Efficacy comparison of PV Panel for Ex environment

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Abstract - The production of electricity from renewable sources, avoiding the use of fossil fuels that are running out, is proposed as an important topic on which to conduct innovative studies in favour of the environment and safety in particularly sensitive areas. Among the production methods, the greatest potential as regards the possible contribution of energy is the photovoltaic one which, with cost of materials accessible and increasing efficiency, is proposed as a solution to the electricity generation needs. In particular, the presence of solar systems on islands, i.e. separated from the public grid, makes it possible to meet the needs of particularly remote areas, difficult to connect or areas with explosive atmospheres (offshore platforms) thanks to the storage systems and connected regulation devices.

A characteristic environment for a possible and essential application is the Explosion Atmosphere, for which energy generation systems, according to necessity, are always a particularly sensitive topic. In these areas, safety is not insignificant and, as can be easily understood, the use of static and combustion-free components can be much more suitable for the environment than traditional methods, i.e. combustion Diesel Engines or other technologies based on the use of fossil fuels or rotating mechanisms. Power generation systems based on solar technology are not, in fact, free from sources of danger for environments at risk of explosion, as it is possible that faults or operating conditions may occur that could trigger an explosion. Leaving each manufacturer the freedom to choose the protection mode he considers the best for this type of apparatus, it has been instead decided to deal with aspects considered "transversal" for the compliance of the photovoltaic panel. The results of a test campaign carried out on photovoltaic panels that can be installed in explosive atmospheres will then be shown in order to assess their efficiency under different conditions according to the impact test.

Index Terms — PV Panel, Efficacy, ATEX, Explosive Atmosphere, Modes of protection, risk assessment, hot spot.

I. INTRODUCTION

In areas at risk of explosion (ATEX), the need for energy supply to plants is a sensitive and delicate issue to be addressed. There are many ways in order to remedy this situation and they are often based on the local production of the energy needed to sustain the activity because many of the areas concerned are far from the main electricity grids. One example is an offshore platform where electricity is of paramount importance, from crane drives for loading and unloading goods to signalling or service lighting for workers. Usually power is supplied by diesel engines or other internal combustion equipment, leading to pollution and waste of the raw resources extracted and CO_2 emissions.

The hazards inherent in the use of devices capable of producing energy using controlled explosions within an ATEX environment must also be considered. There are two main solutions to overcome this problem, namely ignition control of high power equipment (e.g. motors), with high equipment costs, or production through equipment with less risk of ignition and, if possible, eco-sustainable. Photovoltaic systems with suitable energy storage systems [1] are offered as a valid alternative because they are able, if properly sized, to provide the necessary energy supply both during the day and the night. The use of this equipment, however, like any electrical device, is not without risks, so it is essential to evaluate them with the relative EN 60079 standards, which define the protection methods that give the presumption of conformity to the ATEX Directive.

Leaving each manufacturer the freedom to choose the mode of protection for any installation area (Zone 1 or Zone 2), the aim of this work is to deal with aspects considered "transversal" for the conformity of a PV panel. The main aspects to be considered are:

- Risk assessment;
- Impact test (and the related efficiency test);
- Temperature class and thermal test.

II. PHOTOVOLTAIC PANEL

Traditional PV panels for non-architectonic applications are normally built as reported in Fig. 1.

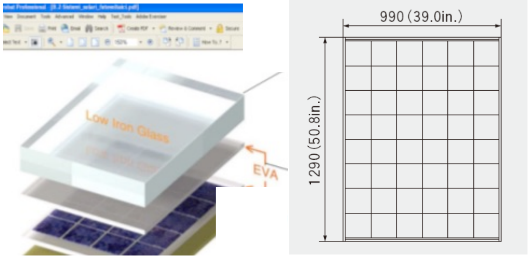


Fig. 1 – Typical PV panel for non-architectonic applications.

Panels are realized by 48-72 series cells, assembled by connecting and welding the cells among each other by means of terminals on front and rear contacts (in a N-P-N-P-N ... sequence) in order to form a string.

