ADVANCEMENTS IN THE DEVELOPMENT OF “ATAMO”: A SOLAR MODULE ADAPTED FOR THE CLIMATE CONDITIONS OF THE ATACAMA DESERT IN CHILE: THE IMPACT OF SOILING AND ABRASION

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ABSTRACT: Dust is currently one of the major problems of PV plants in Chile. In the present study we investigate the influence of abrasion and soiling on solar modules using different combinations of solar module materials and solar cells under simulated test conditions. Indoor and outdoor tests were performed at ISC Konstanz, Germany, and at the Solar Platform of the Atacama Desert (PSDA) in Yungay, Chile, respectively. We fabricated half-size and full-size cell modules employing different cell types, glass thickness, encapsulants, backsheets or glass-glass configurations. Modules were measured in the field for eight months. During exposure time, cleaning was performed every 60 days. Preliminary outdoor results indicate that ARC glass type exhibits higher Isc losses than standard (STD) glasses due to soiling, regardless of the combination of other materials used for the modules. Transparent backsheets (TBS) or glass on the rear side help to compensate the soiling losses due to increased internal reflection of light coming from the rear side of the module. In dirty condition, higher performance ratio (PR) was observed on half-size than on full-size cell modules under monofacial operation condition (the rear side covered: 97% compared to 94%). Under bifacial operation much higher but similar PRs for half- and full-size modules (both 107%) were reached. For the abrasion outdoor test, no damage was observed until now, even on vertical installed glasses which were installed perpendicular to the wind speed and close to the ground. For the indoor abrasion and soiling test, we adapted the standard testing conditions for sand (IEC and MIL-STD) using representative parameters such as temperature and humidity registered by 12 years of measurements and dust from eight PV plants located in the Atacama Desert. For the abrasion indoor test, the ARC layer on the glass was removed by all dust types after one minute of exposure and for 200-500 \(\mu\)m dust grain size. Increasing the exposure time, higher transmissivity (T), reflectivity (R) and Isc losses were detected until the abrasion effect almost reached saturation. When changing the tilt angle from 90° to 30° and reducing the grain size to 63-121 \(\mu\)m, lower losses were observed. Regarding the indoor test, a model was performed to predict the T and R losses according to the geographic place, glass type and sand density on the glass surface. The model predicts 3.5% higher T losses and 2.4% R losses for ARC compared to STD glasses with dust of less than 63\(\mu\)m grain size, regardless of the location.

Keywords: PV Desert Module, Abrasion Test, Soiling Test, ARC Glasses, Bifaciality, Silicon Solar Cell

1 INTRODUCTION

With regard to the quality of solar modules and performance, standard testing conditions as IEC were not developed for solar module applications in climates such as the Atacama Desert which is characterized by extremely high irradiation levels (in particular in the UV-B range), large amount of sun hours per day, low temperature, corrosive environment, partial high humidity known as “Camanchaca” (sea fog) and a really fine dust called “Chusca”.

In February 2016 the PV installed capacity in Chile reached 1 GW, positioning PV as the first source of renewable energy in the country [1]. Currently one of the major problems of PV plants in Chile is the fine “Chusca” dust which - in combination with the hard environment condition in the Atacama Desert - results in huge losses in system performance. A study reported up to 40% soiling losses in the PV plants in Chile [2].

This fine Chusca dust in the presence of Camanchaca creates a hard dust layer on the surface of the PV modules which has a strong effect on the module lifetime, degradation and power achieved by the modules. Furthermore, it strongly increases the cleaning frequency required. As reported by GIZ [3], the maximum clean frequency of 14 PV farms located in the Atacama Desert, which are currently operating and injecting energy to the Chilean grid, is 1.2 times per month. Water consumption is in the order of a couple of liters of water per m² for each cleaning interval. On the other hand, according to a study from SIS-Chile (supervision of health services) [4] a common person in Chile consumes an average of 121 liters per day. Thus, with the amount of water to clean a 1 MW PV plant it is possible to supply water for a typical village in the Atacama Desert, where the scarce of water is a problem.

Recently, studies regarding the performance degradation due to dust accumulation on PV systems in the Atacama Desert have been carried out [5-7]. In order to quantify the performance of PV systems, the IEC defines in indicator called performance ratio (PR) [8]. The PR is a quality factor that describes the relationship between the actual and theoretical energy outputs of the PV plant considering the availability of the solar resource and size (capacity) of the installation. In [5], the PR, decreased at rates of 4.0%/month (5.1%/month) for CdTe and 4.4%/month (6.0%/month) for mc-Si PV plants installed at 1700 m above sea level (the coastal zone of Atacama), respectively. More studies of PV technologies operating at the coastal zone of the Atacama Desert found that a-Si/\(\mu\)-Si and mono c-Si technologies degraded up to 0.18%/day [6]. Further studies regarding soiling in the
Capital of Chile (Santiago) reported degradation rates of 0.13%/day and 0.56%/day [7].

