Chapter

Some Reliability Aspects of Photovoltaic Modules

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Abstract

Solar cells and photovoltaic modules are energy conversion components that produce electricity when exposed to light. The originality of photovoltaic energy as we understand it here is to directly transform light into electricity. Thin-film silicon in particular is better at low and diffuse illuminations and decreases less than the crystalline when the temperature increases while reducing the amount of material and manufacturing costs. However, the quality of the material and the efficiency of the conversion limit their use on a large scale. If the light absorption of the ultra-thin layers of the active material could be improved, this would lead to low recombination currents, higher open-circuit voltages and higher conversion efficiency. PV systems often communicate with utilities, aggregators and other grid operators over the public Internet, so the power system attack surface has significantly expanded. Solar energy systems are equipped with a range of grid-support functions, which—if controlled or programmed improperly—present a risk of power system disturbances.

Keywords: climatic stress factors, useful life, PV module failure, LCoE, EVA, PID, LID, defects, MWT, field failures, failure analysis, influence of temperature, encapsulants, perspectives, conclusions

1. Introduction

Discovered in 1839 by Antoine Becquerel [1], the photovoltaic effect allows the transformation of light energy into electricity. This principle is based on semiconductor technology. It consists in using photons to release electrons and create a potential difference between the cell's terminals that generate a direct electrical current. All photovoltaic devices have a p-n junction in a semiconductor through which PV voltage develops. Production costs have been reduced by about 20% [2] each time the production volume has doubled. The properties of copper oxide for rectifying alternating current were discovered for some 100 years.

Gravure printing electricity appeared in 1930 with copper oxide cells and then selenium. However, it was not until 1954, with the construction of the first silicon photovoltaic cells in the Bell Telephone company laboratories, that we saw the possibility of supplying energy. Very quickly they were used to power space vehicles in the 1960s with space satellite equipment. Then, from 1970, the first land uses the electrification of isolated sites. During the 1980s, terrestrial photovoltaic technology made steady progress with the installation of several power plants of a few megawatts and even became familiar to consumers through many low-power products using it: watches, calculators, radio and weather beacons, solar pumps and refrigerators. In the early 1990s, when solar developers announced the price per kilowatt hour (kWh) of photovoltaic energy, everyone laughed: we were ten times above the price of electricity purchased from classical generators. Fifteen years later, the costs have been cut by two or three, and no one is laughing anymore. Philippe Malbranche, a specialist in solar technologies at the Atomic Energy Commission (AEC), made it clear: "In the long run, solar energy will prevail. Not because of ideological choice or concern for the environment, but because it will be the most economically profitable."

When we look at the energy that comes directly from the sun per m^2, it is 1000–2000 times more, i.e. 1–2 MWh per square meter per year! About 70% of this energy can be recovered in the form of heat thanks to solar thermal energy: this represents a resource of almost 1 MWh/m^2/year. In the case of photovoltaics, with conversion efficiencies of 10–20%, 100–200 kWh/m^2/year can be recovered directly in electrical form.

When a photon interacts with an electron involved in chemical bonds between atoms, it moves it from its equilibrium level (occupied level of the valence band) to a higher excited level of energy (unoccupied level of the conduction band). The electron then returns to equilibrium at its initial level by re-emitting the absorbed energy, which can be in the form of heat, light and chemical energy—as in the case of photosynthesis or electrical energy if it can be recovered. In the latter case, we are talking about photovoltaic energy. In the case of a p-n junction of a semiconductor, an electron–hole pair is created under the action of a photon, the hole being the equivalent of a positive charge. Under the action of the electric field this created at the n-p interface, there is separation of charges and creation of a photocurrent.

At the beginning of studies on the chemistry of plasma-assisted deposition, the growth of deposition was atom by atom. One of the major discoveries was to increase the growth rate of the deposit by generating small clusters in the vapor phase before depositing them on the surface. In this case, silicon nanocrystals are obtained within an amorphous matrix. This technology is currently in full expansion and corresponds to significant yield increase prospects. Although the deposition of each layer requires the control of delicate chemical problems, we now know how to produce and market this type of product on a large scale.

1.1 New thin-film dies: the cadmium telluride dies

The interest in this technology—and this explains its success—is that the deposition processes are extremely fast (from a few seconds to a few minutes), which makes it possible to achieve high production rates and thus reduces production costs (less than one dollar per watt). The arrival of this technology marked a real breakthrough in the competitiveness of photovoltaic.

The copper indium diselenide die (CIS die) is expected to develop significantly as cells based on the same thin-film system achieve yields of more than 20% in the laboratory. Industrial production modules have yields of up to 13%, but this nascent production (1.7% of the market) is in full development. These cells use polycrystalline materials, filled with defects, and grain joints, materials that photovoltaic specialists would not have paid the slightest interest a few years ago. However, through the miracle of understanding the chemistry of these materials and their very complex interfaces, it works and even works very well!

The modulation of thin-film technologies is not based on the serialization of "wafers" glued next to each other, as is the case in conventional silicon technologies. In the case of thin-film modules, all this is done directly on the panel by insulating thin strips, oft using lasers, which are then connected in series with each other.

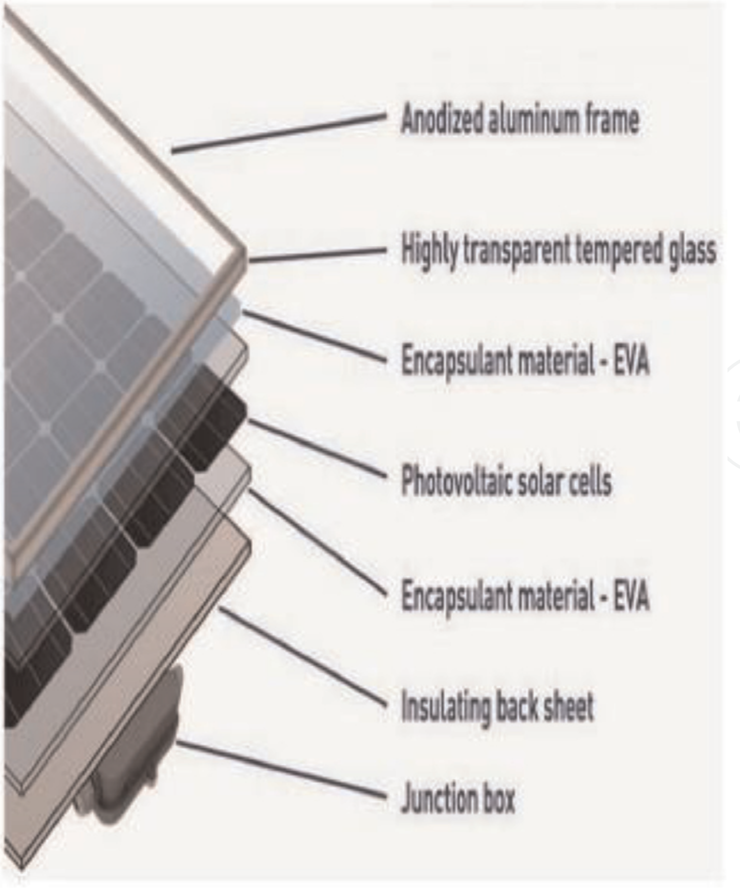

Figure 1.
The structure of a PV module.

