Detecting cell cracks and other PV module failures with UV fluorescence

Module failure | Defective modules causing power losses in PV systems need to be easily detected with a rapid and cost-effective inspection method. Researchers from Institute for Solar Energy Research in Hamelin (ISFH) explain how UV fluorescence of module encapsulation polymers is used for the fast detection of module failures under daylight conditions without disconnection, allowing the inspection of up to 200 modules in an hour during daytime

Finding damaged modules impairing the PV system performance: a cost-intensive issue

Detecting PV module failures to determine the origin of a power loss in an operating PV system is a key issue for the sustainability of that system. To keep operating costs as low as possible the diagnostic methods need to be rapid, non-destructive, allow for a flexible service time and no shutdown during the inspection. Whereas single string I-V curve automated monitoring allows for the localisation of a damaged array, a further technique needs to be employed to identify the module(s) causing a possible power loss.

Commonplace techniques for the detection of PV module damage are the infrared thermography (IRT) and the electroluminescence method (EL). Electroluminescence is usually employed in the laboratory and requires the electrification of a PV module with a current at half or equal to the nominal short circuit current (Isc), which for usual commercial modules implies using a power source on the field with a current output of ~8A @ ~30V per PV module. The EL image is captured in the range of 1000nm to 1200nm with a camera [1]. For the use in the field, whole strings of modules are electrified at once to reduce the rewiring effort, thus requiring a more powerful power source. The capture of electroluminescence images in the field is usually done overnight, and recent developments in unmanned aerial vehicles (UAV) allow for a fast capture of the arrays [2,3]. The use of an adequate camera such as an InGaAs detector [3] opens the potential to capture electroluminescence images during the day in the field.

The throughput of this method is mostly limited by the rewiring effort. However electroluminescence images reveal the current path in the solar cells and thus allow for the detection of cracks in the solar cells and an estimation of the criticality of them. Furthermore, EL reveals interrupted cell interconnection ribbons, short circuits and cell shunts. The infrared thermography reveals temperature inhomogeneity and allows for the detection of hotspots caused by shunts as well as cracked cells or short-circuited bypass diodes [4]. This technique is easier to implement than EL as it does neither require the disconnection of the modules from the rest of the PV system, nor their electrification with an external power source. Nevertheless, the modules need to be in operation under a sufficient solar irradiation (>600 w/μ^2) in order to induce detectable thermal features.

Figure 1. Fluorescence outdoor inspection system (FLOIS) in operation on a PV generator

Principle of UV fluorescence measurements of EVA

The UV fluorescence of ethylene vinylacetate (EVA) used as pottant in PV modules has been investigated as a phenomenon parallel to the degradation of EVA polymer and its additives. The fluorophores' excitation wavelength lies in the near UV range between 300nm and 400nm. The emission spectrum is in the visible range, mainly between 400nm and 600nm. It has been shown that the excitation as well as the emission wavelength increase with the duration of the weathering of a module [5]. In the presence of oxygen and light, the fluorophores are degraded. During field exposure the appearance of fluorophores in the modules is hindered in places where oxygen can diffuse through. Typically oxygen diffuses through the backsheet and through the EVA between the cells. Thus the fluorophores accumulate only in the material encapsulated between the silicon solar cells and the glass. A potential application for the detection of cell cracks has been mentioned by King [6], and used later in the lab by Schlothauer [7] and on a larger scale PV plant by Köntges [8]. When a cell is cracked, oxygen can diffuse through the crack and reach the material in front of the cell, leading to an extinction of the fluorescence on the crack surroundings. The degradation process of the encapsulation material leading to the formation of fluorescent compounds is accelerated by higher temperatures.

UV fluorescence inspection system

We built at ISFH a mobile UV fluorescence outdoor inspection system (FLOIS) consisting of a lightweight aluminum chassis covered with an opaque cloth. The chassis can be dismounted for transport and is adjustable to the size of the common commercial 60-cells modules. The top of the chassis is equipped with UV light emitting diodes (LEDs) and a digital camera. The images are processed and saved by a laptop contained in a backpack along with a lithium battery which supplies the UV LEDs and the camera.

