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Outdoor performance of CIGS modules at multiple temperatures over three years

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ABSTRACT

The performance and degradation rate of photovoltaic (PV) modules primarily depend on the technology type, module design and field operating conditions. The metastability is a known phenomenon in the CIGS (copper indium gallium diselenide) module technology and it depends on the light exposure and operating temperature. This work aims to understand the metastability influence on the performance of CIGS modules exposed outdoor at three different operating temperatures at a fixed insolation over three years. Two types of CIGS modules from two different manufacturers have been investigated in this study. The three different temperatures were achieved by placing three CIGS modules per manufacturer at three different airgaps on a south facing mock rooftop tilted at 20°. The airgaps were 3", 1.5" and 0", and the 0" airgap module was thermally insulated to obtain a higher operating temperature. Throughout the test period over three years, all the modules were maintained at maximum power point using a setup containing optimizers and power resistors. The performance characterizations were carried out before and after exposure using both outdoor natural sunlight and indoor solar simulator. The influence of superstrate type and installation height on the soiling loss have also been investigated.

Keywords: Copper indium gallium diselenide, CIGS, degradation, temperature effect, measurement uncertainty, soiling loss

1. INTRODUCTION

With the increasing penetration of thin film photovoltaic technologies in the global photovoltaic (PV) systems, due to their lower temperature coefficients and manufacturing cost as compared to crystalline silicon, it is becoming necessary to investigate the reliability and durability of these emerging technologies. Accelerated stress tests cannot always predict the long-term behavior of CIGS, copper indium gallium diselenide, modules accurately as these tests often do not incorporate light as a stress factor which is a crucial to understand metastability. The ultimate decisive factor that determines the durability of module components and claimed warranty is outdoor exposure. The identification of the underlying performance degradation modes over the years of operation in different climatic regions can lead to better design and reduce financial risk for investors.

Data from various studies that have been conducted to determine the degradation rates of different PV technologies are aggregated in literature1-2. It was evaluated that regional climatic factors, module technology as well as operating conditions lead to different degradation rates3,4,5,6. The uncertainty associated with the reported degradation rates considered by the researchers include the soiling loss, uncertainty associated with module technology (metastability) and the performance measurement uncertainty etc. Technology-specific metastability effects are observed in crystalline silicon (1-4% Initial Light Induced Degradation (LID)) modules but are found more pronounced in thin film technologies. Among the thin film PV modules, amorphous silicon (a-Si) is mostly influenced by light-induced degradation whereas CdTe (Cadmium Telluride) and CIGS are more sensitive to light exposure history which results in different STC (standard test conditions) power when exposed to varying light exposure, temperature and dark storage.

* First two listed authors contributed equally to this study
conditions. Metastability effects such as short-run transients, initial LID (1-10% increase and decrease) and dark storage impact on power (reversible) are observed in CIGS modules, which complicates the measurement of electrical parameters at STC and the determination of performance degradation rate. Different degradation rates are reported in the literature for CIGS modules: 6%/year in tropical Singapore, 5.13-4.5%/year in hot and humid climate of Florida, 2.3%/year in semi-arid Algeria, 1.93%/year in tropical climate of Thailand, and 1.4%/year in Mediterranean climate of Spain. Thin film technologies undergo different rate of power degradation or gain during initial months of installation as compared to rest of module life. Moreover, the stabilization period and method used for degradation analysis was found to be different in different studies. In this study, six pre-production engineering CIGS modules – three from manufacturer 1 (CIGS1) and three from manufacturer 2 (CIGS2) – have been investigated at three different temperatures installed on a mock rooftop structure at identical light exposure conditions. These CIGS modules were investigated for the temperature sensitivity of degradation rates and effect of height on the soiling loss rates. This study was undertaken at Mesa, Arizona which has a hot-dry desertic climate.

2. METHODOLOGY

2.1 Pre-exposure testing

Before commissioning, a comprehensive stabilization procedure was performed on six CIGS modules to measure power and other electrical parameters at STC with less uncertainties and avoiding the metastability effects as much as possible. Initial STC power of CIGS modules before field exposure is used as reference to measure the performance and degradation of modules throughout the exposure period. The test procedure performed to understand the metastability effects of CIGS modules on performance parameters and to produce repeatable measurements is detailed as follows. Firstly, characteristic parameters such as Pmax, Voc, Isc, Vmax, Imax and FF were determined from outdoor and indoor I-V measurements. Outdoor I-V measurements were performed using DS-100C I-V curve tracer on a clear day between 10am and 2pm to ensure the air mass is close to 1.5 spectrum (AM 1.5) and irradiance is near 1000W/m². Modules were mounted on a manual dual axis tracker and thermocouples were connected to the back sheet. Then a light soaking procedure was carried out according to IEC 61646 standard for thin film modules in which modules were exposed to 2 kWh/m² of sunlight under open-circuit conditions. Outdoor and indoor I-V measurements were performed again, immediately after light soaking, by using the same procedure. I-V characteristic parameters determined by the above-mentioned procedure are deliberately hidden to keep manufacturers and modules anonymous; however, these measurements were used as initial STC parameters during this study.

