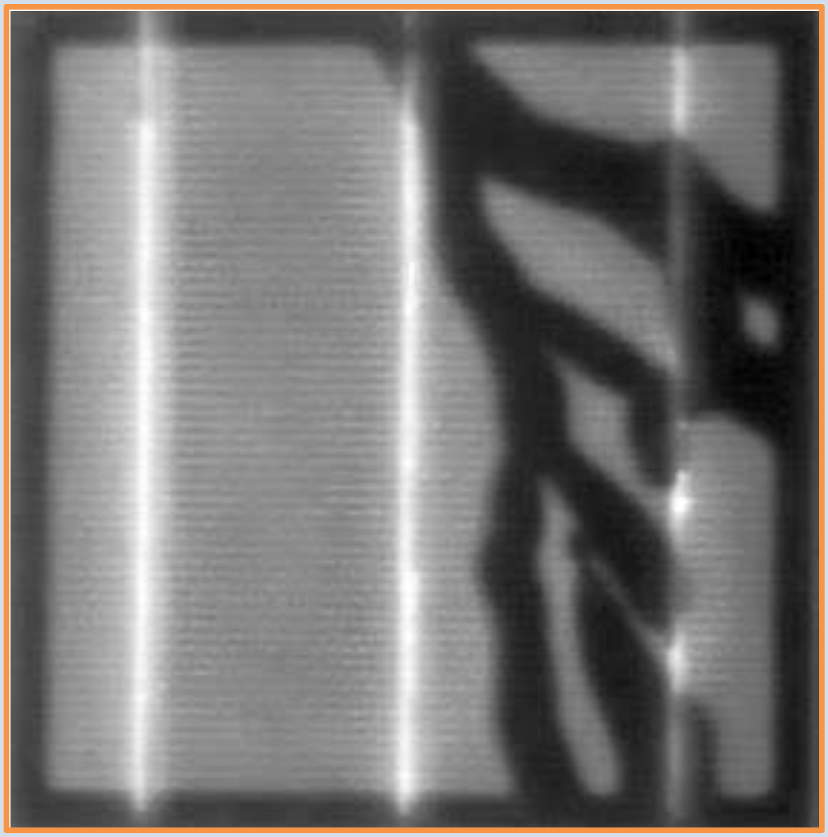
Review of Failures of Photovoltaic Modules



PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

PVPS

Report IEA-PVPS T13-01:2014

Ultraviolet fluorescence image of a cracked solar cell in a photovoltaic module.
Courtesy of Marc Köntges, Institute for Solar Energy Research Hamelin.

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Performance and Reliability of Photovoltaic Systems

Subtask 3.2: Review of Failures of Photovoltaic Modules

IEA PVPS Task 13
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1 Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD) which carries out a comprehensive programme of energy co-operation among its member countries. The European Union also participates in the work of the IEA. Collaboration in research, development and demonstration of new technologies has been an important part of the Agency's Programme.

The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R&D Agreements established within the IEA. Since 1993, the PVPS participants have been conducting a variety of joint projects in the application of photovoltaic conversion of solar energy into electricity.

The mission of the IEA PVPS programme is: To enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems.
The underlying assumption is that the market for PV systems is rapidly expanding to significant penetrations in grid-connected markets in an increasing number of countries, connected to both the distribution network and the central transmission network.

This strong market expansion requires the availability of and access to reliable information on the performance and sustainability of PV systems, technical and design guidelines, planning methods, financing, etc., to be shared with the various actors. In particular, the high penetration of PV into main grids requires the development of new grid and PV inverter management strategies, greater focus on solar forecasting and storage, as well as investigations of the economic and technological impact on the whole energy system. New PV business models need to be developed, as the decentralised character of photovoltaics shifts the responsibility for energy generation more into the hands of private owners, municipalities, cities and regions.

The overall programme is headed by an Executive Committee composed of representatives from each participating country and organisation, while the management of individual research projects (Tasks) is the responsibility of Operating Agents. By late 2013, fourteen Tasks were established within the PVPS programme, of which six are currently operational.

The overall objective of Task 13 is to improve the reliability of photovoltaic systems and subsystems by collecting, analysing and disseminating information on their technical performance and failures, providing a basis for their assessment, and developing practical recommendations for sizing purposes.

The current members of the IEA PVPS Task 13 include:

Australia, Austria, Belgium, China, EPIA, France, Germany, Israel, Italy, Japan, Malaysia, Netherlands, Norway, Spain, Sweden, Switzerland, Turkey and the United States of America.

This report concentrates on the detailed description of PV module failures, their origin, statistics, relevance for module power and safety, follow-upfailures, their detection and testing for these failures. The report mainly focuses on wafer-based PV modules. Thin-film PV modules are also covered, but due to the small market share of these types of PV modules reliable data is often missing. The author team also focuses on types of PV module failures which are not specific for one special manufacturer and have a broader relevance.

The editors of the document are Marc Köntges, Institute for Solar Energy Research Hamlin, Emmerthal, Germany (DEU) and Ulrike Jahn, TÜV Rheinland Energie und Umwelt GmbH, Cologne, Germany (DEU).

The report expresses, as nearly as possible, the international consensus of opinion of the Task 13 experts on the subject dealt with. Further information on the activities and results of the Task can be found at: http://www.iea-pvps.org.

2 Executive summary

One key factor of reducing the costs of photovoltaic systems is to increase the reliability and the service life time of the PV modules. Today's statistics show degradation rates of the rated power for crystalline silicon PV modules of 0.8%/year [Jordan11]. To increase the reliability and the service life of PV modules one has to understand the challenges involved. For this reason, the international Task 13 expert team has summarized the literature as well as their knowledge and personal experiences on actual failures of PV modules.

The target audience of this work is PV module designers, PV industry, engineering lines, test equipment developers, testing companies, technological research laboratories, standardisation committees, as well as national and regional planning authorities.

In the first part, this document reports on the measurement methods which allow the identification and analysis of PV module failures. Currently, a great number of methods are available to characterise PV module failures outdoors and in labs. As well as using *I-V* characteristics as a diagnostic tool, we explain image based methods and visual inspection. For each method we explain the basis, indicate current best practice, and explain how to interpret the images. Three thermography methods are explained: thermography under steady state conditions, pulse thermography and lock-in thermography. The most commonly used of these methods is thermography under steady state conditions. Furthermore electroluminescence methods have become an increasingly popular standard lab approach for detecting failures in PV modules.

A less common but easier to use method is UV fluorescence. This method can be used to detect module failures similar to those detected with thermography and electroluminescence techniques; however, the PV modules must be sited outdoors for at least one and a half years for the method to be effective. For visual documentation of module conditions in the field, we set up a standard which is now accepted and used by all authors documenting such tests. This standard format allows the documentation of visible module failures in standardised way and makes the data accessible for statistical evaluation. Furthermore we introduce a signal transition method for the detection of defective circuits in installed PV modules. All methods are linked to the PV module failures which are able to be found with these methods.

In the second part, the most common failures of PV modules are described in detail. In particular these failures are: delamination, back sheet adhesion loss, junction box failure, frame breakage, EVA discolouration, cell cracks, snail tracks, burn marks, potential induced degradation, disconnected cell and string interconnect ribbons, defective bypass diodes; and special failures of thin-film modules, such as micro arcs at glued connectors, shunt hot spots, front glass breakage, and back contact degradation. Where possible, the origin of the failure is explained. A reference to the characterisation method is given to identify the failure. If available, statistics of the failure type in the field and from accelerating aging tests are shown. For each failure, a description of safety issues and the influence on the power loss is given, including typical follow-up failure modes.

In the third part, new test methods are proposed for detection of PV module failures in the field. A special focus is made on mechanical tests because many problems have arisen in the last few years from the mechanical loading of modules. These mechanical loads occur during transportation and from snow loads on modules mounted on an incline. Furthermore, testing for UV degradation of PV modules, ammonia corrosion (sometimes found in roofs of stock breeding buildings) and potential induced degradation are described. The latter method caused some controversy within the international standardization committee until the finalization of this report because many alternative suggestions from different countries were proposed. The test methods are explained in detail, linked to failure descriptions and the results are compared to real failure occurrences, where possible.

During a past Task 13 project phase, we recognised that the topic "3.2 Characterising and Classifying Failures of PV Modules" is an important on-going subject in the field of PV research. The current review of failure mechanisms shows that the origin and the power loss associated with some important PV module failures is not yet clear (e.g. snail tracks and cell cracks). There are also still some questions as to how best to test for some types of failure (e.g. potential induced degradation and cell cracks). Furthermore, despite the fact that a defective bypass diode or cell interconnect ribbon in a PV module may possibly lead to a fire, very little work has been done to detect these defects in an easy and reliable way once installed in a PV system. However, there are research groups currently working on those topics in order to overcome these challenges. Therefore, it is planed to continue our in-depth review of failures of photovoltaic modules in an extension of the TASK 13 project.

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3 Introduction

Typically failures of products are divided into the following three categories: Infant-failures, midlife-failures, and wear-out-failures. Figure 3.1 shows examples for these three types of failures for PV modules. Besides these module failures many PV modules show a light-induced power degradation (LID) right after installation. The LID is a failure type which occurs anyhow and the rated power printed on the PV module is usually adjusted by the expected standardized saturated power loss due to this failure. LID is defined as no failure in this document as long as the saturated power loss is equal or less than expected.

