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Why Do PV Modules Fail?

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Abstract

PV modules that are sold on the worldwide market today have to pass the relevant IEC tests for certification. These tests are only a mark for a certain quality level, not a reliability test. Nevertheless, manufacturers of PV modules give performance guaranties of 20 to 25 years on their products, some even more. Therefore the question to be asked is: 'How to survive 25+ years between the pole and the equator?' or, seen from the other side: 'Why do PV modules fail?' To answer this important question we will show a global approach, starting with the presentation of general failure reasons. On the one hand, extrinsic PV module failures can be caused by different climatic stress factors and by defective installations. In the following, we will show a classification of those factors, which provides the basis for weathering analyses in the lab. With this data background some major failures and related test methods will be presented. On the other hand, intrinsic failure reasons are to be taken into account. We will exemplify some intrinsic failure reasons on material level. Also, an overview of major failures and their frequency detected during certification will be presented in order to arrive at an assumption as to why modules fail. Finally we will explain adequate test methods to detect and measure the relevant failure factors and to test new materials, components and modules for future photovoltaic systems.

Keywords: PV modules; failure modes; weathering; reliability; testing

1. Introduction

PV modules are sold and installed all over the world. One can find them in any climate and any place, onshore grid connected and as stand-alone system off grid, e.g. in remote rural areas, and offshore as energy source on seamarks. At the end of 2010, a total worldwide capacity of 40 GW_{peak} PV modules

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installed could be assessed [1]. Assuming an average module performance of 150 W/module we can estimate the number of modules in operation at roughly 250 million. Most of the PV modules are certified according to the current IEC standards IEC 61215, IEC 61646 and IEC 61730. These standards are not intended to be a full guarantee for the whole lifetime of a module, but may serve as reference points to secure a certain quality level. New module types tested in the TLPV at Fraunhofer ISE and other test labs [2] show an approximate failure rate of 35%. Also failures of certified modules in PV installations are reported. Based on this observation it is necessary to search for reasons: 'Why do PV modules fail?'

Despite the fact that a common PV module does not seem to be a complicated product, it is not possible today to predict its (service) lifetime [3]. In this paper we will illustrate the state of the art of this subject and give an overview of the failure modes observed in the field during operation and in the laboratory during testing for certification.

2. Modules, components and materials

A common PV module is build up with four different materials: glass, metals, polymers and some type of semiconductor. These materials are used for the front cover (glass), the frame (metal) if there is one, as encapsulation material (polymer), where the active solar cells (semiconductor) are embedded, as back sheet (polymer or glass), as fingers, cell and string connectors and cables (metals) and as junction box (polymers, metals).

3. Climatic stress

One can find PV modules in nearly all places and cities all over the world, onshore and offshore. They generate electricity in stand-alone solar home systems in small, medium and large power plants and are exposed to all climate zones of the earth. For this reason, depending on the installation they can face the following climatic stress factors:

- Solar irradiation
- UV irradiation
- Humidity
- Wind
- Snow
- Rain
- Hail
- High / low temperatures
- Temperature changes
- Salt
- Sand
- Dust
- Gases (O_3, NH_3, ...)

Solar irradiation is obviously essential for the generation of electron-hole-pairs to produce electricity with PV modules. The solar irradiation heats the modules, the high-energy part of the solar irradiation, the ultra-violet irradiation, can cause chemical reactions and degradation processes inside the polymers and on the outside of the PV modules.

Humidity in its different forms of appearance (as constant present air humidity, dew, fog or rain) can have an impact on the performance of the polymers and, in consequence, on the performance of the whole PV module. This can happen when the humidity enters the module package and reaches the active layer and metallic elements like fingers, grids and connectors. Humidity also can affect the adhesion between different polymer layers and induce delamination in combination with heat.

Snow and wind create different mechanical loads on PV modules. With a density from 30-50 kg/m^3 (fresh snow) to 800-900 kg/m^3 (frozen snow), snow is responsible for a heavy static load on the whole PV module depending on the height [4]. Wind can act constantly and dynamically, which defines a static and a dynamic load on PV modules [5].

