Presented at the 4th World Conference on Photovoltaic Energy Conversion, WCPEC-4, June 13 2018, Waikoloa Village, Hawaii USA

Accelerating Cyclic Loading

Hubert Seigneur[1], Jason Lincoln[1], Eric Schneller[1], Andrew M. Gabor[2]
[1]Florida Solar Energy Center, University of Central Florida, Cocoa FL, USA
[2]BrightSpot Automation LLC, Westford, MA, USA

***Abstract* — In this work, we performed four variations of cyclic load testing on four groups of modules using the LoadSpot tool. Each group first underwent 50 thermal cycles (TC50), 10 humidity-freeze cycles (HF10), and a 2400 Pa static load. Then, the baseline group was tested using standard cyclic loading conditions from IEC 62782, another with double the loading frequency, one with larger loading magnitude, and one with smaller loading magnitude and quadruple the loading frequency. Interestingly, we found that increasing the loading frequency actually reduces maximum power degradation with respect to the baseline, whereas increasing or decreasing the load amplitude respectively increases or decreases maximum power degradation with respect to the baseline. In order to confirm the results, we conducted another experiment with a new group using modules of a different make and model. This group did not undergo TC50 nor HF 10, only a 5400Pa static load to create cracks. For this group, the maximum power degradation did not show a dependence on the loading frequency during cyclic loading. We offer a possible explanation for this unexpected result associated with increasing the loading frequency.**

***Index Terms* — cracks, cyclic load testing, mechanical load testing, photovoltaic modules, reliability, silicon.**

I. INTRODUCTION

The continuous reduction in thickness of photovoltaic (PV) module components such as glass, encapsulant, and solar cells together with an increase in occurrence of strong weather events make PV modules in general more vulnerable to cyclic loads potentially leading to more fatigue failures of materials and components, especially ribbons, soldering joints, and edge seals [1]. Recently, we showed that under certain conditions, cyclic loading was an effective way to open existing cracks in encapsulated solar cells inside PV modules [2], [3] affecting LCOE. Such failures and degradation rates are expected to only worsen as PV modules become thinner and experience larger deflections as a result. Thus, cyclic load testing to assess design quality and power degradation of new module sizes and constructions becomes even more valuable.

Even so, because PV module reliability testing generally can take a considerable amount of time to carry out, finding ways to speed up reliability testing while maintaining or improving the effectiveness of existing tests can result in considerable cost savings. This is also the case for the IEC 62782 standards. For example, that standard specifies 1000 cycles at ± 1000Pa. Assuming an average rate of 5 cycles/min, 1000 cycles would take about 3.5 hours. Therefore, an examination of available avenues to further accelerate this kind of test is desirable.

Two approaches considered in this work consist of increasing the load or the frequency of the load. Increasing the load obviously leads to a larger displacement and stress on PV module components, which in turn leads to larger degradation and earlier failure in agreement with fatigue theory. A similar effect can be achieved in principle by increasing loading frequencies. It has been reported in the literature that when loading frequencies approach the natural frequencies of a module, both the displacements and stresses are expected to significantly increase too resulting in larger degradation and earlier failure [4], [5]. It is unclear whether strong weather events, through strong and complex wind flow patterns such as turbulence or stall, are actually able to produce loading frequencies on the order of the natural frequency resulting in unusually large responses. Furthermore, the encapsulant might behave as a viscoelastic damper effectively limiting the strain rate at such elevated loading frequencies. In the laboratory, typical loading frequencies based on standards (0.015-0.15Hz) are out of range of module natural frequencies (10-100Hz). It is worth noting that as modules get thinner or less stiff, their natural frequencies decrease. In this work, we are interested in looking at the effect of using loading frequencies between 0.15 to 1Hz on power degradation.

II. EXPERIMENT

We began this experiment with the selection of 8 standard multicrystalline silicon 60-cell modules with a 3 busbar configuration of the same make and model (Type A). Out of these 8 modules selected, 3 had been previously loaded with an 800 Pa front side static load and the other 5 with a 1200 Pa static load. All 8 underwent 50 thermal cycles (TC50) as well as 10 humidity-freeze cycles (HF10).