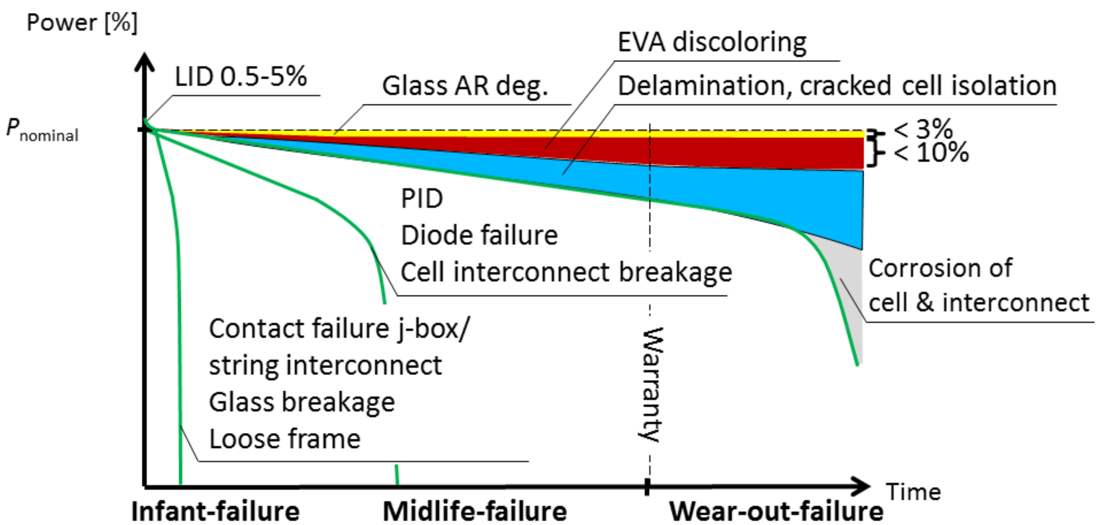

Fig. 3.1: Three typical failure scenarios for wafer-based crystalline photovoltaic modules are shown. Definition of the used abbreviations: LID – light-induced degradation, PID – potential induced degradation, EVA – ethylene vinyl acetate, j-box – junction box.

Infant-mortality failures occur in the beginning of the working life of a PV module. Flawed PV modules fail quickly and dramatically impact the costs of the module manufacturer and the installer because they are responsible for these failures. Figure 3.2 shows the distribution of the failure types at the start of the working life given by a German distributor. Due to transportation damages 5% of all failure cases occur. The most important failures in the field are j-box failure, glass breakage, defective cell interconnect, loose frame, and delamination. Unfortunately the other defects of the statistics are not well defined.

Failures occurring in the midlife of PV modules are described in a study of DeGraff [DeGraaff11]. Figure 3.3 shows the failure distribution of PV modules that have been in the field for 8 years. Two percent of the PV modules are predicted not meet the manufacturer's warranty after 11-12 years of operation. This study shows a quite high rate of defect interconnections in the module and failures due to PV module glass breakage. The relative failure rate of j-box and cables (12%), burn marks on cells (10%), and encapsulant failure (9%) are comparable high.

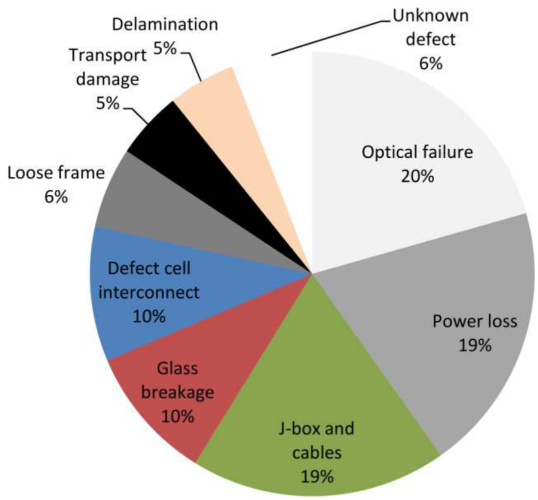

Fig. 3.2: Failure rates due to customer complaints in the first two years after delivery. The rate is given relative to the total number of failures. The PV modules are delivered by a German distributor in the years 2006-2010 [redrawn from Richter11]. The statistic is based on a total volume of approximately 2 million delivered PV modules. Categories not found in other module failure statistics are drawn in grey scale.

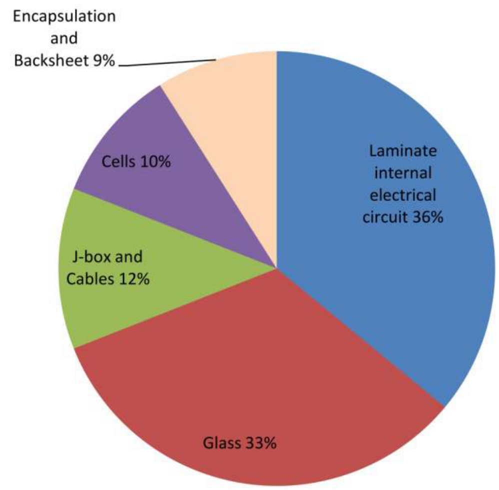

Fig. 3.3: Field study of PV module failures found for various PV modules of 21 manufactures installed in the field for 8 years [redrawn from DeGraaff11]. The rate is given relative to the total number of failures. Approximately 2% of the entire fleet are predicted to fail after 11-12 years (do not meet the manufacturer's warranty).

Most of the PV modules go through the wear out scenario. This scenario is the base for the best case yield analysis and determines therewith the cost efficiency of well operating PV modules.

Wear out failures occur at the end of the working lifetime of PV modules. They determine the maximum working life of a PV module. The working life of a PV module ends if a safety problem occurs or the PV module power drops under a certain level, which is typically defined between 80% and 70% of the initial power rating. Figure 3.4 shows the defect rate of some special PV module types after 15 years of operation and more [Schulze12]. The predominant PV module failures are delamination, cell part isolation due to cell cracks, and discolouring of the laminate. However, all these failures lead to a power loss between 0% and 20%, in the mean 10%. Nearly all of these PV modules meet the manufacturer's power warranty.

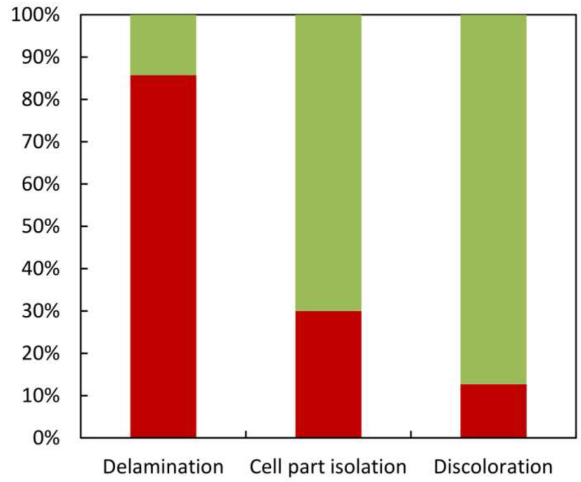

Fig. 3.4: Failures occurring in a fleet of 272 PV modules of 3 different manufacturers after more than 15 years of operation [redrawn from Schulze12]. Each PV module may be affected by more than one failure type. The red and green colours indicate the percentage of modules having or not having a specific failure respectively. Each PV module may show more than one failure type.

However, these PV modules used in the study of Schulze are not representative of today's PV modules. On the one hand the lamination material being responsible for the delamination and discolouration are not used in today's PV modules anymore. On the other hand in former times the manufacturers had no possibility to check the cells for cracking, the cells, and cell metallisation have been much thicker than today and the cell and module sizes deviate strongly from today's PV modules. These facts very much affect the cell part isolation of cells in a PV module. However, the knowledge of the most important long-term degradation mechanisms helps us to look at the most important factors to produce long-term stable PV modules. So it is imperative to understand the degradation mechanisms to enable failure specific tests.

Type approval certifications according to the standards IEC 61215 and IEC 61646 have gained industry acceptance in the past 15 years as a quality label for PV modules [IEC61215], [IEC61646]. Nowadays it is required for most national and international funding programmes. IEC 61215 for crystalline PV modules and IEC 61646 for thin-film PV modules are type approval standards and aim to identify the weaknesses of a product responsible for ''infant failure''. They are not test procedures to determine the working lifetime of a product. These standards do however include several accelerated stress tests derived from real outdoor stresses.

TÜV Rheinland has analysed a total of 2000 certification projects conducted at the Cologne Solar Testing Centre over the past ten years. A certification project may cover several variants of the same module type because manufacturers often exchange and attain qualifications for a variety of materials. These are based on the design certifications in accordance with IEC 61215, IEC 61646, and the safety qualification in accordance with IEC 61730 [IEC61730]. A long-term trend can be clearly identified here as shown in Fig. 3.5. While 54% of all projects were still failing the IEC qualification certifications in 2002, by 2007 this had risen to 67% for the new thin-film modules and 29% for the new crystalline photovoltaic modules. In 2007/2008 many thin-film start-ups entered the PV market and contributed to these failure rates, possibly because they used the test labs to speed their screening of new product designs. Similarly, this high failure rate may be attributed to the large number of new module manufacturers on the market originating from Asia in particular, again, possibly because they had not fully tested their products before attempting certification. By 2012, the rate of failed IEC projects for both technologies had dropped to 10%. The experts ascribe this not only to the fact that manufacturers have learned to better fulfil the IEC standards when constructing new module types but also to the on-going developments of the market.

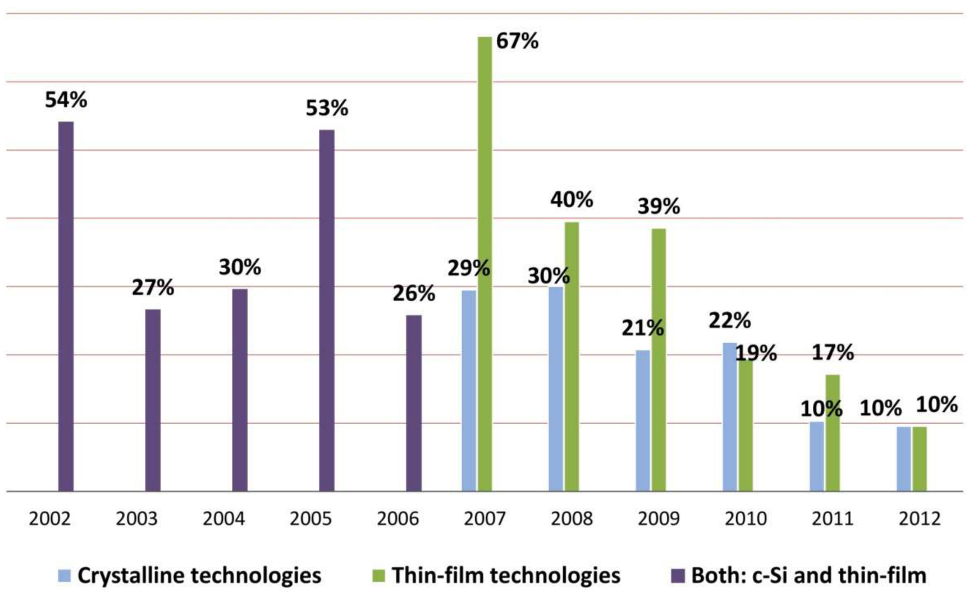

Fig. 3.5: Failure rates of 2000 certification projects for IEC 61215 and IEC 61646 type approval tests for the years 2002 to 2012. The given figures are the annual percentages of IEC projects with at least 1 module test failure compared to the sum of all conducted IEC projects. Since 2007 figures of crystalline and thin-film technologies are shown separately.

