DO THIN FILM PV MODULES OFFER AN ADVANTAGE UNDER PARTIAL SHADING CONDITIONS?

Chris Tzikas[1], Gabriela Gómez[1,2], Menno van den Donker[1], Klaas Bakker[2,3], Arno H.M. Smets[2], Wiep Folkerts[1]

[1]Solar Energy Application Centre (SEAC), High Tech Campus 21, Eindhoven, The Netherlands
[2]Delft University of Technology, PhotoVoltaic Materials and Devices group, Delft, The Netherlands
[3]Solliance Solar Research, Eindhoven, The Netherlands

ABSTRACT: Building Integrated PhotoVoltaics (BIPV) is one of the fastest growing segments of the photovoltaic industry worldwide. More than 25 years development has brought to the market diversified products for seamless integration into the building envelope by using a variety of PV technologies. One of the biggest loss factors, though, for such applications are the partial shading phenomena caused by shading elements on the roof or in close proximity such as chimneys, dormers, trees, poles etc. These shadings may have a detrimental effect mostly on the performance but sometimes also on the reliability of the PV modules used in BIPV applications.
Keywords: Building Integrated PV (BIPV), Thin Film, Shading, Reliability, CIGS

1 INTRODUCTION

This paper focuses on the effect shading has on the performance and reliability of various PV technologies used in Building Integrated Photovoltaics (BIPV). Building Integrated Photovoltaics are photovoltaic materials that are used to replace conventional building materials in parts of the building. The current world market share of BIPV systems is only 3% [1] and can therefore be considered a niche market.

In order for BIPV to move out of the niche market certain challenges must be addressed. One of the main technical challenges is to assure an adequate performance under non-ideal conditions. For the scope of this paper, non-ideal conditions are defined as high operating temperatures and light obstructions. Such conditions can be very difficult to be avoided in these systems and have a drastic impact on the performance and lifespan of the PV installation.

Due to their nature, BIPV applications are often subject to shading caused by obstruction elements such as: trees and poles in close proximity, chimneys, exhaust pipes, dormers or surrounding buildings (see Figure 1). This partial shading effect has detrimental impact on the system's performance but could also sometimes affect the reliability of the PV modules over time.

Figure 1: Light obstruction on rooftop PV systems

In order to study the effects of shading on the performance and the reliability of various PV technologies, a comprehensive range of experiments was designed that included partial shading experiments, EL imaging of the PV modules before and after these experiments and IV tracing under different shading scenarios.

2 EXPERIMENTAL SETUP

The experiments presented in this paper were conducted at the Photovoltaics Laboratory of TU Delft using the following equipment:

- Steady State Solar Simulator, Eternal Sun.
- 650W DC load, BK Precision.
- I-V tracer, ReRa IVtraQ.
- Electro-luminescence (EL) camera with high pass IR filter, Nikon D7200.
- Optical Microscope.
- Resistance Data Logger with temperature and voltage channels, Pico PT-104.
- Opaque cardboard for shading experiments.

Figure 2: Electro-luminescence equipment, I-V tracer and solar simulator used for the experiments

For this study, 11 commercially available PV modules of 3 different PV technologies (crystalline Silicon, Cadmium Telluride, Copper Indium Gallium Selenide) were characterized:

- 2 c-Si modules (c-Si_A, c-Si_B).
- 2 CdTe modules (CdTe_A, CdTe_B).
- 7 CIGS modules (CIGS_A, CIGS_B, CIGS_C, CIGS_D, CIGS_E, CIGS_F, CIGS_G).

The steps of the experimental procedure was followed the steps of which are listed below:

1. Initial electro-luminescence (EL) imaging to corroborate the initial module condition.
2. Unshaded IV tracing to establish initial nominal power.
3. IV tracing with progressive shading stress, depicted in Figure 3 and Figure 4.
4. Unshaded IV tracing to assess possible damage done to the module by the shading stress.
5. Final EL imaging to determine module condition after shading stress.

The IV curves obtained were analyzed and the Nominal Power (P_{max}) was calculated. The maximum power was corrected for module temperature according to equation (1):

$$P_{corr} = \frac{P_m}{1+a(T_m - T_{STC})} \quad (1)$$

where: P_{corr} is the corrected power output, P_m is the measured power, α is the temperature coefficient for P_{max} according to the manufacturer's datasheet, T_m is the module temperature at the time of the measurement and T_{STC} is the temperature at Standard Test Conditions.

