Degradation analysis of 1900 PV modules in a hot-dry climate
Results after 12 to 18 years of field exposure

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Degradation Analysis of 1900 PV modules in a Hot-Dry Climate: Results after 12 to 18 years of field exposure

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ABSTRACT
If the annual degradation rate is known and is assumed to be linear for a PV module throughout its lifetime, then the lifetime can easily be calculated as the degradation limit is typically set at the time of procurement or the project initiation. The degradation rate is dependent on the module design, installation configuration and the environmental conditions of the site. The degradation rate of the individual modules in a module-string may also be influenced by the operating system voltage, grounding polarity (positive, negative or floating) and by the module position in the module-string; these degradations are commonly referred as PID, Potential Induced Degradation. The study presented in this paper was carried out in a PV power plant located in a hot-dry climate of Tempe, Arizona. This study was initiated to determine the annual degradation losses/rates of field aged modules and analyze if these losses are caused or influenced by the PID effects. In this study, about 1900 field exposed modules between 12 and 18 years from several manufacturers were evaluated. This includes modules with different construction schemes (glass/glass or Glass/polymer). In order to carry out this evaluation, the PV systems were shut down, the individual modules were electrically isolated from the string (but not physically removed from the installation) and the I-V curves of every individual module were collected on clear sunny days over several months. Assuming a linear degradation and the conventional 20-year warranty with 20% degradation limit from the nameplate rating, more than 80% of the tested modules in this hot-dry climate do not meet the warranty expectation.

I. INTRODUCTION
The performance degradation rate of PV modules impacts the energy production in a PV power plant or system over its lifetime. The module degradation rate can be as high as 4%/year but the median and average degradation rates in wide ranges of climatic conditions are reported to be 0.5%/year and 0.8%/year, respectively [1]. With the growth of the PV industry and higher capacity power plant installations, modules are now subjected to different system designs and electrical configurations. This includes attaining higher system voltage levels (600/1000 V) by connecting modules in series and using different grounding techniques. The series arrangement of modules to achieve higher voltages in power plants in particular exposes the modules to several hundred volts and these voltages could be positive or negative depending on the grounding polarity. The flow of leakage current, due to these high system voltages, through the glass superstrates and/or the encapsulant into the ground could hamper the long-term durability of the PV module, a phenomenon commonly known as Potential Induced Degradation (PID) [2, 3]. Different module constructions have different mechanisms whereby they may exhibit PID. Apart from the voltage level and grounding polarity, the prevailing climatic conditions (relative humidity/moisture and temperature) in the field also have a high influence on the PID effect of fielded modules [4]. The purpose of this work is to quantitatively identify the annual degradation rates and the potential induced degradation (PID) of about 1900 field aged (12-18 years old) crystalline silicon (c-Si) modules connected in series strings. All series strings at the power plant were positively biased with respect to the ground potential (negative grounded).

II. METHODOLOGY
A total of about 1900 modules were isolated, washed, cleaned and dried before taking I-V measurements of individual modules. All the I-V measurements were carried out at high POA (plane of irradiance) irradiance level on clear days over several months. A calibrated Daystar (DS 100C) curve tracer was used to obtain the I-V curves of each module using a four probe technique and the same connection cable length. A set of c-Si reference cells was mounted on the same plane as that of the modules to measure the irradiance. The K-type thermocouples were attached to the reference cells and on the back of test modules to measure the temperature. All irradiance and temperature data were recorded during the field measurements. The measured I-V curves were then translated to STC (standard test conditions) using the temperature coefficients. The temperature coefficients were determined through baseline testing of each module type in the field. Care was taken to ensure that the module temperature gradually rises from 25°C to 45°C at nearly constant irradiance on very clear days. Table 1 below provides detailed information on the number of models (and the number of modules in each model) investigated along with the type of installation (fixed tilt or 1-axis tracking), number of modules in the series string, the string voltage and the number of years of exposure. All the modules studied in this project carried a superstrate / substrate construction of glass/polymer except the models C11 and C4 which carried the glass/glass construction. It is important to note that all modules evaluated in this study were negatively grounded and thus positively biased.
In order to calculate the average annual degradation rate of each model, the following equation was used:

\[
\text{Average Annual Degradation Rate} = \left( \frac{P_{\text{Initial}} - P_{\text{Final}}}{P_{\text{Initial}}} \right) \times 100 \%
\]