This is called the "monolithic" connection. The serial connection allows increasing the voltage delivered by the module by adding the elementary voltages produced by each cell (here by each band). This specificity in the production technique of thin-film cells allow a great flexibility in the models of cells produced and a great adaptability to the needs according to the field of application.

The first amorphous silicon wafers were made in 1980 by Wolf [3] by simulating the ideal parameters for record efficiencies. Reducing the thickness of the layer, the voltage of the open circuit is increased by saturation of the current, as a result of the reduction of the geometric factor. The first publications concerning the manufacture of amorphous silicon cells (a-Si) appeared late, in 1960 [4, 5]. These entities still consist of silicon but only to a thickness of about 1 μm. The first amorphous silicon solar cell was made by Carlson in 1976 [6], and the first products appeared on the market in 1981. The type of system used influences the cost of the system, the stand-alone systems with batteries and auxiliary power generators which are more expensive than grid-connected systems. The interconnected and encapsulated solar cells form a photovoltaic module (**Figure 1**). Solar products have a great promise for a low-carbon future but remain expensive relative to other technologies.

The components of a photovoltaic power system are various types of photovoltaic/solar cells interconnected and encapsulated to form a photovoltaic module[1] (**Figure 1**).

[1] Photovoltaic modules are typically rated between 50 W and 300 W with specialized products for building-integrated PV systems at even larger sizes. Quality PV modules are typically guaranteed for up to 25 years by manufacturers.

Solar PV has a great promise for a low-carbon future but remain expensive relative to other technologies.

The ugliest problem with the solar cells is decreasing the cell efficiency with the panel temperature increase. The circuit control techniques include things like (1) using a smaller portion of the cells, when the load demand is low; (2) the wear leveling; (3) short-circuit, overload and other types of protections, current limiting, etc. The solar panels are subjected to the following environmental effects: (a) wind stresses and (b) cyclic thermal stresses from day to night and from summer to winter. These are two main observed defects caused by the repetitive environmental effects. Newer techniques involving varying levels of electroluminescence and photoluminescence, better panel coating technologies preventing debris accumulation on the surfaces of panels in the field, and of course, the technological approaches as ways of mitigating cost and risk currently exist in the industry.

Three IEC standards are used: IEC 61215 part 2 through part 4 (for mono- and multicrystalline silicon modules), IEC 61646 (for thin-film modules) and IEC 62108 (for concentrator modules). However, these standards can be viewed as general guidelines. In reality, the life of the PV modules mainly depends on intensity, distribution (UV content) and total dosage of sun radiation energy, ambient temperature, humidity, maximum operational voltage, wind speed and direction of the site. As these conditions vary widely over different sites, it may not be possible to define one standard or test to decide their lifespan. Further, the operation life depends on other conditions like salt and mist conditions and the presence of gases like NH_3, SO_2, etc. Separate IEC standards are available to address these conditions. Therefore, it is very important to know the site conditions. The components that can fail and be repaired are module failure, string failure, DC combiner failure, inverter failure, transformer failure, AC disconnect failure and tracker failure.

Solar PV power plants are composed of thousands of solar modules. It is a known fact that 2% of them will fail after year 10 of operation, causing losses as high as 27% of total income.

Reduced cost of capital has resulted in the out years having real value in discounted cash flow analysis. The advantages and limitations of PV solar modules for energy generation are reviewed with their reliability limits. The high reliabilities associated with PV modules are indirectly reflected in the output power warranties usually provided in this industry (40-year module lifetimes may not sound as exciting as new photovoltaic materials, but it's essential to make solar power economic). Reliability evaluation based on degradation models is commonly applied in highly reliable products as a cost-effective and confident way of evaluating their reliability. About 80% of the current production uses wafer-based crystalline silicon technology [4, 7].

The development of photovoltaic materials comprised of non-toxic, abundant elements is an important step toward increasing the economic viability of solar energy to meet growing global energy needs.

The performance of a solar cell is a sensitive function of the microstructure of the component materials. Recombination of photo-excited carriers at defects is one of the main contributors to low efficiency. The focus of this contribution is on PV modules with crystalline silicon (c-Si) cells, which represent the dominant technology with over 90% of the market share and of cumulative installations. It is expected that a broad variety of technologies will continue to characterize the PV technology portfolio, depending on the specific requirements and economics of various applications [8].

Among the renewables, the conversion of sunlight into electricity by photovoltaic (PV) devices is a reliable choice to cope with the growing energy consumption.

1.2 Testing problem and interactions caused by adhesion between components

Can a module durability of 30 years be guaranteed by combining components found to have no change in physical properties after 5000 h of pressure cooking testing or high-temperature/high-humidity testing? It seems this approach has been investigated, but there is currently deeply rooted resistance to it; it is difficult to confirm the effect that the gases and oxides generated from encapsulant components have on a variety of other components and difficult to estimate how vapor permeability changes over time when non-uniform tensile and other forces are applied by module creation. It is also impossible to determine the interactions caused by adhesion between components. As a wide variety of components are developed, the development of new reliability test methods (service life verification methods) should inevitably follow in the future [9].

The introduction of a new technology must be competitive with the technologies that it is replacing. It must be cost-effective and ensure an appropriate return on investment (ROI) for investors. The return on investment for governments will take the form of job creation and positive environmental impacts. Each new technology must be capable of generating such a high quantity of revenue that the production costs are reduced to a minimum (economies of scale). In an effort to introduce the use of renewable energy sources, governments worldwide have created incentives to encourage the development of renewable technologies in order to improve our environment. These encouragements help to ensure that the desired volumes are achieved at the early stages of market introduction, so that economies of scale drive the prices to the point of being competitive without the need for other motivations.

PV modules are often considered to be the most reliable component of a photovoltaic system. The alleged reliability has led to the long warranty period for modules up to 25 years. Their real lifespan is unknown; some can last much longer, probably 40 years with very little degradation of their performances. However, since the solar sector is relatively young, it is difficult to have figures in the long term; their conditions and lifespan depend on a wide variety of factors related to their location: a panel installed in Germany will not face the same problems as another used in the Sahara or on the top of a mountain. The panels have a guarantee of a maximum yield loss of 0.7% per year, i.e. after 25 years a maximum loss of about 15%.

When assessing the reliability of a PV system, it is important to consider not only the PV module but the system as a whole. An installed PV system can only provide the expected service if all its components function properly and the complete PV system is properly serviced, from the solar cell to the high-voltage connection.

While it is difficult to measure the performance of a single module in a PV system due to the lack of feedback on the different degradation modes of PV modules, errors that lead to module degradation are generally not taken into account. It is important to remember that, from an economic point of view, consumers are increasingly interested in the reliability and lifetime of their photovoltaic systems. The lifetime and reliability of a PV system largely depends on the energy efficiency of the modules and their different degradation modes. Therefore, research must more and more focus on the degradation of photovoltaic modules.