The shading stress was performed using a black opaque cardboard, imposing direct shading, with increments of 5% of the total module area in landscape (see Figure 3) and portrait orientation (see Figure 4). It is important to point out the different cell orientation for the CdTe and CIGS_A modules compared to the rest of the thin-film (TF) modules.

Figure 3: Landscape shading and cell orientation of the PV modules tested

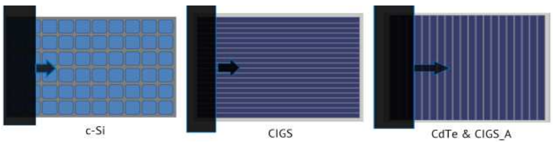

Figure 4: Portrait shading and cell orientation of the PV modules tested. The arrow shows the direction of the progressive shading stress applied.

The performance study aims to investigate if thin-film (TF) modules perform better under partial shading conditions. This is a claim made also by TF manufacturers and attributed to the monolithic integration and long geometry of their solar cells [2].

For the reliability study, the shading pattern was selected in order to simulate the worst case shading scenario for a PV module. It was found from the experiments and literature [3] [4] [5] [6] that covering the whole length of a small amount of TF solar cells causes the most damage as it creates the highest power dissipation for the shaded cells. This shading pattern corresponds to landscape shading orientation for CIGS and portrait shading orientation for CdTe and CIGS_A modules. The size of the cardboard mask was selected so there could be the highest dissipation possible on the maximum number of solar cells. Figure 5 shows a characteristic IV curve for a TF module under shading conditions. In order to obtain highest dissipation, the shaded characteristic curve must have a short circuit current (I_{sc_shaded}) higher than the current at maximum power point (I_{mpp}) of the unshaded module. The 10% module shading percentage was selected for this study.

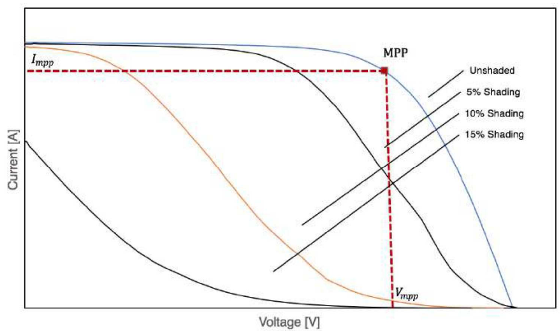

Figure 5: IV curve of a shaded thin-film module

The PV modules were shaded with the selected mask and short circuited while being illuminated by the solar simulator. The experiment was conducted for 10 minutes while current and temperature of the module were being recorded. At the end of the illumination period, an unshaded IV tracing was performed and an EL image was taken.

3 PERFORMANCE RESULTS

In this paragraph the results of the landscape and portrait shading experiments are presented. Both the relative power of the PV modules and the module shading percentage are normalized so that all results are directly comparable regardless of the power rating or the size of the PV module.

The results of the landscape shading experiment are presented in Figure 6. The c-Si modules show a typical behavior with 2 plateaus forming every time a by-pass diode is activated, consequently shutting off one part of the module. The difference between c-Si_A and c-Si_B resides in the number of cells connected to the bypass diodes. The two CdTe and the CIGS_A show the best performance in these conditions with performance reducing linearly as all cells get equally shaded. The CIGS modules lose all power at around 20% module shading as whole cells were shaded and forced into reverse bias.

