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Outdoor detection and visualization of hailstorm damages of photovoltaic plants



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ABSTRACT

Photovoltaic modules can experience damages of varying severity in the case of heavy hail storms. In the worst case, complete glass and solar cell breakage results in efficiency and security losses of the affected modules which therefore have to be replaced. However, there is a strong need to inspect the remaining modules directly in the field in order to assure no hidden damage. Three hail-affected photovoltaic plants in the south of Austria were investigated first with common standard methods like analysis of the plant monitoring data and thermography. Then, these plants were additionally investigated by novel non-destructive methods. With the aid of two innovative characterisation tools, outdoor electroluminescence and UV-fluorescence imaging, hail-induced damaging of solar cells can be detected even when the solar glass of the modules withstood the mechanical impact of the hailstorm and no damages are visible to the naked eye or well recognizable by thermography. The non-destructive, easy to handle and fast characterization technique UV-fluorescence imaging allows the detection and visualisation of hail induced cell damage. Modules showing partial cell breakage and/or micro cracks – as proven by outdoor electroluminescence measurements – and lead to a reduced electrical performance can be unequivocally identified.

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1. Introduction

Reliability and long term performance of Photovoltaic (PV) modules for warranted lifetimes of 20+ years with a total yield loss not exceeding 20% are a crucial request of the market to allow for increasing implementation of photovoltaic technology as strong part in the renewable energy mix.

Several test procedures like IEC61215 or IEC61730 exist to ensure high product quality of PV modules at the manufacturing site. One of the most frequently used methods in the laboratory and

for quality insurance in the module production line is electroluminescence imaging. Electroluminescence provides information on the uniformity of the current flow in individual solar cells and whole modules and allows for detecting cell-cracks and disruptions in the electric connection system comprising of busbars, cell connectors and junction box.

However, once the modules are installed at the PV plant, besides monitoring the generated electrical power over time only limited characterisation methods are available to verify the faultless performance of individual PV-modules directly in the field. The most frequently used inspection method in the field is Infrared (IR)-thermography with a portable camera which can detect thermal (e.g. hot spots or hot cells due to temporary shadowing or impurities) and some electrical failures like unconnected modules or strings or defective bypass diodes [1–4].

As several faults and defects can't be detected in the field by the well-established thermographic method, recently strong efforts

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were undertaken to develop innovative techniques like e.g. outdoor electroluminescence (EL) [5] and UV-fluorescence imaging [6–9] to provide PV-plant operators with a tool for improved non-destructive maintenance. Regular check-ups of the installed PV-modules appear necessary especially after extreme stress imposed by storm events, heavy snow loads or hail storms [10,11].

Although fluorescence effects of the aged and degraded polymeric PV-encapsulation materials were already detected by the group of Pern and Czanderna 20 years ago [12] only in the last years intensified interest to use this effect for a characterisation tool of weathered and aged PV-modules appeared. The characteristic fluorescence pattern of PV-modules obtained from the polymeric encapsulant upon irradiation with an ultraviolet (UV)-lamp contains manifold information connected with the (i) barrier properties of the backsheets used, (ii) degradation of the encapsulant, (iii) time and type of stress impact at the installation site and (iv) the integrity of the solar cells [13–15]. These effects and the fact that this method is fast, cheap and flexible allow UV-fluorescence imaging to be one of the most promising innovative inspection methods for installed PV-modules.

For the work presented, several PV-plants which experienced heavy hail storms were investigated. A decreased power-output after the stress event and numerous modules showing glass breakage were identified. After exchanging these obviously damaged modules, the question came up whether the hail storm also affected the performance of all other modules in the plant. Thus, innovative outdoor characterisation methods such as outdoor electroluminescence and UV-fluorescence imaging were chosen to non-destructively detect hidden hail storm induced damages of all modules in affected PV-plants. In order to prove the conclusions made upon the experimental data, the effect of hail impact on the degradation behaviour of modules was also simulated in the laboratory in accelerated ageing tests of test modules.

2. Experimental & methods

2.1. Description of the hail-affected PV-plants

Three hail-affected PV plants in the south of Austria (Carinthia) were investigated. The distance over air of the 3 plants is approximately 10 km. All three PV-systems comprise of standard glass/backsheets modules installed on flat roofs. PV plant 3 is a research installation, PV plant 2 is a company owned plant on a shopping centre, and plant 1 is a company owned system installed on the roof on a production hall.