The distribution of failed tests as shown in Fig. 3.6 indicates parallels between crystalline modules (1740 projects) and thin-film modules (370 projects analysed): Of those projects in which tests were failed between 2006 and June 2013, 49% of all crystalline module tests (inner ring) and 43% of all thin-film module tests (outer ring) failed during the four test series in the climate chamber of the TÜV Rheinland test laboratory (marked in blue colours in Fig. 3.6), which include 200 cycles thermal cycling test (TCT200), damp heat test (DHT), humidity freeze test (HFT), and 50 cycles thermal cycling test (TCT50). The climate chamber tests are a good indication of the longevity to be expected, the quality of the materials, and the workmanship of the products. However, it is also notable that 11% (crystalline) and 12% (thin-film) of failures occurred during the required initial measurements, that is, before any stress tests had actually been carried out. These modules failed, for example, because the information on the name plate did not meet requirements or because they already exhibited damage by visual inspection. Tests comprising <3% of failures each are summarized under “All other tests (<3%) in Fig. 3.6.

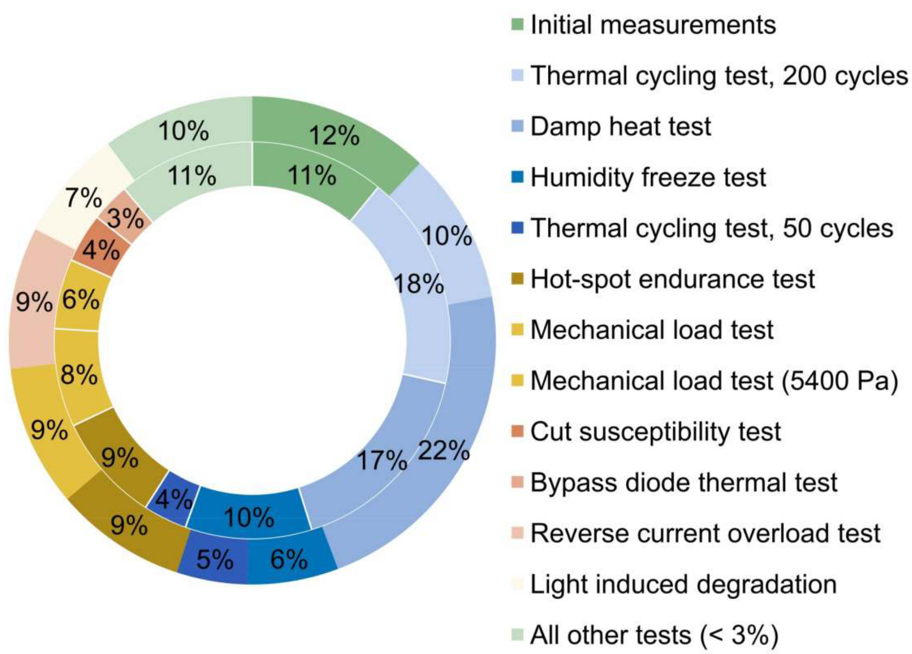

Fig. 3.6: Distribution of failed tests of 1740 IEC projects for crystalline PV modules (inner ring) and of 370 IEC projects for thin-film PV modules (outer ring) between 2006 until June 2013. A test is considered a failure, if one or more PV modules will not pass the specific test. One certification project may contribute to one or several test failures.

The most critical tests for crystalline PV modules are the temperature cycling test 200 (18 %), damp heat test (17%), initial measurements (11 %), humidity freeze test (10%), hot-spot endurance test (9%), and mechanical load test (8%). During the temperature cycles (TCT200) test the solder connection of wafer-based PV modules are stressed; therefore we found a higher proportion of TCT failed modules among crystalline technologies. The TCT200 failure distribution over time dropped from 25% in 2006 to 11% in 2011. Most significant for the quality of lamination to protect the solar cells from humidity ingress is the DHT. The DHT proved critical for crystalline PV module throughout time ranging from 21% (maximum) in 2007 to 13% (minimum) in 2009.

The most critical tests for thin-film modules are damp heat test (22%), initial measurements (12%), temperature cycling test 200 (10%), mechanical load test (9%), reverse current overload test (9%), and hot spot endurance test (9%). However, comparing the two periods 2007 to 2009 vs. 2010 to 2012, for the thin-film PV modules, the key tests with high failure rates are clearly improving: damp heat test (44% in 2007 vs. 11% in 2011), hot-spot endurance test (16% in 2008 vs. 6% in 2011). More or less as for the c-Si modules, the glass quality is the main reason for failures in the mechanical load test. More manufacturers are seeking to have even higher maximum overload protection rate, which leads to the high failure rate of reverse current overload test.

The failure rates for the most critical damp heat test seem to decline during recent years. Many manufacturers have on-site climate/environmental chambers for the pre-testing of new products or new material extension, which is a highly effective way of failure prevention. Furthermore, the improvement of the lamination process and a better protection of module edges, for example, cover bands being introduced, are also key factors for reducing the failure rate of thin-film modules after the damp heat test.

The aim of this document is to review detection, analysis and new tests for failures in PV modules. The document is structured into four parts. The first part (chapter 4) gives definitions about failures in PV modules and defines PV module parts. The second part (chapter 5) reports the basics of the most important and new measurement methods which are used to identify and analyse failures in PV modules. In the third part (chapter 6) failures of PV modules are described in detail, statistics of the failure, the origin of the failure, and a classification of the failure and if possible the dependencies of the failure from time, temperature, humidity, and other parameters are given. In the fourth part (chapter 7) new test methods are presented which test for specific PV module failures which are not yet included in existing standards.

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4 Definitions

4.1 Definition of a PV module failure

A PV module failure is an effect that (1) degrades the module power which is not reversed by normal operation or (2) creates a safety issue. A purely cosmetic issue which does not have the consequences of (1) or (2) is not considered as a PV module failure. A PV module failure is relevant for the warranty when it occurs under conditions the module normally experiences.
A problem that is caused by mishandling or by the local environment is not considered to be a “failure” in this report. Here we give some examples. On the one hand, soiling of the module or a failure due to lightning are not considered to be PV module failures. The soiling problem has to be handled by the operator and the lightning is a force majeure which the module is not designed for. On the other hand, defects due to heavy snow load are considered as module failure if the module is specified for heavy snow load. To clarify the spirit of the definition, we give examples in the next chapters which we define as no module failure although they may lead to power loss or safety issues.

4.2 PV module failures excluded by definition

There may be module defects which originate directly from its production. These defects may be the reason for some modules not performing as well as possible, but as long as the defect is not relevant to safety and the power rating on the label takes account of the power loss caused by imperfect production, this defect is no module failure if the defect does not accelerate power loss or cause safety issues in the future. Moderate crystal defects in multicrystalline solar cells or striation rings in monocrystalline solar cells are examples.

Furthermore, there are production-induced features that may appear to a layperson as a failure. These are also no failures. For instance, Fig. 4.2.1 shows brown marks at the edges of solar cells in a PV module. These marks originate from the solar cell carrier during the deposition of the anti-reflection coating and are not considered to be PV module failures.

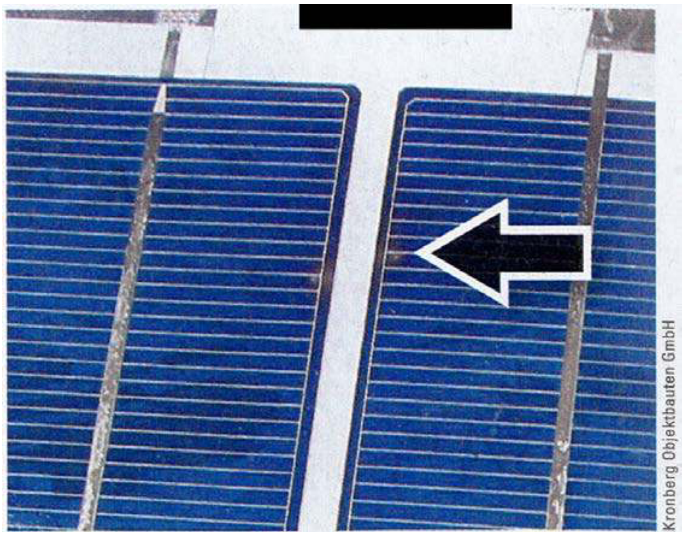

Fig. 4.2.1: Brown marks at the edge of the solar cell are no failure.

Other typical effects that change the module power and are not considered as PV module failures are described in the following.

Light-induced power degradation in crystalline silicon modules due to the well-known boron-oxygen complex [Bothe06] is defined as no module failure, because the manufacturer has to take this effect into account for the power rating of the PV module as it is defined in standard EN 50380 [EN 50380]. It is a PV module failure if the manufacturer has not taken this effect into account for the power rating.

Amorphous silicon (a-Si)-based modules are subject to a light-induced initial degradation, which may account for a loss of power of up to 10-30% within the first months of outdoor exposure [Shah10]. A part of this degradation can be temporarily recovered by thermal annealing during the warm months of the year. The two counteracting effects, light-induced degradation and thermal-induced recovery, lead to a seasonal variation in performance of 0-15% around an average value, which depends on the module technology, local climatic conditions and type of integration [Fanni11, Skoczek11].