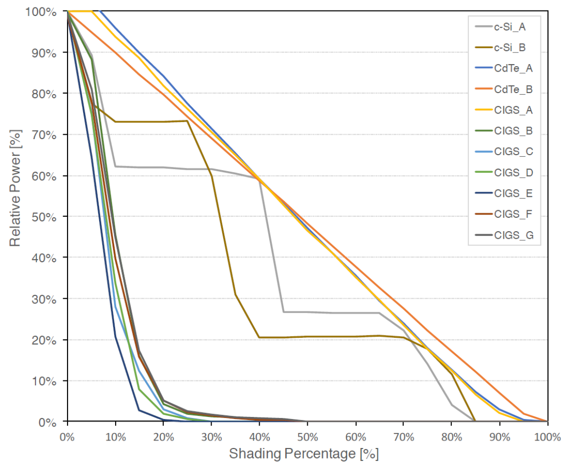

Figure 6: Performance under landscape shading stress

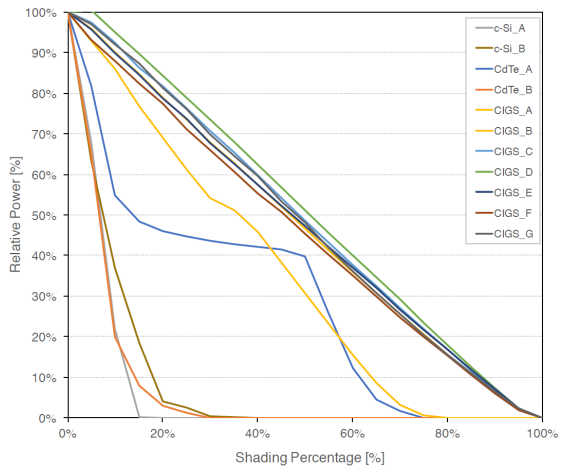

Figure 7: Performance under portrait shading stress

In the portrait shading experiment (see Figure 7), the opposite behaviour is observed for all PV modules apart from the CdTe_A and CIGS_A modules. The CdTe_A presented a plateau from 20% to 50% confirming the presence of two substrings connected in parallel allowing disconnection of the first half of the solar cells when the module is shaded past 20%. The CIGS_A module on the other hand is equipped with multiple bypass diodes allowing it to retain power by shutting down parts of the module up to almost 80% shading.

The overall results show a higher tolerance of the TF modules under partial shading stress compared to c-Si ones. Nevertheless a careful study of the shading patterns for BIPV applications is essential for the proper installation that will maximise the energy yield. In addition to this, modules with integrated bypass diodes (CIGS_A) or more than one substring (CdTe_A), show a superior performance under any shading conditions.

4 RELIABILITY RESULTS

In this paragraph, the reliability investigation is presented. The PV modules were subjected to partial shading with opaque cardboards under short circuit conditions. This allowed to achieve the worst case operating scenario for these modules. The emphasis will be on CIGS modules as both the c-Si and CdTe didn't show any clear signs of damage.

The results on CIGS modules show damage visualised as dark spots in the EL images. These dark spots are shunts located at the areas where the panel was masked for shading (see Figure 8 - Figure 14).

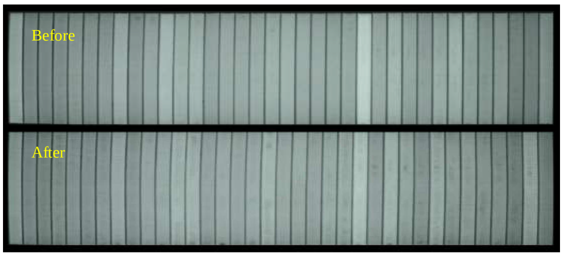

Figure 8: EL image of the CIGS_A module before the shading stress was applied (top image) and after the shading stress was applied (bottom image).

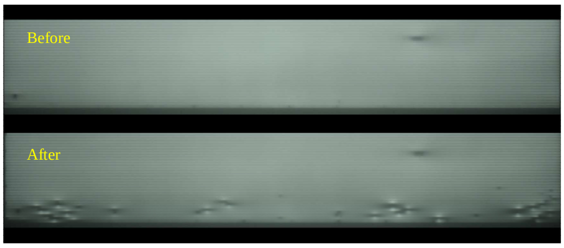

Figure 9: EL image of the masked side of the CIGS_B module before and after the shading stress respectively

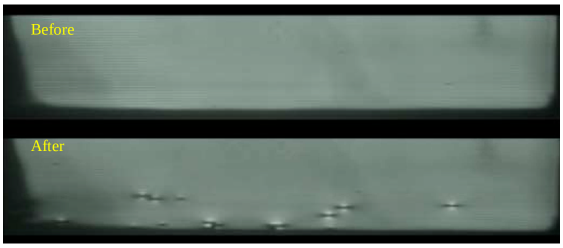

Figure 10: EL image of the masked side of the CIGS_C module before and after the shading stress respectively

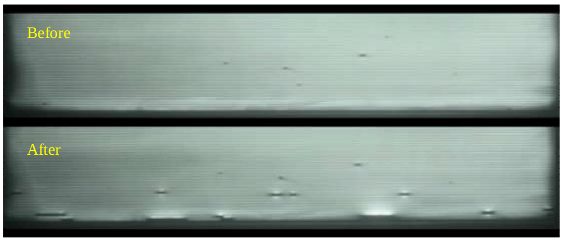

Figure 11: EL image of the masked side of the CIGS_D module before and after the shading stress respectively

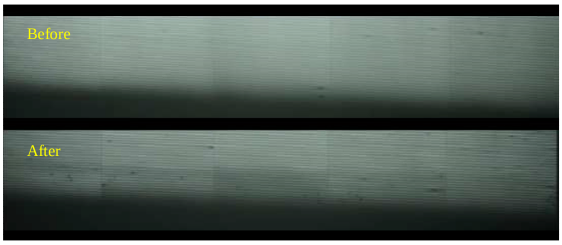

Figure 12: EL image of the masked side of the CIGS_E module before and after the shading stress respectively

