Defect and safety inspection of 6 PV technologies from 56,000 modules representing 257,000 modules in 4 climatic regions of the United States

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Defect and Safety Inspection of 6 PV Technologies from 56,000 Modules Representing 257,000 Modules in 4 Climatic Regions of the United States

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Abstract — Defect and safety inspections were performed on about 56,000 photovoltaic (PV) modules representing 257,000 modules of multiple technologies (mono-Si, poly-Si, a-Si, CdTe and CIGS) aged between 1.3 and 26 years, and operating in four climatic regions (hot-dry, temperate, cold-dry and hot-humid) of the United States. The number (or percentage) and types of defects and safety failures primarily depend on technology, design, installation, climate and age. The results presented in this paper will provide insights into the dominant types of defects and safety failures which are commonly found in multiple climates and that are specific to each climate.

Index Terms — Visual inspection; safety failures; performance defects; amorphous silicon; crystalline silicon; CdTe; CIGS

I. INTRODUCTION

Photovoltaic (PV) module manufacturers are competing to achieve reduced price per watt. Currently, module prices are about $0.5/W, and they are expected to fall further as global PV adoption rises. In the race to reduce module prices, some manufacturers use cheaper (and lower) quality component materials for encapsulants, backsheets, solder, metallization, etc., which could create reliability and durability issues in the field. Modules degrade differently depending on the environmental conditions, and failure modes seen predominantly in one environment might not be present in others. Defects are classified into safety failures (i.e., those that pose safety hazards for people/property; e.g. broken glass, backsheet burn, etc.) and performance defects (i.e., those that might result in performance degradation without causing any safety issues; e.g. encapsulant discoloration, etc.).

A project led by the Electric Power Research Institute (EPRI) was conducted to evaluate module performance and reliability in different climatic regions. As shown in Table I, the Arizona State University Photovoltaic Reliability Laboratory (ASU-PRL) performed visual inspections of about 56,000 modules (representing over 257,000 total modules) of various technologies in four climatic regions of the United States. The visual inspection was conducted in 36 PV power plants owned by either EPRI or its electric utility members in Arizona (Hot-Dry), California & Colorado (Temperate), New York (Cold-Dry), and Florida & Texas (Hot-Humid).

Due to site accessibility, logistics, time/budget constraints, safety and/or unfavorable weather conditions not all of the 257,000 modules could be inspected for visual defects. Therefore, for some of the large systems, a statistically significant number of modules were selected for the defect and safety inspection with 95% confidence level (CL) and 5% confidence interval (CI).

The following commercially available 6 PV technologies were investigated in this study:
- c-Si: Crystalline silicon (mono-Si; poly-Si; HIT)
- a-Si: Amorphous silicon
- CdTe: Cadmium telluride
- CIGS: Copper indium gallium selenide

<table>
<thead>
<tr>
<th>Technology</th>
<th>No. of Modules Inspected</th>
<th>Age (yrs)</th>
<th>Climate Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>8,668</td>
<td>4-16</td>
<td>Hot-Dry</td>
</tr>
<tr>
<td>c-Si</td>
<td>25,088</td>
<td>1.5-5</td>
<td>Temperate</td>
</tr>
<tr>
<td>CdTe</td>
<td>132</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>CIGS</td>
<td>136</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>c-Si</td>
<td>4,487</td>
<td>2-19</td>
<td>Cold-Dry</td>
</tr>
<tr>
<td>c-Si</td>
<td>1,188</td>
<td>3-11</td>
<td></td>
</tr>
<tr>
<td>a-Si</td>
<td>928</td>
<td>5-26</td>
<td>Hot-Humid</td>
</tr>
<tr>
<td>CdTe</td>
<td>14,435</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>CIGS</td>
<td>720</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

The plant evaluation methodology used in this work is based on the approach presented in our previous works [1-3]. In this conference, we are publishing another paper which provides degradation rates for 26 plants of the 36 plants investigated in this work [4]. Due to the issues related to site
accessibility, safety, unfavorable weather etc., not all of the 36 plants were evaluated for the degradation rates. The 10 plants which do not have degradation rates information are: 2 from Buffalo, New York and 1 from New York City (cold-dry climate); 1 from San Francisco, California (temperate climate); 6 from Orlando, Florida (hot-humid climate).

II. METHODOLOGY

The defect inspections were performed on 36 PV power plants in four different climatic regions of the United States using ASU-PRL’s visual inspection checksheet, which includes 86 different types of performance defects and safety failures identified in checklists developed by National Renewable Energy Laboratory (NREL) and ASU-PRL. Of these, 61 defect types are categorized as performance defect types that affect PV module power output and 25 defect types are categorized as safety failures that affect safety (mechanical/electrical safety or fire hazard).

