The Impact of Cracked Solar Cells on Solar Panel Energy Delivery

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***Abstract* — Solar panel degradation is usually assessed by the change in power at standard testing conditions (STC). However, some degradation mechanisms have shunting or recombination characteristics which have the potential to reduce performance at low irradiances significantly more than at 1-Sun conditions. We present data at both the single cell coupon level and at the module level that demonstrate this effect with cracked cells, where the effect scales with the total length of the cracks. The effect is present even for modules with tightly closed cells where the metallization is continuous across the cracks and no dark areas are seen in the electroluminescence (EL) images. Depending on the system geographic location, mounting angles, the time of year, and the clipping characteristics, the daily energy delivery of a system can depend quite strongly on the module performance at low irradiances. We show through simulations that energy delivery may degrade significantly more than P_{max} with damage from cracked cells. Since electricity generated at lower irradiances often has more value than electricity generated at high irradiances, the impact on system revenue may be even larger. We conclude that the degradation from accelerated testing and field exposure should be assessed not just at an irradiance of 1-Sun but also at lower values as well.**

***Keyword* — Electroluminescence, Photovoltaic cells, Power system stability, Solar Panels, Stress, Energy Delivery**

I. Introduction

The PV industry is highly sensitive to the performance of solar panels at Standard Testing Conditions (STC). These conditions correspond to the performance at a temperature of 25°C and an irradiance of 1-Sun (1000 W/m^2), and the term P_{max} generally refers to the maximum power point at STC. Any particular measurement will occur at different temperatures and irradiances, but well-developed equations have been developed to correct each point on the *I-V* curve back exactly to STC conditions [1]. Indoor measurements are generally quite close to the STC conditions, while outdoor measurements are often performed at quite different conditions with larger corrections needed. The selling prices of solar panels are determined by these P_{max} values, and the passing of module certification tests and warranty violations are based on this P_{max} degradation.

In contrast, the economics of system revenues depend on energy delivery over the course of years. Much of the time that a system is feeding electricity into the grid occurs at irradiances significantly lower than 1-Sun, and as PV penetration grows, the value of the electrons generated at the lower irradiances grows as well. Recognizing this, solar panel specification sheets and PAN files show the performance of new panels at lower irradiances. The problem we are addressing in this paper is that degraded panels may degrade quite differently at low irradiances than at 1-Sun, and that this effect is largely ignored in the literature and can have large economic impacts.

Some degradation modes have shunt-like characteristics or low diode quality characteristics that change the slope of the *I-V* curve in the direction of I_{SC} toward P_{max}. As is seen in Fig. 1, a particular level of shunting at a low irradiance can cause a much higher relative percentage degradation in P_{max} than if that same level of shunting occurs at a high irradiance.

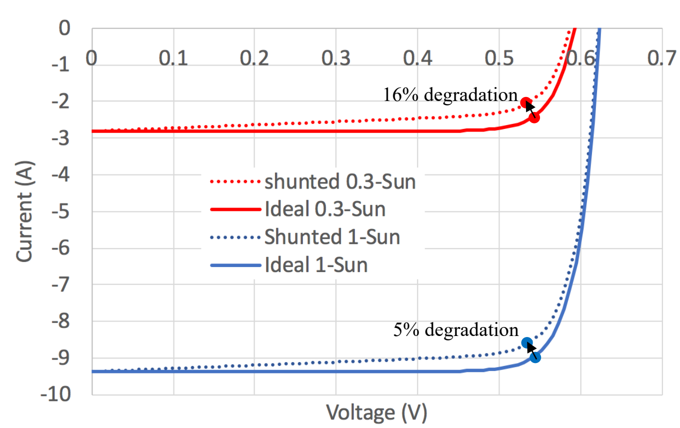

Fig. 1. *I-V* curve simulations of a cell at 1-Sun and 0.3-Sun irradiances for a cell with no shunting and a cell with shunting. The shunting causes a higher relative degradation in P_{max} at low irradiance.

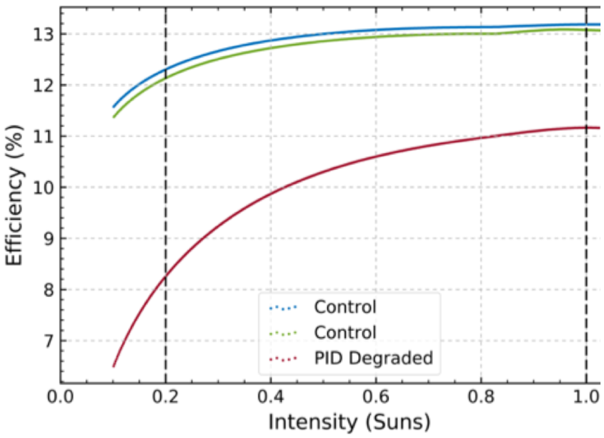

Fig. 2. Module efficiency vs irradiance for undegraded and PID affected modules, taken from [2].

