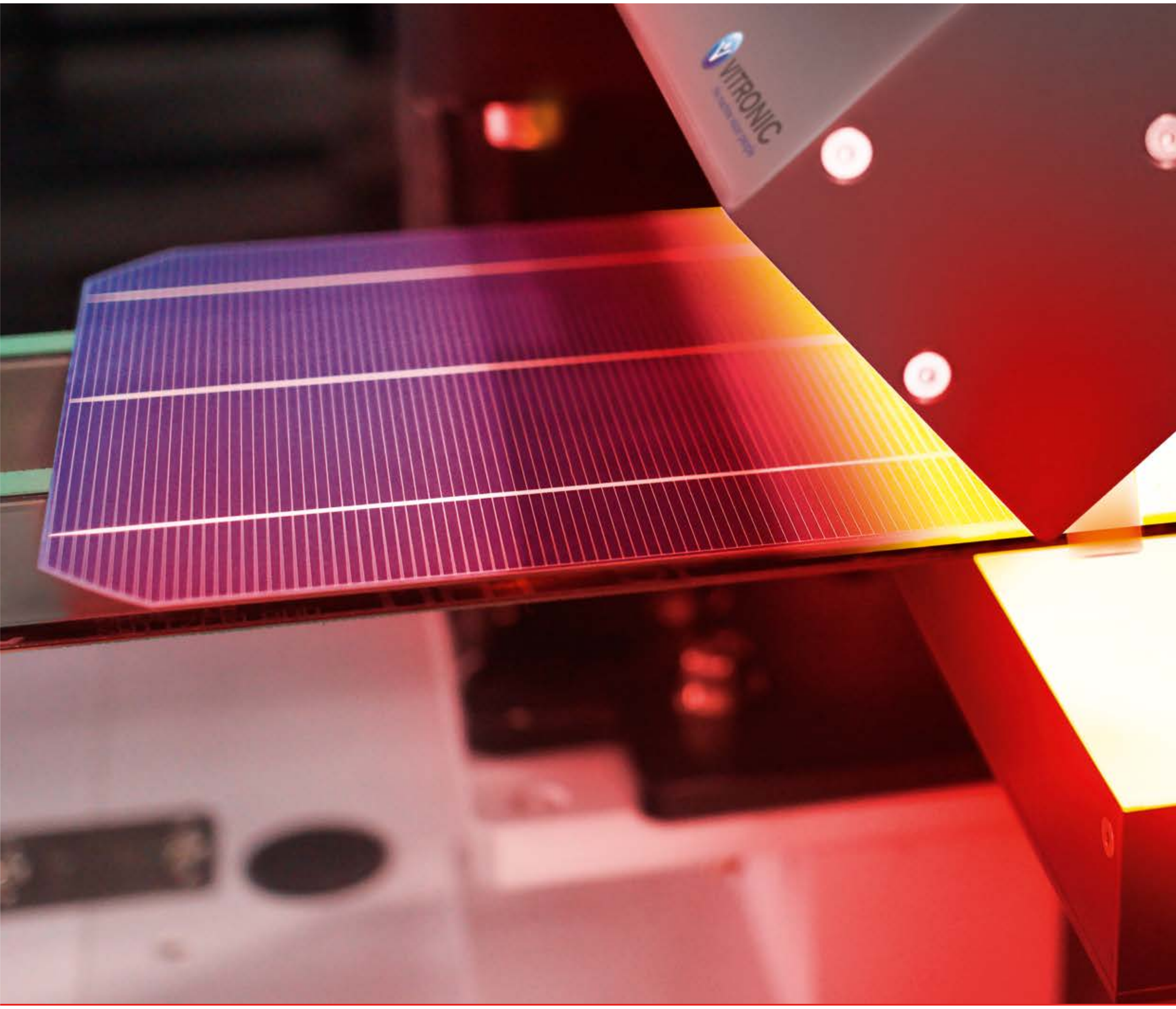
SOLARUNITED QUALITY INITIATIVE

WHITE PAPER ON HARMONIZED DATA COLLECTION FROM THE FIELD



Supported By: PEARL PV, SOLARUNITED, PhotoVoltaic European Technology & Innovation Platform, BECQUEREL INSTITUTE

THE NEED FOR A QUALITY INFRASTRUCTURE

Comprehensive Quality Infrastructure should be in place to assure that PV technologies will deliver reliable and secure services. A well-established Quality Infrastructure framework that comprises metrology, standards, testing methods, inspections, certifications, accreditation, among others, can mitigate development and operational risks, decrease failure rates and improve overall performance of solar PV technologies.

