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Fire Risk Assessment of Photovoltaic Plants. A Case Study Moving from two Large Fires: from Accident Investigation and Forensic Engineering to Fire Risk Assessment for Reconstruction and Permitting Purposes

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Photovoltaic (PV) plants have known a steep increase in number and installed power in the last decade all over the world. Together with this growth, also associated risks grew significantly. Among these fire risk has caught the attention of both Authorities, plant managers and any other stakeholders (such has owners of the property) due to the high number of fire involving solar plants. In 2012 around 600 fires involving solar plants occurred in Italy, with this figure in constant growth. In this paper fire risk assessment of PV installations is presented through several steps since the problem has gained a significant importance.

1. A new fire scenario

The turbulent growth of the photovoltaic roof installed plants as consequence of the public incentives to green energy placed some new fire risk scenarios for the building covered by the FV plants and opened a new field for the fire research and the fire investigators.

After the first fire episodes, with large roof fires often followed by compartment fire, some resulting in the complete loss of the structure, the fire investigations revealed various till unconsidered fire risks related to DC arcing ignition of combustible roof insulation layers, often polyurethane or polystyrene foam.

The heavy loss consequence of those events could be greatly reduced by a risk analysis approach in the early design stage of the plants, evaluating the fire risk and the consequence of the most common failure associated with a PV plant, as cell mismatch, Hot Spot, DC arcing and localized fires in connection boxes or PV modules. On the other hand, the run to the public incentives produced a shortening of the timing for design and preliminary hazard analysis of projects. Also, the pressure on installation timing related to the green energy public program of economic incentives increased the number of workers operating in the photovoltaic field without an appropriate training. At the same time the lack on the field of materials code and standardization for the specific PV application of materials and know-how of in installers teams led to an undervaluation of the fire risk for the PV plant and for the building housing the plant.

2. Some statistical data

The available data on photovoltaic plants fires includes a large range of fire episodes, including connection box fires, fire involving only a few PV modules and large fires (the majority) occurred to plants located on the roof of the building, which spread inside throughout the skylights in the roof.

The above data refer nevertheless to a large group of accidents of different magnitude regarding fires which involved, but not necessary started from, photovoltaic plants in Italy.

The analysis of the data give the evidence of a peak of fires in 2012, following the first wave of installations. As the fire involved in fact new plants, they should be considered as early fires in consequence of lack of qualification of designers/installers .

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Root causes often comprehend the incorrect management of shading, the exposure of plant components to out of standards conditions (heavy water condensation under the panels), low quality components, crushing of cables during the installation, under evaluation of typical DC current behaviour, mismatch of PV cells .
The final effect of those phenomena is often a diffused ground dispersion of DC current, with an immediate loss of power generated and associated to a DC arcing, following the insulation thermal stress induced by over currents flowing as effect of multiple faults.
The multiple fault probability couldn't be considered negligible, It's an important difference between AC and DC circuits, due to the very high number of connection and components offer a large set of scenarios conducting to ground dispersion and to the impossibility to power off the plant.
As from the Figure 1 data the trend of fires involving photovoltaic plants appears to drop after 2012. This could be a consequence of several factors including: 1) out of service of low quality plants as they went on fire, 2) improvement of the actors of the market of PV related services, 3) selection of the producers and installers after the prices decrease consequent to the decrease of public incentives, having the survived societies a general better qualified personnel.
At the same time the lack on codes and standards started to be fulfilled by national regulation, including national standards which considered the results of fire reaction tests more complete than UL 790 and ASTM E 108 requirements.