Baseline I-V measurements were performed to calculate the temperature coefficients of Isc (α), Voc (β), and Pmax (δ). This was accomplished by placing the modules in a cooling chamber that cooled them up to 15°C. The cooled modules were then connected with two thermocouples on back sheet and placed on dual axis tracker under sun. As the modules started warming up, I-V curves were obtained for every 1°C to 2°C rise in temperature. All baseline I-V measurements were taken under same weather conditions as mentioned above.

2.2 Module installation and operating conditions

The installation specifications of modules such as substrate thermal insulation, different airgaps and mounting orientations are given in Table 1 and shown in Figure 1. These modules were installed on a mock rooftop (south facing, 20° tilt angle) in Mesa, Arizona.

Table 1. Module installation conditions

<table>
<thead>
<tr>
<th>Testing Technology</th>
<th>Module Code or Name</th>
<th>Airgap</th>
<th>Back sheet Thermal Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIGS1 (Manufacturer-1)</td>
<td>CIGS1-3”</td>
<td>3-inch</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>CIGS1-1.5”</td>
<td>1.5-inch</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>CIGS1-Insulated</td>
<td>0-inch</td>
<td>R-10 foam</td>
</tr>
<tr>
<td>CIGS2 (Manufacturer-2)</td>
<td>CIGS2-3”</td>
<td>3-inch</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>CIGS2-1.5”</td>
<td>1.5-inch</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>CIGS2-Insulated</td>
<td>0-inch</td>
<td>R-10 foam</td>
</tr>
</tbody>
</table>
Temperature monitoring from thermocouple

Weather Station

DAS
dThermocouple

CIGS1-3” airgap

DAS

CIGS2-3” airgap

CIGS1-15” airgap

CIGS2-15” airgap

CIGS1-0” airgap-insulated

CIGS2-0” airgap-insulated

Rooftop

DC Optimizers

Performance monitoring

Power resistor bank

Each module on the rooftop was connected with two thermocouples, one at center and other on the edge to collect module temperatures and to observe the effect of wind and its direction on the module temperature. The modules were installed at different airgaps and with substrate insulations to study performance at different temperatures. As shown in Figure 1, the modules were connected with DC/DC optimizers to maintain all the six modules under maximum power point tracking (MPPT) condition, a data acquisition system (DAS) was installed to collect the temperature data of the modules and the modules were connected to power resistors to dissipate the output energy. The weather parameters (irradiance, wind speed and direction, ambient temperature and humidity) were also collected using a separate DAS.

3. RESULTS AND DISCUSSION

3.1 Uncertainty in performance measurements

The comparison of indoor and outdoor measurements provides insight into the sensitivity of output power to measurement method and metastability issues of CIGS modules. Figure 2 shows that the outdoor I-V measurements using natural sunlight typically underestimate the performance of CIGS1 modules as compared to indoor I-V measurements using a pulse solar simulator. On the other hand, Figure 3 indicates that the outdoor I-V measurements using natural sunlight typically overestimate the performance of CIGS2 modules as compared to indoor I-V measurements. Different results for both types of modules are due to the uncertainty in measurement method (outdoor IV under natural sunlight or Indoor IV under solar simulator) and module metastability. However, it is difficult to separately quantify the impact of each one, but primarily overall measurement uncertainty is caused by the metastable nature of the CIGS technology. In addition, the observed measurement repeatability error within indoor or outdoor I-V measurements, could be as high as 1%. Therefore, the degradation rate reported in this paper has a significant measurement uncertainty.
The degradations of the CIGS1 modules are nonlinear as evidenced from the poor linearity coefficient shown in Figure 4. As discussed earlier, nonlinearity is primarily caused by the metastable behavior of the CIGS1 modules. These modules gain 8 - 10% power after an initial exposure to sunlight. However, they slowly start degrading after 1 - 2 years of normal field exposure in a hot - dry desert climatic condition. These modules typically operate at daytime average temperature of about 51° C on hot sunny days. An average degradation of 1.59%/year has been observed for these modules; however, this higher than expected degradation rate could have been caused due to the use of engineering modules (rather than production modules) and can also be attributed to the measurement uncertainty of the periodical outdoor I-V measurements over 3.42 years. The degradations of the CIGS2 modules are also nonlinear as evidenced from the poor linearity coefficient shown in Figure 5. Like CIGS1 modules, non-linear degradation of CIGS2 modules is also primarily caused by the metastable behavior of the CIGS2 modules. These modules gain 2 - 8% power after an initial
CIGS1 - Nonlinear Field Degradation (Hot-Dry Desert):
Pmax from Periodical Outdoor I-V Measurements
(100% Pmax before exposure; Average operating temperature = 51-52°C in May 29-Jun 27, 2015; Average degradation = 1.59%/year)

\[ y = -0.0084x + 462.02 \quad R^2 = 0.3659 \]