The observed degradation is due to the well-known Staebler-Wronski effect (SWE) [Shah10, Gostein11] studied since its discovery in 1977 [Staebler77]. Even if still not fully understood, the effect is reported to be associated with light-induced defect centres that lower the carrier lifetime, which can be partially reversed by thermal annealing at high temperatures. Single-junction modules with thicker intrinsic layers are more affected compared to technologies with thinner i-layers such as amorphous silicon multi-junction modules and micromorph (microcrystalline/amorphous) modules are even less affected. The higher the degradation rate is, the greater is also the potential recovery. Figure 4.2.2 shows an example of a first-generation single-junction amorphous silicon PV system, where one of two strings has been insulated to demonstrate the thermal-annealing effect.

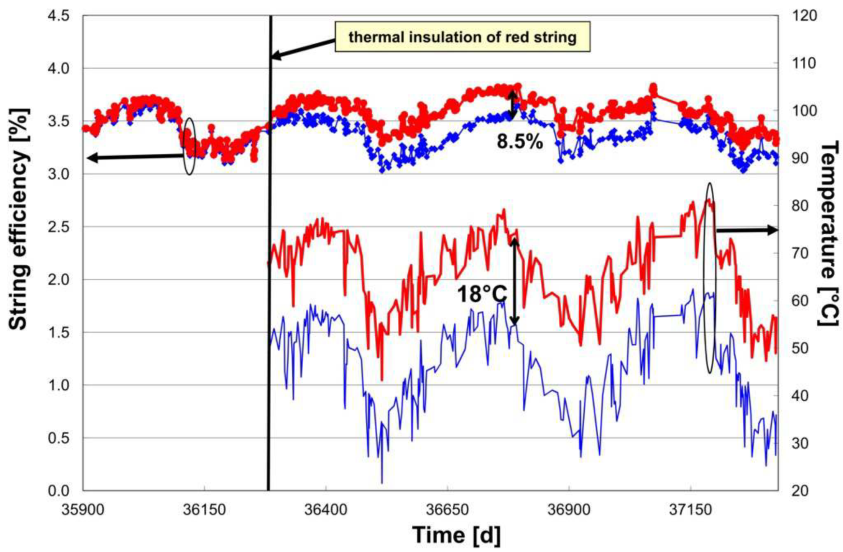

Fig. 4.2.2: Comparison of a ventilated string (blue lines) and a back-insulated string (red lines) of single-junction amorphous silicon PV modules.

The observed instability results in the requirement for stabilisation before determining the power of an amorphous silicon module by measuring the *I-V* curve, see chapter 5.2. The stabiliszation has to be performed according to the light soaking procedure described in [IEC61646]. For amorphous silicon modules light soaking mainly influences the fill factor (and consequently the module power), to a minor extent the short-circuit current of a module and even less the open-circuit voltage. Both initial and stabilised powers have to be stated on the datasheet and nameplate as defined in the standard EN 50380 [EN 50380].

The change in power due to the SWE effect is here considered not to be a PV module failure as long as the stabilised power of the PV module given by the manufacturer is higher than or equal to the measured stabilized value.

4.3 Important PV module failures due to external causes

Some failures are typically difficult to define as a PV module failure or as a failure of the contractor, of the installer or the system designer or even for other reasons. Examples of these types of failures are discussed in this chapter.

4.3.1 Clamping

A relatively often seen failure in the field is glass breakage of frameless PV modules caused by the clamps. In Fig. 4.3.1 two examples from the field are shown.

Glass/glass modules are more sensitive to glass breakage. The origin of the failure is, on the one hand, at the planning and installation stage either (a) poor clamp geometry for the module, e.g. sharp edges, (b) too short and too narrow clamps [Dietrich08] or (c) the positions of the clamps on the module not being chosen in accordance with the manufacturer's manual. The second origin, which induces glass breakage could be excessively-tightened screws during the mounting phase or badly-positioned clamps [Urban09].

Glass breakage leads to loss of performance in time due to cell and electrical circuit corrosion caused by the penetration of oxygen and water vapour into the PV module. Major problems caused by glass breakage are electrical safety issues. Firstly, the insulation of the modules is no longer guaranteed, in particular in wet conditions. Secondly, glass breakage causes hot spots, which lead to overheating of the module.

Fig. 4.3.1: Left figure shows glass breakage caused by too tight screws and the right figure a PV module that broke due to poor clamp design.

4.3.2 Transport and installation

Transport [Reil10, Koentges11] and installation [Olschok12] are the first critical stages in a PV module's life. The glass cover of some PV modules may break or cells in the laminate may break due to vibrations and shocks. In the former case it is easy to attribute the glass breakage to the transportation or installation. This is clearly no PV module failure. However, the cause of cell breakage is much more difficult to decide. Visually it cannot be seen and in many cases it cannot be detected by a power rating of the PV module directly after occurrence of the cell breakage. Only an electroluminescence image (chapter 5.4) or a lock-in thermography image (chapter 5.3.3) can reveal the damage. Some typical situations leading to cell cracks but not necessarily to glass breakage are:

1. A PV module falling over.
2. An insufficiently rigid pallet touching the lowest PV module in the stack during transportation.
3. Too tight transport corners in the transport stack. During de-stacking of the top module of the stack the second uppermost module is also lifted and suddenly drops down.
4. Someone steps on the PV module.
5. Even in well-designed transport containers, the cells of PV modules may crack during "normal" transport.

This damage may have the consequences described in chapter 6.2.1. It is especially difficult to decide who is responsible in case no. 5. Currently there is no definition of what a PV module must be able to withstand during transport. For this reason, chapter 7.1 discusses how to test PV modules for transportation.

4.3.3 Quick connector failure

The quick connector electrically connects solar modules to each other, to fuse boxes, to extension cables, combiner boxes and to the inverter. This element is very important for the safety and reliable power generation of the system. However, there is very little literature on the reliability of quick connectors available in the PV community. Low-voltage DC connectors as a special kind of contact pair are also frequently discussed in respect of (electric vehicle) automotive as well as PV applications. Electrical contacts in general are considered at electrical contact conferences [Schoepf12] with several contributions concerning PV systems. For a brief introduction to the subject, see publications by Rieder [Rieder00, Rieder01].

In most cases problems caused by the quick connector are not considered a PV module failure. Typical failures are caused by using not exactly fitting quick connectors of different types or inaccurately crimped quick connectors to connect PV modules to extension cables, the fuse box, combiner box or the inverter at the installation site.

Ill-fitting or not well-crimped quick connectors may cause a total power loss in a whole string. In even worse cases, they can cause electric arcs and thus fires. In many cases, the quick connectors are much closer to flammable material such as wooden roof beams or heat-insulation materials than the PV module laminate. A statistical review of fire sources in 75 PV systems, which caught fire, shows that the chance of the quick connector causing the fire (29%) is nearly as high as for the rest of the module (34%) or other parts of the PV system (37%) [Schmidt13].

Despite the safety relevance of quick connectors there is, as yet, no standardised quick connector. Quite the reverse - there are many very similar-looking and even apparently fitting quick connectors on the market, which must not be combined.

Currently, only a draft version of an international PV connector standard [IEC62852] exists, while a European standard for PV connectors, EN 50521 [EN50521], has been available since 2008, based on the more general IEC 61984 [IEC61984].

4.3.4 Lightning

A defective bypass diode caused by a lightning strike is caused by an external source, for which the module is not designed. However, this effect has often been found and may cause subsequent safety failures, but the PV module is not the source of the failure. Typical induced defects caused by a lightning strike are open-circuit bypass diodes or a mechanically broken PV module directly hit by the lightning strike. Both defect types may cause hot spots as subsequent failures.

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4.3 Definition of safety failure and safety categories

A safety failure is a failure that may endanger somebody who is applying or working with PV modules or simply passing the PV modules. The safety categories categorise the failure type for the safety of the PV system. In Tab. 4.3.1 three classes are defined. These classes are useful to assess the action needed to be taken if the failure occurs.

Tab. 4.3.1: List of safety categories.

Safety category	Description
A	Failure has no effect on safety.
B(f,e,m)	Failure may cause fire (f), failure may cause electrical shock (e), failure may cause physical danger (m), if a follow-up failure and/or a second failure occurs.
C(f,e,m)	Failure causes direct safety problem (definition of f,e,m see B).

However, the action needed after a safety failure has occurred depends on the application of the PV modules. For example, the criticality of electrical shocks depends on the application class the PV module is used for. The application classes are defined in IEC 61730-1 [IEC 61730-1]. E.g. a C(e) safety classification means a damaged PV module may cause an electrical danger for that application class.

Also, the physical danger resulting from a failure may lead to different courses of action, for example if a mechanical defect occurs in a PV module installed overhead or in a PV module installed in a field surrounded by a fence, to which only skilled people have access. In the former case, a PV module of a B(m) or C(m) safety category should be immediately replaced, but in the latter case, the module may sometimes remain in place.

References

[IEC 61730-1] International Electrotechnical Commission (IEC) 61730-1: Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction, 2004-10-14

4.4 Definition of power loss failure and power loss categories

If the module power P_m measured in accordance with IEC 60904 [IEC 60904] plus the total uncertainty of the measurement ΔP_m is lower than the power printed on the module label P_l minus the tolerance stated on the label ΔP_l a power loss failure occurs:

$$P_m + \Delta P_m < P_l - \Delta P_l \quad . \qquad (4.4.1)$$

The reverse definition is given in the standard IEC 61853-1 [IEC 61853-1] for the case of no power loss. The power loss categories describe how the power loss evolves from the initial power value to a time in the service life of a PV module. In most cases this discrepancy between the reference values may lead to inconsistent results, because the power printed on the PV module label may substantially deviate from the initial PV module power.

However, each definition is useful for its application area.
1. Legal application: power loss failure uses the power printed on the PV module label as reference value.
2. Technical application: the power loss category uses the initial power as a reference value.
The power loss categories given in Tab. 4.4.1 allow the assessment of the impact of the failure over time.

Tab. 4.4.1: Definition of power loss categories.

