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Quality Improvement of PV Modules by Electroluminescence and Thermal Imaging

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Abstract*— The ability of a PV module to withstand the effects of periodic hot-spot heating that occurs when cells are operated under reverse biased conditions is one of the quality characteristics that are verified within IEC qualification testing. The extent of hot-spot heating of solar cells is closely related to the properties of the semi-conductor material. Locally concentrated shunt defects are caused by non-uniformity. The extent of defects is correlated with the slope of the reverse IV-characteristic. In this paper the operational behaviour of crystalline cell types were investigated under reverse biased conditions. These conditions occur within the interconnection circuit of modules when cells are mismatched or totally or partially shadowed, possibly leading to thermal overload (hot-spot heating). This study is focused on the electrical as well as the thermal characterisation of solar cells that are operated under the reverse biased conditions. In connection with reverse biased operating conditions this study is focused on the following points: To identify the cell parameters for a comprehensive description of the electrical and thermal operational behaviour. The knowledge of these parameters is important for design of effective bypass diode concepts in modules. This paper is an insight into the applicability of the simplified method to select the worst case hot-spot cell in a module. The selection of this cell is the first step of hot-spot safety testing.

Index Terms—About four key words or phrases in alphabetical order, separated by commas.

I. Introduction

Zero defect manufacturing and production [1] is today's aspiration for either a single producer or the whole industry. Defects and, especially, cracks in the structure of the materials components are crucial for optimum performance and their detection is essential to ensure secure operation and functionality of the final product. One of the technical requirements of PV modules for qualification according to the standard IEC 1215 is fulfilment of the pass criteria of the hot spot endurance test. A hot spot situation is existent when a solar cell within a module generates less current than the string current of the module or of the PV generator. This occurs when the cell is totally or partially shaded, damaged, or when cells are electrically mismatched. The shaded cell becomes reverse biased and dissipates power in the form of heat. This article focuses on failures due to cell shading which may occur during operation of a PV system. If no measures are taken, i.e. the integration of bypass diodes in the cell interconnection circuit of the modules [2], a shading situation may lead to so-called irreversible hotspot damage of cells [3] where the cell current is concentrated with locally high intensity. This causes focal point heating with temperatures higher than 150°C, which is above the critical temperature of cell encapsulants of commercial modules. As a result of this, deterioration of the encapsulation occurs. In the worst case this leads to a loss of the insulating properties of the module if the delamination forms a continuous path to the module edge. In addition to this safety risk, delaminations leave visual defects on the module which may affect the acceptance of PV technology among the public.

This article focuses on the following points: (1) The characterisation of commercial silicon cells under reverse biased conditions (2) The worst case hot-spot conditions for a PV module (3) A new method for determining the worst case cell within a module for hot-spot testing (4) Requirements for bypass diode concepts to ensure the hot-spot endurance of modules. Because the series connection of the PV generator forces all cells to operate at the same current (string current), the shaded cell within a module becomes reverse biased which leads to power dissipation and thus to heating effects that the worst hot-spot cell which is the cell with the highest concentration of leakage current is correlated with the upper bound of the reverse IV characteristics [4] (Figure 1: upper bound cell). If so, the worst case cell can easily be identified by current measurement at a constant reverse voltage. Because the series connection of the PV generator forces all cells to

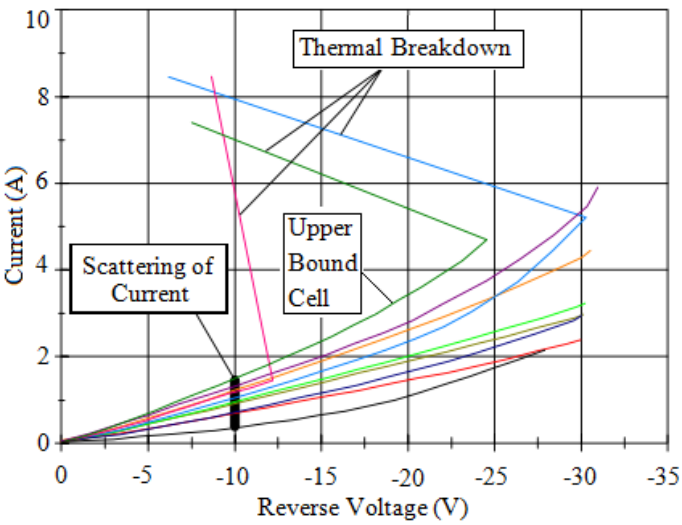

Figure 1 : reverse IV characteristics for a batch of 10 mono-crystalline cells

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Defect Type	Appearance in Thermal Image	Probable Reason
Manufacturing Defect	Hot spot/Cold spot	Impurities and gas pockets
	Cell Heating	Cracks
Damage	Cell Heating	Cracks
	Portion of cell appears hotter	Cracks
Temporary Shadowing	Hot spots	Pollution
		Bird droppings
		Humidity
Defective Bypass Diode	A patchwork pattern	N.A
Faulty Interconnections	Module or string is consistently hotter	Module or string not connected

