Performance Analysis of CIGS, CdTe, and a-Si PV modules in the Hot and Humid Climate

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Introduction

☀ Limitations of accelerated testing
☀ The long-term outdoor testing of PV modules- aids in estimating the extent of degradation in PV modules under actual operating conditions
☀ Helpful in understanding the correlation between PV performance and the meteorological parameters
Selection of Test Site

- Selection of test location PV modules testing is important
- Hot and humid conditions impose harsh conditions on PV modules
Methodology - Measurement of meteorological parameters

- Solar Irradiance
- Relative Humidity
- Ambient Temperature
- Wind Speed
- Back-of-Module Temperature
Early Results: 1st Generation

☀ Florida Power Corp PV Array Orlando, Fl, tilted at ~25° towards the south with operational voltage 300 V DC
☀ Degradation caused by corrosion
☀ Moisture ingress inward and sideways
☀ Electric shorting cracked glass Aluminum frame damaged in several places
Cell Disintegration

Reaction products
Fire Glass Melting

Worst problem with corrosion reaching the junction box
Fire and melting of glass leaving a gaping hole ~7"
Large enough to pass a palm through
a-Si:H 2nd Generation

-600 V – 27 months
-600 V – 12 months

-300 V – 32 months
-150 V – 32 months
Electroluminescence and visual images reveal area (PV activity) loss due to electrochemical corrosion of high-voltage-biased a-Si:H PV modules at FSEC.

Sodium diffusion from the glass caused severe degradation of the TCO.

Short term fix: improved barrier; Long-term fix: edge seals

-600 V – 12 months
PV Module deployment

- A sturdy, hurricane-proof base structure was constructed for the installation of thin-film PV modules.
- The modules were mounted at a latitude tilt of ~29° facing true South.
- All modules types were divided in two sets and connected in series so as to build the maximum open-circuit voltage of less than ±600 V with respect to ground.
- Connected across optimum fixed load resistors of and a current measuring shunt.
Performance Measurement

- A continuous measurement of output current and voltage from PV arrays.
- PV USA regression analysis
- Periodic current-voltage measurements of PV arrays
Outdoor test bed at FSEC

- a-Si:H Single Junction
- a-Si:H Triple Junction
- CIGS
- CdTe

CIGS
Set of CIGS ST-40 modules were deployed during 1999 at FSEC and connected in any array across a fixed load. Continue to remain outdoors to date.

Module were randomly selected from the array and present performance was evaluated with I-V measurement and visual inspection.
CIGS Modules-Visual inspection

- Corrosion of entire scribe line
- Corrosion started on the scribe line
- Dark spotty region throughout the module
- Dark spotty region as a patch near the edge of the module
## I-V measurement of Selected Modules

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Voc (V)</th>
<th>Isc (A)</th>
<th>Pmax (W)</th>
<th>FF (%)</th>
<th>% of Rated Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name Plate Rating</td>
<td>23.3</td>
<td>2.68</td>
<td>40</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>21.9</td>
<td>1.86</td>
<td>18.7</td>
<td>45.8</td>
<td>46.8</td>
</tr>
<tr>
<td>B</td>
<td>20.8</td>
<td>2.48</td>
<td>24.3</td>
<td>47.3</td>
<td>60.8</td>
</tr>
<tr>
<td>C</td>
<td>24.3</td>
<td>2.48</td>
<td>33.5</td>
<td>55.5</td>
<td>83.8</td>
</tr>
<tr>
<td>D</td>
<td>22.9</td>
<td>2.32</td>
<td>23.0</td>
<td>43.4</td>
<td>57.5</td>
</tr>
<tr>
<td>E</td>
<td>23.5</td>
<td>2.63</td>
<td>36.7</td>
<td>59.2</td>
<td>91.8</td>
</tr>
</tbody>
</table>
CIGS Array

- Another set of ST-40 modules were deployed during 2004 and were removed during 2007.
- Data was continuously monitored from the positive and negative arrays connected across an optimum fixed load.
- Performance analysis carried out using PVUSA regression analysis
Degradation rates were calculated to be -5.16±1.53% and -4.5±1.46% per year for the positive and negative string, respectively.
I-V measurements for module sets with the arrays

☀ It was found that three modules in the positive string and two modules in the negative string had shown a power output of less than or equal to 85% of the rated power.

☀ These modules were then relocated within the array towards the high voltage end of the array.