A sandwich is then realized by placing the PV cell in the middle layer that is surrounded by (going from the external layer to the internal one) a glass plate of 4mm, characterized by very good mechanical resistance, an EVA (Ethylene Vinyl Acetate) sealant sheet of 0.5mm, which allows the dielectric insulation of the cell layer, then another identical EVA sheet and then a Tedlar insulant layer of 0.5mm.

The sandwich is then heated in the oven at about 100°C, the temperature at which the components seal to each other. Once this temperature is reached, EVA becomes transparent and the residual internal air, which might cause corrosion because of the presence of water vapor, is then evacuated. Eventually, the sandwich is fixed in an extruded anodized aluminum frame - to be protected against corrosion - and the junction box is placed. Typically, the shape of these PV panels is rectangular.

III. DIFFERENT EX PROTECTION PRINCIPLES

One of the most challenging industrial environments is the Ex environment - such as an Oil & Gas field - where an explosive atmosphere could be often present.

An explosive atmosphere is a mixture of flammable substances in a gaseous, foggy, vaporous state, or powder mixed with air, under certain atmospheric conditions in which, after ignition, the combustion propagates itself to the flammable mixture. A potentially explosive atmosphere is only obtainable if the concentration of the flammable substance is not too low (lean mixture) or too high (rich mixture): in these cases, a combustion reaction may occur, or even no reaction at all, but no explosion [2].

In order to avoid a gas explosion, it is mandatory to exclude one of this three elements: fuel, combustive agent (oxygen) and ignition source. Therefore, an explosion cannot occur if even just one of these three elements is not present, as shown by the explosion triangle of Fig. 2.

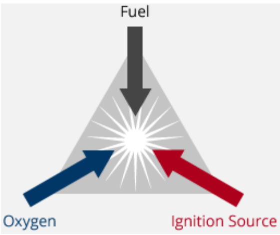


Fig. 2 – The explosion triangle.

Therefore, three different principles, which act differently on these three elements of the triangle can be implemented to be safe the electrical equipment.

These three different principles are:

- *containment method*, the parts that can cause ignition are included in a box made to withstand the pressure of the explosion, preventing the spread of flame;
- *prevention method*, in this method necessary measures are taken to avoid excessive temperatures and creation of sparks, thus eliminating the ignition source;
- *segregation method*, in which active components are separated from explosive mixture using resins, sand, oil, preventing any contact with oxygen and fuel.

All the protection modes for Ex environment, as described in [3] for luminaries, born from these three different principles and it is possible to use these protection solutions for Photovoltaic panel also.

The *containment method* is related to “Ex d” (Flameproof enclosure) mode of protection where the parts which can ignite a potentially explosive atmosphere are surrounded by an enclosure which withstands the pressure of an explosive mixture exploding inside the enclosure itself, and prevents the transmission of the explosion to the external atmosphere surrounding the enclosure [4]. It is very important to design the length, the gap and rugosity of the joint between cover and body of enclosure according to the Standard.

The *prevention method* is related to the “Ex e“ or “Ex i” mode of protection. The “Ex e” (Increased Safety) is where additional measures are applied to the electrical equipment to increase the safety level, thus preventing excessive temperature development and the occurrence of sparks or electric arcs within the enclosure or on exposed parts of electrical apparatus, where such ignition sources should not occur in normal service [4]. The “Ex i” (Intrinsic Safety) is where the value of current, voltage a power are considered intrinsically safe. This means that under any operational condition or unserviceable state, it cannot produce any spark or overheat such as to ignite an explosive atmosphere.

Another mode of protection according to the prevention method is “Ex t”. It is used for DUST atmosphere protection only, so it is not very appropriate for this application.