A heavy hail storm took place in this region in summer 2015 at the afternoon of the 8th of July. Hailstones with a diameter up to 40 mm dropped down on the PV-modules. After the hail storm, all three inspected power plants showed some modules with visible detectable damages (broken glass). The details for the plant construction and module types as well as the number of damaged modules after the hail storm are summarized in Table 1.

2.2. Yield data evaluation

For comparison, the monitoring data of all three power plants is analysed and the performance ratio (PR) for each plant calculated. The PR is the quotient of the actual measured yield (averaged per month) and the targeted yield (calculation based on irradiance measurements and the labelled module/system power) of the PV plant (IEC 61724) and is expressed within the paper in percent.

In addition, the relative yield (RY) of a hail affected and glass broken module compared to a healthy reference module is checked with a module fine monitoring system from Solar Edge at plant 3. It allows for a comparison of string performance ratio and energy

yield per module. In addition, the behaviour of the glass-broken module is monitored over two years at plant 3 (Figs. 1 and 6).

As plant 1 has no own irradiation sensor, the irradiation data are taken from the nearby plant 2 (10 km distance). For all calculations whether PR or RY, a monthly average is used.

2.3. Thermography (TG)

Thermography is one of the common measurement techniques for inspecting photovoltaics plants as all sun illuminated PV modules emit infrared radiation. Thermographic cameras detect radiation in the long-infrared range of the electromagnetic spectrum and produce images of that radiation. The basic requirement for this measurement is sunlight of at least 600 W/m^2 [4] in order to generate measurable temperature differences for the evaluation of PV modules. The most important feature is the evaluation of the temperature homogeneity distribution within a module, as good working modules show equal ($\pm 2 \text{ }^\circ\text{C}$) cells temperatures for all cells. All inspections are made with a high resolution standard infrared camera with a measurement range of 7–12 μm wavelengths. The camera (Testo 890) is equipped with a micro bolometer detector with a resolution of 640×480 Pixels.

2.4. Twilight electroluminescence (TW-EL)

Electroluminescence (EL) is an optical and electrical phenomenon in which a material emits light in response to the passage of an electric current or a strong electric field. When investigating PV modules, current is fed into a solar cell/module and radiative recombination of carriers causes light emission. The PV module string/modules are powered in forward direction and work as large „LED array“, which is emitting light in the near infrared range at 1100 nm (bandgap of Si). For EL measurements it is important to have dark environment, thus, measurements are usually performed in a dark chamber of a laboratory. Recently a corresponding outdoor method for measurements directly in the field has been developed which has to be performed after sunset [5]. For twilight electroluminescence measurements a modified consumer camera without an IR blocking filter is used to detect the emitted 1100 nm infrared light. The used camera is a Canon EOS 700D with picture shooting times of about 2 s.

2.5. UV-fluorescence-imaging (UV-F)

UV-Fluorescence measurements are performed in dark environment (night) by illumination of the PV-modules with UV-light and detection of the fluorescing light in the visible region by the eye or a photographic camera system. In our experimental setup the UV-Fluorescence is detected with a digital photographic camera (Olympus OM D, equipped with high pass filter to cut-off the UV-irradiation). Excitation with UV-light is performed with a self-made UV-lamp consisting of 3 power-tuneable LED-arrays with an emission maximum at 380 nm (exchangeable to 360 nm) and a low pass filter to cut off all visible light. Power supply is a modified DC/DC converter with a controllable and piecewise constant voltage/constant current characteristic, sourced by a 12 cell Lithium-polymer-accumulator with a capacity of 5000 mAh. This characterization method is non-destructive, non-invasive, easy to handle and fast (an exposure time of 30 s is sufficient to achieve a well contrasted UV-fluorescence image of a module).

2.6. Laboratory tests with test modules

In order to gain a better understanding of the fluorescence patterns observed in the field, test modules are manufactured,

Table 1
Hail affected PV plants in comparison.