Table 1 : Identification of the errors/defect from thermal image.

On the basis of these facts in a simplified test procedure for hot-spot safety testing was proposed using the assumption operate at the same current (string current), the shaded cell within a module becomes reverse biased which leads to power dissipation and thus to heating effects. Such a situation is

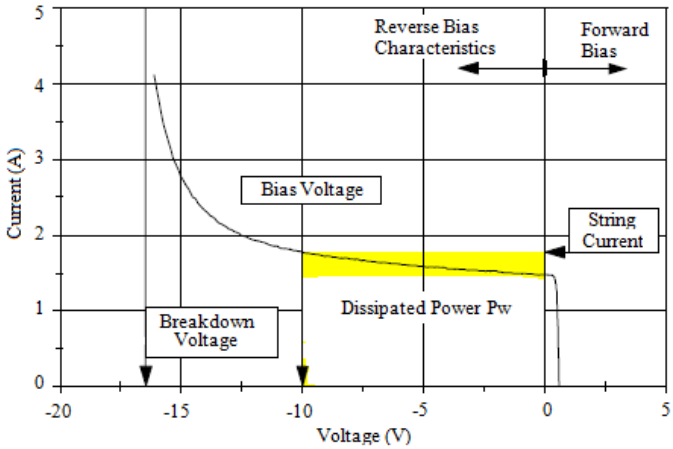

Figure 2. IV-characteristic of a solar cell in the whole voltage range.

illustrated in figure 2 which shows the typical IV-characteristic of a solar cell in the whole voltage range. Whereas the forward characteristic extends to the open circuit voltage of approx. 0.6 Volts, the reverse biased characteristic is much more extensive and limited by the breakdown voltage. If the cell is shaded, its short circuit current is less than the string current so that it is operated at the reverse characteristic, causing power to be dissipated.

For low bias voltages the reverse current is approximately a linear function of voltage (ohmic behaviour). The slope is a measure for leakage currents that appear as an additional component to the dark saturation current of an ideal diode. Leakage currents originate in cell defects and impurity centres in the semiconductor and can be represented by a shunt resistance. At low bias voltages the current is distributed over the whole cell area and heating takes place more or less uniformly. The maximum current density is below a critical limit and the IV characteristic is stable against thermal effects [5]. Figure 2 shows that with rising bias voltage the junction breaks down and conducts very large currents. For solar cells the most important mechanism in junction breakdown is the avalanche multiplication which has its origin in a high electric field in the depletion layer that is generated by the bias voltage. At a certain level of the field strength the generated electron-hole pairs gain enough energy to ionize lattice atoms which again can generate charge carrier pairs. Cells do not have an homogeneous structure, regions with a higher concentration of impurity centres exist. At high bias voltages these points break down earlier. If the current density at this point exceeds a critical limit the cell is irreversibly damaged by thermal breakdown (burnout) that forms a shunt path in the cell structure. Now at reverse biased conditions the current is locally concentrated, focal-point heating is caused and damage to the cell encapsulation is to be expected (hotspot). Hot-spot heating occurs when there is one low current solar cell in a

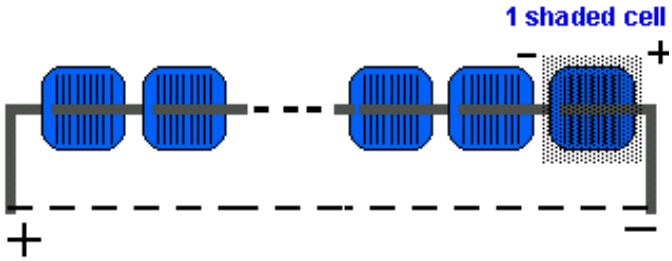

Figure 3. One shaded cell in a string reduces the current through the good cells, causing the good cells to produce higher voltages that can often reverse bias the bad cell.

string of at least several high short-circuit current solar cells, as shown in the figure below.