The *segregation method* is related to the following mode of protection: “Ex m”, “Ex p”, “Ex o”, “Ex q”, and “Ex t”. The “Ex m” (Encapsulation) protection consists of covering the components which might produce sparks or over temperatures, with a resin which is resistant to environmental conditions. The “Ex p” (Pressurized) exploits the segregation technique by impeding the access of explosive atmospheres through an internal pressure due to insufflation of an inert gas or air, maintaining an internal pressure greater than the external one. The “Ex o” (Oil Immersion) exploits the principle of segregation using Oil applied as a filler. Maintenance is evidently difficult as the container must be emptied of oil and, subsequent to any maintenance and/or repair work, refilled. Furthermore, the presence of systems guaranteeing a constant level of oil is required. The “Ex q” (Powder Filling) protection involves the filling of the component casing with a material, normally with quartz powder, which under normal conditions impedes any sparks being transmitted to dangerous atmospheres externally.

IV. RISK ASSESSMENT

The failures in PV systems can be classified in two categories: those related to the overall PV system and those concerning single PV modules. Some of these failures occur because of transportation, installation, clamping, connector failures (fuse boxes, extension cables, inverters or combiner boxes) and lightning [4].

The main reasons for PV plant failures are mainly due to installation errors and design/planning & documentation errors. Among design errors, a very important cause of failure in PV plants is related to lightning and overvoltage systems. According to the literature, 30% of PV plants are subjected to this kind of problems in the first three years of operation. Fig. 3 shows an example of damaging in PV module due to lightning.

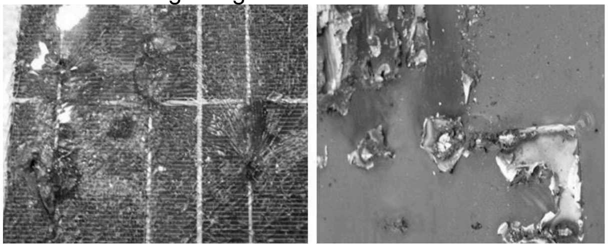


Fig. 3 – Fault due to lightning: (a) front of the module, (b) back of the module.

The serious faults occurring during the PV plants installation are due mainly to lack of heat dissipation in inverter and solar generator cabling not mechanically fastened. Some other faults can be due to the junction boxes or incorrect terminal connection in cables.

The solar module consists of PV cells, encapsulant, bypass diodes, connectors, frame, junction box, cable, glass on the front side of the module for protection, and glass or polymer film on the rear sheet of the module. These components can protect the cells against the climatic stress and various contacts.

During the PV power plant operation, PV modules may be subjected to many different failures and defects (e.g., snail trails, hot spot, micro cracks, cell breakage, delamination, bubbles, yellowing, discoloration, oxidation, corrosion, etc...) due to the weather condition like wind, sand, humidity, high UV radiation and other internal and external stresses. However, most of these stresses cause power losses in the PV systems, hence investigating about inspection methods of PV module is a significant issue to identify the failures in the solar energy field. Thus, the lifetime of PV modules hugely depends on monitoring and maintenance; early defect detection can reduce the degradation of PV modules as reported in [5] and [6].

Typically, any effect on a PV module which decreases the performance of the module, or even influences the module characteristics, is considered as a failure whereas, a defect can be defined as an unexpected or unusual thing which has not been observed before on the modules. However, defects often are not the cause of power losses in the PV fields.

The rated performance of PV modules is at a standard temperature (25ºC). Hence, any increase in PV module temperature will reduce the output vs. the standard performance. Temperature stress can accelerate the chemical degradation of the panels. Therefore, it can lead to creating defects in the PV modules, and the performance of PV systems may decline in a short time.

According to the investigations, most visible failures appear in the PV modules due to the polymers' defects such as delamination, bubbles, cracking, or yellowing. Other phenomena such as snail trails, shading, hot spots, micro-cracks, and cell breakage defects can have the highest influences on the performance of the PV modules. These kinds of failures can, in fact, be better detected also using thermal and infrared cameras.