Next, we loaded all 8 modules with a 2400 Pa static load to normalize the density of cracks producing a comparable %power loss among all 8 modules. This also allowed for the creation of new cracks to be opened during the cyclic loading phase of the experiment. We took EL/IV snapshots every 400 Pa, from 0 Pa up to 2400 Pa. After loading, we took EL/IV data at 0 Pa and 1000 Pa to observe the new cracks in a partially closed and open state, respectively. Applying the 1000 Pa puts the cells into tensile stress, thus propping open some cracks to better measure the potential impact when these cracks do degrade and permanently open up [2].

After that, we split modules into 4 groups, 2 per group. On the first group, we performed the standard cyclic load test

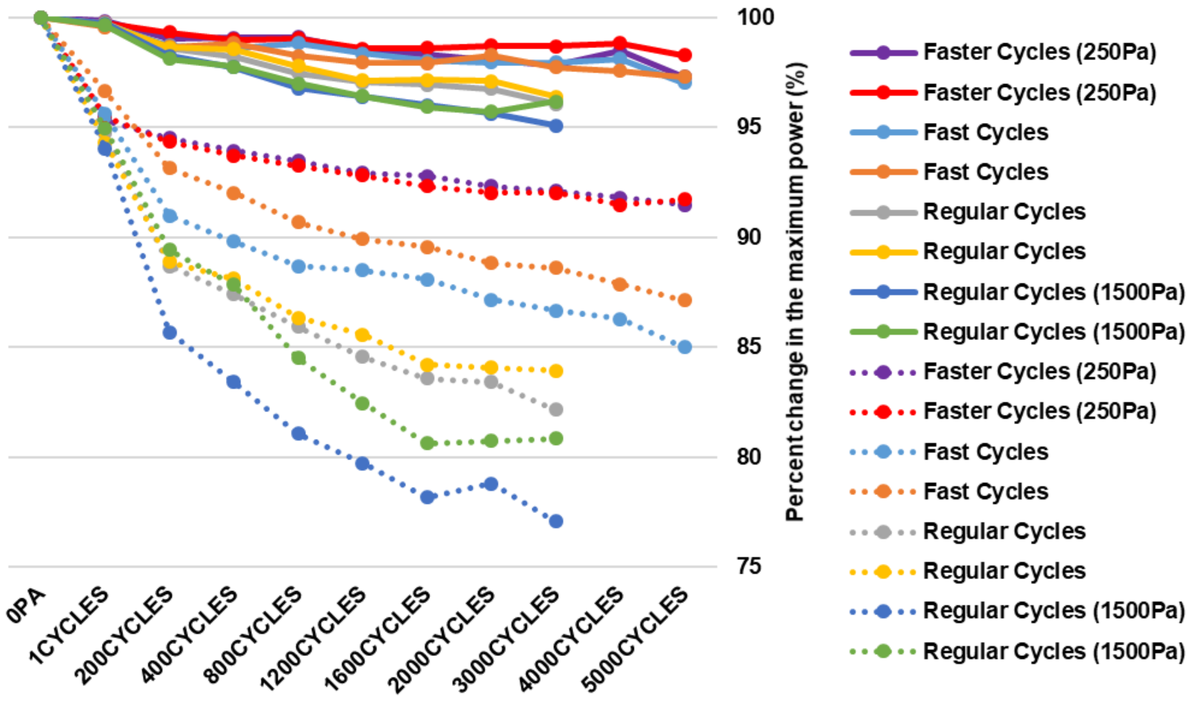

Fig. 1 Percent change in the maximum power as a function of number of cycles measured while at rest or **0Pa** (solid curves) or under a **1000Pa** load (dotted curves) shown for 2 regular cycles (1000Pa and 1500Pa load amplitudes), 1 fast cycle (1000Pa load amplitude), and 1 even faster cycle (250Pa load amplitude)