One degradation mode that has shunt-like characteristics is Potential Induced Degradation (PID). Schneller et. al. [2] showed the irradiance-dependent behavior of PID affected modules as is shown in Fig. 2. At 1-Sun the PID affected module has degraded by ~14.5% relative, but at 0.2-Sun it has degraded by ~32% relative. Projecting future energy delivery of a PID-affected system based on 1-Sun values could significantly overestimate future revenues. The plot of module efficiency vs irradiance is particularly useful for studying these irradiance dependent effects, and such data is generated automatically using the FMT-500 flash I-V tester from Sinton Instruments.

In this paper we use EL imaging and Sinton Instruments *I-V* testing to study such irradiance dependent degradation for different types solar cell cracking.

II. Degradation of Single Cell Coupons

Prior to studying entire modules, we first look at the effects of cracking on individual cells. We soldered interconnect wires on the front and back sides of 156mm monocrystalline solar cells and then encapsulated them within the structure 3.2mm-glass/EVA/cell/EVA/polymer backsheet to form individual cell coupons. We then applied a front side load to several of the coupons as we describe elsewhere [3] until the cells fractured. Fig. 3 shows the EL images of 3 of the coupons biased near the -I_{SC} point. One cell is uncracked (Good), another shows a moderate to high level of cracking (Cracked), and the last shows very high level of cracking (Badly Cracked). Note that most of these cracks are of the "closed" variety determined by the metallization being continuous across the cracks. The degradation is largely linked to recombination and shunting along the cracks rather than due to lost active area.

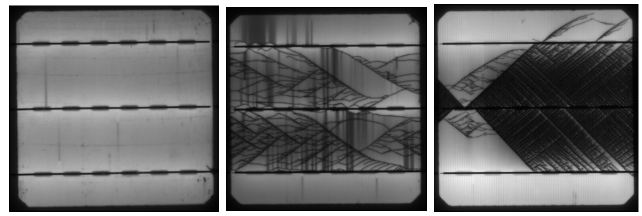

Fig. 3. EL images of 3 coupons showing Good (left), Cracked (middle) and Badly Cracked (right) cells.

Table I. Cell coupon efficiency vs irradiance and cracking level

Cell	Eff @1Sun	Eff @ 0.4Sun	rel. % diff	Eff @ 0.2Sun	rel. % diff
Good	18.7%	18.5%	-1.0%	17.9%	-3.9%
Cracked	15.7%	14.7%	-6.7%	13.2%	-15.9%
Badly Cracked	11.8%	10.0%	-15.4%	8.3%	-29.9%

Table I shows the cell efficiency as measured on the I-V tester at irradiances of 1-Sun, 0.4-Suns, and 0.2-Suns. The higher the level of cell cracking, the worse the 1-Sun performance, but notably, the performance at lower irradiances drops off much more steeply for the cracked cells than is the case for the Good cell. At 0.2-Sun, the Good cell is only down ~ 4% relative, while the Badly Cracked cell is down ~30% from an already low level at 1-Sun. The degradation at low irradiances appears to be strongly correlated to the total length of cracks in the cell.

III. Degradation of Modules

In order to study the effect of cracking vs irradiance on modules, we took EL and *I-V* measurements both before and after loading on the *LoadSpot* mechanical load tester from BrightSpot Automation, as we have described previously [3-6]. Fig. 4 shows EL images captured at the -I_{SC} point for a 4-busbar multicrystalline module. The image prior to loading shows no cracks, while the image after frontside loading to 5400 Pa shows extensive cell cracking. After applying 200 standard cycles of +/-1000 Pa, several of the cracks have opened up, leading to darker isolated regions.

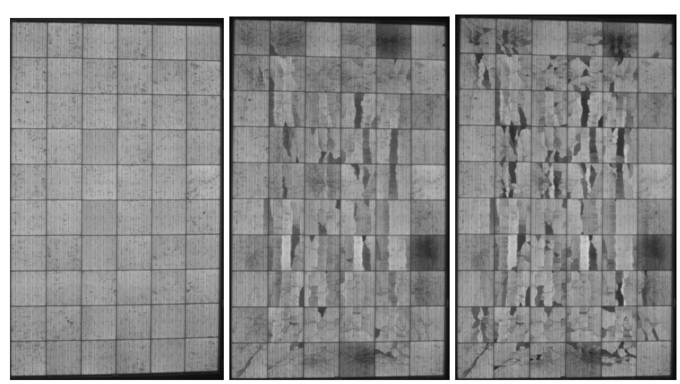

Fig. 4. EL images of a module before loading (left), after loading to 5400 Pa (middle), and after 200 cycles of +/-1000 Pa (right).

