Integrity and durability of photovoltaic modules: an overview of mechanical failure modes

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ABSTRACT. An overview of the principal mechanically-induced failure modes in photovoltaic modules is herein presented. They include both failure and damage at the level of the silicon cell (cracking, cut of metallic fingers due to silicon chipping) and failures involving the layered structure of the module (debonding of the polymeric layer encapsulating the solar cells, interlaminar debonding in the backsheet). These failure modes are expected to be even more critical in the future due to the development of non conventional semi-transparent or flexible modules for architectonic or high-tech applications. From the proposed overview, it emerges that fundamental research on mechanics of photovoltaic modules is relevant to improve safety and durability of this technology in the years to come.

KEYWORDS. Photovoltaic modules; Durability; Structural integrity; Cracking.

INTRODUCTION

Photovoltaics (PV) is a technology designed to convert the incident sunlight into electric energy. For its renewable characteristics, PV is considered, together with wind energy, as one of the most effective methods to replace fossil fuel power plants and significantly reduce the production of CO2, in line with the EU energy policy [1-5]. As a confirmation of the PV technology growth, the price learning curve for PV over the last 25 years (Fig. 1) shows a continuous reduction in prices of approximately 20% for every doubling of the installed amount of modules. The target of 1 Euro/W_p is expected to be achieved by 2020. This price reduction has been made possible thanks to a significant technology progress leading to an increase of cell efficiency, h_{cell}, up to about 20% and a reduction of the solar cell thickness, d, down to 200 μm.

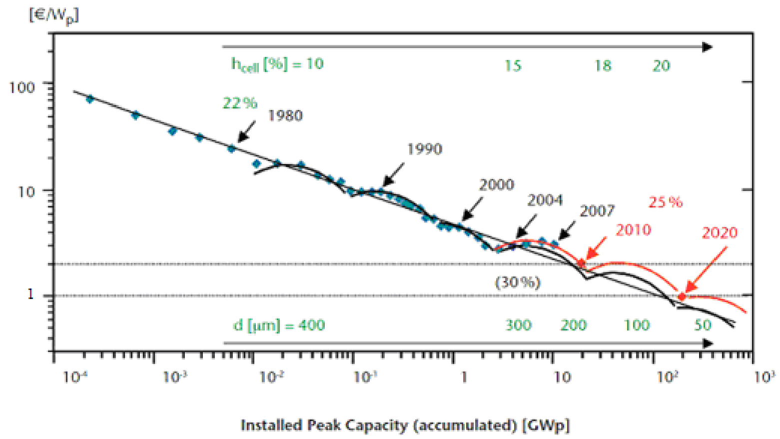


Figure 1: Price learning curve for PV modules made of crystalline silicon [6].

So far, progress in solar cell technology has been achieved almost exclusively by developing the silicon wafer technology which dominates the market. This technology consists of processing monocrystalline or polycrystalline silicon wafers that are 200-300 μm thick. However, the potential for further cost reduction is far from being exhausted. New technologies using thinner and thinner silicon wafers and films to save material have a high potentiality, although silicon cells will be more prone to cracking. New kinds of cell structures and coatings are also explored at the research level to achieve higher solar energy conversion efficiencies.

In this context, research on the durability of PV modules is a topic much less investigated as compared to the enhancement of electric performance, although it is for sure relevant for the long-term reliability of PV technology. To efficiently tackle this issue, a synergy of competences ranging from structural mechanics to solid state physics is required. Photovoltaic cells must be encapsulated to ensure the long-term, safe operation of these energy converters and allow for their integration in buildings and constructions. To resist mechanical loads due to snow, wind and vibrations, as well as environmental aging due to moisture and temperature variations, PV modules are realized with a layered structure [7]. Their stratification can be asymmetric, as for the classical modules installed in PV arrays (Fig. 2), or symmetric with a glass-EVA-silicon-EVA-glass sequence, as in the very recent applications for semi-transparent roofs and walls (Fig. 3).

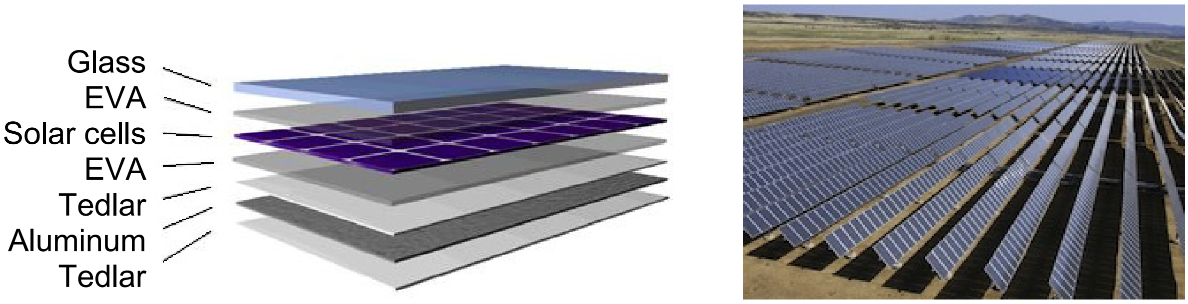


Figure 2: Sequence of layers of PV modules installed in PV arrays.