The panels are materials intended for use under blazing sunlight, in the open air, and therefore subject to the constraints of weather, climate and many other factors. Damage to panels in operation is numerous and can affect different parts of the panels. UV exposure alters the polymers used to encapsulate the photovoltaic cells and modifies the mechanical characteristics of these polymers. Moisture can penetrate the panel and degrade welds, cables and connections. Freezing can cause mechanical stress, while in the desert, sand can erode materials. In very rare cases, the panels can overheat and ignite [10].

While the reliability, quality and lifetime prediction are well established for most products, a complete understanding of these disciplines for PV modules is not yet possible because the desired lifetime is several decades and a first-hand assessment of lifetime predictions is not possible.

However, even today, the risks associated with module in-service performance over long periods of time are not completely clear. High-quality, publicly available field data on the long-term operational performance of PV systems are limited. In most cases, the production of field data takes many years and the technology has changed. That is why independent and high-quality laboratory data have been established in recent years to assess the long-term quality and reliability of photovoltaic modules.

PV systems are rightly regarded as low-maintenance and less susceptible to faults. These positive experiences must not be influenced by difficulties and reliability problems with additional features that may compromise the initial characteristics. For example, electronics on the module might be more susceptible to overvoltages, and this increases the risk of failures.

Comprehensive monitoring, evaluation, inspection and measurement methods detect possible defects and failures at an early stage, which can lead to performance deficits and reliability problems.

Since 2012, PV modules have been included in the EU WEEE Directive [11]. Collection and recycling of discarded end-of-life PV modules are mandatory to an extent of 80%.

2. Climatic stress factors

Solar irradiation, UV irradiation, humidity, wind, snow, rain, hail, high/low temperatures, temperature changes, salt, sand, dust and gases (O_3, NH_3, etc.). The module aging and the decrease in performance with time are complex processes that involve the interaction of several factors, namely, (a) reliability in PV, (b) service use weather conditions, (c) module materials (cell technology, encapsulant material, etc.) and design, (d) module mounting system and (e) module manufacturing process and quality control practices. Discoloration of the polymeric encapsulant is the most frequent degradation mode in hot climates. One degradation mode can be caused by a combination of various environmental stresses.

According to international report [12], at least 2% of the solar photovoltaic (PV) modules in operating solar plants will fail after 10 years of operation. As the modules are series-connected to other “healthy” modules in strings, they can lead to monetary losses as high as 27% of total income—depending on location, type of solar plant and remuneration fee.

3. HALT and HASS

Just like pulling on a chain until the weakest link breaks, HALT methods apply a wide range of relevant stresses, both individually and in combination, at increasing levels in order to expose the least capable element in the system. A highly accelerated life test (HALT) is a process that requires specific adaptation when it is applied to almost any system and assembly. A highly accelerated stress screening (HASS) is an ongoing application of combinations of stresses, defined from stress limits found empirically during HALT to detect any latent defects or reduction in the design's strength introduced during mass manufacturing.

Any stress that exposes design weaknesses that would show up in the normal environments is suitable even if theses stresses do not occur in the normal environments to which the product will be exposed. This is due to crossover effect. High reliability can be attained with careful testing that targets possible design problems, based on the physics of the failure modes, HALT testing and field data.

The highly accelerated stress test (HAST) is a process that applies increasing levels of stress (beyond the environment for which it is intended), for a short period of time, to highlight design and process weaknesses. It consists of a search for the real limits of the product based on its ability to resist environmental constraints such as random vibrations and cold and hot temperatures. This type of test is first of all focused on the very quick identification of defects. Then, corrective actions are implemented to quickly increase the product's robustness. As a result, the product is able to withstand much greater stresses than those it will experience during the normal life cycle. This method is used from the design phase to highlight design problems, also during the production phase to detect process errors. It is essential (i) to reduce product development time, (ii) to increase product reliability and (iii) to reduce after-sales service and other catastrophic youth defects in cost and brand image. It is no longer enough to measure the reliability of a product and perform a simple function test before distribution. It becomes necessary to build reliability from the upstream study around the product. Tests such as HALT and HASS allow this.

Dedicated combined environmental resources and a test time of about a week, combined with product monitoring during the tests, are the key to the success of a fast and efficient method. HALT allows you to do in a week what other environmental tests do in several months. HASS takes place during the production phase of the products. A profile is applied for 4 h (called burn-in) during which it undergoes thermal variations, random vibrations and electrical stresses. This profile allows to transform existing weaknesses on the product into measurable defects. In this way, potentially defective products are not distributed, and after-sales costs are avoided. This test takes place during the production phase of the products.

4. Useful life

The useful life corresponds to the majority of the system's lifetime. During this period, the failure rate may be:

- Increasing for mechanical elements due to wear, fatigue and corrosion.
- Constant for electronic components because there are no aging phenomena.
- Decreasing in the case of software with error correction, to improve reliability.

The age period corresponds to the failures defining the end of use of the product regardless of the type of technology. The default rate in this period is growing rapidly. During this period, products that had not been deficient during the useful period generally become deficient over a very short period.

The lifetime of PV modules is a function of a few key major field stresses such as temperature, humidity, UV light and system voltage. The accelerating factor is the relation between the time spent in the field test (or in use) and the time spent in the accelerated test. The purpose of these tests is to shorten the duration of the tests under simulated test conditions that are much stricter than actual field operating conditions, without changing the actual failure mechanisms in the field. In the AT programs, the stress tests of PV modules are performed at higher levels than the field/use stress levels along with pre- and post-characterization of materials and modules from reliability, durability and safety perspectives.

5. Levelized cost of electricity (LCoE)

The LCoE is a present value assessment of the total system costs over its lifetime and the system returns. Financial factors (the inflation or the cost of capital) are also taken into account and discounted depending on the LCoE formula in use

$$\text{LCoE } (€/\text{Wh}) = \frac{\text{lifecycle cost}}{\text{lifetime energy yield}} \tag{1}$$

To reduce LCoE, current research focuses on a few well-defined topics:

- Decreasing cell-to-module loss to increase module power.
- Simulation and optimization of outdoor module performance for increased energy output.
- Developing new module designs and fabrication processes for cost reduction.
- Understanding degradation mechanisms with the aim to improve module reliability and durability. PV module reliability is dependent on the quality and integrity of the process used to manufacture the module. Even small variations in material quality or manufacturing processes can impact the reliability of a component.

6. Degradation and failure

Multiple factors affect the reliability and long-term performance of PV modules. The quality and characteristics of the used materials, the interaction of the components, the manufacturing process and the local climate at the operating site play a significant role. The main degradation modes are known and their causes have been identified in most cases. To identify the main modes of degradation, accelerated aging is used with climate chambers, in situ monitoring and the variation of test parameters. The nanoindentation was used as a suitable destructive method to investigate the changes in hardness occurred during dampheat (DH) aging of components in the PV modules with a high spatial resolution [13]. Certification tests are designed to ensure a nominal level of safety and design quality, and not to indicate whether or not a product will last for its warranted lifetime; these tests are designed to ensure safety and identify infant mortality issues due to basic manufacturing quality.