Power loss category	Description
A	Power loss below detection limit <3%
B	Exponential-shaped power loss degradation over time
C	Linear-shaped power loss degradation over time
D	Power loss degradation saturates over time
E	Degradation in steps over time
F	Miscellaneous degradation types over time

An appendix to the power loss category adds information regarding the dependency of the power loss. The possible appendixes are explained in Tab. 4.4.2. The following example describes a linear power loss with time C(t,h,u). The power loss for this example increases with temperature, humidity, and UV irradiation.

Tab. 4.4.2: List of possible dependencies of the power loss.

Appendix letter	Power loss increases with
t	Temperature
v	Voltage
i	Current
h	Humidity
m	Mechanical load
u	UV irradiation
tc	Thermal cycling
s	Shading

References

[IEC 60904] International Electrotechnical Commission (IEC) 60904: Photovoltaic devices, 2006

[IEC 61853-1] International Electrotechnical Commission (IEC) 61853-1: Photovoltaic (PV) module performance testing and energy rating - Part 1: Irradiance and temperature performance measurements and power rating, 2011

4.5 Definition of a defect

A defect is everything in a PV module that is not as it is expected to be. A defect may imply a PV module failure or not. A defect is a much broader term than a failure. A defect does not necessarily result in a safety or power loss for a PV module but specifies a part of a PV module that is different from a perfect PV module.

4.6 Definition of PV module parts

Terms for PV module components and different levels of electrical interconnects, in particular, are sometimes used ambiguously or interchangeably, leading to confusion. In the following section, definitions are provided for several module parts to ensure clarity in reference to component-specific defects and failures. Definitions are not provided for module components that are unambiguous (i.e. frame, junction box, encapsulant, etc.) in the interest of brevity or already given in IEC/TS 61836 [IEC61836].

A ‘cell’ is defined as the smallest piece of semiconductor, having a voltage associated with a single junction. In a polycrystalline or monocrystalline silicon module, each cell consists of a single piece of silicon. In a thin-film module, semiconductor material is deposited over a large area, with cells defined by scribing through the material to produce electrically-insulated regions. A ‘string’ of cells represents a set of cells, usually 10 or 12 cells in a wafer-based module or approximately 60-100 cells in a thin-film module, that are electrically connected in series. Two or more strings of cells are sometimes connected in parallel with a bypass diode, creating an electrically independent ‘sub-module’, the function of which is isolated from any cells or strings not in the sub-module.

Up to four levels of metallisation and electrical interconnects are considered. ‘Gridlines’ (interchangeably referred to as ‘fingers’) make up the finest level of metallisation directly on the cells and consist of an array of lines <0.4 mm thick. Current from the gridlines is collected in the ‘busbars’, which are also directly on the cell. Figure 4.6.1 shows a schematic of gridlines and busbars on a mono- or poly-crystalline silicon cell.

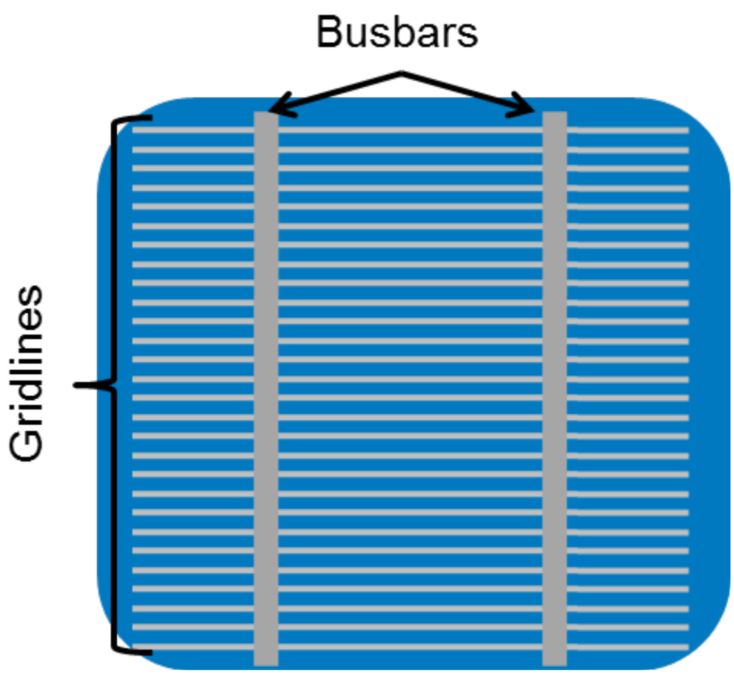


Fig. 4.6.1: Metallisation on a silicon cell consists of gridlines and busbars.

Cells wired in series are connected to form a string by the ‘cell interconnect ribbon’. It should be noted that the cell interconnect ribbon often obscures inspection of the busbars on silicon cells because it directly overlaps them. Multiple strings are connected via the ‘string interconnect’, which is usually located near the edge of the module and may be obscured by the module frame or cover layers. Figure 4.6.2 shows a schematic illustrating cell interconnect ribbons and a string interconnect. The arrangement of metallization and/or interconnects may be less standardized in thin-film modules than that of mono- and polycrystalline silicon modules. In the case of thin-film modules, all four levels of metallisation and electrical interconnects may not be necessary; the naming convention for these modules follows the function of the particular interconnect level described above.

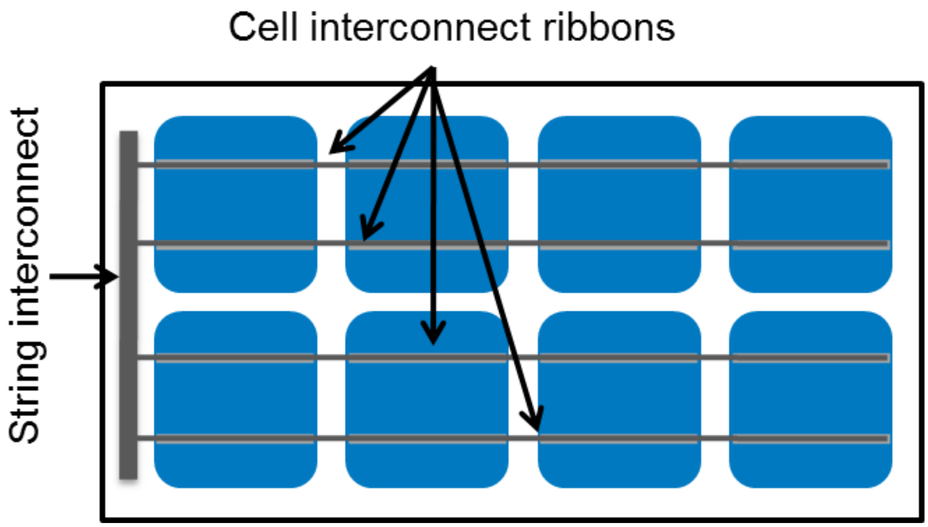


Fig. 4.6.2: Cells are electrically connected into strings via cell interconnect ribbons and the string interconnect connects multiple strings of cells.

References

[IEC61836] IEC/TS 61836 Ed. 2.0 2007-12, Solar photovoltaic energy systems - Terms, definitions and symbols

5 Basics of measurement methods used to identify failures

In this chapter the setup, best practice and the interpretation of the most important measurement methods are described. At the end of each chapter a list of failures are given which may be identified by the introduced measurement method.

5.1 Visual inspection

The most effective and quickest method to find failures and defects in a PV module is the visual inspection. For the sake of completeness we introduce the visual inspection of new modules being tested in standard tests as described in the standards [IEC61215, IEC61646]. This visual inspection method is not well applicable to weathered PV modules. Therefore we introduce an international harmonized “Documentation of visual failures in the field” to collect data from visually inspected modules in a uniform way. This allows defect and failure collection in a way being applicable for statistical evaluations from various experts and countries.

5.1.1 Visual inspection in accordance with IEC PV standards

Visual inspection of a PV module is performed before and after the module has been subjected to environmental, electrical, or mechanical stress testing in the laboratory. Stress tests are usually used to evaluate module designs in the pre-phase of production, production quality, and lifetime of the modules. The most common stress tests are: thermal cycling, humidity-freeze cycling, damp heat exposure, UV irradiation, mechanical loading, hail impact, outdoor exposure, and thermal stress.

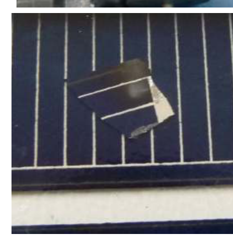
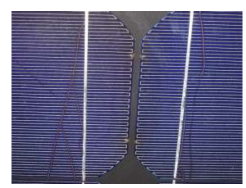
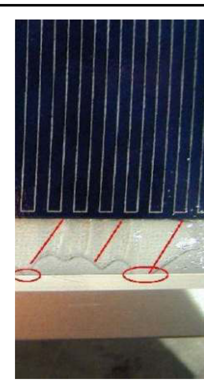
To approach the visual inspection of the PV module it can be divided in its parts and each PV module part is inspected and documented separately with the relative defects. The IEC 61215 and 61646 standards [IEC61215, IEC61646] require an illumination of more than 1000 lux during the visual inspection and only defects detectable with the bare eye are considered. The defects conditions are listed in the IEC 61215, 61646 standards in chap. 10.1.1 as shown in Tab. 5.1.1.

Table 5.1.1: Typical failures found during IEC 61215, 61646 visual inspection.

PV module component	PV module failures
Front of PV module	Bubbles, delamination, yellowing, browning,
PV Cells	Broken cell, cracked cell, discolored anti reflection
Cell metallization / cell and	Burned, oxidized
Frame	Bend, broken, scratched, misaligned
Back of module	Delaminated, bubbles, yellowing, scratches, burn
Junction box	Loose, oxidation, corrosion
Wires – connectors	Detachment, brittle, exposed electrical parts

It is a good laboratory practice to record all visible defects – even if judged irrelevant - because in case of worsened defects during testing sequences the documentation is complete and allows the follow up. For a good documentation the following rules should be taken into account. The photo should be taken without light or flash reflection and mirror image. The position and the dimension of each defect should be documented. Clear terms and definition should be used to describe the defect. Standardization, at least in the same laboratory, for the defect description is desirable to minimize interpretation errors caused by individual judgment. In clause 7 of the IEC 61215 and 61646 standards the major visual defects which cause the failure (not passed) in the design qualification of the PV module are defined and described in Tab. 5.1.2.

