Crystalline silicon PV module degradation after 20 years of field exposure studied by electrical tests, electroluminescence, and LBIC

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ABSTRACT

Standardized tests to assure the reliability of photovoltaic modules and to detect possible early failures of modules when exposed in the field, due to design flaws or to the use of non-appropriate materials, have played an important role in the successful growth of photovoltaic market in recent years. In order for this growth to be sustainable in coming years, it is crucial to keep the confidence of investors in standard well-established technologies and to increase confidence in new emerging technologies. For these reasons, there is an ongoing work for the improvement of current tests and for the development of new ones, which besides assuring module reliability in the field, have also the aim of predicting their lifetime. The analysis of degradation of modules that were field exposed over a long period of time is fundamental to identify the degradation mechanisms and to collect statistics on modules behavior. This work focuses on the analysis of the change of the photovoltaic module electrical characteristics after approximately 20 years of field exposure, considering differences in the design of cells that were used for the production of these modules, which were identified by detailed visual inspection. Failure modes were investigated by comprehensive visual inspection and the use of spatially resolved analysis techniques as follows: laser beam-induced current and electroluminescence. The main failure mode identified was yellowing of the encapsulant. © 2015 The Authors. Progress in Photovoltaics: Research and Applications published by John Wiley & Sons Ltd.

KEYWORDS

PV module degradation; field aging; electroluminescence; LBIC

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1. INTRODUCTION

Photovoltaic (PV) module yield is among the most important factors in determining the cost of solar electricity, together with the system price, the annual solar irradiance at the installation site, and the capital interest rate. For this reason, several activities are ongoing worldwide for the development of models for lifetime prediction by applying accelerated stress tests to PV modules [1,2]. In order to develop accelerated stress test protocols successfully, it is fundamental to study the outdoor performances of PV modules to identify failure mechanisms, which occur with field exposure. The identified failure mechanisms should then be replicated by stress tests that are appropriately designed. The analysis of PV modules that were field exposed for long periods of time allows for a better understanding of failure modes and degradation mechanisms, and this will help to design test protocols for ensuring higher PV module reliability. The aim of this work is the in depth study of degradation mechanisms after almost 20 years of field exposure of crystalline silicon modules by electrical power measurements, detailed
visual inspection according to the protocol proposed in [3], and spatially resolved characterization techniques: electroluminescence (EL) and laser beam-induced current (LBIC).

2. CHARACTERISTICS OF THE MODULES

Seventy crystalline silicon modules were installed at the European Solar Test Installation in Ispra in 1991 with the purpose of a long-term field degradation study. The modules were removed from the field in 2010, and a first analysis based on visual inspection, following the International Electrotechnical Commission (IEC) standard IEC 61215 [4], and electrical characterization was previously reported [5,6]. In this work, detailed visual inspection according to a new protocol [3] has been performed, together with spatially resolved characterization by EL and LBIC of the majority of the modules. Besides the presence of defects, visual inspection highlighted some differences in the cells used for the production of these modules. Three different patterns for the front-side metallization grid were found within this set of modules, and this allowed them to be divided into three groups and to compare their electrical performances in particular regarding the degradation rate. The set of modules used for this study consists of 70 glass–glass modules, with 36 pseudo square crystalline silicon solar cells, each having an area of 96.1 cm². The cells are series connected and are divided into two sub-strings, one consisting of 17 cells and the other consisting of 19 cells, each having a bypass diode. The modules, produced in the early 1990s, were installed in the European Solar Test Installation outdoor testing field at the end of 1991 in an open rack and divided into two strings, each connected to an inverter to keep the strings operating at their maximum power point. The climate where the modules operated is moderate subtropical, with air temperatures ranging between −10 and +35 °C and relative humidity of less than 90%.

3. VISUAL INSPECTION AND ELECTRICAL CHARACTERIZATION

A series of characterizations were performed in 2010, after the modules were removed from the field and have been previously published [5]. The following characterizations were performed in 2010:

- Visual inspection following the procedure of IEC 61215
- Electrical characterization (I–V curves)
- Analysis of degradation of electrical parameters
- Dry electrical insulation test.