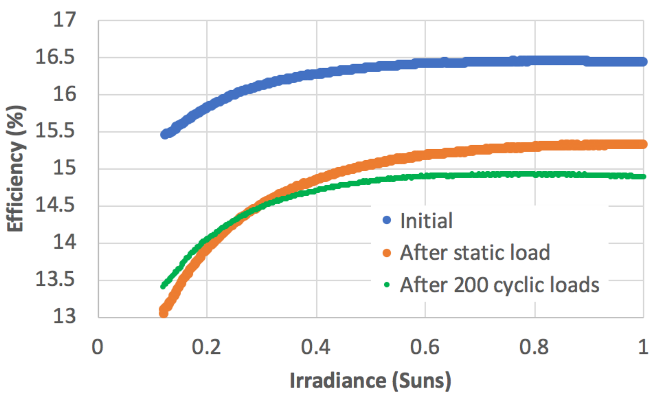

Fig. 5. Efficiency vs irradiance for the module states shown in Fig. 4.

Fig. 5 shows the module efficiency vs irradiance for the 3 cases. As with the single cell coupons, after loading and crack formation, the module has a much stronger falloff in efficiency as irradiance is decreased than it did before loading. The undamaged module falls off 3.9% at 0.2-Suns, while the loaded module falls off 9.2%. Interestingly, after cyclic loading, the 1-Sun efficiency drops still further, but the falloff is less strong at lower irradiances such that the module actually has a higher efficiency below 0.2-Suns than before cycling, with a falloff of only 5.6% at 0.2-Suns. This might be explained in that cyclic loading opened up some cracks such that some regions of the cells that had internal cracks were effectively removed from the circuit. With a lower total length of cracks remaining in active areas of the cells, the shunting/recombination is lower, leading to a less sharp falloff with decreasing irradiance, although the reduced active area reduces the efficiency at higher irradiances.

IV. Energy Delivery

The annual energy delivery of a PV system depends on many factors, including the matrix of module power vs irradiance vs temperature, the geographic location and weather, the mounting angles, the local albedo, shading from neighboring modules or objects, soiling, inverter type, whether the system is tracking or static, whether storage is integrated, and whether the system is clipped to a certain maximum system power. The system revenue is very strongly linked to the energy delivery, but with high PV penetration on the grid, the value of the energy produced during low irradiance times of the day may be higher than during the high irradiance periods. Overestimating the performance at low irradiances by focusing on high irradiance data could result in significant revenue shortfalls.

To explore the impact of cell cracking on energy delivery, we took the "Initial" and "After static load" efficiency vs irradiance curves from Fig. 5, and applied parametric and sensitivity analysis using NREL's System Advisor Model (SAM) [7]. The analysis was performed using module parameters from the specification sheet (namely, V_{MP}, V_{OC}, P_{max} temperature correction coefficient, module area), assuming open rack installation for glass/cell/polymer sheet module configuration, and the remaining inputs were left default. A module that exhibits a strong falloff in efficiency at low irradiances will perform worse in less sunny locations, and thus we chose to explore both a sunny location (Phoenix, AZ) as well as a northern cloudy location (Seattle, WA).

Efficiencies below 0.2-Sun are expected to be dramatically lower than at 0.2-Sun or above for modules with substantial cracks, as shown by the trends in the efficiency vs irradiance curves in Figs. 2 and 5. The nonlinear trend of the efficiency suggests an even more severe efficiency reduction at below 0.2-Sun. However, in our irradiance-dependent analysis, we pulled discrete points off the graph in Fig. 5 (1.0, 0.8, 0.6, 0.4, 0.2 Suns). For irradiances < 0.2 Sun, the model used the 0.2 Sun data point, and thus overestimated energy delivery at the lowest irradiances.

For each location, the analysis was performed at 1) a constant efficiency (1-Sun peak) and 2) using the intensity-dependent efficiency as discussed above. For the static loaded module, Fig. 6 shows that there is a 1.4% error between the 1-Sun and intensity-dependent performance for the sunny condition. In contrast, there is a more severe 2.6% error between the 1-Sun and intensity-dependent performance for the cloudy location. For the baseline condition (before loading), these percent errors are much smaller at 0.4% and 0.9% for the sunny and cloudy locations, respectively.