The root causes of different module failures are (i) snail trails and pearl chains, (ii) cell cracks, (iii) solder joint, (iv) breakages, (v) light-induced degradation (LID), (vi) potential induced degradation (PID), (vii) hot spots and (viii) delamination. Dominant failure pathway (for modules manufactured in the early 2000s) [14]: (1) cell interconnects become more resistive, apparently due either to corrosion or fatigue of the interconnect ribbons or solder connections; (2) interconnects resistively heat, which increases the severity of temperature cycling and leads to even higher resistive heating (3) interconnect overheat or breakage leads to backsheet blackening, power loss, or other failure events. The primary underlying causes of module failures in the field were due to cell/interconnect breakage and corrosion.

In addition to failure rate, power degradation is a critical module behavior; a power degradation of a few percent has a direct effect on production over a module's lifetime, and such a small percent drop would not justify a claim under most module warranties. Subtle variations between cells, such as cell thickness, can have very large impacts to mechanical stability and reliability.

7. Predominant degradation modes

Corrosion, discoloration delamination and breakage of PV modules' encapsulant are the main modes of product degradation. Temperature and humidity are factors of PV module degradation in almost all identified degradation modes. One key factor of reducing the costs of photovoltaic systems is to increase the reliability and the service lifetime of the PV modules. Models can help to overcome the long-term experiments' obstacle in order to study PV module degradation under real conditions. To increase the reliability and the service lifetime of the PV modules, it is necessary to reduce the costs of PV systems.

In addition to degradation analysis, the stress tests available today are very effective at screening for PV module defects that cause severe degradation or safety issues such as bad solder joints or a poorly adhered junction box.

8. Environmental factors influence the degradation

Even bird droppings can significantly reduce the output of a photovoltaic module. However, many causes of faults are not visible to the naked eye. In such cases, special devices such as a thermal imaging camera are required for localization.

With a thermal imaging camera, the following defaults in the modules can be detected: (a) production failures, (b) damage such as cracks, (c) faulty power connections and connections, (d) contamination and shading, (e) defective cables and (f) inverter damage.

9. PID and LID

PID and LID are two different kinds of induced degradation of PV modules. In the first case, *potential induced degradation* (PID) is conducted by high voltages and the other *light-induced degradation* (LID) conducted by sunlight (real or simulated).

PID is the "new disease" of the PV module; highlighted in 2010, it begins to affect more and more photovoltaic modules. The first symptom of this phenomenon is a rapid and unexplained degradation of power. This decrease in module efficiency, which can reach more than 20% in a few months, is neither due to conventional module aging nor to improper module installation. Individual modules in PV systems are often connected in series to increase the system voltage. The potential difference of the chain thus formed can sometimes reach a few hundred volts [15]. In order to protect people from electric shock, all metal structures of the modules are often grounded. Thus, leakage currents can occur due to a lack of insulation between the structure and the active layers (PV cells) [16]. This phenomenon can lead to polarization that can degrade the electrical characteristics of photovoltaic cells. This phenomenon known as potential induced degradation (PID) is characterized by the progressive degradation of the performance of crystalline silicon-based photovoltaic modules due to the presence of an induced electric current at the very heart of the module [17, 18]. Hacke showed that PID was more common in humid climates than in hot and dry environments [19]. Schütze et al. go in the same direction by showing that leakage currents increase with humidity [15]. In his study, a ramp voltage of −600 V at sunrise and 0 V at sunset is applied between the metal structure and the contact of a module composed of 60 cells. His experience has shown that leakage current increases with humidity. The various studies have shown that the main factors favoring PID are the voltage of the system in which the module is used, humidity and operating temperature. PID is triggered by a combination of high temperature and relative humidity. Furthermore, some degradation mechanisms are interdependent. The PID process that occurs more often in p-type cells is a PID of the shunting type, sometimes denoted by PID-s. Other types of PID in p-type cells are the dissolution of the antireflective coating and the corrosion of the cell fingers [20]. Quality control during the module manufacturing process is essential to ensure a good performance in the long run.

ID usually occurs when modules are in strings operating at high voltages (near 1000 V_P, but not only), combined with very warm and humid weather. Dust and glass degradation (releasing sodium ions) may catalyze the PID phenomenon. Potential induced degradation (PID) is an effect that affects some PV modules with crystalline Si cells; the degradation of performance that can occur after a few years can arrive to 30% or more.

Light-induced degradation (LID) has been identified to be a critical issue for the long-term stability of solar cells and modules from boron-doped silicon substrates. Besides the well-known LID of excess charge carrier lifetime within Czochralski-grown silicon substrates induced by the activation of the boron-oxygen complex, significant performance degradation has been observed also for certain multicrystalline silicon (mc-Si) solar cells and modules [21]. This degradation is significantly more pronounced at elevated temperatures and, therefore, referred to as LeTID for "light and elevated temperature-induced degradation." If not controlled, LeTID can induce a decrease of conversion efficiency by more than 10%, particularly for solar cells with dielectrically passivated surfaces. LeTID needs therefore to be suppressed by adapted cell processing.

For the younger installations (less than 10 years of operation), the most observed degradation modes are hot spots and internal circuitry discoloration (both related to electric interconnections), encapsulant discoloration, broken cells and PID (**Figure 2**).

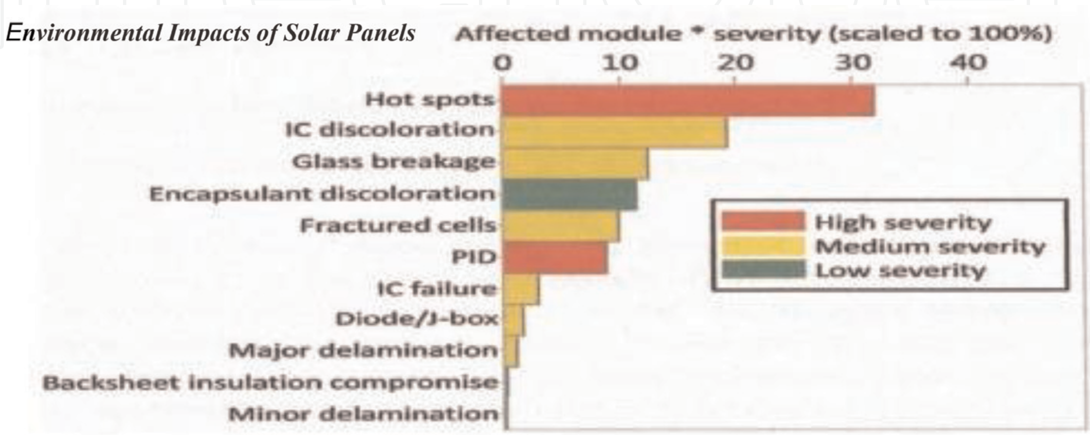

Figure 2.
Pareto chart of the most significant degradation modes for systems installed in the last 10 years. PID is ranked as a high-severity degradation mode. Interconnection failures, which include hot spots and internal circuitry (IC) discoloration, also play a large role in degradation. Image adapted from [22, 23], with kind permission.

The LID for crystalline silicon modules varies between 0.5 and 3%; some modules have a loss of up to 5%. Manufacturers using n-type silicon cells have no loss of LID. Manufacturers take this into account by considering a power loss of 3% during the first year of the module warranty [24].