As PV systems in the future will be more complex systems - due to integration of energy storage and grid stabilization functions - it is of outmost importance that, besides the existing quality control for the system components, an independent quality assurance for system design and engineering is established. This quality assurance needs to focus on the key aspects of system performance, reliability and safety.

Do you want to know more about Quality Infrastructure? Go to page 6.

THE NEED FOR DATA COLLECTION

In the coming years, as the availability of measured data will exponentially increase, it will be important to build large databases which connect manufacturing data with experiences with installed PV modules and systems. Referring to a harmonized method, the database can increase the confidence level of the statistical analysis and thus reduce the perceived risk from investors related to the initial yield assessment. With the availability of these large databases, the necessary information (minimum requirement) can be filtered out to perform tailored analysis in a uniform way, that is, same granularity, same data and same formulas.

Data acquisition is of fundamental importance not only for fast feedback within subsequent steps of the value chain but also between processes which are not directly linked (i.e. manufacturing and installation of components). Reliable, automatized and harmonized measurements and tools can improve quality and allow manufacturer of PV components to maintain a competitive level. Before one starts digging into the different type of failures and the related performance loss, there is a need for the industry and the experts involved to move all together towards a common nomenclature of failures found in the field.

The inclusion of the risks into a risk matrix is considered a fundamental step to enable the possibility to share failure data based on an agreed nomenclature and definition by all different stakeholders.

Key precondition for the advanced data evaluation is that all relevant data can be automatically linked and stored in an easily accessible database.

Due to more rapid climate change the prediction of PV system performance based on historic climate data will face additional challenges.

Do you want to know more about data collection? Go to page 17-18 (Chapter 2), page 27 (Chapter 3), page 42 (Chapter 4)

THE NEED OF FIELD INSPECTION AND OPTIMISED O&M

It is important to put an incentive based remuneration on the O&M rather than a penalty based remuneration. The latter tends to limit the performance at a specific performance ratio whereas the former will push for higher performance ratios.