One shaded cell in a string reduces the current through the good cells, causing the good cells to produce higher voltages that can often reverse bias the bad cell. If the operating current of the overall series string approaches the short-circuit current of the "bad" cell, the overall current becomes limited by the bad cell. The extra current produced by the good cells then forward biases the good solar cells. If the series string is short circuited, then the forward bias across all of these cells reverse biases the shaded cell. Hot-spot heating occurs when a large number of series connected cells cause a large reverse bias across the shaded cell, leading to large dissipation of power in the poor cell. Essentially the entire generating capacity of all the good cells is dissipated in the poor cell. The enormous power dissipation occurring in a small area results in local overheating, or "hot-spots", which in turn leads to destructive effects, such as cell or glass cracking, melting of solder or degradation of the solar cell [6]. For solar cells the most important mechanism in junction breakdown is the avalanche multiplication [7] which has the origin in the high electric field, into the depletion layer that is generated by the bias voltage. Cells do not have a homogeneous structure, regions with higher impurity concentration of centers exists. At high bias voltages if the current density exceeds a critical limit the cell is irreversibly damaged by thermal breakdown (burnout) that forms a shunt path in the cell structure. At reverse bias the current is locally concentrated, focal-point heating is caused and damage to the cell encapsulation is to be expected (hotspot).

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To avoid thermal overload and the formation of hot spots, sub-strings of cells inside the interconnection circuit of modules are

Figure 4 . Heat dissipated in a shaded cell caused the module to crack.

bridged by bypass diodes. This measure limits the bias voltage of the shaded cell and therefore dissipated power too. Partial shadowing has been identified as the main cause for reducing energy output for grid-connected photovoltaic systems. Impact of the applied system configuration on the energy output for partially shadowed arrays has been widely discussed. Nevertheless, there is still much confusion regarding optimum grade modularity for such systems. Shading effect occurs when part of the panels array are shaded which can be caused by a number of different reasons, like shade from the building itself, light posts, chimneys, trees, clouds, dirt, snow and other light-blocking obstacles. Shading on any part of the array will reduce its output, but this reduction will vary in magnitude depending on the electrical configuration of the array. Clearly, the output of any shaded cell or module will be lowered according to the reduction of light intensity falling on it. However, since this shaded cell is electrically connected to other shade less cells, their performance may also be lessened since this is essentially a mismatch situation.

The maximum power output of the total PV array is always less than the sum of the maximum output of the individual modules [8]. This difference is a result of slight inconsistencies in performance from one module to the next and is called module mismatch and is in the amount of to at least 2% loss in system power. Power is also lost to resistance in the system wiring. These losses should be kept to a minimum but it is difficult to keep them below 3% for the all system. Dirt and dust can accumulate on the solar module surface, blocking some of the sunlight and reducing output. Although typical dirt and dust is cleaned off during every rainy season, it is more realistic to estimate system output taking into account the reduction due to dust build up in the dry season. Cell manufacturers generally provide no information about the behavior of their cells under reverse biased condition, but an infrared image can provide the needed feedback to anticipate any internal cell decaying process.

As the temperature coefficient for the power peak of PV modules is negative, it is very important to monitor their temperature in order to verify that the PV plant produces the maximum energy. Moreover, to monitor the temperature allows detecting anomalies before they become failures. Then, thermography [9] can give meaningful support just for this aim. Since a solar cell is forward bias in operation, any shunt current reduces the efficiency of the solar cell. Shunts may be caused by electrical defects of the pn-junction, which may generate lattice defects, as well as by technological imperfections of the production process. IR thermography is currently used to detect local imperfections in the production process, for this case local ariation is used to detect the current density across solar cells.

In figure 5 there are hot spots detected, without externally visible damage on the panel surface. Thus, the problem must be attributed to internal causes, corrosion being one possible candidate. Invisible hot spots corresponding to areas where the internal structure of the panels is beginning to decay is visible with an IR camera help [10].