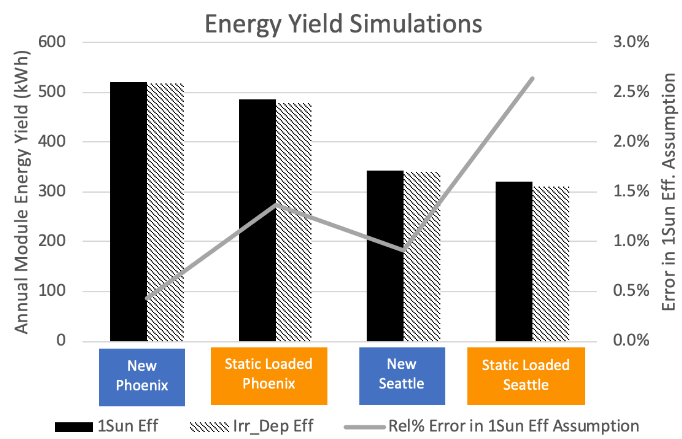

Fig. 6. Using NREL's SAM [7], the energy yield for a module before and after cracking is simulated 1) at constant efficiency (1-Sun peak) and 2) using irradiance-dependent efficiency. The simulations were run using meteorological data from Phoenix, AZ (sunny) and Seattle, WA (cloudy).

VI. Conclusions

We have demonstrated how predicting a degraded PV system performance based on 1-Sun measurements of power can overestimate system revenue due to the deterioration in module efficiency at lower irradiances in cases where the degradation has shunting/recombination characteristics. Specifically, we have shown how a module with many cracked cells has a worse performance at low irradiances, and through simulations we have shown how the impact on system energy delivery is more significant in a less sunny northern location than a sunnier southern location. Cracks in solar cells are often tightly closed with little degradation in STC measurements and with no dark areas in EL images. This may give a false sense of security, as the low-irradiance performance may have degraded significantly more.

While PAN files containing a matrix of module power vs irradiance and temperature are commonly used in energy delivery simulations, these PAN files are always generated using new module data. Degraded modules are usually measured only at STC for insight on their performance. For greater accuracy in energy delivery predictions, we encourage the industry to start measuring the power of aged modules over a range of irradiances and to generate PAN files from modules which have undergone a variety of typical degradation mechanisms. A good place to start would be to perform these tests at certification and testing labs after the modules have undergone the various IEC 61215 test legs. By using such data to simulate degradation in energy delivery at a few standardized worldwide installation locations as figures of merit, module buyers can be empowered with more relevant and accurate data concerning future system energy delivery. This will encourage the adoption of module technologies with superior lifetime energy deliveries.

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number DE-EE0008152.

References

[1] IEC 60891 Edition 2.0, 2009-12, "Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics"

[2] E. J. Schneller et. al., ""Evaluating Module Performance and Reliability Utilizing Multi-Irradiance I-V Measurements, "NREL PV Reliability Workshop 2017.

[3] M.W. Rowell, S.G. Daroczi, D.W.J. Harwood, A.M. Gabor, "The Effect of Laminate Construction and Temperature Cycling on the Fracture Strength and Performance of Encapsulated Solar Cells" *45th IEEE PVSC*, pp 3927-3931, 2018

[4] A. M. Gabor, R. Janoch, A. Anselmo, J. L. Lincoln, H. Seigneur, and C. Honeker, "Mechanical load testing of solar panels - Beyond certification testing," in *IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 2016, pp. 3574-3579.

[5] E. J. Schneller, A. M. Gabor, J. L. Lincoln, R. Janoch, A. Anselmo, J. Walters, and H. Seigneur, "Evaluating Solar Cell Fracture as a Function of Module Mechanical Loading Conditions" in *IEEE 44th Photovoltaic Specialists Conference (PVSC)*, 2017.

[6] E. J. Schneller, H. Seigneur, J. Lincoln, A. M. Gabor, "The Impact of Cold Temperature Exposure in Mechanical Durability Testing of PV Modules" in *IEEE 46th Photovoltaic Specialists Conference (PVSC)*, 2019.

[7] N. Blair, N. DiOrio, J. Freeman, P. Gilman, S. Janzou, T. Neises, and M. Wagner. 2018. System Advisor Model (SAM) General Description (Version 2017.9.5). Golden, CO: National Renewable Energy Laboratory. NREL/ TP-6A20-70414. https://www.nrel.gov/docs/fy18osti/70414.pdf