consisting of a ±1000 Pa load at 8.6 sec/cycle (7 cycles/min) for 3000 cycles. On the second group, we performed a faster cyclic load test using a ±1000Pa load at 4.6 sec/cycle (13 cycles/min) for 3000+ cycles. On the third group, we performed a high-pressure cyclic load test with a ±1500 Pa load at 8.6 sec/cycle for 3000 cycles. On the fourth and last group, we performed a low-pressure cyclic load test involving a ±250 Pa load at 2.6 sec/cycle (23 cycles/min) for 10,000 cycles. Again, we took EL/IV snapshots every 200 cycles (400 for the low-pressure cyclic load test) at 0 Pa and under load at 1000 Pa. Further discussion on the 250Pa group results can be found in [6]

III. RESULTS

Fig 1 clearly shows trends in the maximum power degradation for each group whether snapshots are taken at 0 Pa or 1000 Pa where some cracks are forced partially or fully open. After 3000 cycles, when the modules are at rest (0Pa), the standard cyclic load test showed 3.5-4% power degradation, the faster cyclic load test 2-2.5%, and the high pressure 1500Pa cyclic load test 4.5-5%, and the low pressure 250Pa cyclic load test 1-2%. The results for the high pressure and low pressure cyclic load tests were consistent with our expectations. We were initially surprised to observe that the faster cyclic load test, which was only double the frequency of the standard cyclic load test and an identical load, results in less power degradation. At the very least, we expected a faster convergence to power degradation levels similar to the standard cyclic loading case.

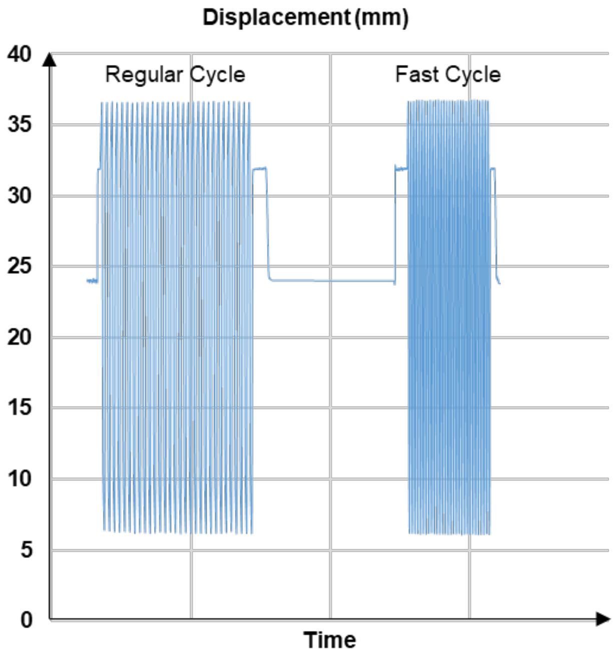

Fig. 2 Displacement for “regular” and “fast” cyclic load tests

We confirm that the displacement experienced in both of these cases is the same. The measured displacements are shown in Fig 2. From that figure, we can clearly see that the fast cycle performed the same number of cycles in half of the time.