The present study corresponds to advancements in the development of “AtaMo” [9]. In this case, we focus our investigation on the performance of different setups of half-size and full-size cell modules under indoor and outdoor abrasion and soiling test in order to find the best material combination against the impact of abrasion and soiling.

2 EXPERIMENT
2.1 Outdoor tests

Outdoor measurements were performed at the Solar Platform of the Atacama Desert (PSDA) [10] in Yungay, Chile, see Figure 1.

![Figure 1: Testing under outdoor conditions at PSDA](Image)

Half-size and full-size single cell modules based on 6” p-type mc-Si and bifacial 6” n-type pseudo-square Cz-Si solar cells with standard 3 busbar metallization patterns, different glasses, encapsulants, and backsheets were designed. The ribbon soldering process on the front and rear side was performed manually or semi-automatically by a stringer machine using the same type of ribbon and flux. The glass thickness was varied using 1.5, 2.0 and 3.2 mm glass. For the 3.2 mm thick solar glass an antireflection coating layer (ARC) was also incorporated. For the encapsulation material ethylene vinyl acetate (EVA), a thermoplastic material (TM) and low UV light cut-off EVA (U) were used. For the backsheet, standard, transparent, and desert type sheets (which are optimized in terms of abrasion and thickness for desert regions), as well as glass, were employed, see Tables I and II.

For characterization, Electroluminescence (EL) measurements were carried out to control the soldering and lamination performance. Peel tests were carried out to monitor the soldering process. IV characteristics were measured by a h.a.l.m. cell- and module-flasher at STC conditions before and after lamination to determine the cell-to-module losses, and to quantify the losses in the environmental tests. For optical investigations, spectral photometer measurements of reflectivity (R) and transmissivity (T) versus wavelength from 300 to 1200 nm were carried out after and before the tests. In addition, for the abrasion test, the depth and the roughness of the glass surface generated by the dust was measured by Laser scanning microscopy (LSM).

<table>
<thead>
<tr>
<th>Glass thickness [mm]</th>
<th>Backsheet (BS)</th>
<th>Encapsulant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>Desert (D)</td>
<td>EVA</td>
</tr>
<tr>
<td>1.5</td>
<td>Standard (S)</td>
<td>EVA</td>
</tr>
<tr>
<td>2.0</td>
<td>Desert (D)</td>
<td>EVA</td>
</tr>
<tr>
<td>2.0</td>
<td>Standard (S)</td>
<td>EVA</td>
</tr>
<tr>
<td>3.2</td>
<td>Desert (D)</td>
<td>EVA</td>
</tr>
<tr>
<td>3.2</td>
<td>Standard (S)</td>
<td>EVA</td>
</tr>
<tr>
<td>3.2</td>
<td>Desert (D)</td>
<td>TM</td>
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<td>3.2</td>
<td>Standard (S)</td>
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<td>2.0</td>
<td>Transparent (T)</td>
<td>EVA</td>
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<tr>
<td>3.2</td>
<td>Transparent (T)</td>
<td>EVA</td>
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<tr>
<td>3.2</td>
<td>Standard (S)</td>
<td>U</td>
</tr>
<tr>
<td>3.2ARC</td>
<td>Standard (S)</td>
<td>EVA</td>
</tr>
</tbody>
</table>

Table II: Experimental setups of n-type bifacial modules for environmental testing (Enc = Encapsulant)

<table>
<thead>
<tr>
<th>Front side glass [mm]</th>
<th>Rear side glass [mm]</th>
<th>Bifacial cell</th>
<th>Enc</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>2.0</td>
<td>FULL</td>
<td>EVA</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0</td>
<td>HALF</td>
<td>EVA</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>FULL</td>
<td>EVA</td>
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<tr>
<td>1.5</td>
<td>1.5</td>
<td>HALF</td>
<td>EVA</td>
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<tr>
<td>1.0</td>
<td>1.0</td>
<td>FULL</td>
<td>EVA</td>
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<tr>
<td>1.0</td>
<td>1.0</td>
<td>HALF</td>
<td>EVA</td>
</tr>
<tr>
<td>3.2ARC</td>
<td>Transparent (T)</td>
<td>FULL</td>
<td>EVA</td>
</tr>
<tr>
<td>3.2ARC</td>
<td>Transparent (T)</td>
<td>FULL</td>
<td>TM</td>
</tr>
<tr>
<td>3.2ARC</td>
<td>Transparent (T)</td>
<td>FULL</td>
<td>U</td>
</tr>
<tr>
<td>3.2ARC</td>
<td>Transparent (T)</td>
<td>FULL 4 mc-Si</td>
<td>EVA</td>
</tr>
<tr>
<td>3.2</td>
<td>Transparent (T)</td>
<td>FULL 4 Cz-Si</td>
<td>EVA</td>
</tr>
</tbody>
</table>