Hail causes an impact stress. When hailstones hit a PV module, they can damage the cover material or the active parts and can have a very high local impact on the performance of the PV module depending on their size and velocity.

According to the Arrhenius law, high temperature itself is a stress and acceleration factor. In general, low temperatures slow down chemical processes, but temperatures approaching the glass transition point can change the properties of polymeric materials drastically [6]. High temperature changes in short time causes thermo-mechanical stress that can result in further defects or defect growth.

Many human settlements are close to the coastline, and PV modules are also a common energy source for seamarks. Here, PV modules are exposed to a high salt concentration that can cause corrosion of the metallic components of PV modules and degradation of the polymers.

Sand and the smaller form dust from different origins are present in the Sun Belt area of the continents. In combination with wind, e.g. sand storms, they work like an abrasion mechanism which damages the surface of all outside surfaces and can result in frosting of the glass and/or damaging of the AR coating e.g. wet and dry cycles conjoint dust can lead to a concrete layer on the module. Thus, this is a process, which is depending on the composition of dust.

PV modules installed close to roads and industries are exposed to certain types of gases, depending on the installation side. These gases, e.g. O_3, NH_3, SO_2, NO_2, H_2S, Cl_2, etc., alone or in combination with humidity (rain, fog, dew, etc.), can cause corrosion as for being acids (HNO_3, HCl, H_2SO_4, etc.).

All stress factors are singular stress parameters, but often they are present and active in different combinations. These combinations have a higher damage potential than the sum of the single tests.

4. Materials, failures and reasons

As described above, four major materials assemble a usual PV module:

- Glass
- Metals
- Polymers
- Solar cells / active semiconductor thin film layer

In this chapter we will describe the failures for each material, which can occur due to climatic stress and discuss the reasons.

4.1. Glass

Glass is used for the front and back side cover of a module. Five failure modes are observed and published regarding glass as cover material:

Glass corrosion is caused by atmospheric humidity in combination with gases. At the beginning of the new century some cases of glass corrosion on Cerium- doped solar glass have been observed. After removing Cerium from the glass, no more glass corrosion in this context was observed. A new form of glass corrosion which is voltage induced is published by Walsh *et al.* [7].

Static and dynamic mechanical loads arising from snow or wind can cause glass breakage. Snow produces a higher static load on the PV module and is sometimes asymmetric. Wind, which is assumed to be also static in the IEC standard, is rather dynamic, as shown by Assmus *et al*. [8]. Both, static and dynamic load, can lead to glass breakage.

In desert regions, the combination wind, sand and dust can cause abrasion of the front glass and frosting of the glass surface and can thus reduce the electrical performance of the PV module. Also it can damage the AR coatings of the front cover.

4.2. Metal

Different metals (aluminium alloys, stainless steel, copper, soldering agents, etc.) are used for frames, connectors, cables, fingers and grids. All these metals can show defects. Corrosion of metals can be caused by atmospheric humidity alone or in combination with gases. Higher temperatures will accelerate the reaction. Figure 1 shows the corrosion of the ribbon at solder joints of a sample exposed to 660 h in the damp heat chamber at 90°C.

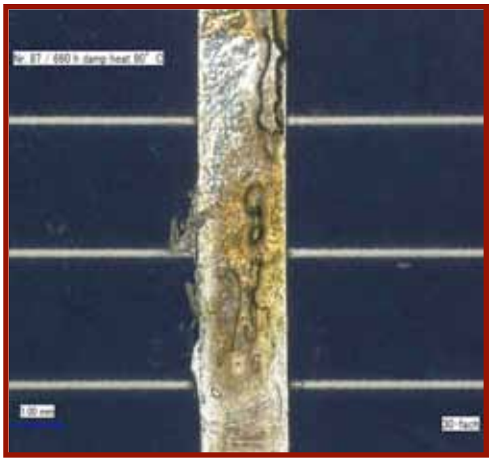

Fig. 1. Details of a connector after an exposing time of 660 h at 90°C and 85% r.H.