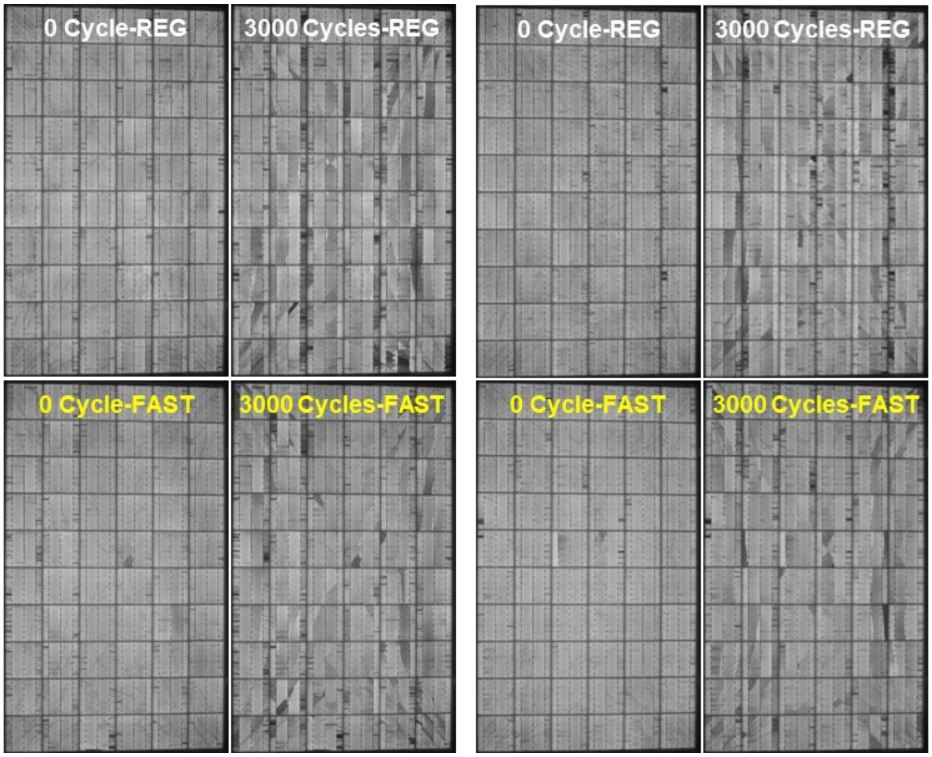

Fig. 3 **Top Left:** Side by side EL images of a type A module taken at rest before and after 3000 regular cycles, **Top Right:** Side by side EL images of another type A module taken at rest before and after 3000 regular cycles, **Bottom Left:** Side by side EL images of a third type A module taken at rest before and after 3000 fast cycles, **Bottom Right:** Side by side EL images of a fourth type A module taken at rest before and after 3000 fast cycles.

EL images were taken at various stages of the cyclic loading for each of the cases presented in this paper. Fig 3 (top and white) shows EL images for the regular cyclic load test from 0 to 3000 cycles while Fig 3 (bottom and yellow) shows EL images for the fast cyclic load for an identical number of cycles. The EL images consistently indicate (1) a random darkening or brightening of cracked areas from one cycle to another, although the general tendency shows an overall darkening of cracked areas with increased cycles, and (2) a darkening of fingers at cells edges. This latter is especially noticeable for the regular cyclic load results in Fig 3 (EL images on top). In general, EL images for the regular cyclic load tests show more darkening than the EL images with the fast cyclic load results for a given number of cycles, which agrees with the power degradation data.

In order to confirm the results, we conducted another experiment, this time using 2 standard monocrystalline silicon 60-cell modules with a 4-busbar configuration of a different make and model (Type B). Unlike the initial set of 8 modules, these did not undergo 50 thermal cycles (TC50) and 10 humidity-freeze cycles (HF10). These were loaded with a 5400 Pa static load in order to create enough cracks to study power degradation. We took EL/IV snapshots while applying the static load every 400 Pa, and every 200 to 400 cycles afterward during