The modules were measured in the field for a period of 8 months. During exposure time the modules were cleaned every 60 days (see Figure 3).

Figure 3: Before and after cleaning every 60 day

In addition to the modules, 3.2 mm glasses with and without ARC were installed at different inclinations. In particular vertical glasses were faced perpendicular to the wind speed and at 15 cm above from ground level. The maximum average wind speed measured at the PSDA was 14 m/s. The glass after abrasion exposure time of 100 days was returned to ISC Konstanz for T, R, and LSM analysis.
2.2 Indoor tests

Dust was collected from the ground at eight PV plants located in the 1st Region Tarapacá, 2nd Region Antofagasta and the 3rd Region Atacama y Coquimbo in Chile: 100 MW Amanecer, 50.3 MW San Andrés, 24 MW Diego de Almagro, 2.8 MW Esperanza, 1.4 MW Huayca 1, 7 kW PSDA Yungay, 5.8 kW San Pedro and 5.8 kW Antofagasta (see Figure 3). The dust was separated with a dry sand sieve shaker in order to use grain sizes in the range of 200 to 500 µm and 63 to 112 µm for the abrasion indoor test and less than 63 µm for the soilindoor test. The dust characterization was carried out by EDX (Energy Dispersive X-ray Spectroscopy) and XDR (X-Ray Diffraction) using the same set of parameters to measure each sample. Note that for grain sizes less than 500 µm, the EDX and XDR analysis of dust from module surface and from the ground provided the same soil composition. This result validates the procedure used to collect the dust and to perform the indoor tests.

The design of the abrasion test adapted to the climatic conditions in Chile was made after reviewing the blow sand standardizations MIL-STD-810G, IEC60068-2-68 and IEC60529 [11]. In the present study, the wind speed was set to 17 m/s according to the maximum average wind speed as registered between 2000 and 2012 by Meteorological Direction of Chile in the central valley of the Atacama Desert [12]. In this region most of the PV farms are installed. The tilt angle was adjusted to 30° and 90° for 3.2 mm glass with and without ARC using the different types of dust collected. The exposure time was 1, 2 and 3 min for all different dust types. For the Yungay samples, additional bifacial 5x5 cm² modules were made for 3, 6 and 9 min exposure time and 90° tilt angle.

To simulate the hard dust layer formed by “Chusca” dust in combination with “Camanchaca” fog, the glass samples with and without ARC were placed in the climatic chamber. This chamber was operated with a humidity (RH) variation according to the metrological data of 12 years as reported in [12]. This data ranges between 61 and 83% and temperatures between 55 and 65 °C corresponding to the operating temperature for c-Si modules registered by the University of Antofagasta. The grain size used was less than 63 µm according to the sand grain found on the modules surface in Yungay. After the exposure in the climatic chamber, the sand deposition was performed by free fall from 1 m height using a cylindrical tube of 8 cm diameter based according to [13]. After sand deposition on the glass, the sample was dried and the dust on the surface weighted with a balance of 0.1 mg sensitivity. Finally, each glass sample was encapsulated with 1.5 mm glass in order to avoid the loss of sand from the glass surface and for characterization.

3 RESULTS

3.1 Outdoor tests

The following results correspond to the short circuit current (Isc) losses and performance ratio (PR) before and after cleaning with an average of a clean step every 60 days in a period of 8 months of exposure time.

Regardless of the module configuration the modules with ARC glasses led to higher Isc losses compared to STD modules, figure 4.

![Figure 4: Glass Type versus relative Isc losses (%) showing higher losses for ARC than STD glasses](image)

The soiling effect on the Isc losses was larger for standard and desert backsheets than for transparent backsheets possibly due to increased albedo light through the rear side that reflects from the accumulated dust layer on the glass and penetrates into the front side of the solar cell, see Figure 5. Additionally, reduced Isc losses for thermoplastic material and thinner glasses were measured. Previous studies have shown that the module performance is mainly dependent on the encapsulation materials, regardless of the backsheet used [9] under high humidity and temperatures after 6000 hours exposure time.
Figure 5: Relative Isc losses (%) for 3 different encapsulants. Lower losses for TBS than for SBS and DBS can be observed.