10. Failures in the electric interconnections

Interconnection failures are generally caused by thermo-mechanical fatigue. Because of the different coefficients of thermal expansion of the materials in the module sandwich (e.g. cells, encapsulant, glass, back sheet), thermal variations result in a displacement of solar cells in the module. The same effect can occur when the module is exposed to mechanical stresses, e.g. due to wind or snow loads.

The reliability of ribbons has gained increasing attention in the last few years. In [23] how the module performance is affected when one or more ribbons are broken was investigated. It was quantified, by experimental measurements, the actual impact on the electric performance when one or more ribbons connecting adjacent cells are disconnected. In [23] a simplified electrical model in LT-SPICE that is able to reproduce experimentally measured IV characteristics and the variation in the module's electrical parameters induced by the breakage of the cell interconnect ribbons were proposed.

11. Defects

A defect is everything in a PV module that is not as it is expected to be. A large number of defects are known in PV c-Si modules. Some of these can be identified by visual inspection [25, 26]:

- Broken glass by volley or mechanical accidents
- Delamination (busbars, EVA foil)
- Broken or deformed frames
- Brownish color caused by hot spots
- Charred electrical connection box
- Defects in connectors
- Environmentally altered surfaces
- etc.

12. Rate of defective panels

The rate of defective panels leaving the assembly lines—evaluated thanks to returns and complaints from customers—is well below 0.1%. Highly demanding quality standards have been defined by the IEC, an international body that sets design and quality standards.

The youth period refers to early failures due to design problems (incorrect sizing of a component, etc.) or production (deriving from a process of manufacturing). The default rate is decreasing in this period. In the case of modules' photovoltaic, youthful failures can be eliminated before delivery to the customer by practicing debugging. Burn-in consists of turning on the components to be delivered under conditions that may reveal failure modes. This practice is expensive and the failure rate at delivery is equal to that at the beginning of the useful period. Many manufacturers do not perform this burn-in on their products for reasons of cost. In this case, a warranty period is put in place during which the manufacturer undertakes to change or repair the defective product. For example, for photovoltaic modules, manufacturers guarantee them for an average of 5 years for mechanical failures (unrelated to the power delivered by the modules). In reliability studies, defects that appear during this warranty period are not taken into account and are mainly concerned with the useful life of the product.

13. Failures

Typically failures of products are divided into the following three categories: *infant failures, midlife failures* and *wear-out failures*. During initial exposure to light, crystalline silicon modules generally undergo a permanent reduction in output power emissions. This phenomenon is called light-induced degradation or LID. On average, the LID for crystalline silicon ranges from 0.5 to 3% due to traces of oxygen included in the molten silicon during Czochralski process. Manufacturers take into account a 3% power loss during the first year of the module's warranty. Be aware of LID degradation [27]. Crystalline p-type boron-doped silicon solar cells generally exhibit a degradation of conversion efficiency during the first hours of exposure to the sunlight. Understanding light-induced degradation of c-Si solar cells is associated with the formation of the well-known boron-oxygen complex which acts as a harmful defect and reduces the minority carrier diffusion length accordingly. LID is therefore related to both, boron and oxygen concentrations.

For thin-film PV modules, there are far fewer experiences accumulated in the past years than for crystalline Si PV modules.

Failure modes are directly related to module material sand; hence, they continuously evolve with the material adjustments made by module manufacturers.

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.

Failures occurring in the midlife of PV modules are described in a study of DeGraff [28]. **Figure 3** shows the analysis and statistics of specific field failure distribution. The predominant PV module failures are delamination, cell part isolation due to cell cracks, and discoloring of the laminate.

Module failure. The so-called ribbon kink (between the cells and the joint between the cell interconnect ribbon and the string interconnect) is prone for fatigue breakage. The possible causes are poor soldering ➔ disconnections. A too intense deformation during the fabrication of the ribbon kink between the cells mechanically weakens the cell interconnect ribbon. A narrow distance between the cells promotes cell interconnect ribbon breakage. Physical stress during PV module transportation, thermal cycle and/or hot spots by partial cell shading during long-term PV system operation forces mechanical weak ribbon kinks to break.

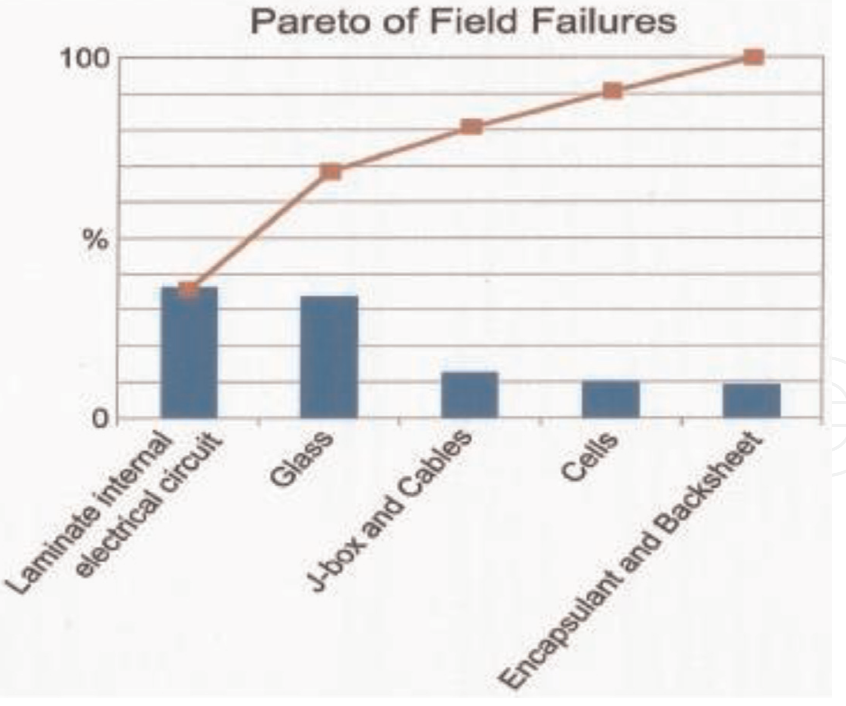

Figure 3.
Analysis and statistics of specific field failures (with kind permission of SunPower Corp.)

13.1 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.

The specific field failures are their analysis and statistics (**Figure 3**).

13.2 Clamping

A relatively often seen failure in the field is glass breakage of frameless PV modules caused by the clamps. Major problems caused by glass breakage are electrical safety issues, because the insulation of the modules is no longer guaranteed, in particular in wet conditions, and because glass breakage causes hot spots, which lead to overheating of the module.

13.3 Transport and installation

Even in well-designed transport containers, the cells of PV modules may crack during "normal" transport. The cause of cell breakage is much more difficult to decide. Only an electroluminescence image or a lock-in thermography image can reveal the damage.

13.4 Quick connector failure

Quick connector failure—in the most cases—is not considered a PV module failure.

13.5 Lightning

A defective bypass diode caused by a lightning strike is caused by an external source, for which the module is not designed.