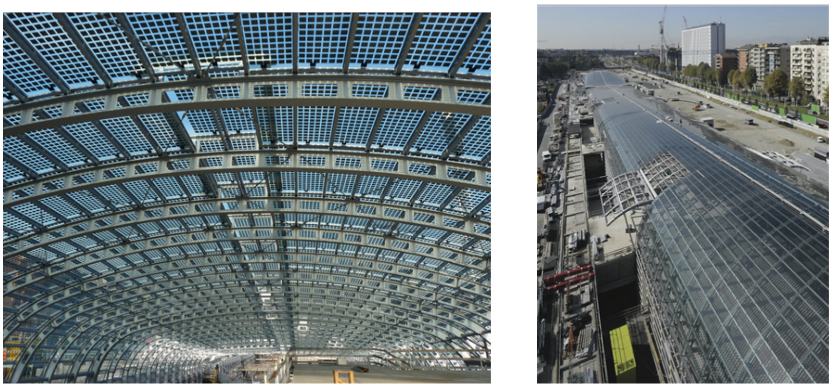


Figure 3: Semi-transparent PV modules used in the shell cover of Porta Susa railway station, Turin, Italy.

Clearly, due to the integration of PV modules in buildings and constructions, the role of these layered composites is no longer purely electrical. Although companies advertise the electric efficiencies of their products in relation to their architectonic properties like the shadowing effect (Fig. 4), structural functionality and durability have also to be assessed and assured. At present, the existing qualification standards IEC 61215 [8] require passing of severe laboratory tests in a climate chamber. In spite of that, additional failure modes not reproduced in the laboratory have been reported in the field and, in some cases, critical conditions for safety have been noticed [9].

Potentially, the shape and the layered structure of PV modules can be generalized from the simple slab to accommodate specific architectonic requirements or high-tech applications. Examples on the market are PV modules where monocrystalline solar cells are encapsulated into thermoplastics without the use of glass and EVA. This allows the modules to achieve a certain degree of flexibility so that they can be glued on curved substrates, see Fig. 5. For all of these variants of PV modules, different polycrystalline microstructures, solar cells spacing and properties of the encapsulant/plastic materials are relevant for the resistance to cracking and durability. Therefore, a systematic investigation on these aspects is essential for improving the mechanical performance of PV modules for the long-term reliability of PV technology.