Table 1: Details of the PV modules investigated in this study

<table>
<thead>
<tr>
<th>Array</th>
<th>Model A15</th>
<th>Model A18</th>
<th>Model B</th>
<th>Model C11</th>
<th>Model C4</th>
<th>Model D</th>
<th>Model E</th>
<th>Model F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>9 kW</td>
<td>11.6 kW</td>
<td>8.9 kW</td>
<td>5.3 kW</td>
<td>12 kW</td>
<td>3.8 kW</td>
<td>14.4 kW</td>
<td></td>
</tr>
<tr>
<td>#Modules (1-axis)</td>
<td>168</td>
<td>1155</td>
<td>176</td>
<td>40</td>
<td>50</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#Modules (Lat. Tilt)</td>
<td>216</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#Modules (String)</td>
<td>3</td>
<td>21</td>
<td>21</td>
<td>8</td>
<td>8</td>
<td>12</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>String Voltage (Voc)</td>
<td>65</td>
<td>455</td>
<td>455</td>
<td>505</td>
<td>455</td>
<td>532</td>
<td>643</td>
<td></td>
</tr>
<tr>
<td>Years Fielded</td>
<td>18</td>
<td>13.3</td>
<td>13.3</td>
<td>11.7</td>
<td>3.4</td>
<td>11.7</td>
<td>11.7</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>Framed</td>
<td>Framed</td>
<td>Framed</td>
<td>Framed</td>
<td>Framed</td>
<td>Framed</td>
<td>Framed</td>
<td></td>
</tr>
</tbody>
</table>

III. RESULTS AND DISCUSSION

a. Degradation Rates of All Modules

After cross checking with the independent data reported in the Sandia database for the models shown in Table 1, the power specified on the module nameplate was considered to be acceptably accurate and was used to calculate the total power degradation and degradation rates [5]. The total degradation of each model investigated in this study is shown in Figure 1. The average annual degradation rate of each model is shown in Figure 2. Excluding model C4, the overall average degradation rate for all the models with different ages (12-18 years) in the power plant varies between 0.6% and 2.5% per year. The annual degradation rate has been compared to some earlier studies done at the same plant with a small sample size of 60 modules as compared to the sample size of 1900 modules of this study [5]. The annual degradation rates calculated in this study provides a better representation of annual degradation rates due to larger sample size. It is clearly evident from the annual degradation rates and respective module age that more than 80% of the total modules tested during the study for this hot-dry climatic condition have failed (assuming linear degradation) to meet the conventional 20 year warranty expectation. A statistical analysis on the distribution of degradation rates of these 1900 modules will be reported in a forthcoming publication. The modules of model C4 showed the highest degradation rate of all with an average power degradation rate of more than 4%/year just in four years of exposure. These modules were the replaced modules by the manufacturer, under warranty clause with the customer, of Model C. It appears that the replaced modules (Model C4) manufactured from the newer production lines degraded at much higher rate than the original modules (Model C11) manufactured from the original production lines. This higher annual degradation rate of replaced modules as compared to the original modules may perhaps be attributed to the quality control issues of the new production lines.