13.6 Defect

Much wider than a failure, the defect does not result in a loss of power or safety of a PV module but specifies a part of a PV module that is different from a perfect PV module.

14. Field failures

Field failures of PV equipment can stem from materials, fundamental product design flaws or failures in quality control during manufacturing. Failure modes in the field which occurred during operation are (a) yellowing/browning of encapsulants and back sheets with and without power loss, (b) delamination of encapsulant and back sheet, (c) bubble formation, (d) oxidation of busbars, (e) discoloration of busbars, (f) corrosion of connections, (g) cracking of back sheet, (h) hot spots, (i) cell breakage and (j) microcracks.

Testing and certification are 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.

Check the module for damage due to transportation before the installation. Do not use or install damaged modules. Damaged modules may cause fire or electric shock, resulting in property damage, fire and or death.

LEDs are gaining an increased market share in applications requiring light in the UV spectrum [29]. This trend is driven by big technological advancements and various advantages of LEDs compared to the conventional UV light sources. These advantages include a higher efficiency, a longer lifetime, more constant radiance and less heat generation [30].

It was imperative to evaluate the option of using UV LEDs in PV module and component degradation. The UV LEDs have proven their long lifetime and slow degradation at room T and RH. However, also polymeric materials only degrade slowly in those conditions. This emphasizes the need to apply UV light and other stress factors at the same time in accelerated aging and degradation testing [31].

15. The most common failures of PV modules

Four major materials are assembled to realize a PV module: glass, metals, polymers and solar cells/active semiconductor thin-film layer.

Aging and failure mechanisms seen over the past several decades have been documented over a wide range of power plant locations and material sets (**Figure 4**).

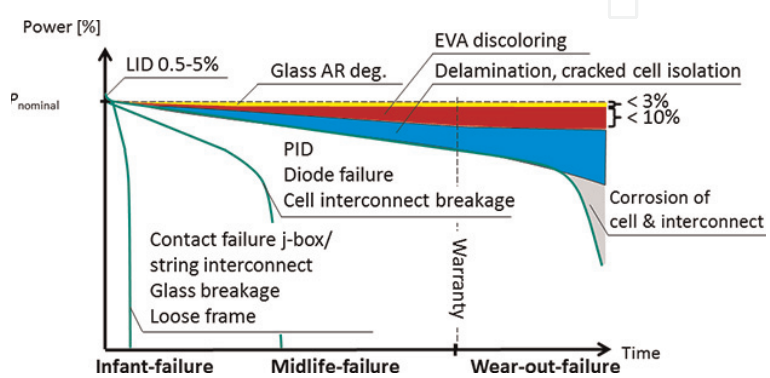

Figure 4.
Three typical failure scenarios for wafer-based crystalline photovoltaic modules are shown. Definition of the used abbreviations: LID, light-induced degradation; PID, potential induced degradation; EVA, ethylene-vinyl acetate; jbox, junction box [32]. With kind permission of IEA.

indicates leading PV module aging and failure mechanisms that occur as infant mortalities, midlife failures and wear out. Laminates containing EVA foils with a systematic variation of the additive formulation, i.e. the crosslinking agents, ultraviolet (UV) absorber, hindered amine light stabilizers and antioxidants, were subjected to UV aging. Failures are the following: EVA discoloration; cell cracks; snail marks; loss of adhesion of the back sheet; interconnection tapes of the cell and disconnected wires; junction box failure; frame failure; burn marks; potential induced degradation; defective bypass diodes; failure of thin-film modules, such as microarcs at hot spots of bonded connectors; shunts and front glass failure; and rear contact degradation [32].

16. Ethylene-vinyl acetate (EVA)

One of the most overt degradation mechanisms for PV modules is the discoloration of the ethylene-vinyl acetate (EVA) or other encapsulation materials (considered as an esthetic issue). EVA is usually formulated with additives, including UV and thermal stabilizers. But if the choice of additives and/or their concentrations are inadequate, the EVA may discolor.

Delamination may be more likely at the interface between EVA and the solar cell, because the interfacial strength may initially be more limited there than at the EVA/glass interface. On the other hand, UV degradation and subsequent embrittlement may limit the long-term adhesion of interfaces exposed to the sun.

It is quite common to see symmetric patterns and sometimes multiple rings based on the effects of limited chemical diffusion, both into and out of EVA and the existence of multiple chemical pathways that produce similar chromophore species.

It was possible to show a link between changes in mechanical properties with both the transient temperature and the degree of long-time thermal aging [33].

The overall EVA degradation is higher in the Indonesian equatorial zone, in the African semi-arid zone and in the Chinese cold desert (**Figure 5**).

Results from environmental degradation simulations highlighted the effect of climatic zones on degradation, with higher degradation in hotter, warmer and more irradiated zones. The overall EVA degradation is higher in the Indonesian equatorial zone, in the African semi-arid zone and in the Chinese cold desert [34]. With kind permission of the authors.

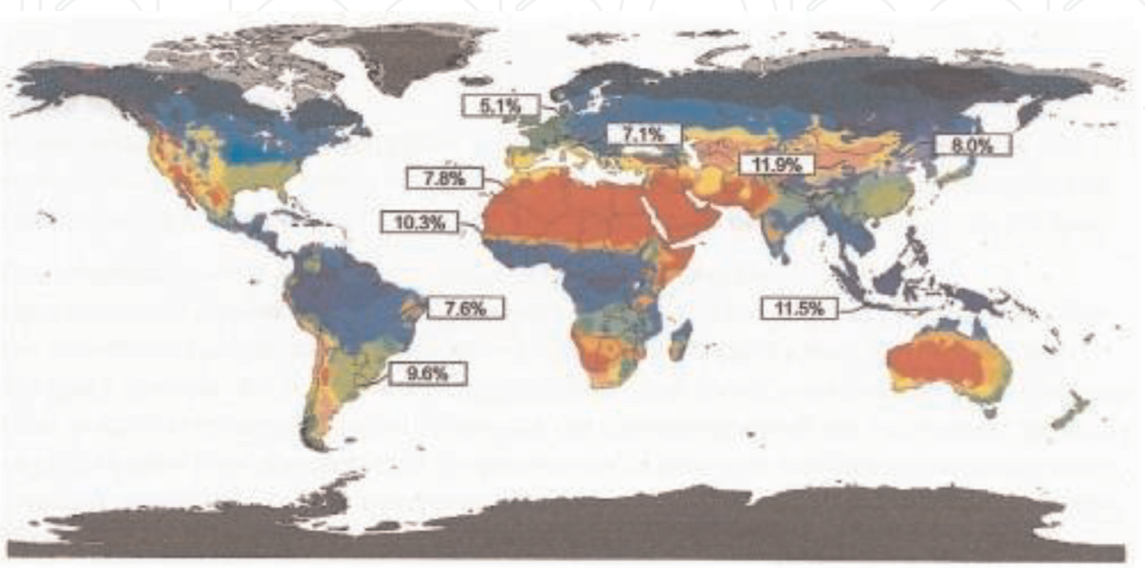

Figure 5.
Köppen's map and overall EVA degradation, calculated after a 20-year exposure in different climatic zones.