Tab 5.1.2: Visual defects as defined in clause 7 of the IEC 61215 [IEC61215] and IEC 61646 [IEC61646]. The failures are described in detail in the chapter referenced in column named “chapter”. The codes used in column “Safety” and “Power” are defined in chapter 4.3 and 4.4.

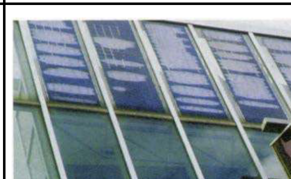
Chapter	Type	Safety	Power	Image
--	Bent or misaligned external surfaces, substrates, frames, and junction boxes to the extent that the installation and/or operation of the module would be impaired Module wire touching the diode with the risk of arcs- operation is compromised Cell fragment laminated in the module, operation could be impaired	B(m,e) B(f) B	A A A	  
6.2.2, 6.2.3	Crack in cell - a propagation which could remove more than 10% of the cell area from the electrical circuit	A	D	 
6.1.1	Bubbles or delaminations forming a continuous path between any part of the electrical circuit and the edge of the module.	C(e)	D/E	 [Zamini07]
--	Loss of mechanical integrity, to the extent that the operation or the installation of the module would be impaired	B(e,m)	A	

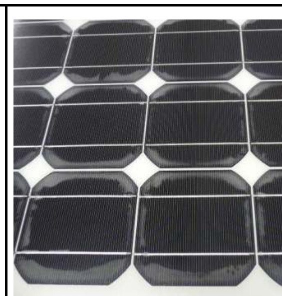
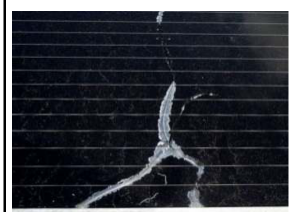
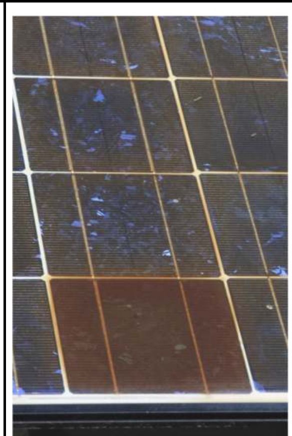
5.1.2 Documentation of visual failures in the field

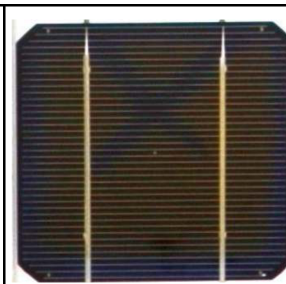
Visual inspection is a powerful tool to identify causes of failures of PV modules or to identify problems that could cause failures in the future. Sometimes changes that lead to aesthetic concerns are considered failure even if the module is functioning well. Many changes in performance are invisible and need to be studied with more sophisticated tools, but the visual inspection is quite effective for identifying hot spots (burn marks), delamination, encapsulant yellowing, back sheet blistering, junction box failure, and many others.

The simplicity of visual inspections allows the possibility of collecting data very widely. Here we attempt to regularize the collection of this data by developing an inspection checklist for the evaluation of visually observable defects in fielded PV modules. A checklist harmonised by the Task 13 group for module conditions can be found in Annex A. This checklist is used for collecting visual failures in this report. We recommend this checklist as an international standard for visual inspection in the field. Table 5.1.3 gives a list and a gallery of failures which are detectable by visual inspection.

Tab. 5.1.3: List of failures detectable by visual inspection in the field. The failures are described in detail in the chapter referenced in column named “chapter”. The codes used in column “Safety” and “Power” are defined in chapter 4.3 and 4.4.

Chapter	Type	Safety	Power	Image
6.2.4	Burn marks at the backsheet, heating along a busbar	B(f,e,m)	D/E	
6.2.4	Burn marks at the front, discolouration of the encapsulant associated with overheating along the metallic interconnections	B(f,e,m)	D/E	
6.1.1	Delamination of a multicrystalline Si module	B(e)	D/E	

6.1.1	Delamination of c-Si module	B(e)	D/E	
-	Electrochemical corrosion of a thin-film module and associated delamination	B(e)	D/E	
6.4.1	Thin-film glass breakage	B(e)	D/E	
6.2.1	Slightly browned EVA in the center of the cell, but bleaching occurs in the parts of the EVA that have access to atmospheric oxygen and/or that are close enough to the edge that the acetic acid diffuses out of the cell	A	C	
6.2.1	A single cell will brown much faster than the others when it is hotter than the others.	B(f)	D	

6.2.1, 6.2.2	Browned EVA on top of a cell with two cracks in a cell. Photobleaching takes also place along cell cracks therefore the crack is visible. The browning takes several year to appear. This may not be mistaken for Snail tracks.	B(f)	C	 [Schulze13]
6.2.3	Snail Track is a discolouration of the silver paste used for the gridlines on the cells. The discolouration appears along cell cracks. This may not be mistaken for photobleaching of EVA along cell cracks.	B(f)	C	
6.1.2	Delamination of backsheet	B/C(e)	D	

Visual defects like bent or misaligned external surfaces, frames or junction boxes may lead to failures in the field. Otherwise defects like cracked cells have a high probability to cause follow-upfailures of the modules with power loss or safety issues. Other defects like delamination or small cell-frame distances can cause safety failures, because the insulation is not guaranteed.

References

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[Schulze13] K. Schulze, M. Groh, M. Nieß, C. Vodermayer, G. Wotruba und G. Becker, Untersuchung von Alterungseffekten bei monokristallinen PV-Modulen mit mehr als 15 Betriebsjahren durch Elektrolumineszenz- und Leistungsmessung, Proc. 28. Symposium Photovoltaische Solarenergie (OTTI, Staffelstein, Germany, 2013)

[Zamini07] S. Zamini, S. Mau, T. Krametz: "IEC 61215 - Erfahrungen aus 4 Jahren Prüftätigkeit." TÜV Modulworkshop, (TÜV, Cologne, Germany) 2007

5.2 *I-V* curve

Measurements of module *I-V* characteristic determine short-circuit current, open-circuit voltage, and other parameters. A typical module *I-V* measurement system consists of a natural or artificial simulated light source, a test bench to illuminate the module under test, module temperature control, monitoring facility, and a data acquisition system to measure the current-voltage curve when the voltage across the module or current through the module is varied with an external electronic load or power supply.

Under natural sunlight condition, a portable *I-V* tracer is often used for measuring module *I-V* curves, but probably not under standard test conditions (STC, 1000 W/m^2, 25°C, AM 1.5G reference spectrum of IEC 60904-3 [IEC60904-3]). Usually, a pyranometer or sunlight irradiance sensor is used as a reference solar device for rating global irradiance. For comparison, e.g. with data sheet values at STC, it is then necessary to correct the measured *I-V* curves, see IEC 60891 [IEC60891].

Under simulated light irradiance conditions, a reference cell or reference module which has identical or similar spectral response characteristics to the module under test is often used as a reference solar device to measure the irradiance of the light source. As the environment of measurement is much easier to control, the test parameters (Isc, Voc, Pmax, temperature) can be translated to STC more accurately. To meet the requirements and characteristics of different PV technologies, the simulated light source (or sun simulator) is a steady state type or pulse type (flash type) simulator. The pulse simulator can be further divided into single pulsed and multi pulse light source. Different artificial simulated light sources can be used for adapting different PV technologies. For instance, the high capacity PV modules need much longer pulse time or a steady state simulator to evaluate module I-V characteristic accurately. The typical duration of light pulses for solar simulators usually varies between 1 ms to 20 ms with different profiles. These time intervals are too short for a proper characterization of some high-efficiency PV modules like heterojunction (HIT) or floating emitter cells (SUNPOWER cells). The cells of these PV modules have a high charge carrier life time and therefore a quite high diffusion capacity which leads to long test durations of 50 ms or more. The long-pulse or steady-state simulators would be more suitable for these modules. The specific procedures and requirements of high efficiency module *I-V* characteristics measurement are described by Mau, Virtuani, and Herman [Mau05, Virt08, Herman12]]. Furthermore thin-film PV modules show several metastable states, which make it challenging to define a standardised PV module power for each technique. Procedures to measure the PV module power of metastable thin-film modules are described by Silverman [Silverman14].

5.2.1 Introduction of the important *I-V* curve parameters

From the *I-V* curve some key parameters can be extracted to access the quality of the PV module. The *I-V* curve of an illuminated PV module has the shape shown in Figure 5.2.1.

The open-circuit voltage (V_{oc}) is the maximum voltage available from a PV module and occurs at zero current. The short-circuit current (I_{sc}) is the current through the module when the voltage across the cell is zero. The maximum power (P_{max}) is defined as a point on the *I-V* curve of a PV module under illumination, where the product of current (I_{mpp}) and voltage (V_{mpp}) is maximal. The fill factor (*FF*) is essentially a measure of the quality of the solar cell or PV module. It is the ratio which compares the maximum power of the PV module to the virtual power (P_T) that would result if V_{mpp} would be the open-circuit voltage and I_{mpp} would be the short-circuit current. The fill factor can be interpreted graphically as the ratio of the rectangular areas depicted in Fig. 5.2.1.

From these parameters optical influences (I_{sc}), cell degradation and shunting (V_{oc}), and series resistance or inhomogeneity effects (*FF*) can be assessed.