Regarding the PR of different solar cell designs, in dirty condition and covering the rear side, better PR values were measured with half- compared to full-bifacial cell modules with 97.2% and 94.2%, respectively. If the rear side is not covered the PR of bifacial modules increased even more, achieving same values in dirty condition, 107.3% for half-size configurations and 107.0% for full cell design.

No damage in terms of abrasion were found for any glass group installed at different tilt angles and heights distributed in several places at the PSDA in Yungay, see Figure 6. Even for the most challenging case, vertical glasses perpendicular to the wind speed and 15 cm height from the ground, no abrasion effect was observed. The reason could be that the frequency of sandstorm in the Atacama Desert in comparison with others deserts is low.

Figure 6: Glass configurations at the PSDA in Yungay

3.2 Indoor tests

Soiling and abrasion indoor experiments were carried out at ISC Konstanz, Germany. As the sand deposition on the glass surface increased, higher losses in T and R were measured. Losses were larger with the use of ARC compared to STD glass type, see Figure 7.

Figure 7: Absolute R & T mean losses (%) versus sand density (mg/cm²) using ARC and STD glasses

Based on the experimental data generated by the use of different dust, a model was developed in order to simulate the losses in T and R for every place. A relationship between glass type and sand deposition was found, see Figure 8. Setting the model to 2 mg/cm², T losses ranged from 34 to 43% and R losses from 30 to 39%. Changing the ARC glass type to STD, a loss reduction of 3.5% in T and in 2.4% R were obtained, regardless the place.

Figure 8: Model to predict the absolute R & T mean losses (%) versus sand density (mg/cm²) using ARC and STD glasses

Although no damage in terms of abrasion was found at the PSDA in Yungay, abrasion indoor tests were performed using parameters from meteorological and measured data in the Atacama Desert. The goal was to predict the damage that could occur. The wind speed was set to 17 m/s according to the maximum average wind speed reported after 12 years of measurements in the...
central valley of the Atacama Desert, where most PV plants are located.

Figure 9 illustrates the results for tests with glass in a vertical position with respect to the wind direction. As the test time increased, the transmissivity curve went down. LSM pictures before and after three minutes exposure time show that the abrasion test was very aggressive, not only removing the ARC layer, but also producing deep holes in the glass surface.

The test for tilt angles of 30° was less aggressive than for 90°, changing the slope of the losses in T and R, and reducing the depth of the holes on the glass surface. In terms of Isc losses, 3.2 mm front glass bifacial modules with and without ARC reveal Isc losses of 3.5% for standard and 6% for ARC modules after three minutes of exposure time. After six and nine minutes, Isc losses slightly increased and the difference between ARC and STD glass type remained almost the same (Figure 10), i.e. the abrasion effect reaches almost saturation after three minutes.

Figure 10: Short circuit current (Isc) losses in (%) versus exposure time for bifacial glass modules (red) and bifacial glass modules with ARC (blue)

In order to characterize the impact of dust abrasion in more detail, 72 LSM measurements were carried out, inside and outside of the abrasion area (Figure 11). If the ARC layer thickness is assumed to be 0.15 µm, it becomes obvious that the ARC layer disappeared. Reducing the grain size of the dust from 200-500 µm to 63-112 µm, which is more realistic, the dust impact still remove the ARC layer.

Figure 11: Depth map (µm) plotted over the position of LSM measurement coordinates in µm for two different grain size ranges, 90° tilt angle, after one minute of exposure for ARC glass

4 CONCLUSION

Soiling and abrasion indoor and outdoor tests were carried out in order to determine the best combinations of materials preventing soiling and abrasion losses.

For outdoor and indoor soiling tests, higher losses in T, R and Isc for ARC compared to STD glass type were measured. An Isc loss reduction was determined for the transparent backsheet or a glass sheet as a rear side.

For abrasion no damage was found at the PSDA in Yungay, possibly due to the low frequency of dust storm on the Atacama Desert (in comparison to other deserts such as the Sahara). For the adapted abrasion indoor test, using parameters that have been reported and measured in the Atacama Desert, good analysis and characterization have been shown. Again ARC glass type shows larger T, R and Isc losses compared to STD glass type. The ARC layer on the glass surface was partially removed for all studied dust samples (places). Nevertheless, long term outdoor characterization is required to validate the indoor tests.

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6 REFERENCES