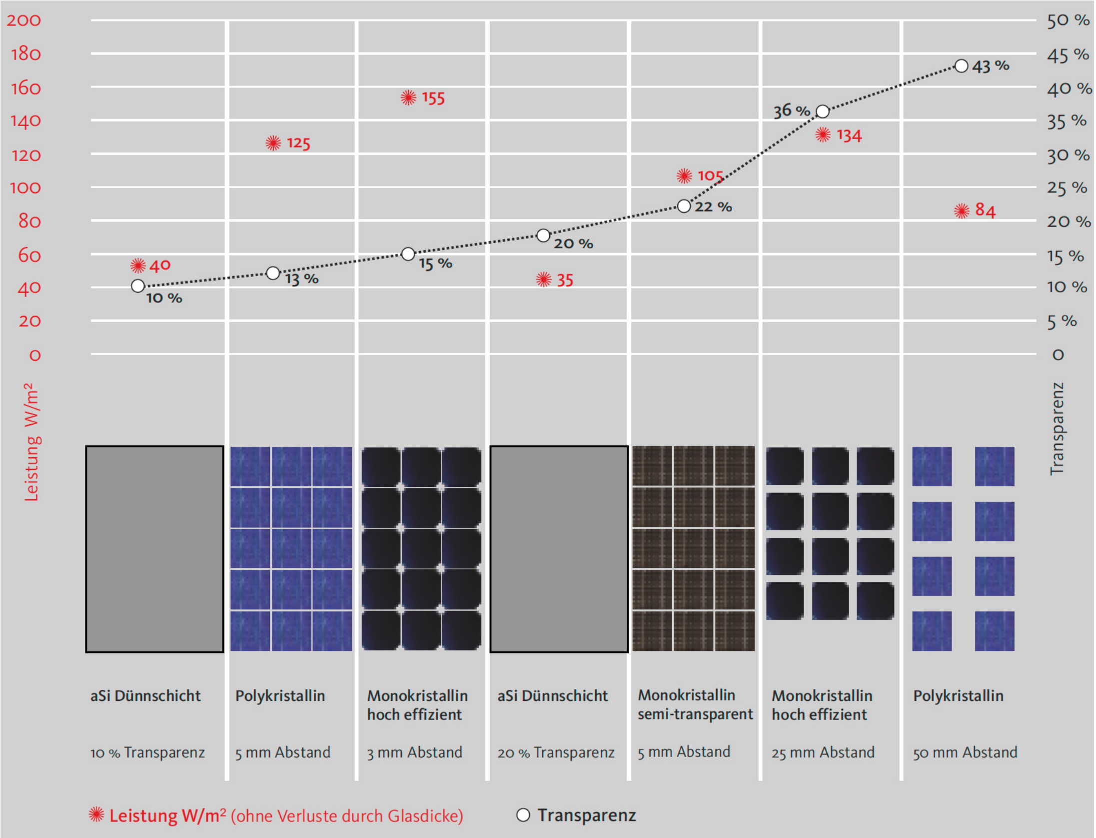


Figure 4: an example of technical data showing electric production and degree of transparency for different PV modules (the name of the producer has been masked).

In the present article, an overview of the main failure modes of PV modules observed in the laboratory or experienced in the field is proposed. This review is mostly based on recent articles appeared in conference proceedings, as a confirmation of the fact that durability of PV modules is a very active and new research topic. Finally, perspectives for future research on mechanical issues are discussed at the end of the article.

Figure 5: an example of flexible PV modules glued on a curved substrate.

MECHANICAL ISSUES AND FAILURE MODES IN PV MODULES

Laboratory tests

In case of PV modules used for solar arrays, research conducted in the laboratory of the Institute of Solar Energy Research in Hamelin, Germany [10-12] has put into evidence the criticality of mechanically-induced cracking on the potential power-loss of PV modules (see the electroluminescence image in Fig. 6, where the dark portions denote electrically inactive cell areas).

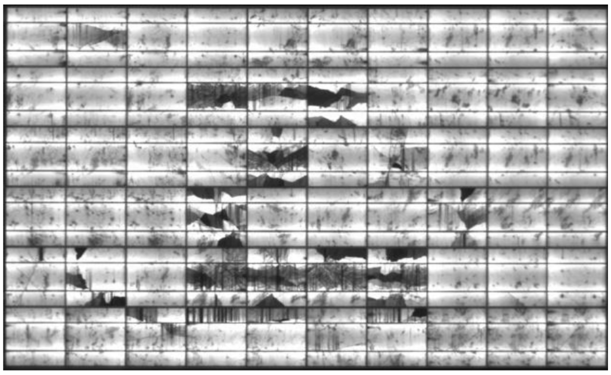


Figure 6: Electrically inactive areas, insulated by cracks, are visible in black [10].

Moreover, the crack orientation in the cells and the spatial distribution of cracks in the module was identified to be dependent on the cell position [10], as a confirmation that cracking is somehow related to the direction of principal stresses induced by snow pressure.
Sander et al. [13] proposed a systematic mechanical testing of mini-modules composed of monocrystalline or polycrystalline silicon cells under four point bending. The resulting crack pattern, shown in Fig. 7, was found to be dependent on the type of silicon and also on the direction of loading with respect to the main electric connections (called busbars). This suggests that the orientation of aluminum fingers and busbars plays an important role and it cannot be neglected.

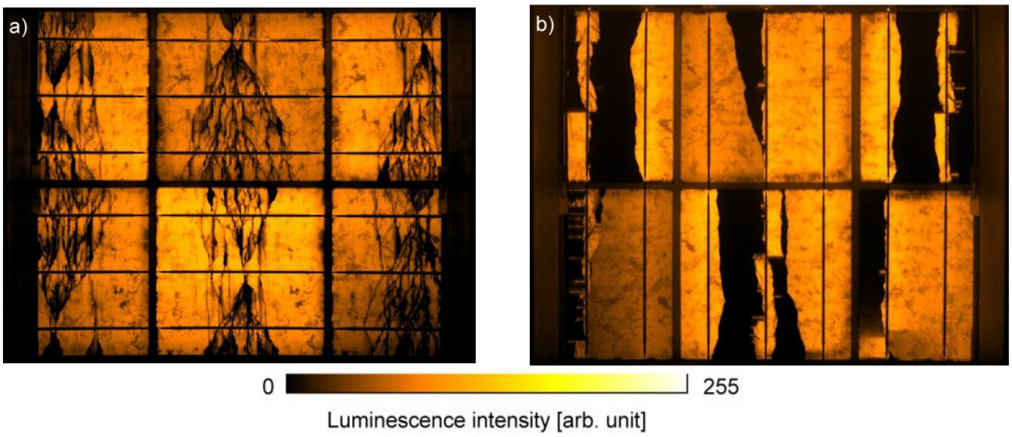


Figure 7: Crack pattern of mini-modules tested under 4 point bending. (a) Line loading perpendicular to busbars; (b) line loading parallel to busbars.