It is interesting to note that the 13-year exposed modules of model A (1-axis tracked modules; 8 kWh/m²/day insolation) have degraded at slightly higher rate than that of the 18-year exposed modules of model A (latitude tilt modules; 6.5 kWh/m²/day insolation) though the overall insolation, over 13 years, is about 11% lower for the 1-axis exposed modules. The 1-axis tracker installed modules are expected to spend more time at daily-maximum-temperature (higher dwell time at daily-maximum-temperature) than the latitude-tilt modules (lower dwell time at daily-maximum-temperature). Also, the 1-axis tracker modules are expected to experience lower daily-minimum-temperature (than the latitude-tilt modules) due to higher sky radiation during the nighttime stow mode (horizontal modules having full sky view). This observation of slightly higher degradation rate of 1-axis installed modules may seem to indicate that the temperature effect (higher dwell time at high module temperature during the day and higher delta of day-night temperature swing) on the module degradation is much higher than the cumulative insolation effect. This temperature effect could cause the encapsulant to degrade at higher rate leading to short-circuit current loss and could stress the solder bonds and/or interconnect ribbons at higher level leading to fill factor loss.

Figure 1: Overall degradation of various PV modules exposed between 12 and 18 years in the field
b. Degradation Rates of Hotspot Modules

An extensive visual inspection and infrared (IR) imaging of all the modules were carried out as a part of this project. The IR study indicated a few modules with hot-spot (hot-cell) issues. As shown in Table 2, the modules with hotspot issues seem to degrade at higher rate than the non-hotspot modules (the models which did not have any hotspot modules are referred as N.A. in the table). Periodic IR scanning may be useful for the early identification and potential removal of the hotspot modules from the power plants to mitigate future module mismatch issues at the string levels.

Table 2: Higher degradation rates of hotspot modules as compared to non-hotspot modules

<table>
<thead>
<tr>
<th>Model</th>
<th>All Modules Degradation/Year</th>
<th>Only Hotspot Modules Degradation/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 13</td>
<td>-2.47%</td>
<td>N.A</td>
</tr>
<tr>
<td>B</td>
<td>-1.53%</td>
<td>-2.95%</td>
</tr>
<tr>
<td>C 11</td>
<td>-0.77%</td>
<td>-1.90%</td>
</tr>
<tr>
<td>C 4</td>
<td>-4.14%</td>
<td>N.A</td>
</tr>
<tr>
<td>D</td>
<td>-0.83%</td>
<td>-1.25%</td>
</tr>
<tr>
<td>E</td>
<td>-0.57%</td>
<td>N.A</td>
</tr>
<tr>
<td>F</td>
<td>-1.40%</td>
<td>-4.96%</td>
</tr>
</tbody>
</table>

The purpose of the potential induced degradation (PID) evaluation is to determine if the field exposed modules installed in a hot-dry climatic condition undergo any PID effect due to leakage of small current from the active circuit to the ground. In order to proceed with this investigation, a detailed string / system level circuit / connection diagrams was required and was generated for each system of the power plant. The open-circuit voltage (at STC) of the investigated strings is ranged between 445 V and 532 V. As an example, model B results are discussed here. There are 55 strings in the model B based system. Each string of Model B is composed of 21 modules leading to 1155 modules in the entire system. The position of each module in a string is shown in Figure 3. In this figure, 10 strings leading to a row (composed of the left wing with 5 strings and of the right wing with 5 strings) is shown. The power degradation of each module was plotted against the position of the module in each string.

If there is a PID effect in a string, the modules in the string farthest from the ground potential would be expected to degrade at progressively higher rate leading to the highest degradation rate for the last module in the string. Referring Figure 3, module ‘1’ should degrade at the lowest rate whereas module ‘21’ should degrade at the highest rate. Three random strings out of the total 55 strings are shown in Figures 4A, 4B and 4C. These plots show different trends (higher, lower and no degradation rate difference than that of the first module) in power degradation with respect to their voltage/module position, when plotted in a scatter plot from the ground potential position of zero. The plot shown in Figure 4A indicates an increasing trend of degradation with the voltage level (positive slope). The last module experiences about 20% higher degradation than the first (grounded) module. In contrast, Figure 4B indicates a decreasing trend of degradation percentage with the voltage level (negative slope). Here, the first (grounded) module has 20% higher degradation than the last module of that string. Figure 4C, however, shows nearly constant performance degradation trend throughout the string (near-zero slope). The total number of strings exhibiting an increasing slope, decreasing slope and constant slope of performance degradation with respect to voltage position in a positively biased series string were 18, 24 and 13, respectively. Thus, as shown in Figure 5, no real positive or negative trend, on an average, is seen in the 1155 modules of model B.
Figure 4A: Higher performance degradation trend towards the far end of a string (+455V). Each data point corresponds to a specific module position in the string.