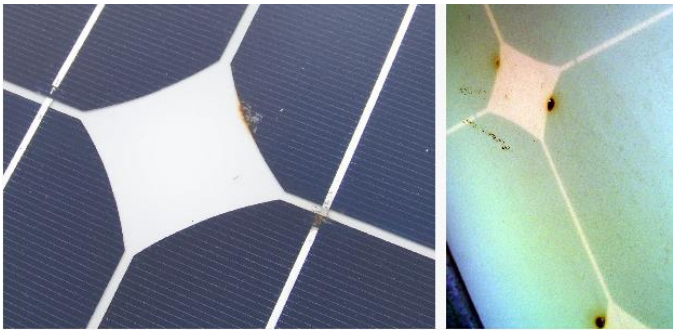

Figure 5. Hot spots at solar cells.

A thing that is good to be remarked is that some spots are by their nature invisible to the naked eye, contrary to the dust and impurities deposits, but with the infrared equipment even those ones are easily seen removed as quickly as possible. Infrared analysis allows a reliable evaluation on the state of health of the power plant and, at the same time, the detection of the actions needed for maintenance.

The work has shown that the infrared analysis can be usefully utilized for the efficiency analysis of PV plants. In

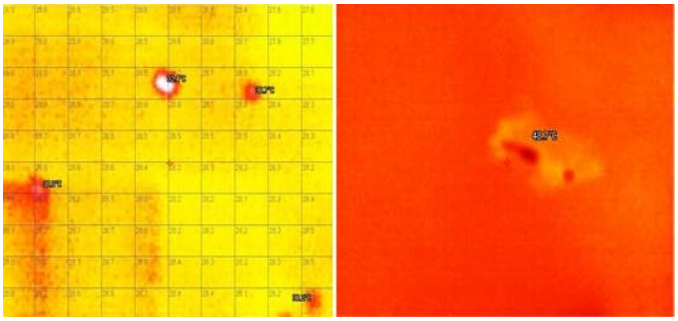

Figure 6 . Internal structural defect of a PV cell.

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fact, efficiency depends strongly on the temperature of the PV modules and an overheating causes a decrease of the produced energy. In figure 6 hot spots are detected, without externally visible damage on the panel surface. Thus, the problem must be attributed to internal causes, corrosion being one possible candidate. Invisible hot spots corresponding to areas where the internal structure of the panels is beginning to decay is visible with an IR camera help. Grown-in or structural defects in electronic materials as well as electronic discharges or conducting particles are possible reasons of unwanted leakage in electronic devices. These currents may result in a decrease of the efficiency for a produced assembly or, even, in its complete failure.

A thing that is good to be remarked is that some spots are by their nature invisible to the naked eye, contrary to the dust deposits, but with the infrared equipment even these ones can be seen and problems be removed as quickly as possible. Refined thermal methods are needed to detect a wider variety of shunt conditions, particularly those below a solar cell's metallization layer. Increased temperature can cause components to fail, potentially resulting in unplanned outages and injuries. Thus, is also part of the case regarding photovoltaic panels, but increasing temperatures also occurs when shunts are created by dust and all other kinds of impurities, physical material defects and/or structural defects.

(1) If a part of the solar cell is shaded the cell can heat up to such extreme temperatures that the cell material as well as the encapsulation (EVA) [11] and backsheet will be permanently damaged. A so called hot spot develops.

(2) Under normal operation condition the cell generate current. In contrast, a shaded cell not produce any electricity any more but uses the current from the other cell. The current from the other cells of the strings is driven through the darkened cell. The current flow is then converted into heat.

(3) To prevent the cells from hot spots bypass diodes are used in all standard modules nowadays. If a cell is shaded, the bypass diodes get into operation and redirect the current for the full cell string via a bypass and prevent the cells from the hot spot effect.

(4) Hotspots may still occur. For example, if the bypass diodes are faulty, or if only a very small part of the cell is shaded and thus the bypass diode is not enabled.

Other reasons for hotspots can be high contact resistance at the busbars of the cells . Reasons for high contact resistance can be cracked solder joints on the busbars. The power loss of a module with a hotspot is often very low. Unless there are already big areas with hotspots. Nevertheless, these modules should be replaced, especially when not the cell only but also the surrounding encapsulation material burned.

The thermographic inspection of photovoltaic systems allows the fast localization of potential defects at the cell and module level as well as the detection of possible electrical interconnection problems. The inspections are carried out under normal operating conditions and do not require a system shut down. For correct and informative thermal images, certain conditions and measurement procedures should be observed: a suitable thermal imaging camera with the right accessories should be used; sufficient solar irradiance is required (at least 500 W/m2 – above 700 W/m2 preferred); the viewing angle must be within the safe margins (between 5° and 60°); shadowing and reflections must be prevented.