Here, the corrosion process was caused by humidity penetration of the sealant in combination with high temperature. Additives of polymers can also cause corrosion, e.g. acetic acid (CH_3COOH), which cannot evaporate because of a non-permeable back sheet. Mechanical loads, resulting from snow or wind, can cause distortion of the metal frame which as a consequence leads to a weakening of the static systems of the PV module and can even result in the total collapse of the PV module. Mechanical loads can also cause stripping of the connectors and, ultimately, their disconnection as a consequence, which may lead to higher electrical resistance.

4.3. Polymers

Even though polymers are a very promising material for the construction of PV modules, they are the reason of many failures and seem to be the weakest point of PV modules of our days. They are used for encapsulation, back sheet, cable insulation, front cover and adhesives to construct a PV module.

Yellowing or browning of encapsulation and polymeric back sheets can be caused by heat, humidity and UV irradiation (see Fig. 2). Until today there is no clear relation between the yellowing level and the electrical performance, see e.g. Ref. [9]. Heat and humidity are also reasons for blistering and, in an extended form, for delamination. This is a process where the different polymeric and/or other layers are not adhesive anymore. The reduction of adhesion of adhesives e.g. for the junction box causes by UV irradiation, heat and humidity can result in a detachment of it. If water vapour and/or gases penetrate the sealant, it can cause chemical changes of the polymers. UV irradiation is a reason for the bleaching respectively fading of the module, e.g. cable envelope. Dry heat like in a desert climate can lead to exsiccation of the polymer material and as consequence to embrittlement and at the end to cracks in the polymer surface.

Fig. 2. Aged PV module after damp heat test (left) and unaged PV module as reference (right).

4.4. Solar cells

The most important part of a PV module is obviously the solar cell or in case of thin-film technologies, the active semiconductor thin-film-layer. At the cell vibrations and both types of mechanical loads can induce micro cracks and/or enhance already production induced ones. As consequence they can cause cell breakage. Cell breakage can be already part of the uncontrolled production process. As another effect of vibrations and mechanical loads or thermo-mechanical stress a disconnection of fingers can occur. Cell corrosion is observed at thin-film PV modules during operation with a bias voltage [10].

5. Failure analysis

5.1. Failure modes in the field

From retest projects and monitoring programs and publication of long-term studies we have identified the following failure modes in the field, which occurred during operation:

- Yellowing / browning of encapsulants and back sheets with and without power loss
- Delamination of encapsulant and back sheet
- Bubble formation
- Oxidation of busbars
- Discolouration of busbars
- Corrosion of connections
- Cracking of back sheet
- Hot spots
- Cell breakage
- Micro cracks

Mostly observed and thus most obvious failure modes are all defects of the polymers as yellowing and browning, delamination, formation of bubbles and cracking of polymers used for encapsulants and back sheets. Until now, there are no evident results which show a direct relation to power losses in case of yellowing. Surface changes of metals like oxidation and discoloration of busbars and corrosion of connectors are also easy to detect without special measurement equipment. They have an effect on the electrical characteristic of PV modules, like increasing the series resistance. Defects of the cells, like micro cracks, cell breakage and hot spots, have higher impacts on the performance. The detection of these defects requires technical equipment like IR cameras. Other details of the long-term studies are presented below.

5.2. Failure modes and analysis in the laboratory

The list of failure modes observed in the laboratory mentioned in the previous chapter is equal to the list of failure modes during testing for certification projects. Just the almost total disintegration of junction boxes is observed only during indoor testing, until now.