Adherence loss among PV modules' layers usually causes delamination. Typically, it happens between cells and front glass or between polymeric encapsulant and cells. This defect can increase reflection, and the water can then penetrate into the module itself. Nevertheless, a delamination defect in the borders of the PV module causes both electrical and installation risks and likely transmittance losses. On the other hand, a bubble defect is more similar to delamination, while adherence losses occur only in some areas of PV modules due to chemical reactions. Bubble defects arise in the backside and not on the front side of the PV module. In fact, any object in the back cover or polymeric encapsulant prevents the dissipation of heat from the solar cells.

Yellowing and browning can appear in PV modules due to dry heat (e.g., due to desert climate), high UV radiations, and humidity. Moreover, it can occur because of insufficient adhesion between cells and glass material. However, this creates an obstacle between solar cells and sunlight, which leads to reduction in PV modules' voltage output.

The corrosion will occur in the PV modules' glass and metal because of the combination of gasses and humidity. Snow and wind can produce a higher static load; hence, they can break PV modules' glass due to the mechanical load for dynamic and static reasons. In the desert climate, for example, sand, wind, and dust significantly decrease the performance of PV modules. Furthermore, glass breakage can be caused by object impacts (see Fig. 4).

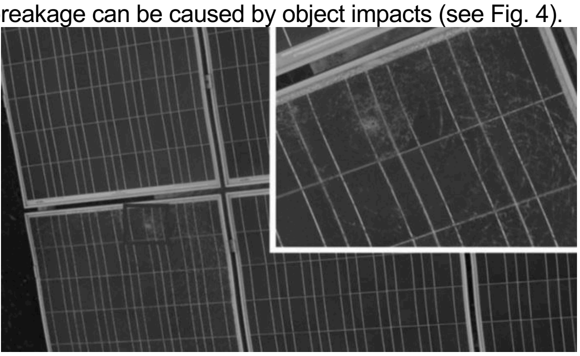


Fig. 4 – Picture captured by a visual camera of a particular shock-defect.

Micro-crack defects can appear as some different color lines on both sides of the PV module, and they can be detected only using special devices such as thermal and infrared cameras or by optical methods. Cracks and micro-cracks are formed in PV modules due to mechanical loads or during the process of lamination and soldering. Cracks in solar cells can influence the performance of PV modules, thus investigation about the formation of the cracks is required.

The PV modules can be subjected to a defect known as the snail trail phenomenon. The snail trail impact emerges on the PV modules' edge because of both environmental conditions and manufacturing process. They appear as dark and small lines or solar cell discoloration on the PV modules. Furthermore, snail trails can occur if the PV cell is produced as a thin thickness, and in this case, it cannot compromise efficiency too much [6].

One of most significant defects is the hot spot phenomenon, which is defined as an area on the PV module with a higher temperature. Typically, the reasons of the hot spot defect include mismatch of solar cells, partial shadowing, or any failure in the interconnection between the solar cells. Hot spots can easily be detected by thermal cameras. Fig. 5 shows some hot spots detected by IR inspection and also the corresponding visual images [8].

The hot spot defect is very critical because increasing temperature could ignite the explosive atmosphere. For this reason, it is very important to evaluate the maximum temperature during his failure also in order to determine the Temperature Class of the Ex panel.

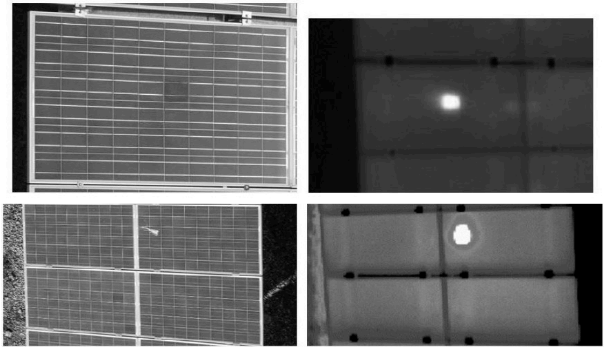


Fig. 5 – Hot spot due to corrosion or dirt

Some failures occur within the first two years of the PV modules installation which impacts the costs of PV modules installers and manufacturers (because they should be responsible for these failures and defects).