Figure 13: EL image of the masked side of the CIGS_F module before and after the shading stress respectively

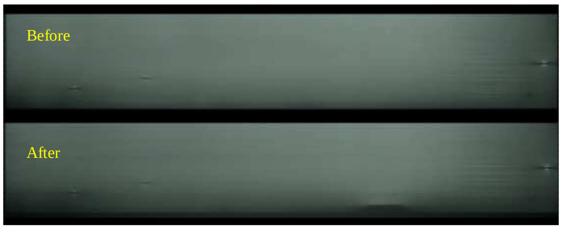

Figure 14: EL image of the masked side of the CIGS_G module before and after the shading stress respectively

Shunting due to reverse bias in the masked cells was evident in the majority of the CIGS modules. The most severe effect was observed for the CIGS_B, CIGS_C, CIGS_D and CIGS_F modules. CIGS_A didn't show any signs of shunting while also the effect on CIGS_E was very small.

The outstanding tolerance of CIGS_A module can be attributed to the different solar cells' interconnection design. Contrary to the rest of the CIGS modules of this study, which use a monolithic integration, the solar cells' interconnection in the CIGS_A module rely on a conductive metal grid (also known as shingle overlap). The shingled interconnection allows for a distribution of current on a wider area. This reduces the stress due to reverse bias. Moreover, the integrated bypass diodes of this module help in avoiding a high reverse bias stress on the shaded cells. Along with the CIGS_A, also the CIGS_E module appears to be more tolerant to partial shading. This is due to the partiotioning of the cells which helps reducing the effect of reverse bias on the shaded cells.

In some cases, the shunts created due to partial shading produced a visible defect to the naked eye. Figure 15 shows the visible worm-like defect. These defects are localised close to the scribing lines.

Figure 15: Worm-like defects that were created by applying shading stress on CIGS modules

After the reliability experiments, unshaded IV tracing was performed for each module to determine potential performance losses due to shunting. The losses were limited (2% - 8%) and affected mostly the heaviest shunted modules (CIGS_B, CIGS_F). Furthermore, a partial healing phenomenon was observed after storing these modules in dark for a couple of weeks.

5 CONCLUSIONS

TF modules have in general better performance under partial shading due to their unique cell layout. The TF modules consisting of more than one string (CdTe_A) or having more than one bypass diode (CIGS_A) have superior performance and improved reliability.

Despite the aforementioned advantages of TF modules in terms of performance, in extreme partial shading conditions, cell defects were evident, potentially causing shunt paths in areas where power is dissipated. Also in some modules worm-like defects visible to the naked eye were formed. Module partitioning (CIGS_E) and multiple strings (CdTe_A) can mitigate the problem.

6 REFERENCES

[1] A. Reinders, P. Verlinden, W. van Sark and A. Freundlich, Photovoltaic Solar Energy: From Fundamentals to Applications, Wiley & Sons, 2017.

[2] Solar Frontier, "High shadow tolerance," Solar Frontier, [Online]. Available: https://www.solar-frontier.eu/en/cis-technology/high-shadow-tolerance/. [Accessed 2017 April 13].

[3] T. J. Silverman, M. G. Deceglie, C. Deline and S. Kurtz, "Partial Shade Stress Test for Thin-Film Photovoltaic Modules," NREL, California, USA, August 2015.

[4] J. E. Lee, S. Bae, W. Oh, H. Park, S. M. Kim, D. Lee, J. Nam, C. B. Mo, D. Kim, J. Y. Yang, Y. Kang, H.-s. Lee and D. Kim, "Investigation of damage caused by partial shading of CuInxGa(1-x)Se2 photovoltaic modules with bypass diodes," *Progress in Photovoltaics*, vol. 24, no. 8, pp. 1035-1043, April 2016.

[5] T. J. Silverman, L. Mansfield, I. Repins and S. Kurtz, "Damage in Monolithic Thin-Film Photovoltaic Modules Due to Partial Shade," *IEEE Journal of Photovoltaics*, vol. 6, no. 5, pp. 1333-1338, July 2016.

[6] P.-O. Westin, U. Zimmermann, L. Stolt and M. Edoff, "Reverse bias damage in CIGS modules," in *24th European Photovoltaic Solar Energy Conference*, Hamburg, DE, September 2009.