During the years 2006-2009 we performed 297 tests projects for certification. In 105 projects of this 297 at least one of maximum 11 PV modules failed in one test. These are 35% of the performed projects, which have contained 7% PV modules with thin-film technologies and 93% crystalline technologies (35% mono-crystalline wafer, 58% polycrystalline wafer). The diagram (Fig. 3) shows a more detailed view on the test where PV modules failed during the certification testing. The most severe tests for PV modules in these projects were the hot spot test (HS) with a failure rate of 20%, followed by the mechanical load test (ML) with 17%. The climate chamber tests are responsible for roughly 40% of the failures during testing, in detail: humidity-freeze test (HF) with 16%, damp heat test (DH) with 15% and finally the thermal cycling test with 7%. All five tests are responsible for 75% of all PV modules with failures in the 105 certification projects.

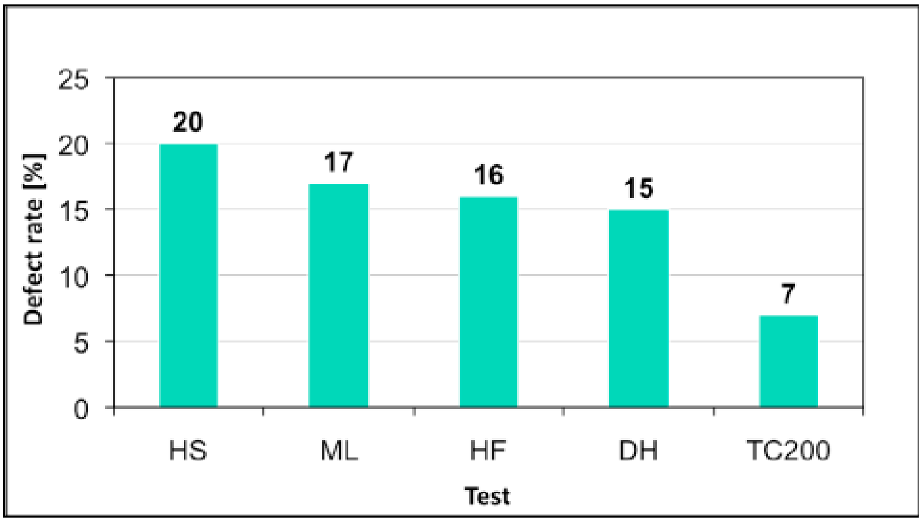

Fig. 3. Defect rate related to the performed test: Hot spot test (HS), mechanical load test (ML), humidity freeze test (HF), damp heat test (DH), thermal cycling with 200 cycles (TC200). From Ref. [11]

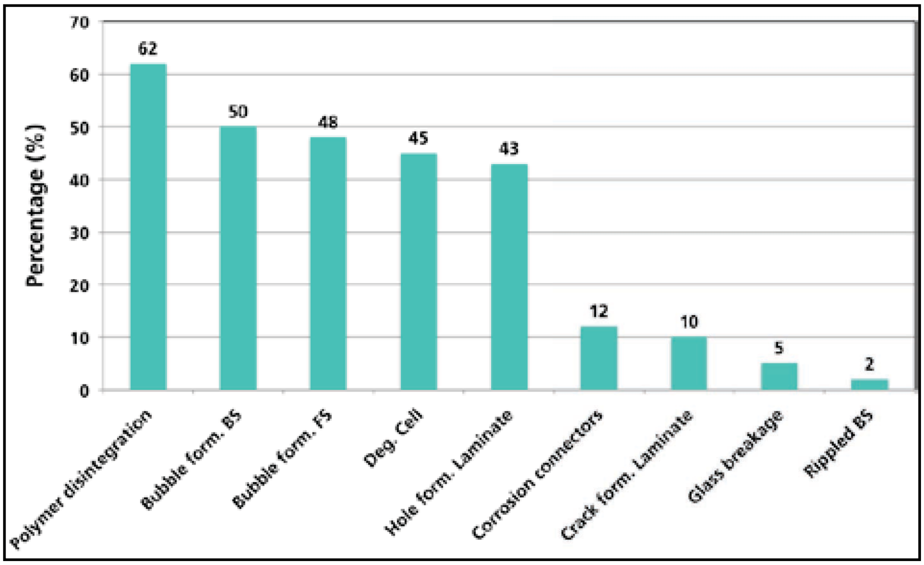

Fig. 4. Percentage of defects modes observed after hot spot test. From Ref. [11]