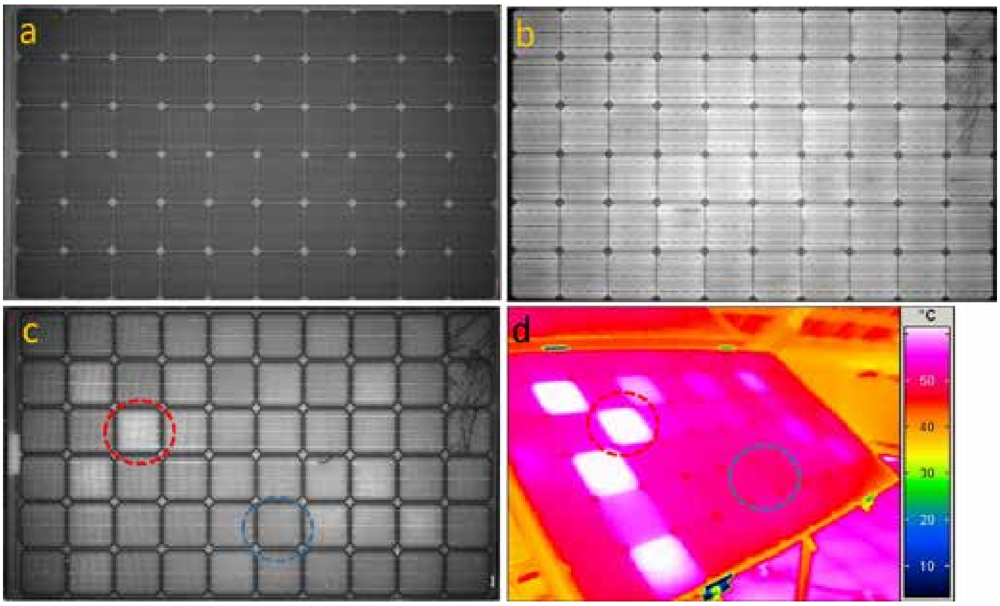

Figure 2. Fluorescence (a) and electroluminescence (b) images of a transport-damaged new PV module before sun exposure. Fluorescence image (c) of the module after 70 days of sun exposure in short-circuit and infrared thermography image (d) of the module under an irradiance of 780W/m² [9]

To perform a measurement the chassis of the inspection tool is simply laid down on the tested PV module for the duration necessary to capture the dark field image and the fluorescence image – usually about five seconds, depending on the integration time chosen by the operator. The dark field image is subtracted from the image taken under illumination in order to suppress the noise generated by the light ingress from the backsheet and from the module edges in the eventuality of an imprecise positioning of the hood. The operator triggers the measurement and checks the images in real-time with a smartphone attached to his forearm. As the fluorescence emission is in the blue-green wavelength range, only the blue and green channels of the pictures are processed. To reach the upper rows of PV modules on a rack system, the measurement device can be equipped with telescopic handles. An image of the device in operation is shown in Figure 1.

In the following, we show the application potential as well as the limitations of the UV fluorescence for the detection of module failures. We show how to interpret the features seen in the UV fluorescence images and compare them to the same features from the EL and IRT images.

UV fluorescence image features

We show here an example of the temperature dependence of the fluorophore formation in a module. Figure 2 shows (a) a fluorescence and (b) an electroluminescence image of a new module with three cracked cells. At this stage nearly no UV fluorescence is detectable (Figure 2a). Figure 2c shows the UV fluorescence image of the module after being installed outdoors in short-circuit mode for eleven weeks in summer.

After 70 days of exposure, the module accumulated a sun irradiation of about 360kWh/m². The fluorescence (Figures 2a and 2c) and electroluminescence (2b) images are taken in the lab at a temperature of 25°C. An IRT image is taken outdoors under a sun irradiance of 780W/m² at an ambient temperature of 28°C [9].

The first thing to note on the UV fluorescence image 2c is the typical black framing around the cell edges showing the fluorescence-quenching effect of oxygen diffusing through the backsheet and over the edges of the cells. Furthermore, the cracks in the cells on the upper right corner of Figure 2b and 2c also appear black on the fluorescence image due to the same quenching effect.

The comparison of the fluorescence image with the infrared thermography image of the module reveals that the encapsulating material shows a higher fluorescence intensity where the cell operating temperature is higher. To put this effect better in light, we show in Figure 3 the fluorescence intensity as function of the outdoor exposure duration of the two marked solar cells in the Figures 2c and 2d. During IR measurement, the cell rear side temperatures are measured by thermocouples to respectively 56°C and 65°C. The fluorescence intensity as function of accumulated global irradiation on the module (Figure 3) shows that the EVA material in the module contains fluorophores before it has been exposed to the sunlight. It is known that the lamination process of the module generates fluorophores in the EVA [10, 11]. This initial fluorescence is nevertheless rapidly degraded over the first days of exposure and the fluorescence intensity of the material over both cells increases again with time. After a day of exposure, it is already possible to see a color difference in the fluorescence emission