	PV-Plant 1	PV-Plant 2	PV-Plant 3
Installation Date	Summer 2014	Summer 2013	Summer 2012
PV module type	250 Wp polycrystalline Si; glass/backsheet	245 Wp polycrystalline Si; glass/backsheet	240 Wp polycrystalline Si; glass/backsheet
Number of modules	80	510	32
System power	20 kWp	125 kWp	7.5 kWp
Inverter type	Transformerless, 2 × 10 kWp three phase	Transformerless, 4 × 27.6 kWp three phase	HF-Trafo, 3 × 2 kWp one phase
Mounting system type	12° flat roof system	12° flat roof system	34° roof system
Orientation	40 modules south, 20 east, 20 west	south	south
Grounding of substructure & module frames/conductor	Yes	Yes	Yes
Visible damage after hailstorm	4 modules with glass breakage (5%)	3 modules with glass breakage (0.6%)	1 module with glass breakage (3%)
Monitoring System	Inverter based web portal monitoring, without irradiance measurement Updated power and yield data every few minutes	O&M company with string based monitoring incl. irradiance measurement	Module based scientific monitoring installation incl. irradiance measurement Updated power and yield data every few minutes

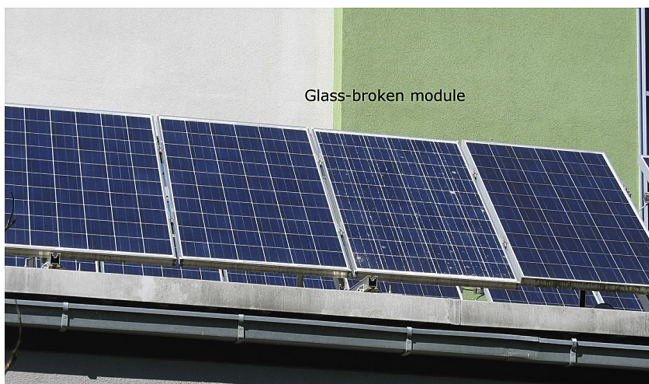


Fig. 1. Module with broken glass after hail storm (plant 3).

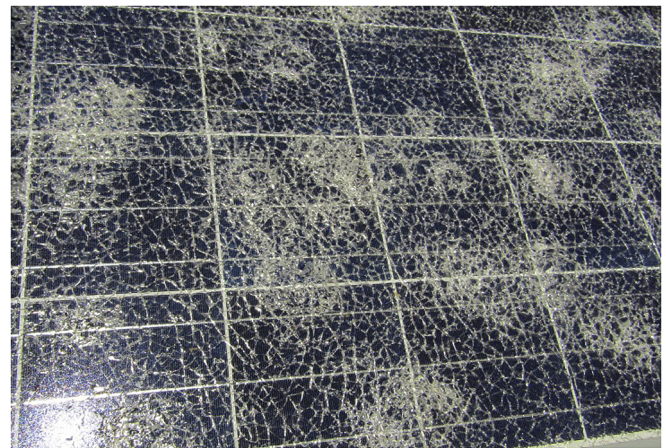


Fig. 2. Module with broken glass after heavy hail storm (plant 1).

partially mechanically treated in order to generate failures (micro-cracks, glass breakage) and artificially aged in accelerated tests. These mini modules (2×3 c-Si cells) resemble in composition and design standard glass/backsheet modules with EVA encapsulation. Accelerated ageing is performed for 1000 h under irradiation with artificial sunlight at 1000 W/m^2 ($T_{\text{chamber}} = 60 \text{ }^\circ\text{C}$, rel. humidity = 40%). An intermediate assessment is performed every 100 h when UV-fluorescence images are taken of all samples.

3. Results

3.1. Visual inspection and yield data evaluation

After a heavy hail storm in summer 2015, all three PV power plants showed visible damage with some glass-broken modules: 4 (out of 80), 3 (out of 510) and 1 (out of 32) were affected for plants 1, 2 and 3, respectively. Modules with broken front glass count as severe/strong damage (Figs. 1 and 2) as this damage has a direct impact on the yield of the PV-plant.

The immediate effect of heavy hail storm can be detected in the monitoring portal of the whole plant 1 (Fig. 3). A loss in the PR of plant 1 of about 10–20% could be observed directly after the hail event. In other cases, like for plant 2 and 3, the effect of the storm is inconspicuous in the PR (Figs. 4 and 5).