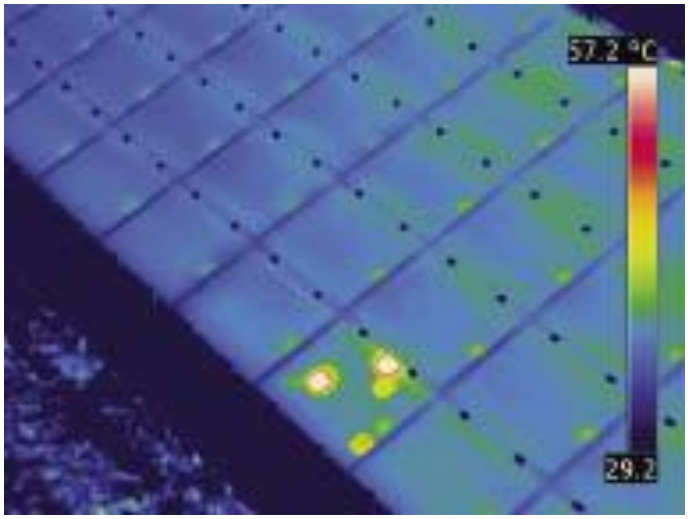

Figure 7 : The thermal image of the so-called 'patchwork pattern', which indicates that this panel has a defective bypass diode.

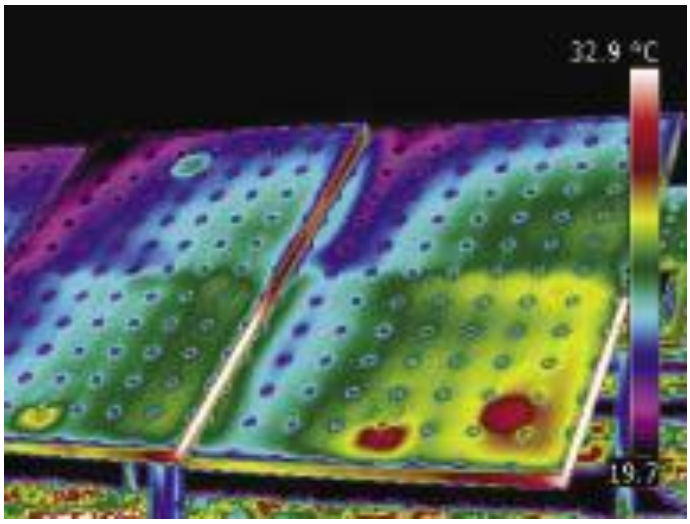

Figure 8 : The red spots indicate modules that are consistently hotter than the rest, indicating faulty connections.

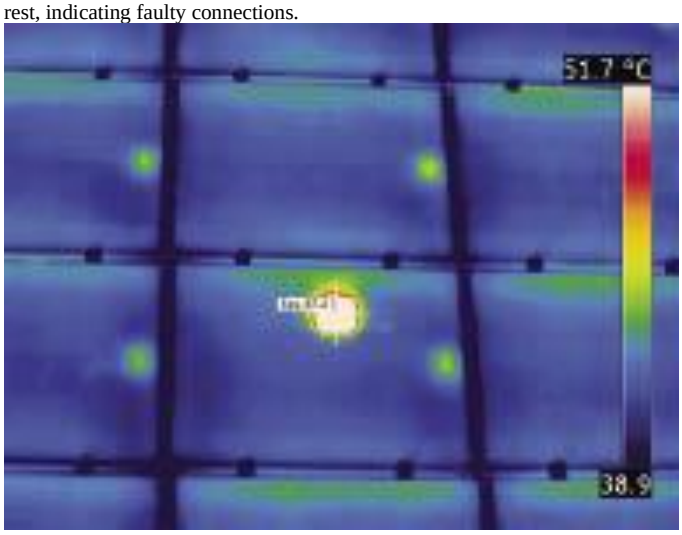

Figure 9 : The hot spot within one solar cell indicates physical damage within the cell.

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Based on IR-image (or IR-VIS-image fusion) the local breakdown ranges of the cells can be easily identified [12]. Such analyze are imported for the fundamental investigations on the hot spot reason. The following figure displays the study result (period: 2009-2012) on the breakdown ranges at hot spot tests on c-Si modules [13].