☀ During February and April 2007 another set of I-V measurement was carried out for the entire array, for modules that had shown lower than 85% performance and for modules that had continued to show performance over 85%.
**I-V Data Comparison**

- Comparison of peak power values obtained from I-V measurements carried out on LACSS solar simulator and Daystar Curve tracer
- Most of the modules continued to show consistent performance except for a few modules
Comparison of peak power from a set of modules within the positive array array

<table>
<thead>
<tr>
<th>Module sets</th>
<th>Peak power Feb-07</th>
<th>Peak power Apr-07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three modules with performance lower than 85%</td>
<td>79.9</td>
<td>79.2</td>
</tr>
<tr>
<td>Remaining 21 modules that performed better</td>
<td>98.6</td>
<td>99.3</td>
</tr>
<tr>
<td>Entire array</td>
<td>96.3</td>
<td>95.6</td>
</tr>
</tbody>
</table>
**Comparison of peak power from a set of modules within the negative array**

<table>
<thead>
<tr>
<th>Module sets</th>
<th>Peak power Feb-07</th>
<th>Peak power Apr-07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two modules with performance lower than 85%</td>
<td>85.5</td>
<td>83.8</td>
</tr>
<tr>
<td>Remaining 22 modules that performed better</td>
<td>96.2</td>
<td>96.7</td>
</tr>
<tr>
<td>Entire array</td>
<td>96.6</td>
<td>94.9</td>
</tr>
</tbody>
</table>
CdTe Array
A cosine function was used to model the seasonal variation in CdTe PV array. The cosine function very closely matches the seasonal trend shown by the PTC power for the given time period. Used to correct seasonal variation.
PTC power trend corrected for the seasonal variation for positively and negatively biased module

Annual performance changes were 0.14±2%/year and -1.3±2%/year for positive and negative array respectively.
Performance Variation from I-V Measurements

Annual performance variation changes were -0.67% for positive array and -0.925% for negative array respectively.
Average annual energy yield calculated from the data collected through continuous monitoring of PV performance is approximately 1187 kWhr/kWp/Year.
Single Junction and Triple Junction a-Si:H PV Arrays
Single Junction and Triple Junction a-Si:H

PTC Power Trend for Positive Arrays of a-Si:H
PV modules from Oct’05- Sept’07

- Single Junction
- Triple Junction

PTC Power (W)
0 100 200 300 400 500 600 700 800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

y = 0.2133x + 603.09
R² = 0.0027

y = 0.5098x + 323.21
R² = 0.0329

PTC Power Trend for Negative Arrays of a-Si:H
PV modules from Oct’05- Sept’07

- Single Junction
- Triple Junction

PTC Power (W)
0 100 200 300 400 500 600 700 800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

y = 0.2739x + 590.61
R² = 0.0042

y = 0.6698x + 321.58
R² = 0.0531

NREL PVMRW 2013
# Performance Variation

<table>
<thead>
<tr>
<th>Performance Variation rate (% per annum)</th>
<th>Single Junction</th>
<th>Triple junction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Array</td>
<td>+1.89 %</td>
<td>Positive Array</td>
</tr>
<tr>
<td>Negative Array</td>
<td>+2.49 %</td>
<td>Negative Array</td>
</tr>
</tbody>
</table>

☀ Annual performance variation from October 2005 through September 2007

NREL PVMRW 2013
Energy yield for the combined positive and negative arrays was 1300 kWh/kWp/year and 1425 kWh/kWp/year for the single junction and triple junction a-Si:H PV arrays respectively.
So far we discussed corrosion and delamination caused by humidity, heat and voltage.

Other modes: Glass breakage especially in the case of untempered glass, experience also with heat-strengthened glass mostly caused by microcracks generated during processing, handling and possibly high wind loads.
The earlier generation CIGS modules have showed a significant degradation rate for the time they were deployed in the field in the hot and humid climate of Florida. The estimated degradation rates calculated during this time frame were -5.13% and -4.5% per year for positive and negative strings, respectively. It was found that the overall degradation observed within the array strings was on account of few modules in the positive and negative array strings that had shown signification degradation. The remaining modules within the array continued to shown consistent performance.
Conclusions

☀ PV modules in another CIGS PV after about 13 years in the hot and humid climate showed performance ratios ranging between 0.5 through 0.9

☀ An attempt was made to model the seasonal variation for CdTe modules using cosine function.

☀ Power performance variation showed +1.89 % and +2.49 % for positive and negative array of single junction a-Si:H PV modules and +0.42 % and + 0.56 % for the positive and negative array of triple junction a-Si:H PV modules respectively.

☀ The annual energy yield was found to be 1300 kWh/kWp/year and 1425 kWh/kWp/year for
Conclusions

- the single junction and triple junction a-Si:H PV arrays respectively.
- Optimization of manufacturing processes and packaging schemes is very essential for long term stability of PV modules.
- Failure Modes and Mechanisms, corrosion and delaminatyon caused by humidity, heat and voltage, Glass breakage caused by microcracks
- It is, therefore, necessary to carry out long-term studies of this nature in order to test the reliability and durability of PV modules of any technology.
Questions and Comments
Cracked glass

Reaction continuing around cracks
Corrosion
Molten Glass