Of the 61 performance defect types, 7 defect types are known to affect glass (front/rear), 22 defect types affect the cell (hotspot defect detected using IR camera), 5 defect types affect the frame, 4 defect types affect the edge seal, 5 defect types affect the encapsulant, 5 defect types affect the junction box, 3 defect types affect the backsheet, 5 defect types affect the wires/cables/connectors, 3 defect types are specific to thin film PV modules, 1 defect type affects bypass diode short-circuit (detected using circuit continuity detector) and 1 defect type affects module mismatch and solder bond fatigue/failure (identified through I-V measurements) - were identified to be responsible for performance loss.

Of the 25 safety failures, 4 failures affect glass (front/rear), 5 failures affect frames, 5 failures affect junction boxes, 3 failures affect wires/cables/connectors, 5 failures affect backsheets, 2 failures affects cell (hotspot detected using IR camera) and 1 failure affects bypass diode open-circuit (detected using circuit continuity detector).

This paper does not attempt to quantitatively correlate the defects with degradation. A quantitative correlation between each defect and degradation rate can be obtained through the determination of risk priority number, RPN [5]. The defects observed in the field are recorded in a MATLAB program to automatically generate RPN charts [6]. Based on the recorded defects presented in this paper, the degradation rates reported in reference [4] and the MATLAB program developed by this research group [6], RPN can be automatically generated for each observed defect and will be reported in a future publication.

III. RESULTS AND DISCUSSION

A. Safety Failures – Thin film modules

16,351 thin film modules belonging to CdTe, CIGS and a-Si modules were evaluated in the temperate and hot-humid climatic regions. Unfortunately, no thin film modules were evaluated in the hot-dry and cold-dry climatic regions. The plot in Fig. 1 shows the distribution of safety failures in the thin film modules. Less than 0.3% of the thin-film modules, exposed between 1.3 and 26 years, experienced 4 types safety failures (out of 25 safety failure types) in the hot-humid and temperate climates. In hot-humid climate, the glass breakage and edge seal damage were observed to be top two safety failure modes in thin-film modules. In temperate climate, the glass damage was observed to be the only safety failure mode in thin film modules. The photographic images of these failures are shown in Fig. 2. The a-Si modules shown in Fig. 2 have been in operation for over 19 years in Orlando, FL. This figure shows the extent of edge seal damage that led to moisture penetration creating a current leakage path which in turn poses a serious safety issue.

![Fig. 1. Safety failures observed in 16,351 thin film modules (aged between 1.3 and 26 years).](image)

![Fig. 2. (top-left) Broken CdTe module-front glass (TX); (top-right) Broken CdTe module-rear glass (TX); (bottom-right) Missing J-box cover in an a-Si module (FL); (bottom-left) Edge seal damage in an a-Si module (FL).](image)
B. Safety Failures – crystalline silicon modules

39,431 crystalline silicon modules belonging to mono-Si, poly-Si and HIT technologies were evaluated in the four climatic regions. The plot in Fig. 3 shows the distribution of safety failures in the crystalline silicon modules. About 2.2% of the c-Si modules, exposed between 1.5 and 19 years, experienced 12 types of safety failures (out of 25 safety failure types) in all the four climates. In the hot-dry climate, the top two dominant safety failures were the front encapsulant delamination and backsheet burns. Since the encapsulant delamination does not fully extend from the active circuit to the frame though it was observed close to the frame, this failure may or may not be considered as a safety failure at the moment but it could become a safety failure over time if the delamination fully extends to the frame (causing ground fault during rainy or dew conditions). In the hot-humid climate, the front encapsulant delamination was the only safety failure. In the cold-dry and temperate climates, the most dominant safety failure mode was the backsheet bubble and the other safety failure modes were practically negligible. The crystalline silicon systems in the hot-humid regions are only about 5 years old and haven’t shown any significant safety failures, probably due to less exposure to the environment.

Fig. 4 provides representative photographs of the dominant safety failures observed in different climates. The bypass diode failures were rarely seen in any of the power evaluated plants except one: about 1.1% of the modules in one specific 1-axis tracking plant exposed in Arizona over 12 years experienced bypass diode failures. The reason for the bypass diode failures in this specific plant is not known but it could be due to faulty diodes, faulty module design or the moving shadows on the modules as these failures were seen mostly near one of the malfunctioning tracker motors. It is possible that the repair personnel of the tracker motor might have been the source of moving shadows repeatedly triggering the bypass diodes over the years.

C. Performance Defects – Thin film modules

For the safety failures, 16,351 modules were inspected in temperate and hot-humid climates (see Fig. 1) but for the performance defects only 2002 modules were inspected due to time constraints and unfavorable weather conditions. About 37% of the thin-film modules, aged between 1.3 and 26 years, showed only 2 types of performance defects (out of 61 performance defect types) in the hot-humid and temperature climates. A quantification of the effect of each defect type on the module performance can be obtained through the RPN analysis which will be a subject of future investigation by this research group.