The broken modules were exchanged shortly after the hail event due to safety and performance reasons. For plant 1 the change was at 21st of July 2015, for plant 2 the change was at 11th of August 2015.

In system 3, however, the glass-broken module was kept deliberately within the research plant. As plant 3 is equipped with a

module based monitoring system (Solar Edge), it is possible to analyze the effect of the broken glass on the module performance in greater detail and over two years after the hail event (Fig. 6).

Despite a PV module with broken front glass, which is caused by the hail storm, we do not find a drop in the PR of plant 3. Therefore we evaluate the yield of the broken module relative to an undamaged PV module. In Fig. 6 we show the monthly relative yield as quotient of the yield for the glass-broken module to the adjoining reference module. Before the hail storm, the selected two modules showed nearly identical yields with a deviation of only 1–2% from the expected value. After the hail a drop in the relative yield of –10% is observed and in the following an accelerated degradation rate is found for the broken module.

3.2. Thermography (TG)

All three power plants are analyzed with thermography in order to find out if damaged modules with broken glass are detectable by their thermographic images (see Figs. 7–9). It can be seen that modules with hail affected damages show no or very little features in their thermographic image when investigated after the hail event.

3.3. Twilight electroluminescence (TW-EL)

In the following outdoor EL an UV fluorescence measurements are performed of all three plants in darkness, representative EL-images are given in Figs. 10–12. By analyzing the TW-EL-images

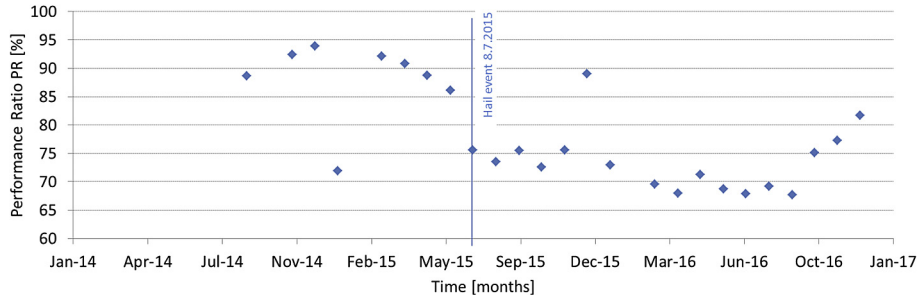


Fig. 3. PR before and after hail event for Plant 1.

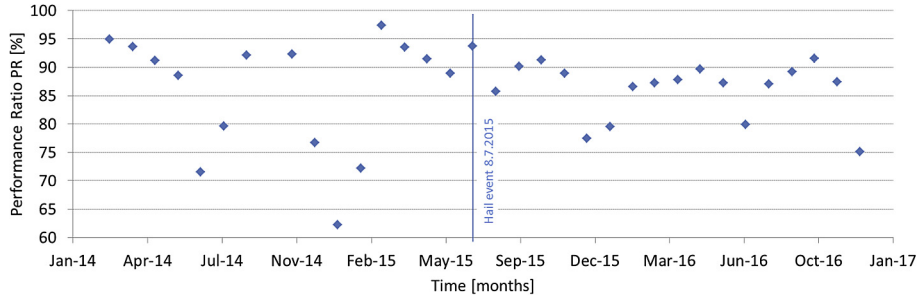


Fig. 4. PR before and after hail event for Plant 2.

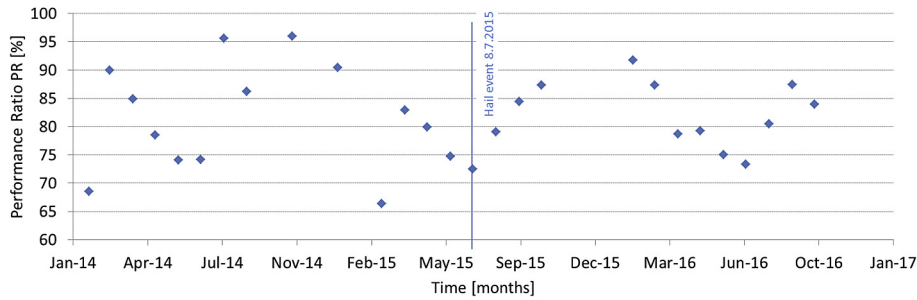


Fig. 5. PR before and after hail event for Plant 3.