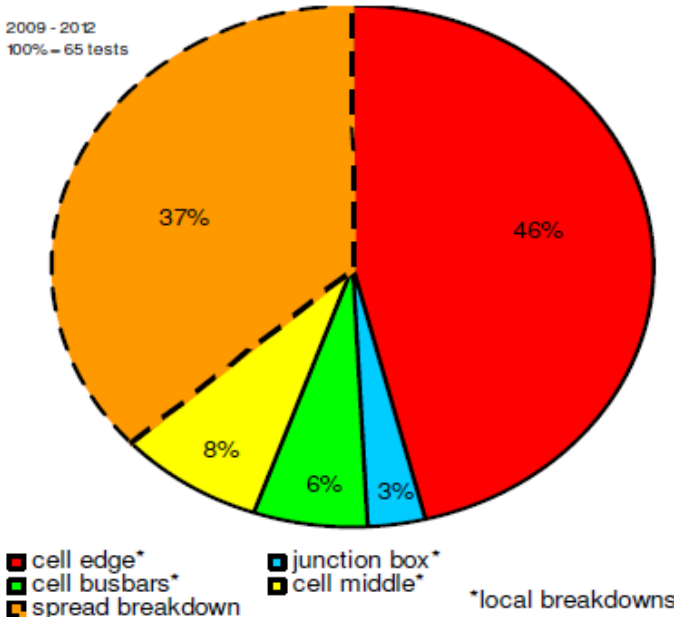

Figure 10 : : Measured results (2009-2012) for the breakdown ranges.

The study made clear that the breakdowns can divide into two types: Type 1: Spread breakdowns over the complete cell area or a large part of the cell. Figure 7 displays that 37% of the hot spot test modules had cells with a spread breakdown. For spread breakdowns cells typically show lower temperature. Type 2: Local breakdowns at the cell. The local breakdowns can be subdivided into the cell edge (possible causes: bad pn junction insulation), the cell bus-bars (possible

Module	Visual Inspection	IR Thermography Inspection	Electroluminescence Inspection
1	Passed	Passed	Passed
2	Passed (minor defects)	Failed	Failed
3	Passed (minor defects)	Passed	(*) Failed
4	Passed (minor defects)	Passed	(*) Failed
5	Passed (minor defects)	Passed	(*) Failed

Table 1 : Comparison of results.

causes: to deep burnt in contacts), the junction box (possible causes: bad convection) and the cell middle (possible causes: material defects like SiC inclusions). In sum the local breakdowns have a ratio of 63%. Thereby is the breakdown at the cell edge with 46% dominant. Typical for cells with local breakdowns is the higher temperature. The results of the breakdown rages showed that the local breakdown / hot spots are that mostly occur and these through the higher temperatures are more critical than spread ones. From all hot spot tests done at Berlin 23% failed it (mostly local breakdowns). The main fail reason was the lost of electrical isolation through melted foils.

IV. CONCLUSION

The thermographic inspection of photovoltaic systems allows the fast localization of potential defects at the cell and module level as well as the detection of possible electrical interconnection problems. The inspections are carried out under normal operating conditions and do not require a system shut down. For correct and informative thermal images, certain conditions and measurement procedures should be observed: •a suitable thermal imaging camera with the right accessories should be used; sufficient solar irradiance is required (at least 500W/m^2 – above 700 W/m^2 preferred); the viewing angle must be within the safe margins between 5° and 60°) and shadowing and reflections must be prevented.

The analysis suggest that the EL should be introduced as additional non-invasive test in the laboratory procedures to evaluate the PV modules reliability. The EL-inspection is very useful on the quality control of the module supply for PV Plant, acting as an ideal complement of tests used nowadays for this purpose. This is very important, especially in large PV plants where large amount of modules from different manufacturers or different lots of the same manufacturer are installed. Moreover, information regarding how the EL-test can be implemented in a simple way without affecting the time schedule of the quality control has been provided in this
paper. The EL-test has been carried out in modules randomly selected in which a quality control had been performed. Results indicate that the additional information provided by electroluminescence imaging has permitted to detect defective modules which have passed previous quality control. Specifically, the EL- test results have correlate visual minor defects, such us visual non-uniformity in cell fingers, with severe damages as cracks in cells. It can be concluded that the imaging methods are useful and quick tool to detect defect in PV modules. Each technique is suited to detect different kind of failure. It is important to compare results obtained from more techniques to assess the cause of defects. A combination of IR and EL methods is necessary in order to identify as many defects as possible.

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