Thermoelastic deformations related to the day and night temperature excursions are also source of damage for the interconnections between the cells, as experimentally investigated by using the digital image correlation technique in [14]. From the theoretical point of view, this has been proven to be the result of the thermoelastic mismatch between the materials composing the PV module, characterized by very different stiffnesses and thermal expansion coefficients [7].

Field conditions

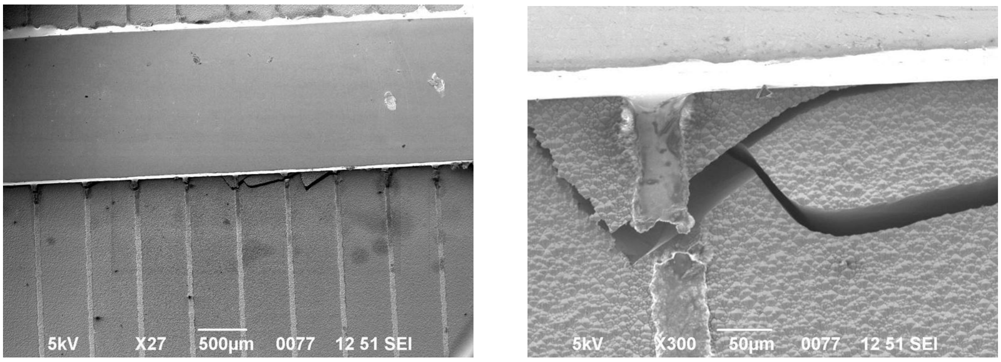
The examination of field conditions shows additional failure modes that are hard to be simulated in the laboratory. They regard broken electric interconnections, broken cells with hot spots very dangerous for safety, corrosion, delamination of the encapsulant, encapsulant discoloration, solder bond failures, broken glass due to impacts, electric circuit failures (junction box and module connection failures, arcing), and structural failures.

Among them, encapsulant delamination (Fig. 8a), backsheet interlayers delamination (Fig. 8b) and splitting delamination of the backsheet (Fig. 8c) are related to the degradation of cohesion at the various bi-material interfaces of the layered composite, presumably caused by moisture and thermal aging/fatigue. Encapsulant discoloration (Fig. 9) is often originated by UV radiation and high local temperatures. Hence, although discoloration is not originated by purely mechanical effects, it is a good index of possible hot spots and cracks. At a much smaller scale, but even more critical than the previous forms of damage, cracks in silicon near busbars leading to large disconnected cell areas (Fig. 10(a)), and cut metal fingers due to silicon chip out (Fig. 10(b)) can occur.

(a) (b) (c)

Figure 8: (a) Encapsulant debonding [15], (b) backsheet debonding [16], (c) splitting delamination of the backsheet [17].

Figure 9: Encapsulant discoloration [18].



(a) (b)

Figure 10: (a) SEM image of cracked silicon near the busbar; (b) SEM image of a cut metal finger due to silicon chip out [19].

DISCUSSION AND CONCLUSIONS

Most of the failure modes shown in the previous section are originated by mechanical loads, or by thermo-hygrometric effects leading to aging of the component materials. Information on in situ electric degradation rates of PV arrays installed since more than 10 years starts being available and it is essential for a critical examination of the actual durability of installed PV modules. Although preliminary data seem to confirm that degradation rates have improved for installations after 2000 [20], there are also other reported data [9] showing power-losses larger than 10% after 10 years of installation, exceeding the worst case scenario expected by producers' warranties. Due to a lack of suitable mathematical and computational models describing the aging of these composites, the various uncertainties can result in significant warranty risk for the end user. As pointed out in [9], the power-loss is not the only parameter to check. For safety reasons, high local temperatures near hot spots can be very harmful for the module and also for the substrate. Hence, the idea of PV modules that can provide energy in a reliable and efficient way without any kind of maintenance is just an illusion.

To make a significant progress towards the understanding of the origin of damage in PV modules, fundamental research on the interplay between the electric, thermal and mechanical fields has to be promoted. A first attempt to address the durability of PV modules within a multi-physics framework has been proposed in [21]. The development of computational models, able to simulate cracking and the interaction between the various fields involved, are expected to be extremely useful for simulating accelerated tests under conditions closer to reality that cannot be easily tested in the laboratory.

Indeed, further investigations are needed to greatly expand the service life of PV modules and develop new module technologies optimally modified for the aesthetics and mechanics of specific applications. All these open issues are of fundamental nature and they are worth investigating for the future of PV technology, regardless of the latest market trends.

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