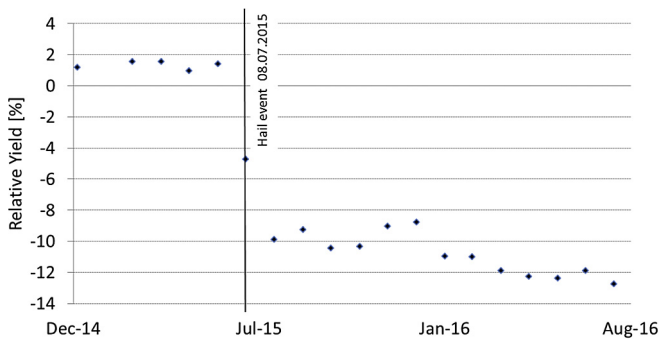


Fig. 6. Yield of a hail affected module relative to a reference module before and after the hail storm (Plant 3). The module front glass broke during the hail storm.

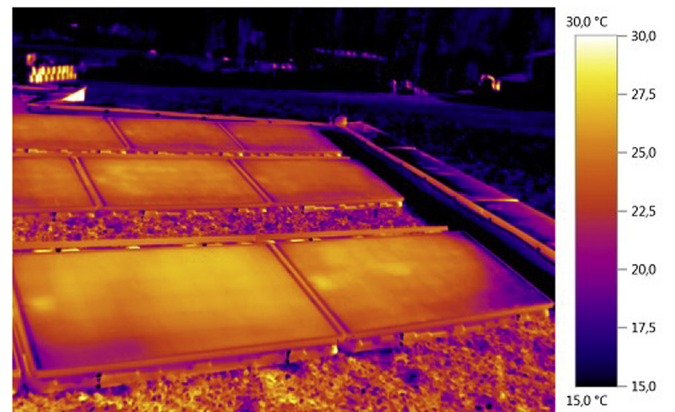


Fig. 7. TG image of plant 1.

it can be clearly seen that many modules of plant 1 show countless broken cells. Although the glass of these modules is still intact, the cell damage as detected by EL is severe (as shown in Fig. 10) and explains the measured yield, respectively the performance loss of this plant after the hail event. Two sample-modules were taken from the plant and tested in the laboratory with a module flash test

system. Sample module one shows a power drop from 250 Wp to 163 Wp (−35%) and sample module two from 250 Wp to 177 Wp (−29%) relative to the initial flash report.

In contrast, the PV-modules installed in plant 2 showed hardly

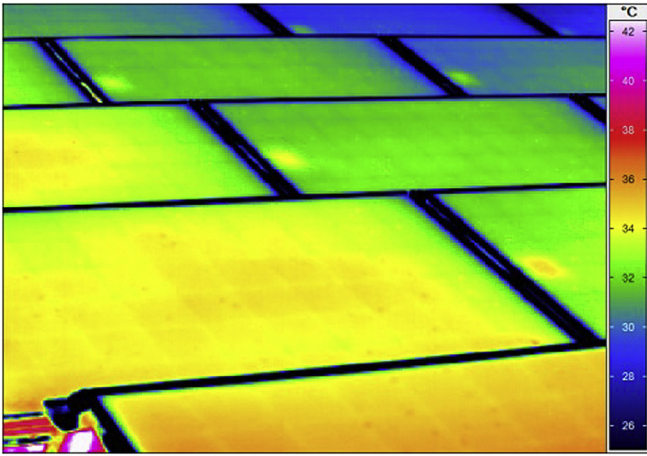


Fig. 8. TG image of plant 2.

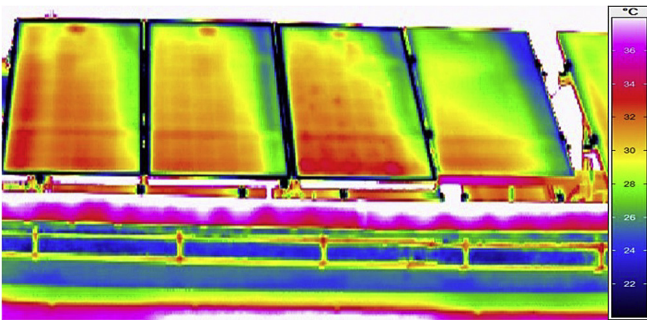


Fig. 9. TG image of plant 3.