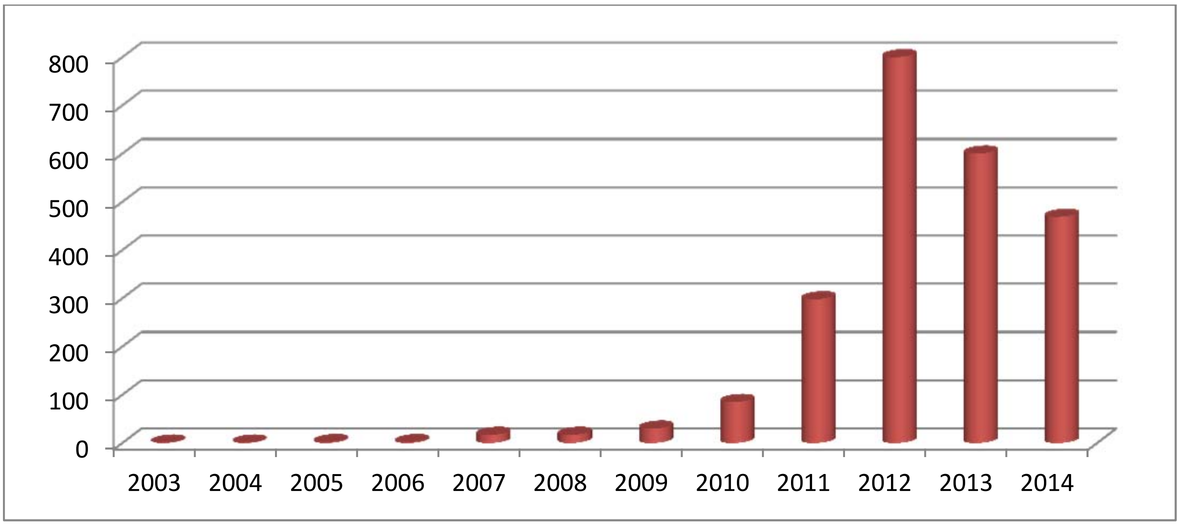

Figure 1: Fire related to Photovoltaic Plants in Italy, Courtesy of Italian National Fire Corp, Statistical Service.

Moreover, after the first relevant fire events all over the world, most of PV panels producer started to include fire resistance requirements in the user manual installation prescriptions.
The decreasing number of fires is probably the evidence that the peak on fire number war related to faulty components or poor installations in the dash to economic green energy incentives, but as the knowhow of workers and designers increased, it could be expected a second peak in next years (5 or 10 y) as the ageing of components, mainly insulations, will lead to an increase of faults.

3. Some case studies

Various fire events involved roof housing photovoltaic plants, some with bad damage of the building roof and with the consequence of large compartment fires inside the structure, consequence of fire spread inside the building.
In Figure 2 a 1000 m2 warehouse housing a PV plant keep on fire. The evidence of the fire investigation conducted evidenced various elements in charge of PV Plant. In that case a conventional PV plant was installed on a thermally insulated roof. The episode evidenced the lack on fire regulation related to the introduction of photovoltaic plants on existing roof coverings, designed and installed years earlier with the aim of a better thermal insulation by mean of thick combustible foam layers but potentially offering a tremendous fire load.
The typologies of fires resulted in various magnitudes from a small fire ignited in an electric box (Fig. 3) to the complete ignition of the cover, spreading the fire inside the compartment with a top down pattern, until now uncommon (nearly unknown) in the fire investigation literature.

Another new evidence resulted in the fire of some photovoltaic panels as effect of mismatch of single cell, or an incorrect installation or an electric fault creating loops or connection between different strings, with the immediate consequence of the behaviour as an electric charge of various panels, the overheating, the loss of electric insulation and the final scenario of the fire of combustible layers of the panels (Ethil vinyl Acetate, Tedlar).
Also non-conventional PV plant adopting the in-roof technology were involved in fires of, in some circumstance, large magnitude. This is the case of the fire of a 6000 m2 roof plant depicted in Figure 5.
The resulting fire produced large plumes spreading on city skyline, which produced citizen concern on environmental pollution and public safety.

Figure 2: a 1000 sq meters warehouse housing a PV plant keep on fire. The evidence of the fire investigation conducted reported various elements in charge of PV Plant.

Figure 3: the Fire of a Connection Box in a ground PV Plant.

Figure 4: the The DC arcing effects on a external side of a polyurethane sandwich.

Figure 5: A large warehouse involved by a fire, probably external at the PV plant but strongly influenced in his growth and propagation by the photovoltaic layers.

4. Dynamics of fire growth and propagation

As from the fire risk assessment, the photovoltaic plant components (on a roof or on a building façade) are for sure able to:
-modify the propagation of fire outside or through the building;
-interfere with the smoke and venting systems of the combustion products;
-obstacle the fire extinction operations;
-introduce a further hazard through electrical shock for fire-fighters and rescue operators for the presence of circuit energized components.
As the case depicted in Figure 5 concerns, a preventive fire risk assessment on the photovoltaic roof configuration should have early identified the inherent fire hazard produced by coupling a strong fire load to a new ignition source (i.e. the fire load inside the compartment and the in-roof installation of PV panels).
Various concerns arise from the "ante" and "post" solarisation conditions, following different propagation scenarios:
-Compartment fire spreading through openings and propagating on the roof;
-Fire starting from PV modules integrated on the roofing and propagating to compartment.

The investigation had established whether the solarisation of the roof led to an increase of the fire risk and how the PV modules, the insulating roof coverings and the underlying compartments interact with each other in case of fire. Ante and post solarisation fire events were individuated and classified in function of different fire propagation, as shown in Table 1.
Frequencies of these events were estimated using fault tree analysis coupled with an event tree analysis in which probabilities have been derived from recognized literature data (Ramachandran).
Figure 6 shows the event tree related to the Top Event defined 2C in Table 1.