The additional characterizations performed in 2013 consisted of the detailed visual inspection following the protocol proposed in [3], which is based on a quantitative classification of defects. It was possible to identify three different cell front-side metallization patterns used for the production of these modules, having different number of fingers, different distances between fingers, and different distances between busbars. The analysis of electrical parameters and their degradation after field aging was performed by considering the performances of the three groups of modules separately. Electrical characterization included I–V curve measurements for all modules and spectral responsivity measurements for a number of selected modules. Finally, the analysis based on spatially resolved imaging techniques with EL and LBIC was performed on the majority of modules.

3.1. Detailed visual inspection

The aim of the proposed visual inspection data collection protocol is to develop a tool for the evaluation of visually observable defects in fielded PV modules, thus monitoring also their evolution over time. The approach is a quantitative one, with the collection not only of the defects types, but also of their occurrence and area covered by them. This differs from the approach of IEC 61215, where the defects are
categorized as “minor” if they are allowed for type approval or “major” in case of defects not acceptable for type approval, but without requiring the quantification of defects in most of the cases. The detailed visual inspection was performed on all 70 modules, and the results are summarized in Figure 1.

In order to visualize the results of the visual inspection easily in one single graph, for each defect, a level of severity from 1 to 4 (1 being the lowest severity and 4 being the highest severity) was introduced. Depending on the type of defect, severity is related to its occurrence (e.g., number of glass cracks) or the area that it covers (e.g., percentage of module area that presents yellowing). As an example, for delamination, severity 1 means that less than 5% of the total area of the module is delaminated, and severity 2 means that an area between 5% and 25% is delaminated; severity 3 indicates delamination in an area between 25% and 75%, and severity 4 indicates delamination in an area larger than 75%.

Thanks to this approach, it is possible to follow how each single defect type develops with time in field-aged modules and easily shows if there are defects that affect a large number of modules with high severity. One example of which was the discoloration that was found in all modules, which can indicate a defect because of the materials or processes used in manufacturing. Yellowing of EVA encapsulants has been reported in a number of studies and is associated with chromophore production in the encapsulant, with possible oxidation bleaching also occurring depending on the design, materials, and construction of the particular module [7–10].

The quantification of each defect could also help in finding correlations between electrical degradation and defects occurrence. This was not possible with the set of modules analyzed in this work, because of the very low electrical degradation exhibited, as will be shown in the following paragraphs.

### 3.2. Electrical characterization

The procedure used for measurement of I–V curves for these modules in 1991 and in 2010 has been described in detail [5], in particular with regard to the reference cell used for all the measurements in order to make them comparable. The change of average electrical parameters, in absolute values and in percentage, for all the 70 modules that occurred between 1991 and 2010 is reported in Table I. Results show an average $P_{max}$ decrease of 0.22% / year, which is lower than figures that are generally reported for long-term field-aged modules [11–15]. It should also be noted that one of the modules had a complete sub-string failure, resulting in a loss of $V_{oc}$ and $P_{max}$ greater than 50%, while $I_{sc}$ was only partly affected, as the second sub-string was still working correctly.

During visual inspection, modules could be divided into three groups, according to the pattern of the front-side metallization grid of the cells used for their production (Figure 2).

Three different patterns (A, B, and C) were identified, which differ in the number of fingers, the distance between the busbars, and the distance between the fingers (Table II). Besides the characteristics reported in Table II, it was also possible to notice a difference in the width of the fingers, with the ones of pattern C being the largest. However, because of the presence of the glass over the cells, it was not possible to measure these accurately. The difference of patterns could have an impact on the electrical parameters, for example, in the value of $I_{sc}$, if the area covered by metallization grid is different in the three patterns, thus causing a difference in the active area of the cells. The behavior with respect to aging could also be impacted by the difference of the cells patterns. The electrical parameters were therefore analyzed by dividing the modules into three groups, according to their cell metallization pattern. With regard to the I–V measurements of 1991, the comparative analysis could be carried out only for 49 modules out of 70, because for the remaining ones, the code numbering was no longer visible in 2010; so in these 21 cases, it was not possible to relate the single module and therefore its cell metallization pattern with its corresponding I–V curve measured in 1991.