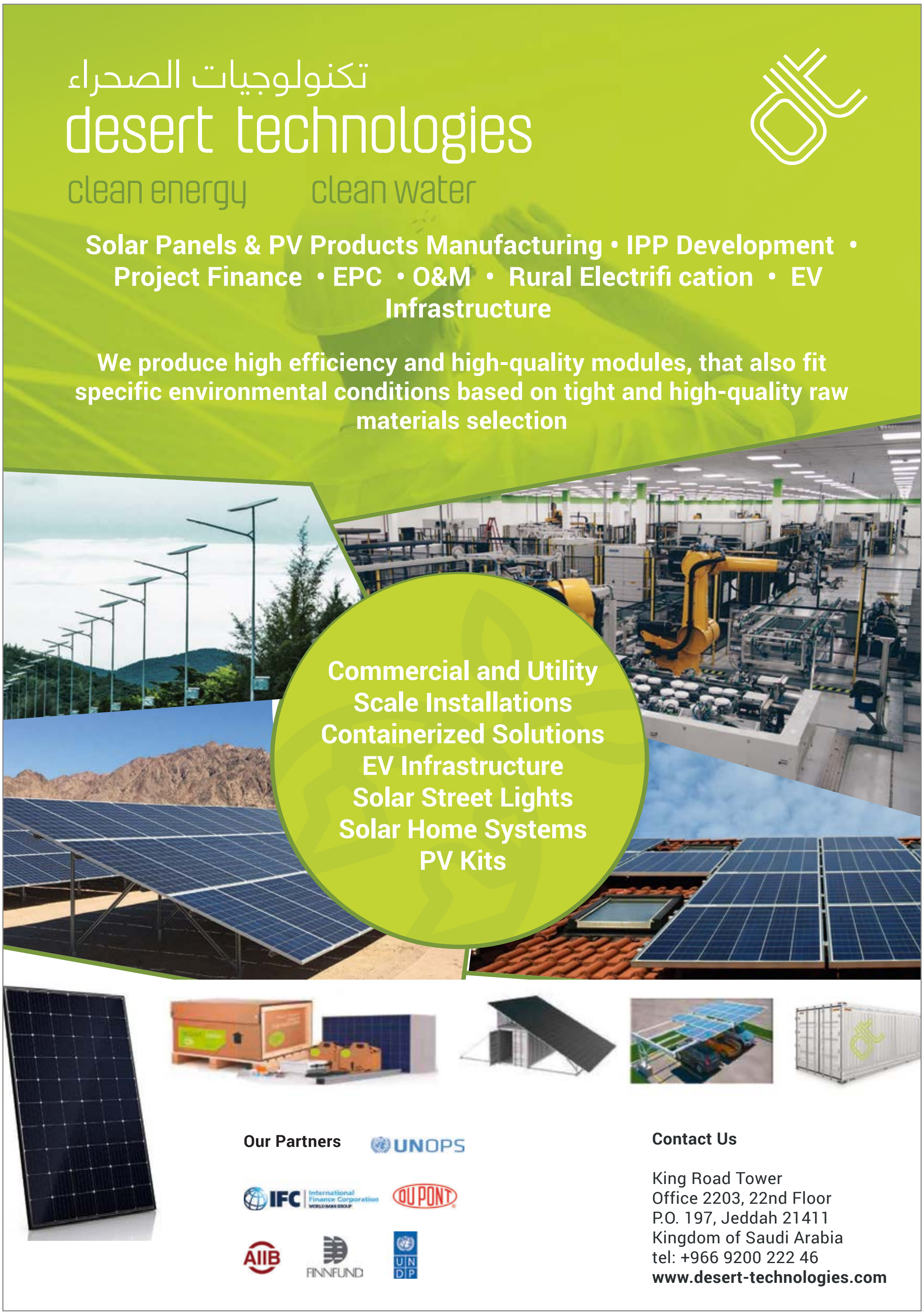
Besides the inspection on wafer, cell and module level, it is required to continuously monitor the material quality of the major process materials as well as the most important process parameters which not only needs state of the art AOI in the Cell Tester/Sorter, but also after major production steps (especially after metallization). Ideally, these data should automatically be linked to the device data (MES). This will help to identify the potential root cause of reliability or durability issues in the field more effectively.

A mitigation option, especially in large projects, is to consider the use of 3rd party onsultants to evaluate the quality from upstream to downstream. As independent 3rd party does not have conflict of interest, they can really stand on the investors' side and protect the investment.

In order to clarify the responsibility of cell breakage, it is recommended to check with electroluminescence (EL) images the modules before installation. After the installation is completed, string EL inspection is also recommended in the acceptance tests, so the investor can assure the system is in healthy operational conditions.

The systematic use of visual inspection enables the collection of a large dataset of failures. Care must be taken in understanding the frequency and statistics of failures as the dataset will be biased by failures which are detectable with visual inspection.

**Do you want to know more about the use of field inspection and optimised O&M?
Go to page 34 (Section 3.1.2), 36-38 (Section 4.1.2), page 45 (section 4.1.6)**



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RATIONALE

This paper was prepared with the help of Laura Azpilicueta, Bryan Ekus, Richard Moreth, David Moser and Giulia Serra.

Several attempts aiming to improve Photovoltaics (PV) quality and reliability have emerged in recent years [Figure 1]. Nonetheless, such initiatives do not comprehensively make an impression on theentire global value chain, nor highlight the technological achievements made by state-of-the-art PV power plants. In that respect, SOLARUNITED offers to capitalize on its unique position, global and technology focused, to bring the PV industry as a whole one-step forward in terms of quality and reliability.