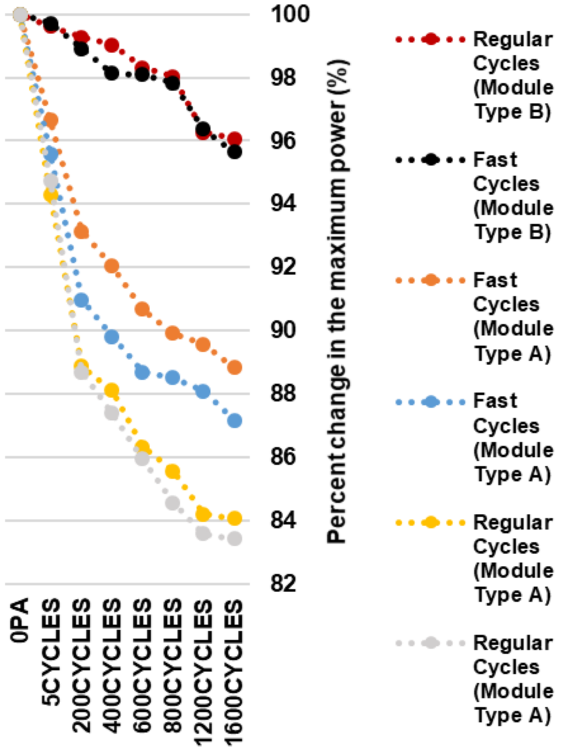

Fig. 4 Percent change in the maximum power as a function of number of cycles measured while subjected to a **1000Pa** load

cyclic loading. During cyclic loading, the EL/IV snapshots were taken at rest (0 Pa) and under a 1000 Pa.

The power degradation as a function of the number of cycles is shown in Fig 4 under a 1000Pa load in order to prop open cracks. Unlike the previous experiment where fast cyclic load test (orange and blue curves) clearly experienced less power loss than the regular cyclic load test (yellow and gray curves), these latest results indicates that the regular (red) and fast (black) cyclic load tests produce identical levels of power degradation. Also worth mentioning is that the overall magnitude of the degradation is much less that what we originally observed in the other modules (~4% versus 11-17%).

Fig 5 (top) shows EL images of a type B module before and after 1600 regular cycles while Fig 5 (bottom) shows EL images of another type B module before and after 1600 fast cycles. There are few noticeable differences between type A and type B modules. Metal fingers did not get disconnected at the edges of the cells in type B modules. Additionally, cells in type B modules needed a much heavier load to crack.

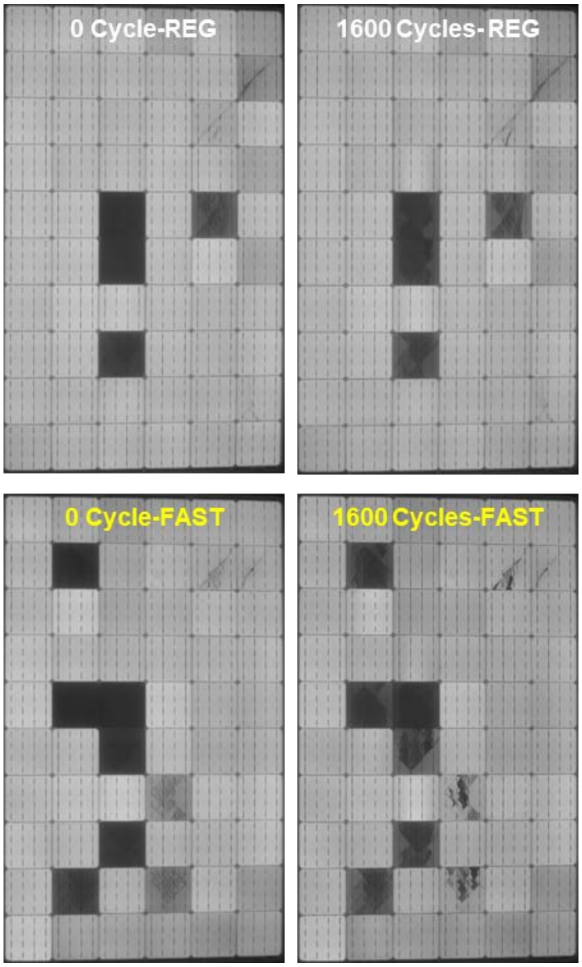

Fig. 5 **Top:** Side by side EL images of a type B module taken at rest before and after 1600 regular cycles, **Bottom:** Side by side EL images of another type B module taken at rest before and after 1600 fast cycles