### 3.3. Electrical characterization in 1991

The electrical parameters of the three groups of modules measured in 1991 were compared in order to understand

![Table II. Characteristics of different cells pattern.](image)

| Pattern | A | B | C |
|--------|---|---|---|
| Number of fingers | 30 | 34 | 28 |
| Distance between busbars (cm) | 4.1 | 5.1 | 5.1 |
| Distance between fingers (mm) | 3.3 | 2.9 | 3.6 |
| Number of modules | 4 | 50 | 16 |

![Figure 2. Different patterns of cells front-side metallization grids.](image)
if a statistically significant difference was present for some of the parameters. The electrical parameters were extracted, and the analysis of variance (ANOVA) test was performed. The $p$-value limit set for the ANOVA tests is $p < 0.05$, corresponding to a confidence level of 95%. The results show that the only electrical parameter for which there is a statistically significant difference between the groups is $V_{oc}$ (resulting in $p < 0.05$). Statistically significant difference between the groups was not found for the remaining electrical parameters. Box charts of the results of the three metallization patterns are reported in Figure 3.

3.4. Electrical characterization in 2010

In 2010, all modules were re-measured, and in this case, it was possible to have the information about all the I–V curves related to all modules grouped according to their cell metallization patterns. One module of type A was not considered in the ANOVA analysis, as it was an outlier having experienced losses of $P_{max}$ larger than 50% during the years of field aging. One module of type C was not considered as well, as it showed much lower electrical performance than the other modules of the same group and eventually experienced a complete sub-string failure when retested in 2014. Also in this case, the only electrical parameter that was found to have a statistically significant difference between the three groups was $V_{oc}$. Box charts of the results of the three metallization patterns are reported in Figure 4.

3.5. Electrical parameters change from 1991 to 2010

The change of electrical parameters, which occurred with field aging from 1991 to 2010, was analyzed with the modules divided into three groups according to their cell metallization patterns. The comparison was possible only for 49 modules out of 70; as for some of the modules, the original code was no longer readable in 2010. The results of the averages are reported in Figures 5 and 6, where for the analysis reported in Figure 5, the module having a complete sub-string failure was removed, while in Figure 6, all modules were considered. Figure 5 shows that the average of the modules with cell pattern of type A exhibited a slightly larger change of electrical parameters compared with the other two cell types and the average of all modules. In particular, modules with cells of type A exhibited a higher average decrease of $I_{sc}$ ($-3.9\%$ compared with less than $-2.7\%$ for the complete set of modules) and $P_{max}$ ($-4.8\%$ compared with $-3.2\%$ of all modules). However, the numbers of modules in the three groups are not evenly distributed; for this reason, the average of $I_{sc}$ change for all modules is not strongly affected by the larger $I_{sc}$ change found for modules of type A.

For modules with cells of type A, two columns are reported in Figure 6, one corresponding to the average data of the complete module set and another without the module, which had one sub-string failure. It is possible to notice that the main driver for electrical parameters change between these two sub-set groups is $V_{oc}$ as was to be expected when one of two sub-strings in a module fails. If we take into account all modules with type A cells, we can see that they have a $P_{max}$ change of $-18.9\%$, mainly, because of $V_{oc}$ change of $-15.7\%$. It should also be noticed that all groups showed an increase in Fill Factor (FF) following field aging, and this suggests that the series resistance of the modules was not affected by aging; therefore, a decrease in $I_{sc}$ by keeping almost constant the $R_s$ (and therefore the shape of the I–V curve) resulted in an increased FF. This can be

![Figure 3. Box charts of electrical parameters measured in 1991. Group B consists of 38 modules; group C consists of seven modules, and group A consists of four modules.](image-url)
seen in the I–V curves in Figure 7, measured in 1991 and in 2010, from module IR462, which had a decrease of 3.7% of $I_{sc}$ and an increase of 2% of FF.