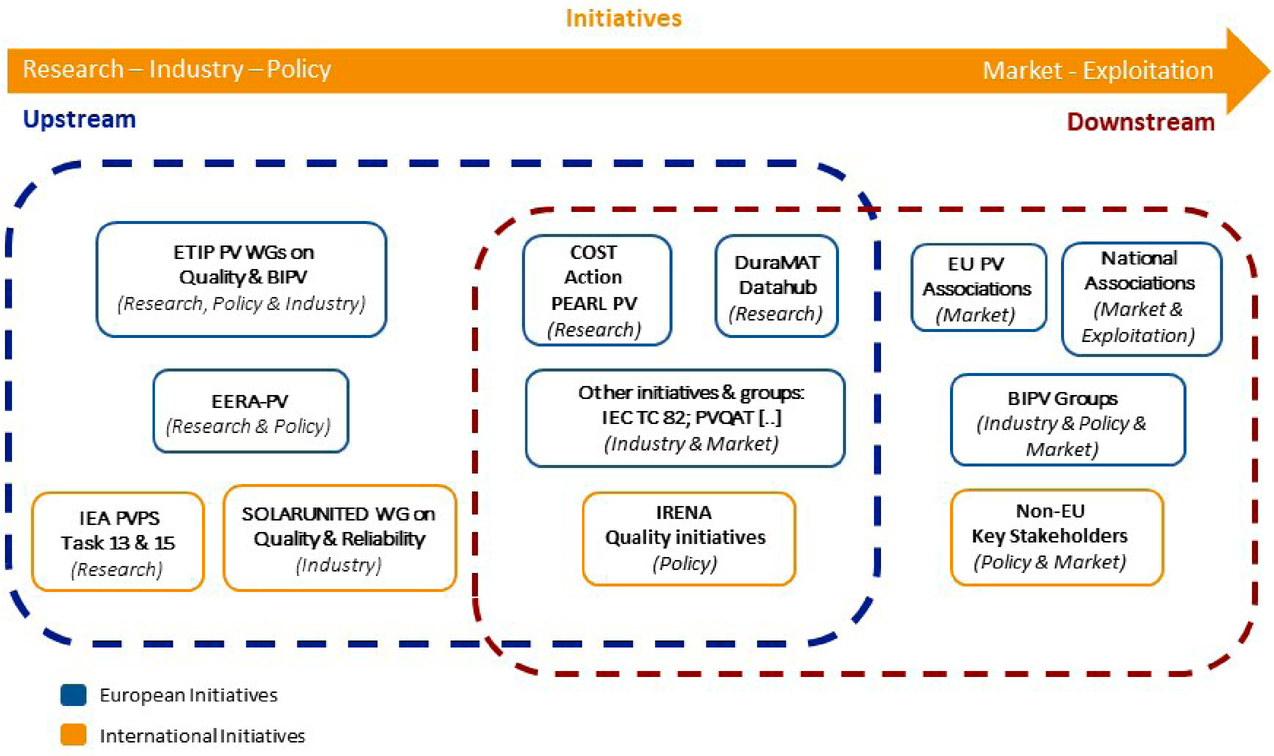


Figure 1: Schematics of various actors and initiatives active in the field of PV quality (Source: Becquerel Institute)

SOLARUNITED combines the strength of all parts of the value chain, globally, with a core of actors coming from the technology side of the PV industry (e.g. equipment manufacturers, materials, components providers, cells, modules, and inverters manufacturers). The initiative on “Quality & Reliability” intends to link the different sectors of the value chain, to ensure PV plant quality everywhere [Figure 2].

The upstream part of the PV value chain intends to play a major role in the improvement of the quality of PV components and installations: through new and improved production processes, the industry will contribute to increase the durability and reliability of PV systems. The SOLARUNITED white paper focuses on setting up recommendations for the downstream part of the value chain regarding data collection from the field and it will be a continually updated, living document.

