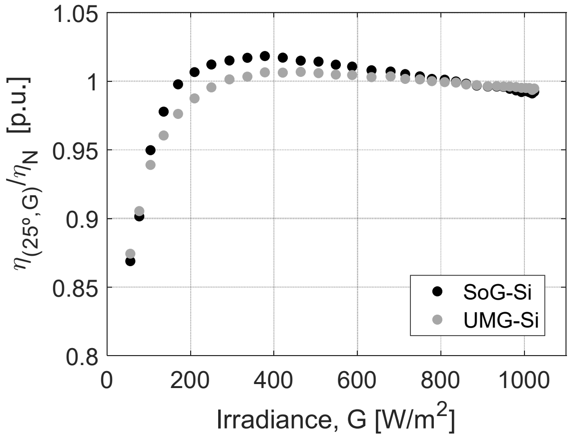


**Fig. 3.** Relative efficiency of each generator (at 25°C) as a function of the incident irradiance for a sunny and windless day (operating conditions were extremely similar and stable in both PV generators).

TABLE 5
AVERAGE EFFICIENCY FOR EACH IRRADIANCE LEVEL IN BOTH GENERATORS

| Irradiance interval [W/m$^2$] | Efficiency (at 25°C) [p.u. in relation to $\eta_N$] | | Difference UMG-Si vs SoG-Si [%. in relation to $\eta_N$] |
|---|---|---|---|
| | UMG-Si | SoG-Si | |
| [50 - 100] | 0.891 | 0.885 | +0.6 |
| [100 - 200] | 0.959 | 0.975 | -1.6 |
| [200 - 300] | 0.996 | 1.011 | -1.5 |
| [300 - 400] | 1.006 | 1.018 | -1.2 |
| [400 - 500] | 1.008 | 1.016 | -0.8 |
| [500 - 600] | 1.006 | 1.012 | -0.6 |
| [600 - 700] | 1.004 | 1.008 | -0.4 |
| [700 - 800] | 1.002 | 1.003 | -0.1 |
| [800 - 900] | 0.999 | 0.999 | 0.0 |
| [900 - 1000] | 0.997 | 0.995 | +0.2 |
| [1000 – 1100] | 0.995 | 0.992 | +0.3 |

A slightly lower efficiency (between 1.2 and 1.6% lower) was measured in the UMG-Si modules for irradiance levels between 100 and 600 W/m2. However, the differences in the relative efficiency of both generators are less than 1% for irradiance levels higher than 600 W/m$^2$. As will be shown in subsequent sections, the differences in the efficiency of both generators as a function of the irradiance level are of very little significance in energy terms for a climate zone like this.

### *B. Degradation*

The normal degradation rate of a PV generator is generally a small value (between 0.2 and 0.5%/year) (Jordan & Kurtz, 2013) and *PR* is an index that varies considerably with the operating temperature conditions, making it unsuitable for characterizing the degradation of a PV installation over a relatively short period. Thus, in this paper the degradation suffered by the PV generators over the two first year period was estimated using two different procedures:

1) **Classical decomposition of the monthly PR.**
This commonly used technique [18], [21], [38]–[40] consists on dividing the *PR* time-series into three separate components that can be identified as seasonal, trend and irregularity. The trend component will give the degradation. The classical decomposition method is expected to reduce the impact of the seasonal variation on the Performance Ratio (*PR*). Figure 4 shows the results of the decomposition of the monthly *PR* (figure 4 (a)) in its trend (figure 4 (b)) and its seasonality (Figure 4 (c)). Given the fact that the data only cover a two-year study period, the irregularity component would show a constant value. Therefore, this component has not been included.