Figure 4B: Lower performance degradation trend towards the far end of a string (+455V). Each data point corresponds to a specific module position in the string.

Figure 4C: Constant performance degradation trend throughout the string (+455V). Each data point corresponds to a specific module position in the string.

Figure 5: Average Performance degradation for all 55 strings (1155 Modules) of model B. Each data point corresponds to the average of 55 modules in each position of 55 strings.

Figure 6: Position of modules in a string for model C

A total of 27 strings were evaluated for PID effects by plotting the module degradation according to its position in the string for model C. The highest bias voltage in the case of model C was +505 V. The investigation on this model (and also other models) also indicated the absence of any specific position-specific degradation of the modules as explained below. Figure 7A indicates that Module 8 of model C has the highest degradation and the trend of degradation is higher for modules at higher bias voltages (positive slope). An opposite trend is seen in Figure 7B where the module 1 has the highest degradation which is at the lowest potential with respect to ground. Also, the trend line in Figure 7B suggests that modules at lower voltage bias exhibited higher performance degradation than those at the higher voltage bias (negative slope). Some strings for Model C suggest that there is no specific trend of degradation with respect to module position and voltage bias as seen in Figure 7 C (near-zero slope). The total number of strings exhibiting positive slopes, negative slopes and a near-zero slopes for model C were 13, 9 and 5,
respectively. When all 27 strings containing 216 modules are plotted in one graph as shown in Figure 8, the overall trend line suggests that there is no overall effect of voltage bias on Model C as well.

Since there were only 3 modules per string for model A18, no PID investigation was carried out for A18. The PID investigation was extended to all other models of the power plant listed in Table 1. Based on the analysis of the results obtained on more than 100 strings of this power plant with modules from different manufacturers, it may be concluded that the modules investigated in this power plant at this hot-dry climatic condition do not seem to experience the PID effect. The absence of PID effect could possibly be attributed to the hot-dry climatic condition of the test site (Tempe, Arizona).

**IV. CONCLUSIONS**

The degradation rate of 12-18 years old modules exposed in the hot-dry climatic condition of Tempe, Arizona is ranging between 0.6%/year and 2.5%/year depending on the manufacturer or model. Assuming a linear degradation and the conventional 20-year warranty with 20% degradation limit from the nameplate rating, more than 80% of the tested modules in this hot-dry climate do not meet the warranty expectations. A statistical analysis on the distribution of degradation rates of the modules studied in this project will be published in a future paper. The modules with hotspots appear to degrade at a higher rate than the non-hotspot modules.

A slightly higher degradation rate observed on the 1-axis installed modules as compared to the latitude-tilt modules of the same model may seem to indicate that the temperature effect (higher dwell time at high module temperature during the day and higher delta of day-night temperature swing) on the module degradation is much higher than the cumulative insolation effect. This temperature effect could lead to both short-circuit current loss and fill factor loss; however, this...
preliminary conclusion may need to be confirmed by extending this type of investigation to the other models which are installed in the same location but with different tilt angles and/or tracking methods.

The PID investigation of more than 100 strings (with STC string voltage of about 500 V) in a hot-dry climatic condition indicates that the negatively grounded c-Si modules (or positively biased modules) do not appear to experience the PID effect. The absence of PID effect on the modules investigated in this project could possibly be attributed to the dry climatic condition of the test site (Tempe, Arizona).

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REFERENCES