V. IMPACT TEST AND ENERGY PERFORMANCE

All the previous modes of protection summarised in section III above can be used for an Ex Photovoltaic panel both for Zone 1 and Zone 2. Each of them has advantages and/or disadvantages over the others. Whichever mode of protection is used to make the photovoltaic panel usable in explosive atmospheres, first of all it is mandatory to follow the General Rules and all the general tests must be taken into account.

In particular, for this kind of products, the impact test according to IEC/EN 60079-0 (General Rules) could be a problem, because it is a little bit different from the test performed according to the photovoltaic industrial panel Standard IEC/EN 61215-2 [9]. In fact, according to the Standard IEC/EN 60079-0 [10], the impact test shall be performed using a spherical mass of 1 kg that fall down in order to have an impact of 4J (high risk) on the transparent part (where the cells are) or 2J (low risk). In case of the test should not be positive, the manufacturer could install on the transparent part a metallic grid. The individual openings of the grid can be realized from 625mm^2 to 2500mm^2.

So, in order to pass positively the impact test, it is necessary to have a sufficient thickness of the glass. If this is not enough, it is necessary to apply an additional glass or an additional guard grid. These additional protections reduce the efficiency of the photovoltaic panel, so it is necessary to choose the best configuration in order to have the maximum result.

For this reason, we prepared and tested the following three configurations of photovoltaic panel (Fig. 6):

a) Standard photovoltaic panel (as Reference);
b) Reference panel in which an additional 5mm Glass has been added in the front of each module (as Double Glass);
c) Reference panel plus a Grid in the front of each module (as Grid). The dimension of the individual opening of the grid is 2500mm^2.

Fig. 6 – Reference, Double Glass and Grid

The test has been performed by connecting two modules (module A and module B) of the same typology in series and then to the grid by using a single inverter. This means that every configuration is composed of module A and module B, so in the following table it is possible to check both the results of single module (A or B) and the result of A+B for Reference, Glass and Grid configuration.

Table 1 shows the results of the characterizations tests.

TABLE 1 – Maximum Power Determination measured in some days of 2019

Sample Type	T (°C)	G (W/m^2)	V_{MPP} (V)	I_{MPP} (A)	P_{MPP} (W)	Eff (%)	P_{dat} (W)
Reference A	49.9	978	16.45	7.12	117.4	96.5%	121.6
Reference B	54.0	968	15.90	7.05	112.2	95.2%	117.8
Reference A + B	50.1	1000	31.85	7.31	232.8	93.7%	248.5
Double Glass A	50.2	945	15.85	6.08	96.4	82.2%	117.3
Double Glass B	49.5	949	15.70	6.23	97.8	82.7%	118.2
Double Glass A + B	48.8	983	32.00	6.36	203.7	82.8%	245.9
Grid A	50.4	928	16.40	5.35	87.7	76.2%	115.1
Grid B	47.4	922	16.45	5.51	90.6	78.0%	116.1
Grid A + B	48.8	977	32.3	5.83	188.3	77.1%	244.1

The ambient temperature has been measured by using a meteo-station with calibrated sensors, while the panel temperature is measured by using an IR camera [11]. Table 1 shows the results of the tests in term of the Maximum Power Determination, considering Reference A+B, Double Glass A+B and Grid A+B configurations. The data sheet power (P_{dat}) at temperature (T) and irradiation (G) measured during the test is also reported. Finally, the efficiency (Eff) is evaluated comparing the power at maximum power point (P_{MMP}) and the data sheet power.

The measured I-V and P-V curves of these three different cases are reported as follows:

- Ref. A+B (Fig. 7);
- 2Glass A+B (Fig. 8);
- Grid A+B (Fig. 9).