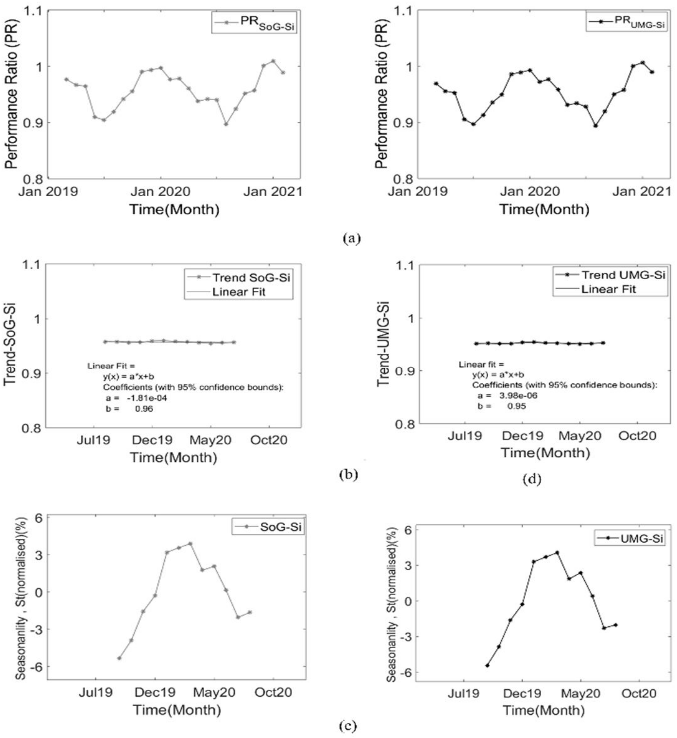
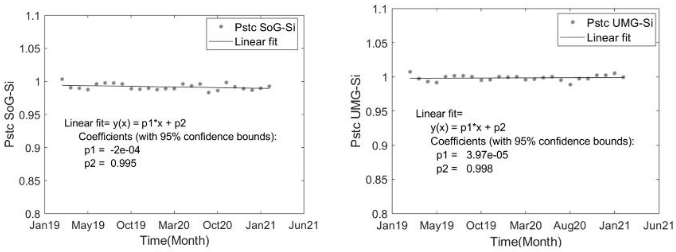


**Fig. 4.** Time series decomposition of the monthly *PR* for both technologies; (a) Original signal; (b) Trend and its linear regression line; (c) component of seasonality. *It is not possible to calculate the component of irregularity with only 2-year data.

In the case of the SoG-Si generator, the mean degradation estimated by this method would be around 0.2%/year, while it would be virtually non-existent for the UMG-Si generator

2) **Evolution of $\mathbf{P_{MPP}^{STC}}$, calculated by linear regression:**
This method uses the evolution of the maximum power point of the generator under STC ($P_{MPP}^{STC}$) over the analyzed period. $P_{MPP}^{STC}$ is monthly calculated by means of a linear regression [36] from the data collected at ten-minute intervals, requiring data filtering and post-processing. The specific filters implemented in this study for the monthly calculation of $P_{MPP}^{STC}$ were those proposed in [41]. Figure 5 shows the value of $P_{MPP}^{STC}$ calculated for each month of the period. The degradation is obtained by a linear fit of the monthly $P_{MPP}^{STC}$ values. Yet again, the

value calculated for the SoG-Si generator is 0.2%/year while it was not possible to measure any degradation for the UMG-Si generator.



(a) (b)

**Fig. 5**. Monthly reference yield of $P_{MPP}^{STC}$ and its linear regression line; both technologies. a) SoG-Si b) UMG-Si

### C. Energy performance over the study period.

Given the simplicity of its calculation, the Performance Ratio (*PR*) is currently the most-used index to describe the energy performance of a PV installation. However, *PR* definition does not include the operating temperature and, as said in section 2.2, the operating temperatures of two near generators are not exactly the same due to the different cooling conditions that originates their exposure to the wind. As this index is also unsuitable for an accurate comparison of the performance of two PV systems operating under different temperature conditions.

An alternative to the traditional *PR* consists on correcting the said index in order to eliminate the temperature influence. The resulting new index is equivalent to the *PR* if cell temperature was kept at 25°C, thus named $PR_{25}$ [38], [42]. The use of $PR_{25}$ makes it possible a better comparison of the energy performance of both generators over the study period but requires an adequate measurement of the operating temperature conditions. Figure 6 shows the monthly $PR_{25}$ values obtained during the study period and the differences in this index for the two PV generators.