Glass can be a source of module reliability problems if not properly fabricated. Glass reliability issues can include brittle failure due to mechanical and thermal stresses, surface weathering, lamination adhesion, transparent conductive oxide (TCO) adhesion, moisture ingress and antireflective coating durability.

17. Failure analysis

The search for physical-failure root causes is aimed at breaking through any technology barrier in each stage of chip development, package development, manufacturing process and field application, offering the real key to eradicate the error. Testing provides us with information on the electrical performance; FA can discover the detractors for the poor performance [15].

Failure modes in the field which occurred during operation are analyzed [31]: microcracks, cracking of back sheet, corrosion of connections, hot spots, cell breakage, delamination of encapsulant and back sheet, oxidation of busbars, yellowing/browning of encapsulants and back sheets with and without power loss, bubble formation and discoloration of busbars.

Most of the failure modes observed are polymer defects such as delamination, yellowing (there are no obvious results that show a direct relationship to power losses in the event of yellowing) and browning, bubbling and cracking of polymers used for encapsulants and back sheets. Oxidation and discoloration of busbars and corrosion of connectors are also easily detected without special measuring equipment; they lead to increased resistance in series. Microcracks, cell failure and hot spots have a greater impact on performance [31]. The detection of these defects requires IR cameras.

Modul**e**s under test both in the field and during qualification testing have exhibited several types of failure resulting from moisture intrusion. Poorly designed cell assemblies can damage or break the cells.

Failures observed during the analysis are the following: (i) moisture intrusion, (ii) differential thermal expansion, (iii) plus UV exposure, (iv) wind loading, (v) off-track charring and (vi) hot spot. The types of failures resulting from moisture intrusion are (1) cell strings shorting to ground; (2) terminals shorting to ground; (3) high ground fault currents, preventing inverter from coming on; (4) modules filling with water; (5) corrosion; and (6) degradation of optics.

18. New techniques for failure analysis

Dark lock-in thermography (DLIT) has recently emerged as a new powerful technique for failure analysis of PV modules; it provides information on the thermal behavior across the whole module at high spatial resolution, besides complementing and overcoming some of the limitations of electroluminescence (EL) and conventional passive infrared (IR) cameras. Its basic principle consists in stimulating the module by applying a periodic current signal, while a highly sensitive IR camera detects and measures the surface temperature stimulated by the current signal.

Scanning acoustic microscopy[2] (SAM) has proven to be a powerful technique for the investigation of failures and defects in solar cells and modules [35]. This technique is needed to advance the assessment of module quality and, thereby, improve

[2] SAM is a non-invasive and non-destructive technique that can be used to manage the internal features of a specimen, in particular its interfaces. SAM is a superior tool to detect delamination even of submicron thicknesses (down to 100 nm).

their long-term performance. The PV modules were placed flat into a water tank and scanned.

PV modules (20 × 20 cm^2) were prepared by laminating a layer of polymer-based backsheet foil (BS) and two layers of ethylene-vinyl acetate (EVA) sandwiching a monocrystalline silicon cell and a transparent glass cover.

The very fine resolution achieved with SAM allowed a clear visualization of the location and shape of the air pockets detected on the rear side of the module. These air pockets seem to form only on the silver pads next to a ribbon, which may indicate that the EVA did not adhere completely to the silver pads, thus giving rise to air gaps. In acoustic micrographs, air pockets and delaminated areas are easily detected as very bright features because air-filled interfaces reflect almost all incoming sound.

The depth profile analysis indicated that SAM can be applied to detect thickness variations within the BS and encapsulant layers. SAM has proven to be a very sensitive technique to detect interfacial faults, such as cracks on the solar cell, bubbles and air pockets at different interfaces. A correlation between SAM and DLIT images with regard to the encapsulation homogeneity and adhesion defects could be verified, suggesting both techniques are complementary to study defects of this nature. Therefore, SAM is a reliable and complementary technique to DLIT and EL in investigating PV modules [10].

19. Influence of temperature

Temperature is extremely significant to the PV module degradation process, especially hot spots, encapsulant bleaching, delamination failure on interconnections, corrosion, discoloration and bubbles on the panel's surface.

Crystalline silicon PV cells/module degradation—exposed under temperature and heat effect—has been investigated. This revealed:

- Delamination of encapsulant and back sheet.
- Bubble formation, oxidation of busbars, yellowing/browning of encapsulants and back sheets with and without power loss.
- Discoloration of busbars.
- Corrosion of connections.
- Cracking of back sheet.
- Hot spots, cell breakage and microcracks are the dominant modes of degradation.

Temperature is responsible for most of the chemical reactions and extremely significant to the PV module degradation process, especially hot spots, encapsulant bleaching and delamination failure on interconnections, corrosion, discoloration and bubbles on the panel's surface.

The leakage current increases rapidly with increasing number of hot spots. The effect of discoloration causes loss of transmittance of the encapsulant EVA and reduces the photocurrent density (J_{ph}) owing to a decrease of absorption and therefore the power loss. Discoloration does not affect the fill factor (FF) and (Voc) more, but the corrosion causes a decrease of the PV module maximal power (P_{max})

Accelerated Stress Test	Failure mode	International regulation
Thermal cycling	Broken interconnections	
	Cell cracks	
	Solder bond failures	
	Module open-circuit	
	Potential for arcing	
	Junction box adhesion	
Dampheat	Corrosion	
	Delamination	
	Encapsulant loss of adhesion & elasticity	
	Junction box adhesion	
	Inadequate edge deletion	
Humidity freeze	Delamination	
	Junction box adhesion	
	Inadequate edge deletion	IEC 61215
UV exposure	Delamination	
	Encapsulant loss of adhesion & elasticity	
	Encapsulant & backsheet discoloration	
	Ground fault due to backsheet degradation	
Static Mechanical Load	Structural failures	
	Broken glass	
	Broken interconnect ribbons	
	Broken cells	
	Solder bond failures	
Dynamic Mechanical Load	Broken glass	
	Broken interconnect ribbons	
	Broken cells	
	Solder bond failures	
PID test	Potential-induced degradation	IEC62804 [59]

Table 1.
Summary of the main accelerated tests for c-Si PV modules (Adapted from [37]).

	Qualification	Comparative	Lifetime
Purpose	Minimum design requirement	Comparison of products	Lifetime estimation
Quantification	Pass/fail	Relative	Absolute
Climate	Not differentiated	Differentiated	Differentiated

Table 2.
Three types of accelerated tests employed in the PV industry.

when the delamination of the PV module reduces the thermal conductivity locally and hence increases the temperature of the cell [36] (**Tables 1** and **2**).

20. Accelerated tests

The *International Photovoltaic Quality Assurance Task Force* (PVQAT) gathers the efforts of many research groups worldwide in order to improve the understanding of the reliability of PV modules. One goal is to propose a climate-specific test protocol.

21. Qualification tests

The qualification tests have been essential to identify materials that lead to early failures in the field and to achieve a high reliability for PV modules. However, they present some limitations if one wants to interpret them as reliability-predictive tests. Presently, PV modules are only going through qualification tests (such as performed according to the IEC 61215 for crystalline silicon-based modules) which provide limited information as (i) they do not provide information on the maximum lifetime that can be expected and (ii) they do not consider climate specificities [39].