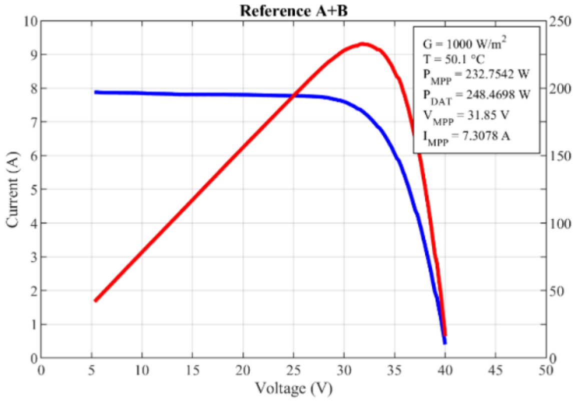


Fig. 7 – IV (blue) and PV (red) line curves for Reference A+B panel.

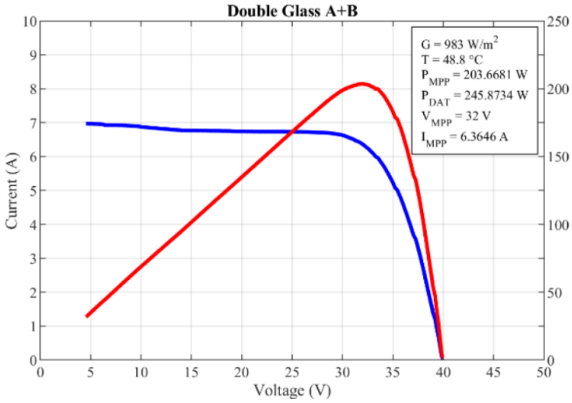


Fig. 8 – IV (blue) and PV (red) line curves for Double Glass A+B panel.

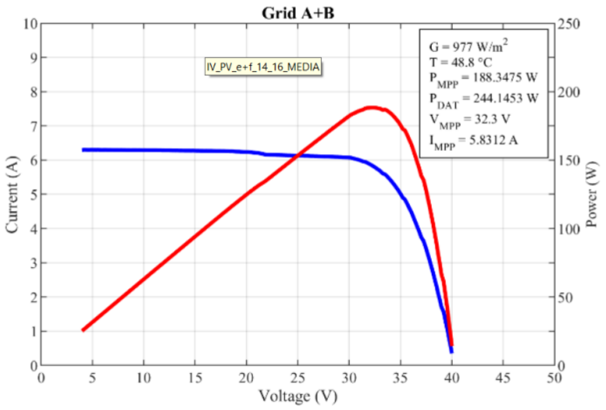


Fig. 9 – IV (blue) and PV (red) line curves for Grid A+B panel.

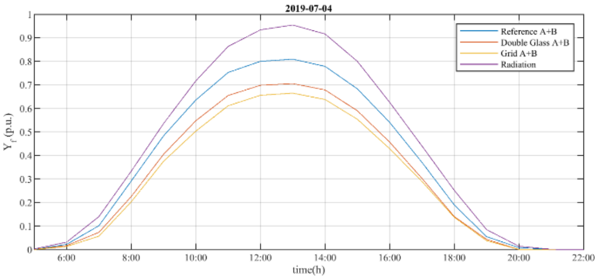
The box in each figure reports the temperature of the panel (T) and irradiation (G) measured during the test and also the values of current, voltage and power at MMP.

Table 2 shows the results of the test of Energy Performance for the three different configurations analyzed. The energy is calculated day per day for 9 different days in 2019; the total amount of radiation (I_{rr}) and the average ambient temperature (T_{av}) for each day is also reported. Δ% represents the difference in term of energy produced by Double Glass and Grid respect to Reference panels.

TABLE 2 – Energy performance for nine different days

Day	Ref. A+B (Wh)	Double Glass A+B (Wh)	Δ%	Grid A+B (Wh)	Δ%	I_{rr} (Wh/m²)	T_{av} (°C)
04/07	1826	1550	-15.10	1446	-20.77	7644	25.7
05/07	1868	1583	-15.22	1482	-20.65	7865	27.6
06/07	1748	1486	-15.02	1383	-20.91	7370	27.1
10/07	1732	1495	-13.67	1393	-19.57	7141	24.4
11/07	913	764	-16.29	710	-22.26	3459	23.6
12/07	1849	1577	-14.72	1476	-20.20	7741	24.9
13/07	1818	1521	-16.32	1419	-21.95	7578	25.5
14/07	1859	1581	-14.97	1485	-20.13	7738	24
15/07	787	664	-15.57	608	-22.68	3019	19.4

As showed in Table 2, the energy performance of the Double glass panel is about 15% less than the Reference and the energy performance of the Grid panel is, more or less, 20% less than the Reference panel. Fig. 10 shows the measured final yield for the three different configurations and the radiation for three days of the nine tested.