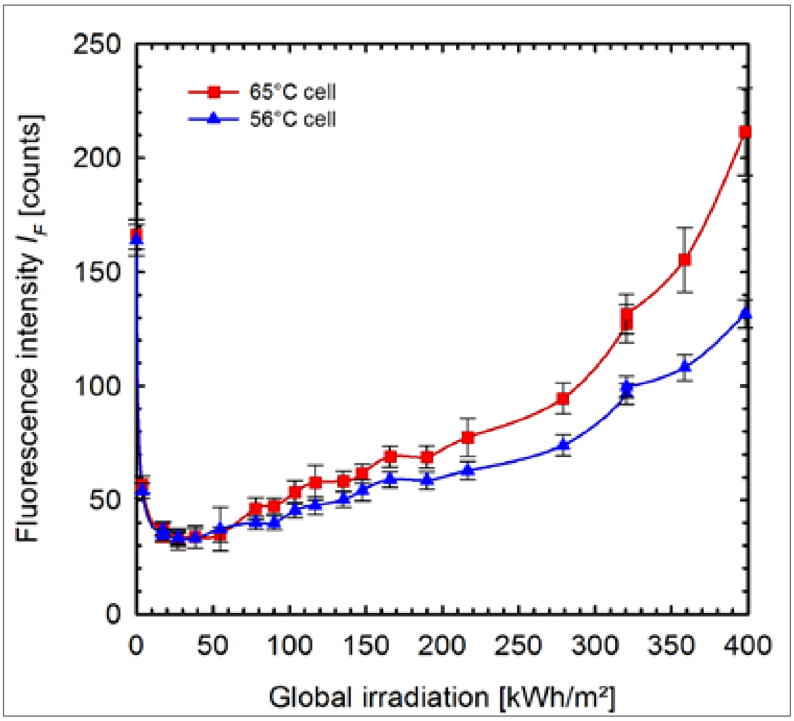

Figure 3. Fluorescence intensity over time measured on two solar cells with different operating temperatures. The lines are guides for the eye

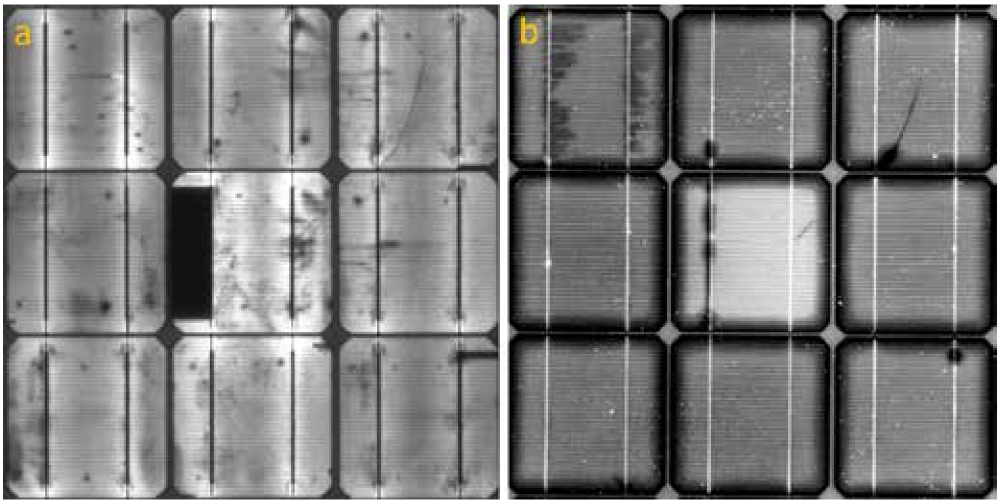

Figure 4. Electroluminescence (left) and UV-fluorescence (right) images of a PV module area showing a cell in which a quarter has been electrically isolated by a crack and which subsequently reaches a higher temperature in operation