Further analysis, e.g. after the hot spot test (which is the test most failures were detected in), show that defects are mostly on polymers. The reasons for the failures are the high temperatures produced during the hot spot test. These high temperatures, with an average of 240°C, cause multiple failure modes simultaneously. An analysis of failure modes observed after the hot spot test is shown in Fig. 4. Figures 5(a) to 5(c) present examples of the first most found failures after the hot spot test. These are the disintegration of polymers (62%) and the formation of bubbles at the back (50%) and the front side (48%), caused by the high temperatures during the hot spot test. These high temperatures are causing also degradation of the solar cell (45%), formation of holes in the polymers (43%). Failure modes with less occurrences are corrosion of the connectors (12%), crack formation of the laminate (10%), glass breakage (5%) and rippling of the back sheet (2%).

(a) (b) (c)

Fig. 5. Examples of the first most found failures after the hot spot test: (a) Bubble formation at the front side; (b) Bubble formation at the back side (50%); (c) Disintegration of polymers after hot spot test. From Ref. [11]

Visible defects after the damp heat test (1000h, 85°C, 85% RH) are caused mainly by penetration with humidity on the polymer material, so the humidity gets in contact with the embedded metals and the active layers. Most of the effects are caused by chemical reactions. The failure modes are similar in the humidity freeze test. In most tests defects appear simultaneously. Most observed failures are corrosion of connectors, degradation of coatings (both 30%) and the formation of bubbles (20%).

Performance losses are measured after the climate chamber tests and the mechanical load test. The highest performance loss is detected after the TC200 test (41%), where two types are observed. First, the total loss of performance, so no electricity is produced by the PV module and second, the reduction of the performance of between 10% and 20%. PV modules that have been exposed to the mechanical load test show an average performance loss of 24%. After the humidity freeze test PV modules with performance losses are measured with an average degradation of 14%, after the damp heat test with 10%.

5.3. Long term studies

There are only a few long-term studies on the degradation of PV modules published. Skoczek *et al.* [9] have measured the performance of 204 field-aged crystalline Si based PV modules (53 module types). Exposing started in 1983 at the Joint Research Center in north Italy with a moderate subtropical climate (-10 to 35°C, > 90% RH). They find that applying the performance warranty of 90% initial maximum power after 10 years and 80% after 25 years only 17.6% of installed modules failed. These high performance losses (> 20%) are related to losses of the fill factor, caused by an increased series resistance. The moderate performance losses (< 20%) can be related to losses of the Isc, caused by degradation of the optical properties. The long term losses are determined to be between 0.2% and 1.0% per annum.

6. Conclusions

In this paper a number of failure modes of PV modules are presented which are observed in the field during operation and in the laboratory during testing for certification. As failures in the field are observed also on certified PV modules, this underlines the fact that tests according to current IEC standards are not severe enough to cover the lifetime stress. On the other hand, production quality assurance still needs to be enhanced to improve the continuity of the product quality. Despite of this, testing and certification is an important to assure a certain quality level, taking into account that more than 1/3 of new module types still fail during testing for certification in the laboratories. At the moment a large number of failure modes are observed. Climate chamber tests (damp heat, humidity freeze, temperature cycle 200), hot spot test and mechanical load test are identified as most severe tests in the current standards. One promising approach for more robust testing is to develop combined tests, like UV+DH, mechanical load test at temperatures below 0°C or DH tests with bias voltage. Comparing documented outdoor and indoor failure modes it is found that the failure modes are similar. A direct relation between indoor and outdoor tests is not defined yet, because of the complex interaction and the variation of stress factors in the field and missing detailed long-term studies. Further research and development projects have to investigate the relation between outdoor and indoor stress factors and failure modes so that in future a general lifetime prognosis will be possible.

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