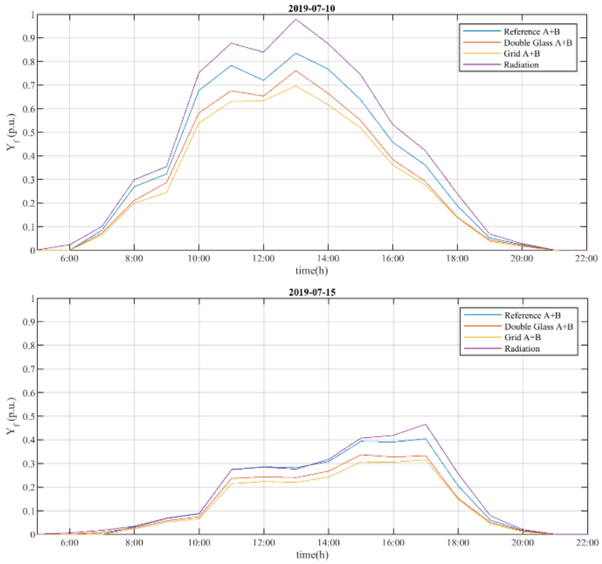


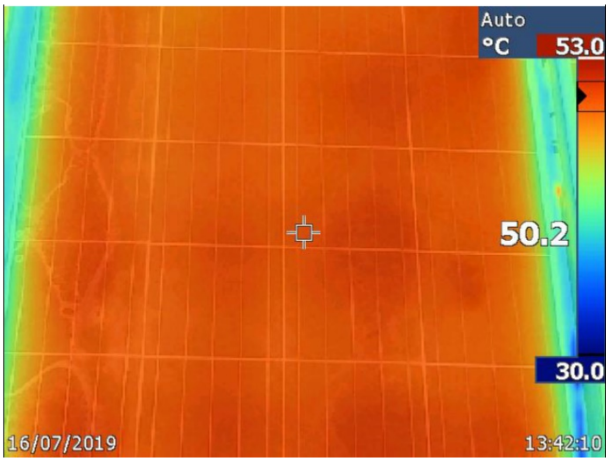
Fig. 10 – Final yield and irradiation measured in three different days.

Double Glass configuration always outperforms the Grid configuration. The addition of a second glass reduces the amount of radiation reaching the photovoltaic cell, consequently reducing the efficiency of the photovoltaic module. The addition of the grid, which makes the module more robust in term of Ex environment, causes local shading which reduces the performance of the module even more.

VI. THERMAL TEST

The maximum temperature reached by the panels during the normal running of the photovoltaic panel is a very important data, because that value determines the class of temperature of the panel. The Class of Temperature is a classification of an Ex apparatus and it is important because it gives an indication about where the apparatus can be installed according to the presence of gas type. In order to determine the Class of Temperature it is important to know the maximum temperature of the apparatus during its running.

All the configuration tested have showed, more or less, the same maximum temperature on the surface (see Table 1). The grid seems to show a temperature a bit less, but it may be due to the shading of the grid itself. Anyway, the maximum temperature is around 50°C, as showed in Fig. 11.