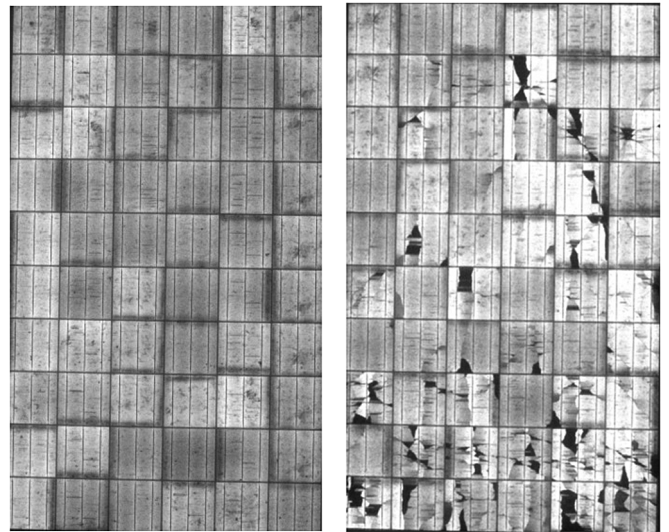


Fig. 12. a, b: EL image of hail affected modules of plant 3 (left – hardly damaged, right – glass-broken module with a relative yield loss of –10% due to cell cracks).

any abnormalities after the hail storm: the main fraction of the solar cells does not show any cracks, only a detailed analysis of individual cells give evidence for the presence of micro-cracks. Detection of micro-cracks by twilight EL in combination with UV-fluorescence measurements is described in detail in [chapter 3.4](#).

3.4. UV-fluorescence imaging (UV-F)

UV-Fluorescence images are taken of the hail-affected power plants ([Figs. 13 and 14](#)). The direct impact of larger hail stones on the cells can be seen in the UV-F pattern ([Fig. 13a, b](#)) which directly



Fig. 10. a, b: TW-EL image of hail affected modules of plant 1 (glass not broken, ~ –30% power loss due to micro cracks).

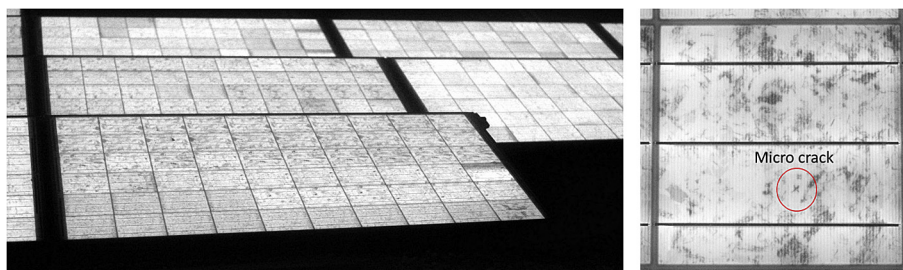


Fig. 11. a, b: TW-EL image of hail affected modules of plant 2 (no loss detectable, only tiny cross micro cracks).

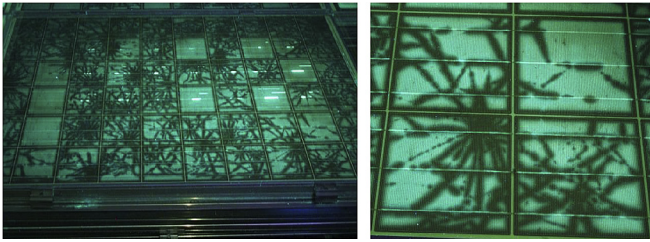


Fig. 13. a,b: UV-F image of a hail damaged module of PV-plant 1 and details with spider web appearance due to micro cracks.