In order to investigate the series resistance from the beginning and the end of the aging period, the curves of module IR462 (which exhibited a typical degradation of electrical parameters) were fitted. The fit was performed using the standard one diode model. The measured I–Vs and the fitted curves are plotted in Figure 8.

Several parameters were extracted from the fitting routine including series resistance ($R_s$), shunt resistance ($R_{sh}$), diode ideality factor ($n$), dark saturation current ($I_0$) and are reported in Table III.

Results reported in the table show that there was a decrease in $I_{sc}$ of 3.4% that was already evident from the first analysis of the I–V curves. The fitting showed an
increase in $R_s$ from 1991 to 2010 and a slight decrease of the diode ideality factor. These changes of parameters led to a change in the geometry of the $I-V$ curve, and despite an increase in $R_s$ of 5.6%, from 411 to 434 m$\Omega$, the FF increased by about 2%.

3.6. Analysis of variance of electrical parameters change from 1991 to 2010

Although it was possible to see a difference in the degradation of electrical parameters based on the different module groups, it was investigated if these differences were statistically significant. Therefore, an ANOVA test was performed on the degradation of the electrical parameters divided by groups. The module with complete string failure was not considered for this analysis; moreover, only data from those modules in which the original code was still readable in 2010 could be used.

The parameters that showed a statistically significant difference (ANOVA test with $p < 0.05$, corresponding to a confidence level of 95%) with regards to their change during the outdoor field exposure were $I_{sc}$ and $P_{max}$.

Therefore, modules with different cell metallization pattern behaved in the same way with respect to $V_{oc}$ and FF change, while modules of type A degraded more in $I_{sc}$ and $P_{max}$ compared with the other two groups (Figure 9). These results show that module manufacturing and differences in materials had an impact not only in the electrical performances measured before installation in the field, but also on their change with aging.

3.7. Spectral responsivity measurements

The spectral responsivity of one representative module of each group was measured in order to study the differences because of cell types incorporated. Measurements were performed using the differential spectral responsivity technique, with a large area pulsed solar simulator, equipped with a number of filters to obtain illumination of modules with monochromatic light [16]. The curves representing the external quantum efficiency are reported in Figure 10. It can be seen that the differences between the curves of different module groups are not pronounced, showing that raw material and production technology used to process the three different groups of cells were similar.

4. ELECTROLUMINESCENCE AND LASER BEAM-INDUCED CURRENT CHARACTERIZATION

The majority of modules were analyzed by spatially resolved imaging, using EL and LBIC.

4.1. Electroluminescence

Electroluminescence images were obtained only in one condition, with the module biased at $I_{sc}$ and with an exposure time of 240 s, as biasing these modules at levels around 10% of $I_{sc}$ resulted in a poor signal to noise ratio. All images were analyzed by classifying the type and severity of defects that could be detected from a visual inspection of each image. The typical defects that could be identified comprised cracked cells, cells with dark areas, finger interruptions, and scratches on the cell surface. The graph in Figure 11 shows for each defect the number of modules that exhibited each kind of defect. In nearly all modules, it was possible to detect scratches on the cell surface and finger interruptions, while the other two types of defects, cell cracks and dark areas, were present in approximately 60% of modules. It should be noticed that in most of the cases observed in this analysis, the dark areas do not indicate a completely inactive cell area. In fact except for a limited number of cases, the dark parts of the EL images are not black, but darker relative to other brighter areas, indicating that the carrier diffusion length in those regions is lower than in the rest of the cell [17]. Moreover, the injection current level also has an influence on the amount of light that a particular region of the solar cell will emit, and therefore on how bright it will appear.
Because the EL images were all performed under the same conditions (same exposure time, same distance between module and camera, and keeping the bias of each module at the short circuit current that was previously determined with the measured I–V curves), the intensity of the EL signal could be directly related to the module performance, as it is related to the minority carrier diffusion length. To investigate this possibility, graphs in Figure 12 show the integration of the histograms of pixels intensity for several modules having a range of Isc between 2.77 and 3.04 A and a range of Pmax between 40.43 and 44.87 W. The histograms and therefore their integrals were obtained by processing the raw files of the

Figure 9. Box charts of difference, in absolute values, of electrical parameters measured in 1991 and in 2010. Group B consists of 38 modules; group C consists of seven modules, and group A consists of three modules.