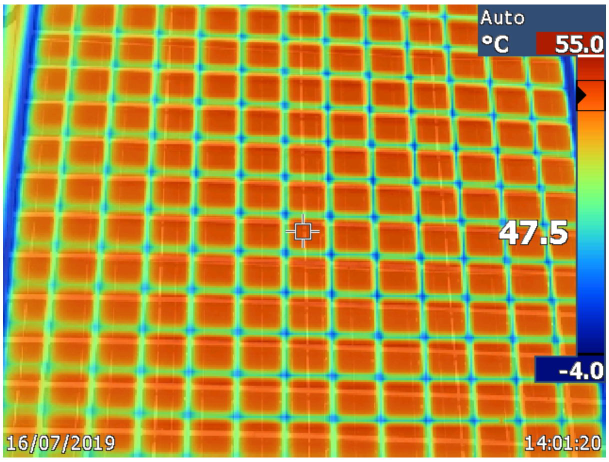


Fig. 11 – Thermal result in normal running for the Double Glass and Grid configuration respectively.

The same test shall be also performed in case of failure (if present), in order to evaluate if the temperature increase in that specific condition.

According to the risk assessment explained in the paragraph IV, the only critical cause of failure is when a hot spot happens. The IEC or EN Standards do not explain the test procedure in order to determine the max temperature on the photovoltaic panel. It works differently from other electrical equipment, so the result of the maximum temperature depends on the solar condition during the test.

VII. CONCLUSION

As for the test result: adding some “transparent” material on the reference panel, in order to pass positively the impact test per IEC 60079-0, causes a reduction of performance of the panel. This means that the manufacturer has to think regarding the mode of protection to use for this kind of apparatus. For example, it is absurd to use an Ex d enclosure with a big window (15-20 mm of glass) for this kind of application.

Moreover, another problem remains unsolved, that is the procedure for thermal test both in normal condition and in failure condition. As explained before, the IEC/EN Standard 60079-0 does not explain the test procedure in order to determine the max temperature on the photovoltaic panel. It works differently from other electrical equipment, so the result of the maximum temperature depends on the solar condition during the test. In conclusion the test is not repeatable.

VIII. BIBLIOGRAPHY

[1] R. Faranda, K. Fumagalli e M. Bielli, Lithium-ion batteries for explosive atmosphere, EUR 19_32, PCIC 2019, Paris.
[2] ATEX Directives 2014/34 EU.
[3] K. Fumagalli, R. Faranda e P. Corbo, Different protection modes of Ex LED luminaires, BER-89, PCIC 2016, Berlin.
[4] K. Fumagalli, R. Faranda e L. Farnè, Analysis of possible LED failure mode, AM-14, PCIC 2014, Amsterdam.
[5] S. Leva, M. Aghaei, Chapter 3 - Failures and Defects in PV Systems, in “Power Engineering: Advances and Challenges Part B: Electrical Power”, CRC Press, 2018, pp. 55-83.
[6] F. Grimaccia, S. Leva, A. Dolara and M. Aghaei, "Survey on PV Modules’ Common Faults After an O&M Flight Extensive Campaign Over Different Plants in Italy," in IEEE Journal of Photovoltaics, vol. 7, no. 3, pp. 810-816, May 2017, doi: 10.1109/JPHOTOV.2017.2674977.
[7] A. Dolara, G. C. Lazaroiu, S. Leva, G. Manzolini and L. Votta, "Snail Trails and Cell Microcrack Impact on PV Module Maximum Power and Energy Production," in IEEE Journal of Photovoltaics, vol. 6, no. 5, pp. 1269-1277, Sept. 2016, doi: 10.1109/JPHOTOV.2016.2576682.
[8] F. Grimaccia, S. Leva, A. Niccolai, PV plant digital mapping for modules’ defects detection by unmanned aerial vehicles, IET Renewable Power Generation, vol. 11, n. 10, 16 August 2017, p. 1221 – 1228, DOI: 10.1049/iet-rpg.2016.1041.
[9] IEC/EN 61215-2: Terrestrial photovoltaic (PV) modules - Design qualification and type approval.
[10] IEC/EN 60079-0: Explosive atmospheres - Part 0: Equipment - General requirements
[11] [Online]. Available: www.solartech.polimi.it. [Accessed: 09-Nov-2019]

IX. VITA

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