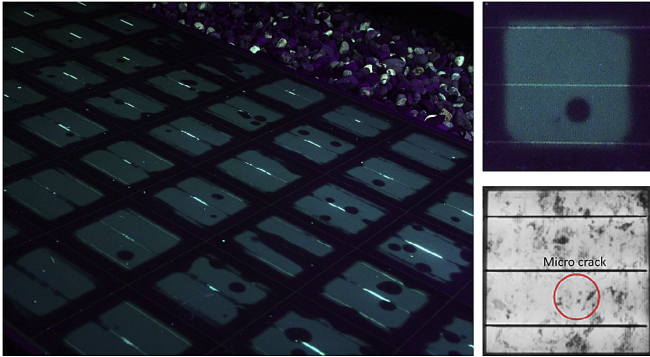


Fig. 14. a,b,c: left: UV-F images of a module in PV-plant 2 and details of one cell with cross-micro crack (UV-F and EL).

reflects the cobweb-shaped cracks in the cells starting from the impact-centre. Next to strongly affected cells with numerous cell-cracks also intact cells exist within the same module. The extinctions of the UV-fluorescence above cell cracks allows for the clear visualisation of cell-damages without interfering with the electrical system of the module. The cell cracks visualised with UV-F are in perfect agreement with cell breakages as detected by EL (Fig. 10a, b).

In addition to the line-shaped extinctions of the UV-F above cell

cracks, especially in plant 2 there are several modules found with extraordinary point-shaped extinctions (Fig. 14) of the UV-F which cannot be explained unambiguously at the first sight. Additionally performed high resolution EL-measurements of the effected cells directly in the plant suggest, that small cross-shaped micro-cracks in the cells lead to the extinction-points in the UV-Fluorescence pattern. In order to prove this assumption, an imitation of this effect was performed with specially prepared test modules in accelerated aging tests (see Chapter 3.5).

Additional power measurements on several modules within the investigated PV plants proved, that not all modules with glass breakage show identical behaviour in respect to performance loss, thermographic image and UV- fluorescence. However, a direct correlation exists between the power of the affected modules and the observed EL and UV-F: The more the cell breakage and UV-F tracks, the less the power and performance.

3.5. Laboratory test to simulate the UV-FL-effects observed

In order to prove that the point shaped extinctions in the UV-F observed in plant 2 originate from (possibly hail-induced) micro cracks in the cells, test modules were produced and part of them deliberately stressed in order to simulate local mechanical impact. EL proved the formation of micro-cracks (see Fig. 15). These test modules were then subjected to accelerated aging and the development of characteristic UV-F patterns is monitored in Fig. 15a–c.

The comparison of the EL and UV-F images in Fig. 16 clearly proves that the point-shaped UV-extinctions originated from cross-shaped micro cracks in the cells.

The effect of glass breakage on the formed UV-F pattern is visualised in Fig. 16. Beneath the glass breakage a line shaped extinction of the UV-F takes place, the broadness of the extinction increases with increasing exposure time.

4. Conclusions

Three PV plants were inspected with non-destructive characterisation tools after a heavy hail event in July 2015. By comparing the monitoring data and the calculated performance ratios for each

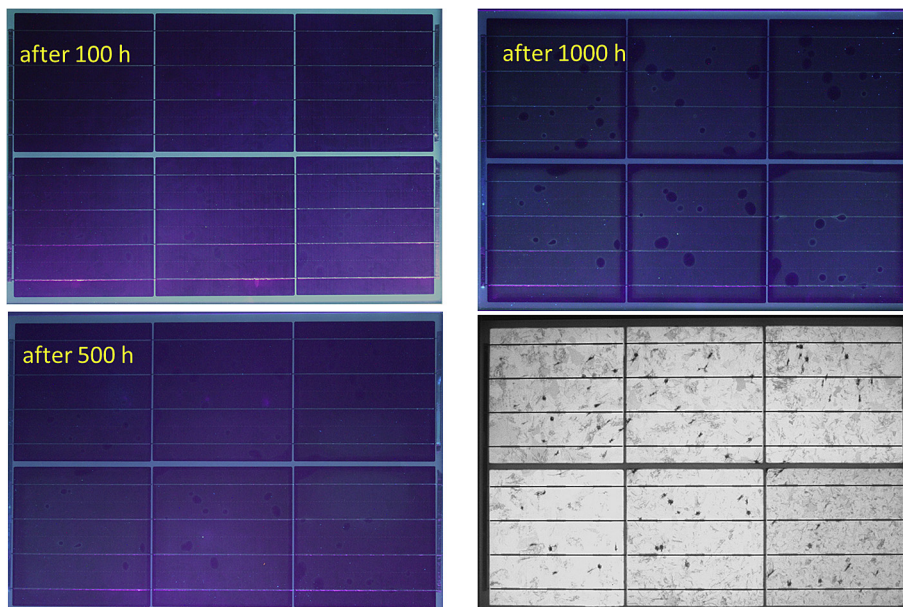


Fig. 15. UV-F images of test module with micro cracks after a) 100, b) 500 and c) 1000 h of artificial sunlight at 1000 W/m² and d) initial EL-image of test module.