Figure 10. External quantum efficiency (EQE) plots of modules from different groups.

Figure 11. Number of modules where each type of defect was identified with electroluminescence.

Figure 12. Integral of the histograms of electroluminescence images for several modules. In green and red are the modules with best and worst electrical characteristics respectively.
images, so that the pixel intensity is the one detected by the camera, and was not modified by subsequent image processing. The curves relating to the modules having the extreme electrical characteristics (lowest performance for module IR443, with $I_{sc} = 2.77 \, A$ and $P_{max} = 40.43 \, W$ and highest performance for module IR466, with $I_{sc} = 3.04 \, A$ and $P_{max} = 44.87 \, W$) are highlighted in thick red and green lines, respectively. It is possible to see that the electrical characteristics of these two modules are not directly reflected in the pixel intensity of the EL of the complete module. In fact, the curves of the integral of pixel intensity are not at the extremes of the values calculated for all modules. We think that this can be attributed to the noise level in the camera when taking the picture, because of very low signal and long exposure times.

### 4.2. Laser beam-induced current

For most of the modules, a complete scan of the surface was performed with a large area fast LBIC apparatus, having a beam from a HeNe laser with wavelength of 633 nm. The signal from the laser is chopped, and the output current from the module is detected via a lock-in amplifier. The system and its principle of operation have been described previously [18]. The measurements with LBIC were performed with the module in the dark, without electrical bias, and the output current was measured as the voltage drop across a resistor of 10Ω. As the module was in the dark and the cells are connected in series, the value of current that can flow through the string depends on the characteristics of all cells of the string [19]. The maximum current that can flow through the string when only one cell is illuminated by the laser while the others are kept in the dark is strongly influenced by the shunt resistances of all cells. This means that the values of current measured with the complete scan of a module are relative and cannot be used to compare the electrical performances of different cells. The magnitude of the LBIC signal can be extracted for all the cells in one module, as shown in Figure 13, and because its level is closely related to the shunt resistance values of the cells in the module, it is possible to understand if this parameter is uniform within one module. The values of LBIC signal for three modules having three different types of cells are reported in Figure 14. A difference in the behavior of the LBIC signal was observed. Modules of type C have the greatest shunt resistance uniformity, and modules of type B have the lowest shunt resistance uniformity.

A quantitative analysis of the LBIC was performed by extracting for each cell a value of LBIC calculated as the average value over a part of the cell. For each group of modules divided according to their cell metallization pattern, the parameters were analyzed by extracting the average, the standard deviation and the median, with the results reported in Table IV.

Data in Table IV show that if we consider the average value of LBIC, all module types behave in a similar way, with similar averages for the three groups. While modules of type A and type C exhibit similar values with regards to
the standard deviation, modules of type B have a significantly higher value (2.71 compared with 1.5 of group A and 1.32 of group C). This result confirms the higher non-uniformity of modules with pattern B with respect to LBIC values and therefore greater variation of $R_{sh}$. Although this information cannot be related to the electrical performances of the modules, cells with low values of shunt resistances may make a module more vulnerable to shadowing, causing high reverse currents, and potentially hot spots [20]. The scan of single cells gives high resolution LBIC images, and the differences of the signal within the cell area can reveal defects and non-uniformities that are present within a single cell. Some selected cells were analyzed by high resolution LBIC scanning of the complete cell area, and the resulting image was then compared with the images obtained with electroluminescence and with visual inspection. Figures 15–17 show the comparison of the three images (visual, LBIC and EL) for three cells from different modules, highlighting the following features: in Figure 15 it is possible to notice a clear yellowing, in the visual image, over a large area of the cell. This cell is on the corner of the module, and the fact that the yellowing is not present in two outer sides of the cell can be explained by the oxidative bleaching process because of oxygen ingress from the edge of the module [7,8]. It is interesting to notice that the areas with yellowing of the encapsulant show different behavior in the LBIC image, but not on the EL image. This is due to the different wavelength of the light that has to cross the glass / encapsulant layers. In the case of LBIC, the laser beam that hits the cell has a wavelength of 633 nm, while the light emitted from the cell in the case of EL has a peak of intensity at a wavelength of approximately 1150 nm. From the comparison of the images we can see that the former is attenuated by the yellowed encapsulant, while the latter is not affected. The EL image in Figure 15 also clearly reveals a long crack in the cell, going from one side to the other and this is barely visible with the LBIC image,