Table 1: Ante and post solarisation fire event individuated and respective frequencies.

Top Event	Description	Frequency	Probability class
1A	Fire extended inside the compartment	2.64*10-1	Probable
1B	Internal fire propagating outside	5.81*10-2	Probable
1C	Fire propagating outside and spreading on roofing	2*10-2	Probable
2A	as 1A with PV panels	2.64*10-1	Probable
2B	as 1B with PV panels	5.81*10-2	Probable
2C	as 1C with PV panels	2.0*10-2	Probable
2D	Ignition due to PV modules, propagating along the roofing	6.36*10-11	Extremely improbable

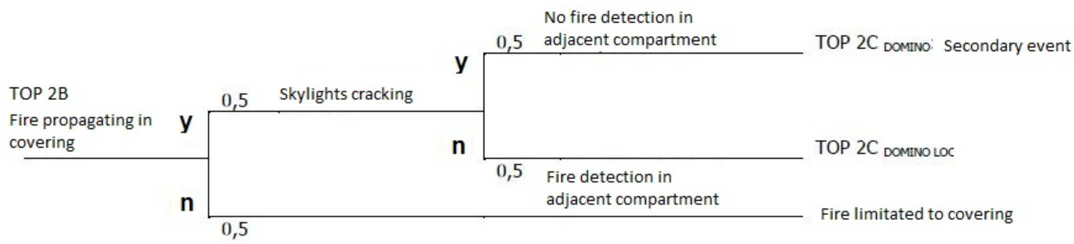

Figure 6: Event tree analysis, from fire propagating in covering to fire extended to adjacent compartment (secondary event).

This "Top Down" fire spread scenario /from roof to underlying compartment) probably constitutes a rather new entry in fire investigation science, as produced by the interaction of a combustible insulating layer, earlier installed on the top of the building and the ignition sources inducted by the photovoltaic plant.
The incorrect installation, or simply a fault in a component, could easily ignite a severe DC arcing, with a stable current flow enough intense to drill a metal layer of a sandwich, and consequently ignite the combustible layer below it.
Also, the light openings or even the fire and smoke evacuation system could be a way of internal spread of the fire ravaging the insulating cover, so the combined effect of those elements resulted in most of the destructive fire originated by the photovoltaic plants.
Due to this, in order to verify any eventual impacts on existing buildings, it is important to verify how the new PV installation modifies the existing fire risk. In order to perform this evaluation a fire risk assessment of both existing and future situations should be conducted. As briefly described this can be accomplished with a three step analysis: identification of the fire propagation mechanisms that are applicable to the specific case (specifically those associated to the layout); identification of the main top events (TEs) including secondary and domino effects; evaluation of the probable failures of the PV plant components and those risks associated with the already in place existing components, systems, etc.; identification of the frequencies of both TEs and

associated resulting scenarios for ante-post comparison and verification against a tolerability criteria definition. This activity can be performed by the use of FTA and ETA coupled with data coming from literature and increasing operational experience.

5. The fire requirements of PV panels

The fire regulation on PV panels is based on simple test included in UL 790 or ASTM E 108. A number of tests were conducted after the concerns following the first fires by UL and Solar America Board for Codes and Standards (Solar ABCs), with various results, all indicating the negative influence of a PV panel over a roof covering in terms of heat dissipation, smoke trapping, and fire spreading.
Also the results underlined that the coupling of two good fire rating elements could even result in a worse fire rating for the overall package.
The evidence of DC arcing impact is driving on a most appropriate fire evaluation of covering and to dedicated active elements for early DC arcing detection.
On this basis the NFPA 70 (National Electric Code) introduced the Arc Fault Detection Interrupter as mandatory on last edition, after a number of fire resulted on private dwellings as effect of photovoltaic system malfunction/fault.

6. Lessons learnt and conclusions

The photovoltaic technology for green energy production could produce severe fires on roof building not rated to be coupled with a inherent ground dispersion source. As a completely incombustible roof could be a good solution to limit the risk to the acceptable fire risk connected with this technology, an early fire risk assessment conducted by the risk analysis tools could be a strong tool to improve fire safety on by now installed roof plants.
The fire investigation results evidenced on various devastating fire the need of a comprehensive revisit of fire codes on photovoltaic building roof installed, mainly with insulating or combustible coverings immediately under the active components of the plant.
The photovoltaic producers indicating strong fire requirements on installation manuals after the first relevant fire episodes introduce various question on the standard conformity and in fire code enforcement on existing photovoltaic roof, with various items on plant documentation legal soundness .

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