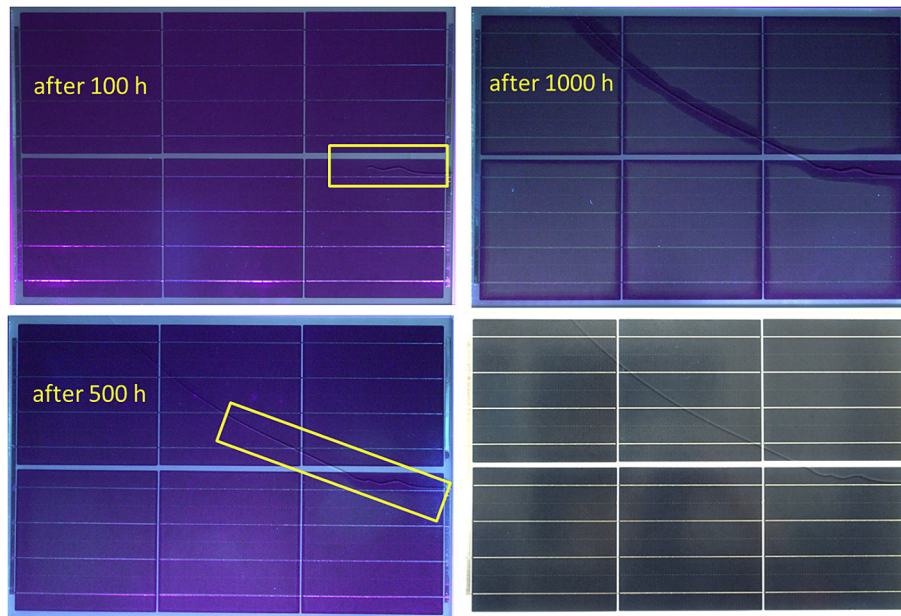


Fig. 16. UV-F images of test module with glass breakage after a) 100 h, b) 500 h and c) 1000 h of an artificial sunlight at 1000 W/m^2 and d) photograph after 1000 h.

plant before and after the hail storm, only one plant (plant 1) showed significant degradation on system level after the exchange of all visually damaged (glass broken) modules with new ones.

Plant 3 showed no significant degradation although one glass-broken module was deliberately kept in the plant over a time of two years after the hail. Thus, on string level, one glass-broken module within a string is sometimes not possible or difficult to identify. However, with a controlling system on module level it could be clearly shown in the monitoring portal that a module with a glass and initiated cell damage is underperforming: the affected module in plant 3 had a performance loss of about 10% due to the hail impact. In the worst case, modules with complete glass and solar cell breakage exhibit total efficiency losses and in addition impose a high security risk and therefore have to be replaced.

However, there is a strong need to inspect the remaining modules (without glass breakage) directly in the field, in order to assure no damage/partial cell breakages. Further inspection with thermography pointed out that it is difficult to detect hail damaged PV modules. With the aid of two innovative characterisation methods, outdoor electroluminescence and UV-fluorescence imaging, hail-induced damaging of solar cells could be detected even when the solar glass of the modules withstood the mechanical impact of the hailstorm and no damages were visible to the naked eye or well recognizable by thermography. Depending on the degree of damage, completely fractioned cells, line-shaped cracks and small cross shaped micro-cracks were visualized by UV-F imaging and confirmed by EL-measurements. Parallel power measurements confirmed that these “hidden” damages (no visual indication) of affected modules can cause power losses in the range of 30%.

Consequently, the use of the non-destructive, easy to handle and fast characterization techniques UV-fluorescence imaging and electroluminescence allow for the detection and visualisation of hail induced cell damage. Not only obvious damages such as glass-breakage induced cell fracture but also partial cell breakage and micro cracks of otherwise intact modules can be detected. With time, however, these cell defects might even increase in severity leading to severe under-performance of the power plant and, thus, have to be replaced.

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