**Figure 15.** One cell from module 428, corner position of the module. From left: visual, laser beam-induced current, and electroluminescence images.

**Figure 16.** One cell from module 469, edge position of the module. From left: visual, laser beam-induced current, and electroluminescence images.

**Figure 17.** One cell from module 419, edge position of the module. From left: visual, laser beam-induced current, and electroluminescence images.
while in the visual image the cell appears intact. Some areas appear darker than others in the EL image, revealing parts of the cell being less active, these features being visible only with EL imaging. The same observations regarding the yellowing of EVA and the oxidative bleaching can be made for images taken from the cells in Figures 16 and 17 although in these cases the oxidative bleaching occurs only from one side of the cell, as these cells are not located in the corner of the module, therefore oxygen ingress is happening predominantly from one edge. One crack on the upper right side of the cell is visible in Figure 16, in both LBIC and EL images, causing complete loss of a part of the active area, but this defect cannot be detected by visual inspection. The cell in Figure 17 shows non-uniformity between its right and left half sides, as can be seen from the EL image. This is not revealed by the LBIC image, where, except for the areas with yellowing of encapsulant, only some defects in the center-bottom part of the cell can be noticed, as slightly darker spots.

5. FUTURE ACTIVITIES

Sixty-four modules of the original 70 were selected for reinstallation in the outdoor field. This will enable more information on their continuous degradation behavior to be collected in the coming years, including data on the system performance from the inverter. One of the modules that was chosen not to be reinstalled in the field had a complete sub-string failure, while the choice of the other five modules to be kept indoor was performed based on their electrical parameters. In particular, we avoided reinstalling the modules that had the lowest values of Impp, as they would limit the output parameters. In particular, we avoided reinstalling the modules that had the lowest values of Impp, as they would limit the output current of the complete string. The monitoring of the system will be carried out by gathering data of energy production from the inverter output as well as from DC current and DC voltage measured prior to the inverter.

6. CONCLUSIONS

The detailed analysis of the modules used for this study allowed for the identification of mechanisms that led to a decrease in electrical performances during long-term field exposure. The yellowing of the encapsulant, which was found in all modules and is therefore to be related to the material and the process used for their production, was responsible for the decrease in Impp that is the electrical parameter that experienced on average the highest degradation. The yellowing of the encapsulant was detected with the visual inspection as well as with the LBIC, showing that light of the wavelength used for LBIC measurements is attenuated by the yellowed encapsulant, thus reducing the current that can be generated by the module. The long-term performances of this set of modules, considering all modules including the two outliers, were found to be particularly good, as they had an average degradation rate of 0.22% / year for Pmax, a value that is lower than the averages reported in other long-term aging studies. Besides the average performance of the complete module set, it was possible to divide the modules into three groups according to differences in their manufacturing highlighted by visual inspection, in particular regarding the pattern of the front-side metallization grid. Analysis of electrical performances showed that these groups differed in their initial electrical performances, and they also had different behaviors regarding the degradation after long-term field exposure. These results stress the importance of avoiding variations in the manufacturing process, and the need to control the uniformity of the modules that are used for an installation, as those that degrade faster could affect complete strings of modules. The reinstallation in the field of the majority of these modules will enable data to be gathered for several more years, gaining useful information about the mechanisms causing long-term degradation.

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