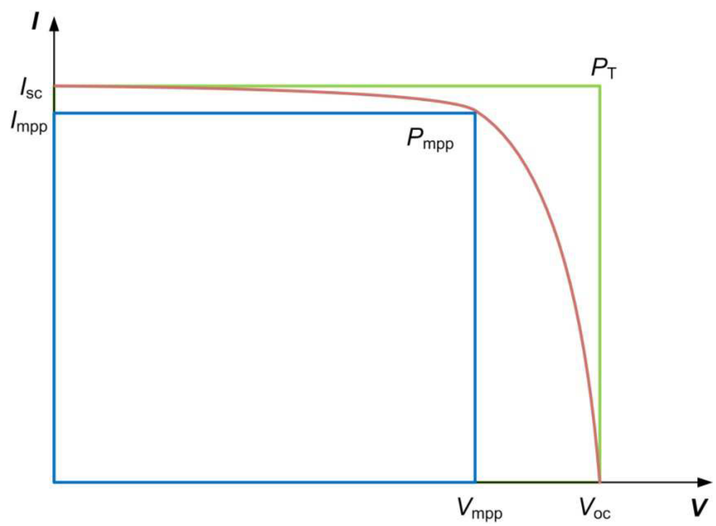


Fig. 5.2.1: The figure shows a schematic *I-V* curve of an illuminated PV module and the most important parameters: short circuit current I_{sc}, open-circuit voltage V_{oc}, the maximum power point P_{mpp}, the current and voltage belonging to the maximum power point I_{mpp} and V_{mpp}, and the virtual power point P_T.

5.2.2 Series resistance and shunt resistance

In order to understand more about the *I-V* characteristic of PV modules, it is necessary to define the slopes at each of the intercepts. These slopes will be denominate numbers with units of resistance. They are called series resistance (R_s) and shunt resistance (R_{sh}). These resistances are defined as depicted in Fig. 5.2.2.

The series resistance is a lumped parameter. All series resistances of the solar cells and interconnects affect this parameter. So it may be used to access the effect of series resistances in the PV module. However for the production of a PV module various cells with various *I-V* characteristics are used. The difference in *I-V* characteristics also affects the lumped parameter R_s in a PV module. So a high series resistance may be caused by the addition of series resistances in the module or caused by a mismatch of the individual cell characteristics.

The shunt resistance illustrates a shunt path for the current flow bypassing the active solar cell. If the shunt resistance of a cell is low, the shunt path shows higher leakage currents. A change of shunt resistance in single solar cells is not detected by the shunt resistance of the module because all the other cells block the additional current from the cell. Only in the very unlikely case that all cells have a low shunt resistance will the shunt resistance of the PV module also be low. In all other cases shunts of single cell affect the Fill Factor of the module and not the shunt resistance. The shunt resistance also influences short-circuit current and open-circuit voltage (V_{oc}) of *I-V* characteristics of cells especially when a hot-spot endurance phenomenon occurs.

It should be noticed that the interpretation of R_s and R_{sh} as shunt and series resistance only apply if all solar cells in the module are quite comparable. In many practical cases the value of R_s and R_{sh} is just a lumped parameter which can be obtained from the *I-V* curve slope at I_{sc} and V_{oc}. In some cases, for analyzing the behavior of the PV module it is necessary to give the R_s and R_{sh} parameters physical meanings.

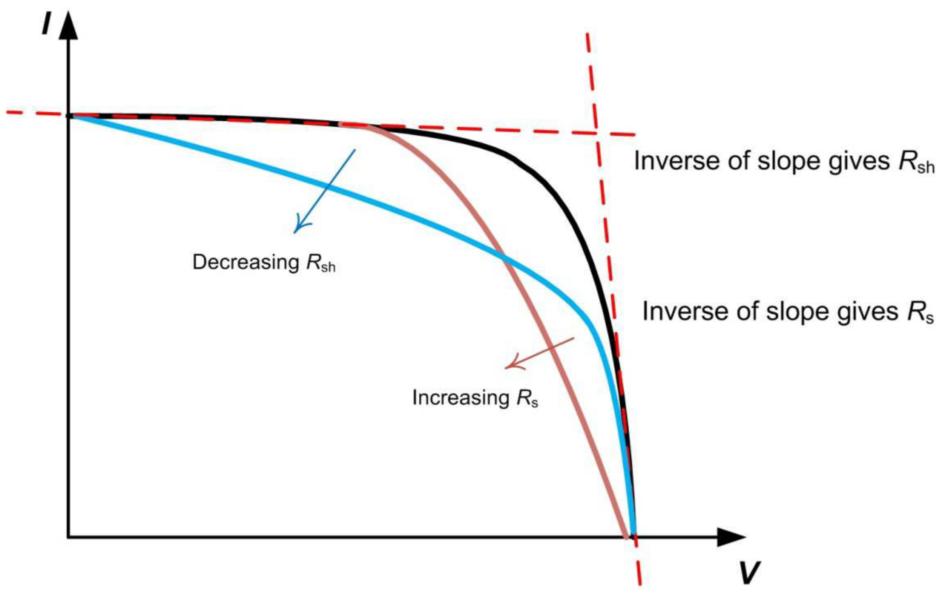


Fig. 5.2.2: Schematic *I-V* curve of an illuminated PV module and the influence of a series resistance R_s and a shunt resistance R_{sh} to the *I-V* curve.

5.2.3 Accuracy

For *I-V* characteristic measurement, there are many aspects affecting measurement accuracy. To improve accuracy of measurement, each channel performance of the *I-V* acquisition system must be calibrated in an accredited laboratory or institution to ensure proper dynamic behaviour including time response and current, voltage bias. For accurate measurement, it is important to know the module under test characteristics, high capacitance of some high efficiency modules can influence the measurement results. Measurement problems due to high capacitive modules may be detected by comparing *I-V* characteristics measured from short-circuit current to open-circuit voltage conditions and in the reverse direction, with the other parameters unchanged. The detailed procedures are described by Mau, Virtuani, and Herman [Mau05, Virt08, Herman12].

It is strongly recommended that the spectral response of a module under test be performed before *I-V* measurement. Normally, a typical represented encapsulated cell can be a sample for spectral response measurement. To minimize the spectral mismatch effect, the reference solar device should have identical or similar spectral response to the module under test. If the *I-V* measurement is performed under outdoor condition, the pyranometer or other thermopile irradiance sensor must be calibrated against an accredited laboratory.

For all *I-V* measurements of PV cells and modules, the real time measuring result should be translated to the STC or SRC (standard report condition), so the sunlight or simulated irradiance should be measured by calibrated reference solar device which can be traced to accredited laboratory of ISO 17025 [ISO 17025]. For indoor measurement, the spectral irradiance distribution of light can not be identical to natural sunlight. It is recommended that the simulator spectrum should meet the requirement of IEC 60904-9 [IEC 60904-9] standard. On the other hand, non-uniformity of irradiance and light instability can affect the *I-V* result simultaneously. The module under test should be mounted in the area with the most homogeneous light distribution and measured in the time period of the flash with almost constant intensity level and light spectrum.

For both indoor and outdoor measurements, the environmental parameters should be monitored to keep the temperature homogeneous and constant as far as possible. As different PV modules have specific temperature coefficients, the temperature should be controlled close to the desired temperature level to reduce voltage and current correction.

At present, four laboratories maintain the World Photovoltaic Scale to give PV metrology and reference solar device to other laboratories, institutions, and manufacturers. It is commonly difficult to obtain better than 3% certified accuracy of module *I-V* characteristic for the majority of PV laboratories.

5.2.4 Effect of failures on the *I-V* curve

An *I-V* curve measured with suitable equipment as described in chapter 5.2 gives information about module failures. The interpretation of the *I-V* curve depends on the available data:

a. In case that we have only the measured *I-V* curve without information on the specific electrical values of the PV module we can evaluate the following values:

- the I_{sc} current is consistent with the cell area, cell technology and cell connections in the module - number of cells in series and strings parallel (see values in Tab. 5.2.1),

- the V_{oc} is consistent with the cell technology and cell connection in the module - number of cells in series and parallel strings, see values in Tab. 5.2.1,
- the fill factor is as expected from the module technology
- in addition the shape of the *I-V* curve reveals two defects:
  non-active cell parts due to cell cracking or other reasons (grid defects) short-circuit of a bypass diode.

b. If we have the specific electrical data for the PV module - from label or, even better, flash report from the manufacturer - the comparison of the measured values give a good indication of potential failures and technical problems.

c. If we have a previous *I-V* curve of the same PV module measured with comparable equipment and conditions such as a class AAA flasher, reference cell and module temperature, we can obviously evaluate the *I-V* curve for degradation effects and failures.

Tab. 5.2.1: Typical electrical values at STC conditions.

	Polycrystalline silicon cell	Monocrystalline silicon cell	Expected value for the PV module
J_{sc} Current density [mA/cm²]	28 - 33	30 - 35	cell area * current density
V_{oc} Open curciut voltage [mV]	550 - 600	600 - 700	number of cells in series * V_{oc}
FF Fill factor	0.75 - 0.80	0.80 - 0.85	--

Deviations between measured and expected *I-V* curve, values obtained from the data sheets or previous measurements, could be divided into the following categories as listed in Tab. 5.2.2:

1. A lower short-circuit current I_{sc} than expected, case S1 in Tab. 5.2.2, is likely caused by the loss of transparency of the encapsulation due to browning or yellowing, glass corrosion which reduces the light trapping of the module or delamination causes optical uncoupling of the layers. These effects on the *I-V* curve are like a reduction of the irradiance and as shown in Tab 5.2.4 the curve shape changes differently if the effects are homogenous or heterogenous.

2. The *I-V* curve near I_{sc} becomes sloped. Case S4 in Tab. 5.2.2, means that the shunt resistance decreased due to shunt paths in the PV cells and/or the interconnections. Slight cell mismatch or slight non uniform yellowing, may be another cause.

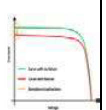
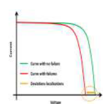
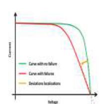
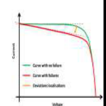
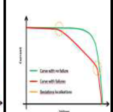
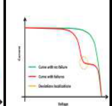
3. In case S3 the slope of the *I-V* curve near V_{oc} is lower indicating an increase of the series resistance in the PV module. The series resistance in the module could increase by the increase of interconnections resistance, corrosion in junction box or interconnects and slacks joints.

The two previous points decrease the fill factor of the module and therefore the maximum power output of the module.