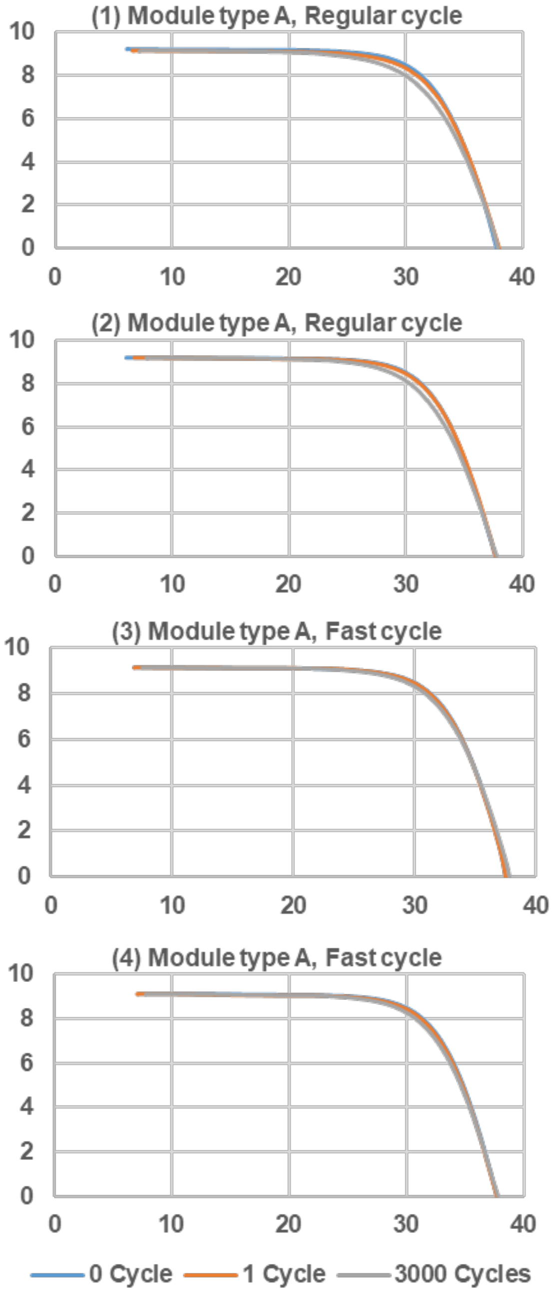

Fig. 6 Evolution of the IV curve from 0 cycle (blue), then 1 cycle (orange), to 3000 cycles (grey) when different type A modules are subjected to a regular cyclic load test in (1) and (2) or a fast cyclic load test in (3) and (4).

IV. ANALYSIS

These experiments indicate that including 50 thermal cycles (TC50) and 10 humidity-freeze cycles (HF10) in addition to a static load followed by cyclic loading is having a greater effect on the electrical properties of PV modules as seen in the darkening of fingers at edges of cells (Fig 3) but also in the magnitudes of the power degradation in Fig 4.

What's unexpected though is the clear dependence of the power degradation on the rate of cyclic loading. In Fig 6, the evolution of the I-V curves confirms the dependence on the rate of cyclic loading and points toward greater losses in the series resistance for regular cyclic load versus fast cyclic loading after 3000 cycles. Therefore, to understand why a faster cyclic load would result in less power degradation for a given load magnitude, it is useful to consider the materials in direct contact with the solar cells and their dependence on strain rates. Any time-dependent stress or strain produced from an external force on the module will have to be transferred to the solar cells through these stress or strain rate dependent materials.

First, both the solder and the copper from the ribbon are known to be viscoplastic materials [7,8]; their behaviors vary based on strain rate, temperature, strain rate history, strain hardening, and the dynamic recovery restoration process. Thermal cycling has been reported to induce cyclic axial deformation and causes the busbars to experience plasticity and hysteretic energy dissipation [9]. It is unclear whether the TC50/HF10 steps alone influenced the solder bonds and busbars to become more sensitive to various strain rates during the subsequent cyclic loading contributing to the observed results in the initial experiment. This cannot be asserted for certain since the modules used in the second experiment were of different make and models.