As shown in Fig. 5, about 98% of the observed defects in hot-humid climate for a-Si are related to delamination of TCO (transparent conducting oxide) and/or absorber layer. Similarly, about 98% of the observed defects in temperate climate are related to apparent cell/TCO discoloration or color difference within a CIGS module. Due to possible optical interference patterns in thin film technologies, which might have been existing since the inception of the system, the observed color difference may or may not be a source of performance degradation.

Fig. 6 shows the photographs for the TCO/absorber layer delamination in a-Si modules and for the discoloration in CIGS modules. It is evident that the extensive TCO/absorber layer delamination observed in these modules will have serious effects on performance.
D. Performance Defects – Crystalline silicon modules

For both safety failures and performance defects, 39,341 modules were inspected in all four climates as shown in Fig. 3 and Fig. 7, respectively. About 31% of the c-Si modules, aged between 1.5 and 19 years, showed only 8 types of performance defects in all four climates (out of 61 performance defect types). A quantification of the effect of each defect on the module performance can be obtained through the RPN analysis which will be a subject of future investigation by this research group.

As shown in Fig. 7, about 12,175 defects belonging to 8 performance defect types were identified with encapsulant discoloration being the most significant defect (68%) in three out of four climatic regions with an exception of the temperate climate. The encapsulant discolored modules were mostly observed only in the older plants of the hot-dry climate of Arizona (>8 years) and of the cold-dry climate of New York (>18 years). The c-Si modules evaluated in the hot-humid climatic region are only about 3 years old but about 43% of the modules already showed mild encapsulant discoloration defect. We speculate that the presence of encapsulant discoloration in the hot-humid climate (about 3 years of age) and the absence of encapsulant discoloration in the temperate climate (about 2 years of age) could be due to the mild temperature/humidity conditions of the San Francisco bay area site as compared to the hot-humid climate of Orlando, Florida and San Antonio, Texas sites.

It is to be noted that the hotspot defect (ΔT<20°C) shown in Fig. 7 differs from the hotspot failure (ΔT>20°C) shown in Fig. 3 as the hotspots with greater than 20°C is considered to be a safety hazard in the near future (due to expected thermal runaway issue) and lower than 20°C but higher than 10°C is considered to be a performance defect (due to performance variation between cell to cell within a module). Similarly, the front encapsulant delamination shown in Fig. 3 considers delamination very close to the frame (safety failure) whereas the delamination shown in Fig. 7 considers delamination farther away from the frame (performance defect).

Excluding solder bond degradation defect (detected using I-V curves and not discussed in this paper), Fig. 8 shows the photographs of top three performance defects (encapsulant browning, encapsulant delamination in double glass modules and cell chipping) observed in hot-dry climate of Arizona.

A quantification for the effect of each defect on the module performance can be obtained through the RPN analysis and this will be a subject of future study by this research group.

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Fig. 6. (left) Discoloration of the CIGS modules (CO); (right) Delamination of the absorber/TCO of a-Si module (TX).

Fig. 7. Performance defects observed in 39,431c-Si modules (aged between 1.5 and 19 years)

Fig. 8. (top-left) Encapsulant discoloration in crystalline silicon modules (AZ); (top-right) chipped cell (AZ); (bottom) Encapsulant delamination (AZ).
IV. SUMMARY

A detailed field inspection for the safety failures and performance defects have been conducted for 6 PV technologies from 56,000 modules representing 257,000 modules in 4 climatic regions of the United States.

Safety failures: Less than 0.3% of the thin-film modules, exposed between 1.3 and 26 years, experienced safety failures in the hot-humid and temperate climates. In hot-humid climate, the glass breakage and edge seal damage were observed to be top two safety failure modes in thin-film modules. In temperate climate, the glass damage was observed to be the only safety failure mode in thin film modules. About 2.2% of the c-Si modules, exposed between 1.5 and 19 years, experienced 12 types of safety failures (out of 25 safety failure types) in all the four climates. In the hot-dry climate, the top two dominant safety failures were the front encapsulant delamination and backsheets burns.

Performance defects: About 98% of the observed defects in hot-humid climate for a-Si, aged 26 years, are related to delamination of TCO (transparent conducting oxide) and/or absorber layer. Similarly, about 98% of the observed defects in temperate climate are related to apparent cell/TCO discoloration or color difference within a CIGS module (aged 3 years). About 31% of the c-Si modules, aged between 1.5 and 19 years, showed only 8 types of performance defects in all four climates (out of 61 performance defect types). The encapsulant discoloration defect is determined to be the most significant defect (68%) in three out of four climatic regions with an exception of the temperate climate. It is clear that the encapsulant discoloration depends on the age, temperature, UV level and humidity level of the operating sites.

A quantification for the effect of each defect on the module performance can be obtained through the RPN analysis and this will be a subject of future study by this research group.

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REFERENCES