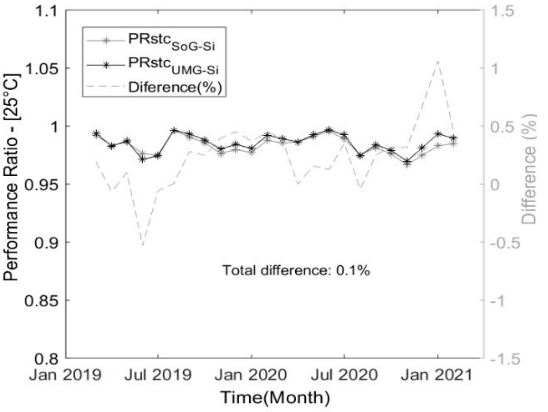


**Fig. 6.** Monthly values of $PR_{25}$, differences in the monthly $PR_{25}$ values and total difference in the accumulated $PR_{25}$ over the two-year study period

The difference in the accumulated value of $PR_{25}$ measured over the two-year period is only a 0.1%, which gives an idea of the extremely similar energy performance of both types of materials. It is worth noting that most of the differences in the monthly $PR_{25}$ values are within ± 0.5% around the mean value. This provides an indication of the uncertainty associated to the relative measurements in both generators.

The small differences in the $PR_{25}$ values registered in the two PV generators can be due to the combined effect of the different degradation suffered over the study period and their different efficiency as a function of the operating conditions ($G^{ef}$ and $T_C$). Thus, the insignificant differences measured in the degradation of both generators also suggest that the influence of their different efficiency under low irradiation conditions is of little relevance in energy terms. Indeed, the difference in the energy performance of both generators due to their different irradiance response can be approximately calculated by combining the efficiency values showed in table 5, with the incident irradiance distribution represented in figure 2. The result of this calculation, for the considered location and study period, is that the UMG-Si generator produced around a 0.3% less energy than SoG-Si generator due to their different irradiance response. Such small value is of the order, or even below, of the estimated uncertainty mentioned before.

## IV. CONCLUSION

The exhaustive analysis conducted over a PV generator made of a recently developed UMG-Si and another identical generator made of SoG-Si showed an extremely similar energy performance of both types of materials, with a difference of around 0.1% in their $PR_{25}$ values during the two-year study period.

Regarding the power and efficiency under Standard Test Conditions, the UMG-Si modules showed similar initial values to those measured on the SoG-Si modules. However, the efficiency of the UMG-Si modules in the irradiance range between 100 to 500 W/m$^2$ was up to a 1.6% less than the efficiency of SoG-Si modules. These differences were of little significance terms of energy production for the location considered in this paper, since a final difference of less than 0.5% in their energy production was due to their different irradiance performance.

The temperature response measured in both types of modules was practically the same, which appear to differ from the results published in the available literature. However, it should be noted that today´s conventional SoG-Si modules present a lower temperature coefficient than those SoG-Si modules considered on the studies published some years ago, equaling the value of UMG-Si modules temperature coefficient.

The degradation of both types of material over the two-year study period was calculated by means of two different procedures, which led to exactly the same result: a mean degradation of around 0.2%/year could be measured in the SoG-Si modules, while no measurable degradation was found on UMG-Si modules during the first two years of operation. It is possible to affirm that this type of material did not suffer any additional degradation with regard to SoG-Si.

In summary, the in-field energy performance of the analyzed polycrystalline UMG-Si modules were essentially the same to that of today´s conventional SoG-Si modules. It is worth noting that the differences here found on the performance of both modules are strictly due to the silicon used on each. The influence of cell manufacture and cell-to-module losses can be dismissed since both types of cells and modules were made exactly in the same way, in the same production lines and by the same manufacturer (one of the top five main producers in the world). Thus, the results here presented can be considered as highly representative of the current state-of-the-art of UMG Silicon technology at an industrial level. Several tests have also been done in single crystal (monocrystalline) growing using 100% of the same UMG-Si here analyzed, with good results. However, further work is being carried out on this usage and such tests have not been brought to mass production yet.

## ACKNOWLEDGMENT

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