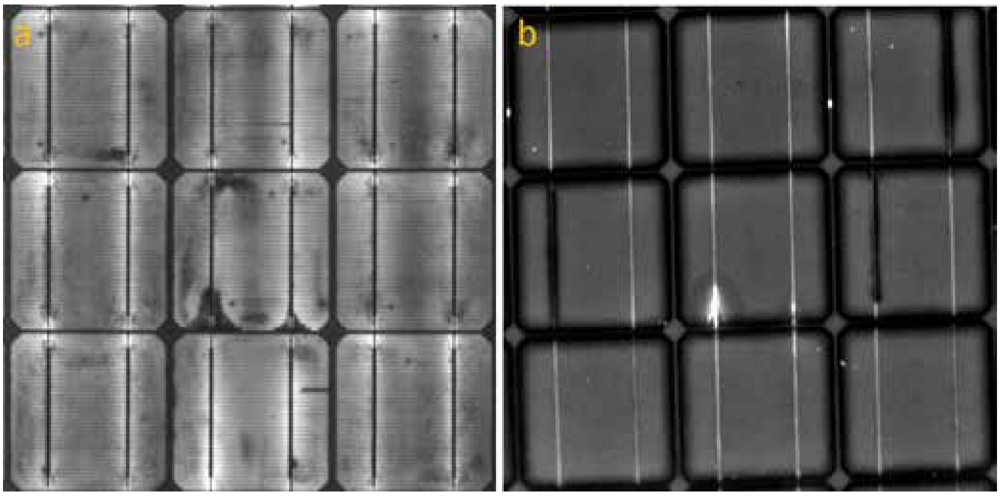

Figure 5. Electroluminescence (left) and UV-fluorescence (right) images of a PV module area with a cell showing damages correlated with a local overheating

between the cells with the human eye. After an irradiation of 360kWh/m^2 (70 days), the measured fluorescence emission is significantly more intense over the hotter cell.

The ability to detect the areas where the fluorophore formation is accelerated by an increased temperature allows one to detect several types of defects.

With this module coming directly out of the production, it is possible to discern the cracks caused during the transport or the handling of the module after 11 days of sun exposure (55kWh/m^2).

Not all cell cracks lead to a power loss but may potentially evolve to power-impairing damage. Electroluminescence is useful to detect cell cracks and determine if a crack is critical as EL allows one to see if a crack is electrically isolating a part of a cell. This information is not directly obtainable with the UV fluorescence technique. Nevertheless, in cases where the cell area disconnected by a crack is large enough to bring the cell to function in reverse bias mode and act as a power drain, the heat generated by the damaged cell results in a locally accelerated formation of fluorophores. Figure 4 shows (a) and EL and (b) an FL image of such a cell in a PV module. The EL image taken at Isc clearly reveals that one of the cracks electrically isolates a quarter of a cell. The corresponding fluorescence image shows that this cell shows an increased UV FL intensity. This cell is dissipating heat and therefore reveals the criticality of the crack.

Shunts in cells or short circuits causing hot spots in modules are also easily observable as shown in Figure 5, where cell damage seen on the EL image results in a bright local spot of fluorescence. A localised intense fluorescence spot is therefore an indicator of the presence of hotspots.

Occurrence of new cell cracks and comparison of cell crack age

New cracks generated after the installation of modules, caused for example by mechanical loads or shocks, may also be detected by UV fluorescence. We characterise the behavior of new cell cracks in a module by introducing new cracks. Before cracking the cells, the module has been exposed for four years to sunlight. Afterwards it is remounted on an outdoor test stand. Figure 6 shows a series of fluorescence images of the newly broken cell in the module at different sun irradiation levels.

The fluorescence along the fresh crack decreases with increasing global irradiation. Already after one day of outdoor exposure the fresh cracks are detectable, as the fluorescence decrease starts immediately. Nevertheless, the decrease rate of fluorescence intensity along these new cracks is low and after a three-month outdoor exposure (85kWh/m^2), it is still possible to distinguish between an older crack and a fresh crack.

Therefore, this feature can be used to detect new cell cracks caused by a hail storm. The module depicted in Figure 7 has been dismounted from a roof PV system that had been installed for 2.5 years in northern Germany. The system has been affected by a hailstorm eight weeks before the measurement, including some modules displaying glass breakage. A star-shaped crack can be seen on a cell (middle row, right) of this module, which evocates the typical breakage pattern due to a hail impact. On the fluorescence image (7b), this crack as well as some other cracks (bottom row, left) show only a partial extinction of fluorescence, while cracks on other cells appear as dark as the framing around the cells.