Second, the encapsulant is EVA (ethylene vinyl acetate). EVA is a viscoelastic copolymer with mechanical properties also dependent on strain rate and temperature in addition to the level of crosslinking. Furthermore, it was recently reported that for solar cells encapsulated in EVA, cracks can propagate during cyclic bending with a phenomenon analogous to fatigue under certain conditions [10]. Also, it is common for polymers that damping increases with faster loading. However, it is unlikely that the encapsulant can effectively dampen the load transferred to the solar cells as the loading frequency doubled for the faster cyclic load test, leading to less power degradation. Otherwise, the power degradation curves from second experiment (red and black curves in Fig 4) would have had different trajectories.

IV. CONCLUSION

This experiment confirmed that it is possible to obtain comparable damage from 3000 cycles of the standard cyclic load test with 400 to 800 cycles of the high pressure cyclic load test. On the other hand, applying the cyclic load faster for a given load actually results in less power degradation when 50 thermal cycles (TC50) and 10 humidity-freeze cycles (HF10) in addition to a static load are performed first as opposed to just a static load alone. The actual mechanism causing this discrepancy in the power degradation is unknown. Further investigation is needed.

IV. ACKNOWLEDGEMENTS

This material is based upon work supported in part by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, in the Solar Energy Technologies Program, under Award Number DE-EE0008152.

REFERENCES

[1] D. Wang and C. G. Wei, "An Introduction to Cyclic Load Test on Photovoltaic Modules," *Key Eng. Mater.*, vol. 726, pp. 13–17, 2017.

[2] E. J. Schneller, A. M. Gabor, J. Lincoln, R. Janoch, A. Anselmo, J. Walters and H. Seigneur, "Evaluating Solar Cell Fracture as a Function of Module Mechanical Loading Conditions," 44th IEEE Photovoltaic Specialist Conference, Washington D.C., June 25-30, 2017.

[3] J. Lincoln, A. M. Gabor, E. J. Schneller, H. Seigneur, J. Walters, R. Janoch, A. Anselmo, V. Huayamave, W. Schoenfeld, "Forecasting environmental degradation power loss in solar panels with a predictive crack opening test," 44th IEEE Photovoltaic Specialist Conference, Washington D.C., June 25-30, 2017.

[4] M. Assmus, S. Jack, K.-A. Weiss, and M. Koehl, "Measurement and simulation of vibrations of PV-modules induced by cyclic mechanical loads," *Prog. Photovolt. Res. Appl.*, vol. 19, no. 6, pp. 688–694, Sep. 2011.

[5] J. Dong, H. Yang, X. Lu, H. Zhang, and J. Peng, "Comparative Study on Static and Cyclic Analyses of an Ultra-thin Double-Glazing PV Module Based on FEM," *Energy Procedia*, vol. 75, pp. 343–348, Aug. 2015.

[6] H. Seigneur, E. J. Schneller, J. Lincoln, A. M. Gabor, "Cyclic Mechanical Loading of Solar Panels – A Field Experiment," 7th World Conference on Photovoltaic Energy Conversion, Waikoloa Hawaii, June 10-15, 2018.

[7] Y. H. Kwon, H. S. Bang, H.S. Bang,"Viscoelasticity Behavior of a Solder Joint on a Drilled Cu Pillar Bump Under Thermal Cycling Using FEA", *Journal of Elec Materi*al (2017) 46: 833.

[8] S. R. Bodner, A. A. Merzer, "Viscoplastic Constitutive Equations for Copper With Strain Rate History and Temperature Effects", *ASME. J. Eng. Mater. Technol.* 1978;100(4):388-394.

[9] C. Borri, M. Gagliardi, M. Paggi, "Fatigue crack growth in Silicon solar cells and hysteretic behaviour of busbars", *Solar Energy Materials and Solar Cells*, vol. 181, p. 21-29, 2018.

[10] M. Paggi, I. Berardone, A. Infuso, M. Corrado, "Fatigue degradation and electric recovery in Silicon solar cells embedded in photovoltaic modules", *Scientific Reports*, vol. 4, 4506, 2014.