CIGS2 - Nonlinear Field Degradation (Hot-Dry Desert):
Pmax from Periodical Outdoor I-V Measurements
(100% Pmax before exposure; Average operating temperature = 49-51°C in May 29-Jun 27, 2015; Average degradation = 0.15%/year)

\[ y = -0.0042x + 277.87 \quad R^2 = 0.543 \]
CIGS1 & CIGS2 - Outdoor Testing at High Temperature Hot-Dry Desert:

Pmax from Periodical Outdoor I-V Measurements
(100% Pmax before exposure; Operating temperature = 59-61°C in May 29-Jun 27, 2015)

3.3 Performance degradation at high temperatures

Figure 6 compares the degradation rates of pre-production engineering CIGS1 and CIGS2 modules for high temperature operating conditions in the field. This high-temperature test condition was instituted in the outdoor test program to understand if the modules could withstand the prolonged high-temperature operating condition that may be experienced by the modules, though infrequent on most/all of the days in most climatic conditions in the world. As shown in Figure 6, the CIGS1 modules experienced about 9% gain over 18 months of exposure at high temperatures whereas the CIGS2 modules experienced about 2% degradation over 18 months of exposure at high temperatures. This testing condition is expected to help the CIGS manufacturers to understand the degradation mechanisms when the daily average operating temperatures are higher than 60°C over an extended period.

3.4 Summary of performance degradations

As shown in Figure 7, the CIGS1 modules tend to degrade, on an average, between 0.7% and 1.5% per year depending on the measurement method, natural sunlight or solar simulator. This reported degradation rate could still be influenced by the measurement uncertainty along with the metastable nature of the technology. The CIGS1 modules with 1.5" airgap tend to degrade at slightly higher rate than that of the 3" airgap modules, probably due to slightly higher operating temperatures of the modules with slightly restricted airflow on the back of the modules over 3 years. Figure 8 shows that the CIGS2 modules tend to degrade, on an average, between 0.15% and 0.20% per year depending the measurement method, as mentioned above. Again, this determined degradation rate could still be influenced by the measurement uncertainty along with the metastability issue of the technology. As seen in CIGS1, the CIGS2 modules with 1.5" airgap tend to degrade at significantly higher rate than that of the 3" airgap modules, probably due to higher operating temperatures of the modules with slightly restricted airflow on the back of the modules over 3 years.
Figure. 7 Summary of degradation rates of CIGS1 modules at normal operating conditions (free air flow on the back of the modules) with about 51°C on hot sunny days in a dry desert climate.

Figure. 8 Summary of degradation rates of CIGS2 modules at normal operating conditions (free air flow on the back of the modules) with less than 50°C on hot sunny days in a dry desert climate.

SOILING LOSS
As the soil layers build up on the superstrate of the PV modules, the light transmittance is reduced and consequently the current and power are reduced. The performance reduction due to soiling depends on the module superstrate, installation and site-related factors. The module superstrate-related factors include the surface roughness and surface anti-soiling properties (hydrophobic, hydrophilic, electrostatic etc.). The installation-related factors include the height of the modules from the ground level and fixed tilt, 1-axis tracker or 2-axis tracker. The site-related factors include the rain frequency and level, humidity level, dew formation, soil spectral absorption properties, wind speed, wind direction, windborne pollen etc. In a short-term study, we investigated the superstrate-related and installation height-related influence on the soiling loss of CIGS modules. Typically, at this test site (Mesa, Arizona) with the current rooftop installation, the crystalline silicon modules experience about 0.065% soiling loss per day during the dry season between April and late July. Figure 9 indicates that the soiling loss in the CIGS modules is pretty similar to the crystalline silicon modules, except for the CIGS1 modules, at less than 100 cm height, which experience about three times higher soiling loss as compared to all the other modules. It is recommended that the CIGS1 modules are installed at a height higher than 100 cm from the ground level to minimize the soiling loss.
Soiling Loss (SL) and Module Installation Height
(June 30 - July 7, 2015)

CIGS1 - SL  CIGS2 - SL  CIGS1 - Height  CIGS2 - Height

Airgap

Fig. 9 Dependence of soiling loss on the superstrate type and installation height of CIGS1 and CIGS2 modules.

CONCLUSION
This research investigates the behavior of thin film CIGS modules, exposed outdoor at different installation conditions for three and a half years in a hot desert climate of Arizona. The degradation rates reported in this paper are influenced by the measurement uncertainty and metastability issues of the technology. Metastability causes difficulty in calculating the real degradation rates from performance measurements and it is hard to quantify its effect on the determined degradation rates.

A nonlinear trend is observed in the degradation of CIGS modules, as they show a gain in power during the initial period of outdoor exposure and then start degrading after 1-2 years. On average, CIGS1 modules degrade 0.7% and 1.59% annually, whereas CIGS2 modules degrade between 0.15% and 0.20% annually for 3" and 1.5" airgap, respectively.

Soiling loss results of all modules show that the daily power loss of the CIGS modules due to soil accumulation is close to the crystalline silicon modules at this site; however, the soiling of CIGS1 modules are more influenced, compared to CIGS2 modules, by the installation height.

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