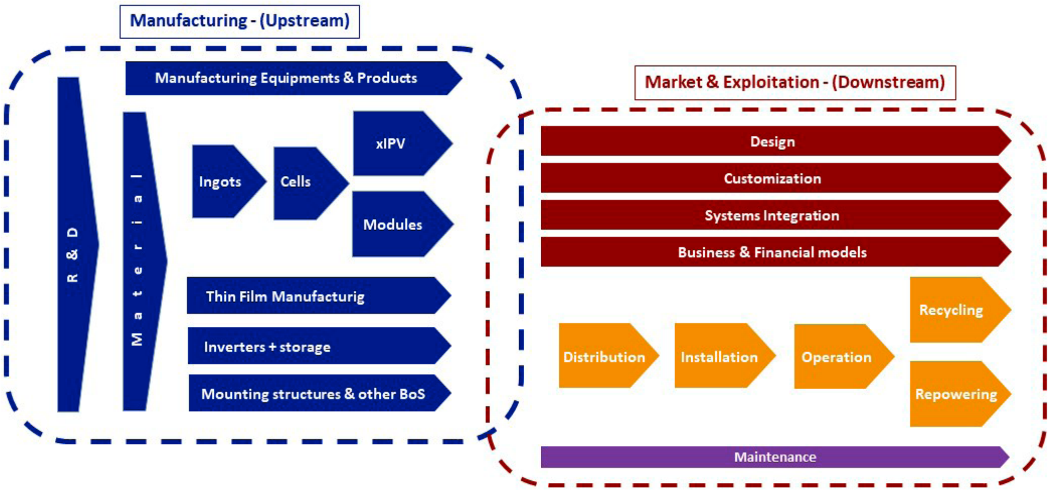


Figure 2: Representation of Upstream and Downstream sectors in the PV value chain (Source: Becquerel Institute)

Data acquisition is of fundamental importance not only for fast feedback within subsequent steps of the value chain but also between processes which are not directly linked (i.e. manufacturing and installation of components). Reliable, automatized and harmonized measurements and tools can improve quality and allow manufacturer of PV components to maintain a competitive level.

It has been identified that failures and defects in the field are causing performance losses that are uneasy, in some cases, to recognize. Several studies have so far tried to identify and study the main causes of failures and evaluated their effect on the profitability of PV systems. Meanwhile, the subject remains largely untapped.

This working document aims at proposing requirements for collecting defects and failures in the field in a standardized way, enabling its tracking and structured evaluation. The data on defects and failures collected in the field have been provided by installers, developers and O&M companies and come from the experience gathered in several independent initiatives.

This very first step should allow defining common reporting procedures that could be disseminated through downstream PV associations, global institutions, intergovernmental organizations – such as the International Renewable Energy Agency (IRENA) – and international efforts – such as IEA PVPS Task 13[1], PV QAT[2], and Cost Action Pearl PV. This paper consists of a series of simple recommendations regarding all significant segments of the PV market.

The white paper is structured in a way to enable the reader to go through a process of understanding the need for quality along the value chain by analysing the following steps:
i) Does performance of PV systems reach expectations?
ii) What are the failures in the field that have an impact on the expected performance?
iii) How failures can be tracked in the field to generate a feedback loop?

1) IEA PVPS: International Energy Agency Photovoltaic Systems Programme
2) PVQAT: International Photovoltaic Quality Assurance Task Force

TABLE OF CONTENT

1. INTRODUCTION

This Chapter sets the scene for the following ones, highlighting how the quality infrastructure is fundamental to strengthen the solar PV market by making the technologies technically reliable and more affordable.

The following sections will give an insight on how to develop a quality infrastructure for PV systems and the benefits that its implementation bring to key stakeholders in the renewable energy sector.

1.1. The need for a quality infrastructure

The solar photovoltaic (PV) market has experienced an accelerated growth, accompanied by remarkable cost declines for solar PV technologies. The levelized cost of electricity (LCOE) from solar PV decreased by 73 % between 2010 and 2017 – coming well into the cost range of fossil fuels [1]. As solar PV power systems become increasingly competitive, continued market growth depends on assurances of performance and durability. In 2017, the International Renewable Energy Agency (IRENA) released the report “Boosting global PV markets: the role of quality infrastructure” [2], displaying quality assurance (QA) as an essential instrument for the deployment of renewable energy.

Quality assurance (QA) guarantees that certain minimum requirements of interoperability, safety and performance are accomplished. At the same time QA protects and accelerates future PV investments, decreases capital costs, extends module lifespans and lowers the resulting electricity costs. However, comprehensive QA requires physical and institutional infrastructure. ***The so-called Quality Infrastructure (QI) comprises the total institutional network and legal framework that formulates and implements standards, testing, certification, metrology and accreditation.***

Deploying QI plays a key role in the mitigation of technology risk, as well as, the improvement of equipment design, performance and maintenance. Thus, the adequate establishment of QI should be across all the technology life cycle to minimize the rate of failures observed for PV projects in their “bathtub failure curve” [Figure 3]. Getting in place the right quality infrastructure can tackle the so-known infant and wear out failures, helping greatly to mitigate risks of the different project stakeholders.