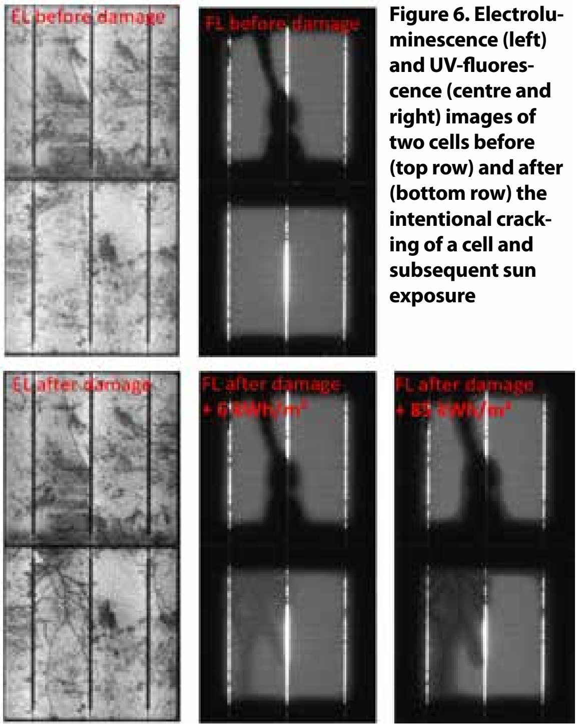

Figure 6. Electroluminescence (left) and UV-fluorescence (centre and right) images of two cells before (top row) and after (bottom row) the intentional cracking of a cell and subsequent sun exposure

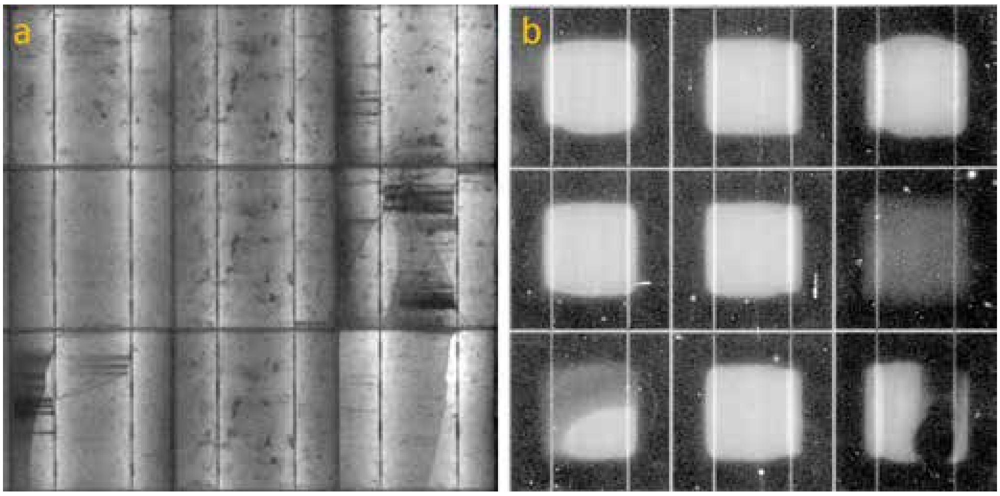

Figure 7. Electroluminescence (left) and UV-fluorescence (right) of a PV module eight weeks after a hailstorm and showing recent and older cracks

We can deduce from the partial extinction along the cracks that these cracks are caused by the hailstorm. We inspected another megawatt-scale field PV system in the same area five months after the hailstorm. It has shown that after this time period, the photobleaching of the fluorophores is so advanced that no contrast between newer and older cracks is measureable anymore. We can recommend the use of the UV fluorescence technique for the detection of damages due to a sudden event in a period of time between one week and six weeks after the suspected occurrence of damages. The timeframes we indicate here are deduced from our experience in the field in Germany in the summertime. For other regions, the local temperatures and irradiation may affect these estimates. The fluorescence in new modules as well as the quenching over new cracks will appear faster in hotter regions. In wintertime, the process will be slowed down due to the lower temperatures and irradiations.

Summary

UV fluorescence of EVA allows detecting cracks in new PV modules as soon as two weeks after their installation and the presence of hot cells three weeks after their installation. The method allows also to indirectly determine if a given crack is so critical that the concerned solar cell dissipates heat, leading to a power loss in the module. The fluorescence method is also able to reveal short circuits and hot spots.

Due to its rapidity, allowing a measurement throughput of up to 200 modules in an hour, this technique can be employed to large parts of a PV system to scan each module for defects. A subsequent electroluminescence measurement on modules with defects might be used to get more detailed information of the failure patterns on the fluorescence images. This technique has been experimented at ISFH with different module encapsulation materials such as several EVAs as well as with silicones.

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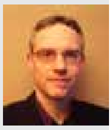

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