Testing and certification of a PV module focuses on verifying that the fundamental design requirements have been fulfilled. Reliability testing increases confidence in production quality and usually takes less time and costs less than durability tests [40].

The purpose of the qualification tests is to screen new designs and new production runs for susceptibility to known failure mechanisms: (1) The tests do not establish field lifetimes; (2) cell assemblies and complete modules are tested separately.

22. Photometric testers

Measurements with photometric testers give additional hints on defect PV modules (defect bypass diodes, broken or delaminated connectors and wires). These inspections of modules often can be done while these modules are still installed. However, analysis with photometric testers addresses the modules as a whole and cannot localize the defect within the module; defects may be localized by thermographic cameras.

All critical areas that are detectable via the IR camera at long wavelength could as well be detected with the near-infrared (NIR) camera. However, NIR images are more suitable for the defect analysis since they have higher local resolution [41].

Typically the NIR images show an affine distortion. This has to be corrected carefully to an orthoimage. Furthermore NIR image is brighter at the center than in the outer regions. This must be numerically compensated.

23. Combining up to three stress factors targeting specific mechanisms

The necessity for combining multiple stress factors into fewer tests has been recognized for some time, as demonstrated by efforts made by various other groups [42–45]. While important results have been produced, these efforts are typically limited to combining up to three stress factors targeting specific mechanisms. In this work, a combined-accelerated stress testing (C-AST) capability has been developed which combines multiple stress factors from the natural environment including light, humidity, temperature, rain, mechanical loads and voltage stress. The test has been developed with the philosophy that it is agnostic to a priori known failure mechanisms such that mechanisms in new module designs or materials may be identified before deployment. C-AST is applied here to mini-module specimens to allow for possible adverse material interactions.

The test includes six 4-cell p-PERC mini-modules with three back sheets based on polyvinylidene fluoride, polyamide and polyvinyl fluoride, as well as two types of polyethylene-co-vinyl-acetate (EVA), one UV blocking and one UV transparent. The experiment demonstrated C-ASTs' ability to identify backsheet cracking and other failure mechanisms such as UV-induced degradation, solder bond breakage, minor corrosion and cell cracking.

24. Encapsulants

Encapsulation materials are of critical importance for long-term reliability and safety of PV modules. Only months in the field may lead to drastic power output degradation, for example, due to potential induced degradation (PID), and also in the longer run adhesion and discoloration issues (hot spot) can reduce power output or even may lead to critical electrical safety issues. These findings are not sufficiently covered by IEC 61215 and other standard testing. Additional and different types of tests are required for an in-depth understanding of the encapsulation material's impact on PV module performance [46]. PID can be critical for many of the solar parks built in the early phase of PV deployment (2000–2012); however, it can still occur in modern modules when lower encapsulants are used in PV manufacturing, a choice often driven by the need for cheap solar electricity.

25. Key performance indicators

Typical key performance indicators (KPIs) used in solar industry for assessment of the performance of solar modules and balance-of-system (BOS) components were investigated in [47]. From the point of view of an investor in PV systems, it is important to have a comprehensive insight into the reliability of solar modules. Since reliability and longevity of such components are crucial for the long-term financial success of the project, corresponding KPIs are desired. To this end solar industry has traditionally provided KPIs for both solar modules and inverters on the base of relating the number of failed (claimed) product to the number of installed (or sold) product. The denominator of these KPIs may be referred to as either related to the same period as the numerator or to a cumulated number of installations. The study [48, 49] has shown that currently used KPIs are not sufficient when comparing the ability of solar manufacturers to produce reliable solar modules or inverters.

Presently, PV module manufacturers typically guarantee 80% of the nominal power for 25 years. If we assume a linear power degradation rate, this corresponds to an annual degradation rate D of 0.8%/year.

To recover the losses, a continuous repowering would be necessary, substituting the modules that fail with new ones. Failures in modules lead to hot spots that can be detected by visible (VIS), IR thermography and electroluminescence (EL) images. This inspection, mainly manual, is rapidly reducing costs by the increasing penetration of drones, which will very probably become soon the state of the art [50–53].

26. Metal-wrap-through (MWT) concept

The metal-wrap-through (MWT) concept, which was developed in 1998 by Kerschaver et al. [54], represents an alternative approach for reducing shading while at the same time ensuring reliable measurability and purely rear-side contacting. MWT solar cells differ from conventional solar cells in that the front-side contact finger is not routed to busbars, but to the rear side via metallized vias. This makes it possible to connect the cells on the rear side only, but the cell structure otherwise corresponds to that of conventional solar cells.

Critical points such as the recombination in the area of the vias, the influence of the rear n-contacts to the series resistor as well as the arrangement of the rear contacts for a reliable and low-loss external circuit are to be dealt with in simulations and experiments. The selection of suitable passivation layer systems as well as the reliable insulation of the vias and the rear side n-contacts against the p-base is also the central aspects regarding the minimization of leakage currents. Another important factor for reliable module integration is the behavior of the cells when negative voltage is applied externally.

This operating state can occur during partial shading of photovoltaic modules and can lead to local overheating within the cell if the current flux is not controlled. Investigations into the backward behavior of the developed solar cells are, therefore, of great importance for the long-term stability of the solar cells and the modules produced from them.

The reliable connection of the front contact grid with the rear contact surface through vias is a central task in the development of MWT solar cells.

The efficiency of solar cells available in practice is reduced by a multitude of further loss mechanisms [55] and depends both on the quality of the materials used and on the available technologies. Predictions of the practical reachable maximum are, therefore, highly error-prone.

High reliability: service life between 10 and 20 years, depending on location installation.

27. Perspectives

The continuous evolution in cell technologies and the implementation of new encapsulation materials will lead to the appearance of new degradation modes, which might require years before being detected in the field. The case of the so-called light and elevated temperature-induced degradation (LeTID) effect that was observed in PERC cells only in 2015 is an example. Also new applications of PV such as building-integrated photovoltaics (BIPV) lead modules to operate in new conditions (resulting, e.g. in higher module temperature excursions) and employ new materials, which may result in a different evolution of the typical degradation modes as well as in the appearance of new degradation modes.

With regard to new cell technologies, we expect that in passivated emitter and rear cells (PERC), where the only differences with respect to standard p-type cells lay in the rear surface, the mechanism of PID is in general the same as for the standard p-type cells. It is expected therefore that the study of PID mitigation strategies [23] is applicable to PERC cells as well. The mechanism of PID in silicon heterojunction (SHJ) cells is instead very different in that it does not consist of cell hunting, but corrosion of the transparent conductive oxide (TCO) layer (similar to thin-film modules) requires a different study.

28. Conclusions

The reliability of PV power plants and modules has been—and will continue to be—an issue for investors, owners and utilities.

A global network is required to improve the quality and reliability of PV systems and components by collecting, analyzing and disseminating information on their technical and financial performance.

PV will utilize new materials, manufacturing methods, module and systems designs in order to lower costs and hopefully increase or maintain reliability.

New module materials and constructions and new system concepts are necessary for increased reliability and lifetime [56].

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