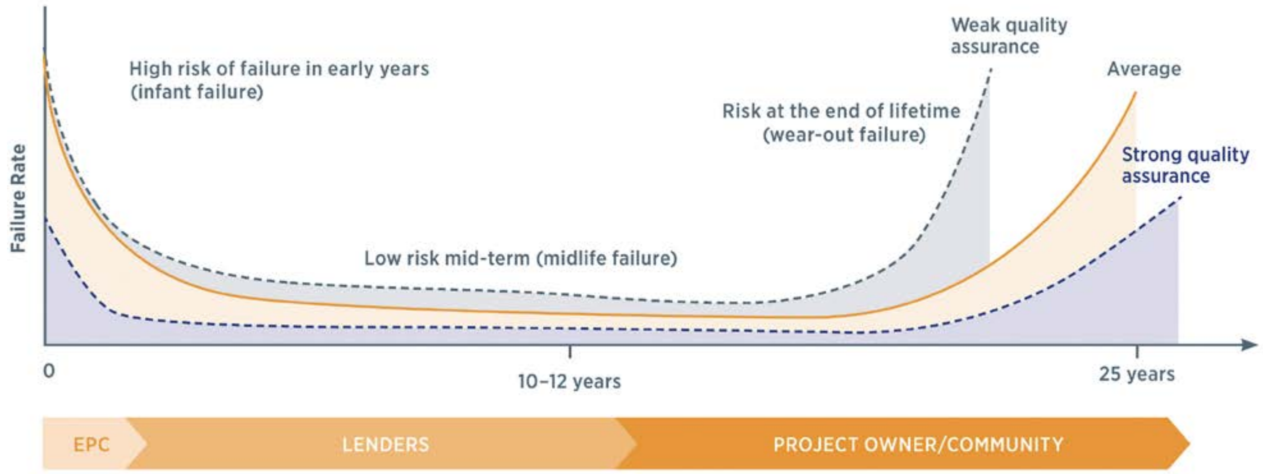


Figure 3: Failure curve of solar photovoltaic systems (Source: [2])

Once focusing in how to develop QI, its implementation should be incremental, going hand in hand with the market context and PV maturity of each country. Therefore, it is proposed to key stakeholders a step wise approach, in which they can follow a set of mechanisms and best practices in each market stage in order to strengthen the market quality assurance.

Figure 4: Steps in quality infrastructure development linked to market maturity indication (Source: [2])