4. The *I-V* curve has a lower V_{oc} value than expected, case S2 in Tab. 5.2.2. Failures which lower the V_{oc} are failed cell interconnections, short circuits from cell to cell or a failure of the bypass diode. The open-circuit voltage of the module can be reduced also by the light-induced degradation (LID) of crystalline silicon modules or potential induced degradation (PID).

5. The *I-V* curve shows steps (see table 5.2.2 S6). The reasons of the steps in the curve could be a defect in the bypass diode, damaged cells or heavy mismatch of the PV cells in the module.

Tab. 5.2.2: Table of PV module failures detectable by the *I-V* curve.
* Only possible with several strings of cells protected by working bypass diodes.

			P_{max}	S1: I_{sc}	S2: V_{oc}	S3: R_{oc}	S4: R_{sc}	S5: change in slope*	S6: inflex points*
Failure	Safety	Power							
Disconnected bypass diode	B	A							
Short-circuit bypass diode	B	E	**X**		**X**				
Inverted bypass diode	B	E	**X**		**X**				
Homogeneous loss of transparency	A	C	**X**	**X**					
Heterogeneous loss of transparency	A	E	**X**	**X**			**X**		**X**
Homogeneous glass corrosion	A	D	**X**	**X**					
Heterogeneous glass corrosion	A	D	**X**	**X**			**X**		**X**
Homogeneous delamination	B	D	**X**	**X**					
Heterogeneous delamination	B	D	**X**	**X**			**X**		**X**

Homogeneous corrosion AR coating of the cells	B	C	**X**	**X**						
Heterogeneous corrosion AR coating of the cells	B	C	**X**	**X**				**X**		
Passivation degradation	A	D	**X**		**X**					
PID polarization induced degradation	A	C	**X**		**X**			**X**		
LID light-induced degradation for crystalline solar cells	A	D	**X**	(X)	**X**					
Short-circuited cells, e.g. by cell interconnection ribbon	A	E	**X**		**X**					
Solder corrosion	A	C	**X**			**X**				
Homogeneous soldering disconnections	B	E	**X**			**X**				
Broken cell interconnect ribbons	B	E	**X**			**X**			**X**	
Cracked cells	A	E	**X**	**X**					**X**	

P_{max} = failure is detectable as power loss
R_{oc} = open-circuit resistance (slope at V_{oc})
R_{sc} = short-circuit resistance (slope at I_{sc})

The power degradation of some of the failures mechanism mentioned in the table above is limited. The power loss caused by the corrosion of the antireflection coating is usually limited to 4% which is the initial improvement of the coating. Some others failures are limited like the delamination with values of 4%, the initial light-induced degradation with 2 - 4%, glass corrosion with maximum of 3%. Failures like cell cracks, solder corrosion, broken cell interconnects have no limits in power loss and the PV module may be unusable.

References

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[IEC 60904-9] International Electrotechnical Commission (IEC) 60904-9 ed2.0: Solar simulator performance requirements, 2007-10-16

[ISO 17025] International Organization for Standardization 17025: General requirements for the competence of testing and calibration laboratories, 2005

[Mau05] S. Mau, Influence of Solar Cell Capacitance on the Measurement of *I-V* curves of PV Modules, Proc. 20th EUPVSEC (WIP, Barcelona, Spain, 2005), pp. 2175-2177

[Silverman14] T. Silverman, U. Jahn, “Characterization of Performance of Thin-film Modules”, Technical Report IEA-PVPS T13-02: 2014, in preparation.

[Virtuani08] A. Virtuani, H. Müllejans, F. Ponti, E. Dunlop, Comparison of indoor and outdoor performance measurements of recent commercially available technologies, Proc. 23rd EUPVSEC (WIP, Valencia, Spain, 2008), pp. 2713-2718

5.3 Thermography

There are basically three different types of thermography methods to detect failures in PV modules. The most common and easiest to apply technique is the thermography under steady state conditions. This method allows the analysis of PV modules in the field under working conditions. The pulse thermography and the lock-in thermography allow a more detailed view into the PV module but both techniques need to be done under lab conditions. These three techniques are described in the next three chapters.

5.3.1 Thermography under steady state conditions

Thermography or infrared (IR) imaging [Tscharner85] is a non-destructive measurement technique, which provides fast, real-time, and two-dimensional distributions of characteristic features of PV modules. It can be used as a contactless method for diagnosing some thermal and electrical failures in PV modules. The measurements can be performed during normal operation for both individual PV modules and as a scan of large scale systems. It has to be assured that the measurement is done under steady state conditions of the PV module.

The thermography measurements show temperature differences induced by an external current or by applying light to the PV module. During measurements in the dark, there is no light applied to the module but external current (typically comparable to short-circuit current I_{sc}) is supplied in the forward direction [Hoyer09]. In order to avoid thermal damage to thin-film modules it must be ensured that the I_{sc} of the modules is not exceeded by more than 30%.

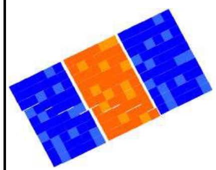
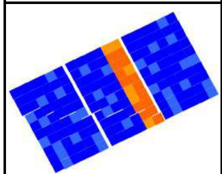
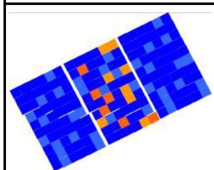
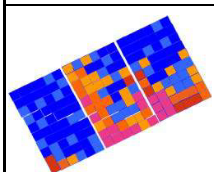
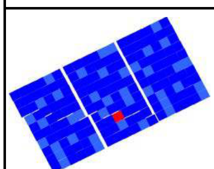
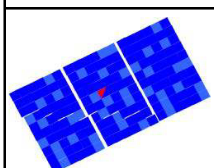
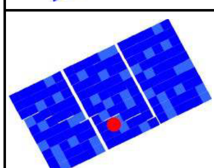
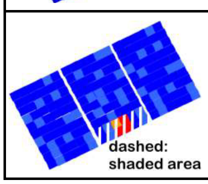
During illumination heat and current are generated by incident light (e.g. the sun) which can cause inhomogeneous temperature of the PV module. For more precise defect detection, thermography imaging is performed under illumination of the PV module and the temperature distribution of various load conditions have to be compared: short circuit, open-circuit, and at maximum power point.

By means of an appropriate IR-camera the temperature distribution can be measured. Thermography imaging is performed mostly by means of a portable, uncooled IR-camera. The wavelength of the used IR-detector is typically between 8 and 14 µm [Zamini12].

Illuminated (outdoor) thermography measurements should be performed on a sunny cloudless day, with min. 700 W/m^2 irradiation at the module array. Ideally the ambient temperature as well as the wind speed is low. The angle of view should be set as close as possible to 90° but not less than 60° to the module glass plane. The operator should be aware of reflections, e.g. buildings in the neighborhood, clouds or self radiation of operator or camera [Buerhop07]. For correct temperature measurement the camera must be set to the correct ambient temperature and the emissivity values for the surface inspected, see [Buerhop11a]. Typical emissivity values are 0.85 for the glass and 0.95 for the polymer backsheet, respectively, if the angle of view is within 90°-60° (glass) and 90°-45° (polymer). Measurements from the backsheet side, when possible, are more accurate than from the glass side.

When illumination is uniform and viewed under operating bias, cell temperatures may differ by only a few degrees. If the module is short-circuited or if defects are present, the temperature variations may be much larger. Multiples of 10 K temperature differences may be reached between hot spots in comparison to the normal operating parts in the vicinity. In addition it must be considered that there is a temperature gradient within the PV-plant (e.g. up to 13 K in ~8 m of modules on the roof) or even in a module (3-5 K), which is due to convective heat transfer [Buerhop11b]. In the Tab. 5.3.1 the possible failures which can be recognized by an IR-Camera are listed.

Tab. 5.3.1: Summary of PV module IR image patterns observed in outdoor measurements, their description, possible failure modes, and its influence on the electrical output. The table is originally from [Buerhop07] and is modified and extended.

Pattern	Description	Possible failure reason	Electrical measurements	Remarks, Chapter	Safety	Power
	One module warmer than others	Module is open circuited - not connected to the system	Module normally fully functional	Check wiring	A	System failure
	One row (sub-string) is warmer than other rows in the module	Short circuited (SC) or open sub-string - Bypass diode SC, or - Internal SC	Sub-strings power lost, reduction of V_{oc}	May have burned spot at the module 6.2.7 One diode shunted	B(f)	const. or E
	Single cells are warmer, not any pattern (patchwork pattern) is recognized	Whole module is short circuited - All bypass diodes SC or - Wrong connection	Module power drastically reduced, (almost zero) strong reduction of V_{oc}	Check wiring 6.2.7 all diodes shunted	A *when ext. SC*, B(f) *when Diodes SC*	const. or E
	Single cells are warmer, lower parts and close to frame hotter than upper and middle parts.	Massive shunts caused by potential induced degradation (PID) and/or polarization	Module power and *FF* reduced. Low light performance more affected than at STC	- Change array grounding conditions - recovery by reverse voltage 6.2.5 (PID)	A	C (v,h,t)
	One cell clearly warmer than the others	- Shadowing effects - Defect cell - Delaminated cell	Power decrease not necessarily permanent, e.g. shadowing leaf or lichen	Visual inspection needed, cleaning (cell mismatch) or shunted cell 6.1.1 (delam.)	A B(f)	A, B, or C(m, tc, h)
	Part of a cell is warmer	- Broken cell - Disconnected string interconnect	Drastic power reduction, *FF* reduction	6.2.2 (cell cracks) 6.2.4 (burn marks) 6.2.6 (interconnects)	B(f)	C(m, tc)
	Pointed heating	- Artifact - Partly shadowed, e.g. bird dropping, lightning protection rod	Power reduction, dependent on form and size of the cracked part	Crack detection after detailed visual inspection of the cell possible 6.2.2 (cell cracks)	B(f)	C(m, tc)
 	Sub-string part remarkably hotter than others when equally shaded	Sub-string with missing or open-circuit bypass diode	Massive *I*sc and power reduction when part of this sub-string is shaded	May cause severe fire hazard when hot spot is in this sub-string	A, B(f)	A, C