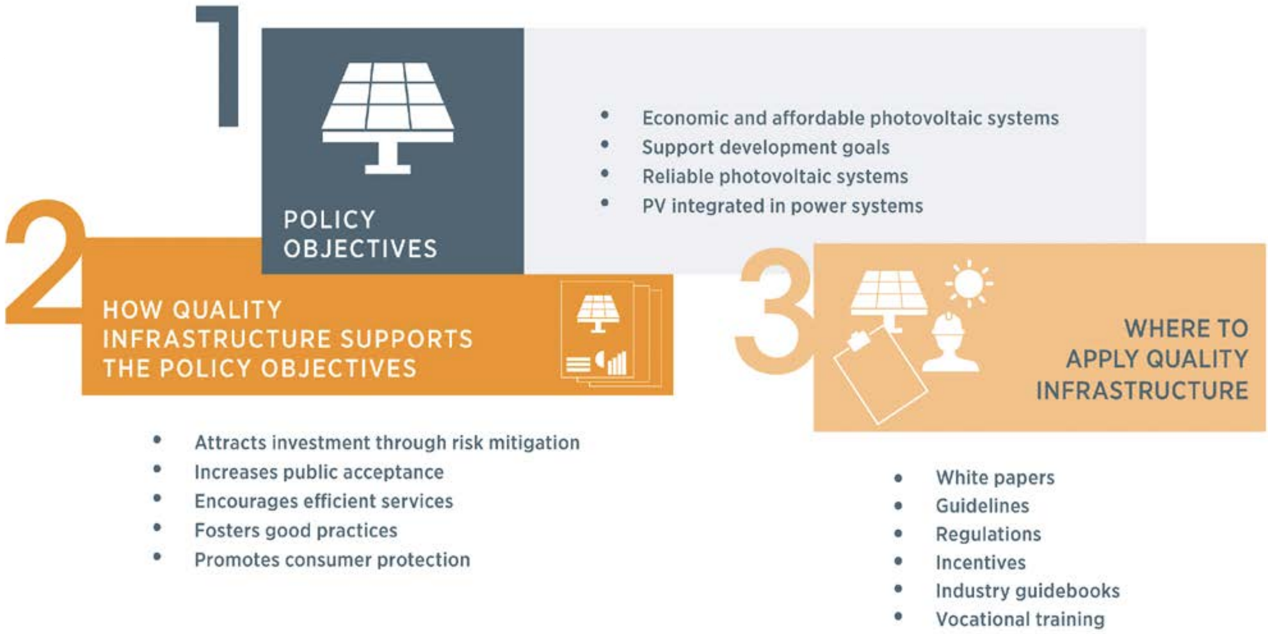


Figure 5: Contributing to policy objectives through the implementation of quality infrastructure (Source: [2])

Comprehensive Quality Infrastructure should be in place to assure that PV technologies will deliver reliable and secure services. A well-established Quality Infrastructure framework that comprises metrology, standards, testing methods, inspections, certifications, accreditation, among others, can mitigate development and operational risks, decrease failure rates and improve overall performance of solar PV technologies.

1.2. The role of system design in the quality of the installation

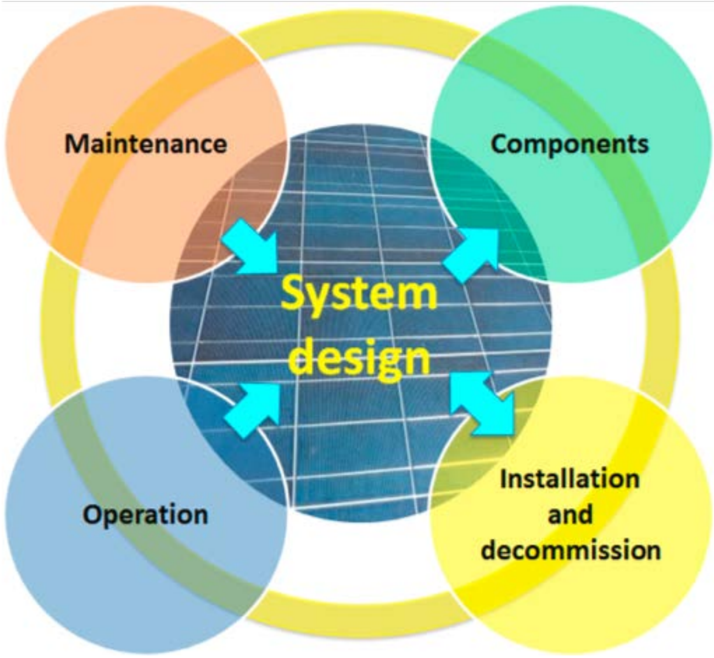


Figure 6: Quality issues often stem from poor design choices (Source: DuPont)

Figure 6 shows how the system components, the installation (together with the decommissioning) of a PV system, the maintenance and the operation contribute all together to the system design. In this section we will attempt to explain how each aspect shown in Figure 6 can influence the final quality of a PV project.

The system should be designed with the constrains of the installation in mind (e.g. roof access, ground topography, shading conditions, presence of soiling sources). A poor design might ignore practical considerations with an impact on the installation phase. Under tight targets, installers may therefore alter the design instructions to complete the work faster to the detriment of quality (such as walking on panels). The relationship between design and installation is therefore a two-way relationship and not, as often presented, a dominant cause-effect relation with the design commanding the installation. In fact, common mistakes during the installation phase can be easily avoided through site survey and installation monitoring and the design should command the choice of components. For example, if partial shading is allowed on a roof installation, one may choose to use microinverters or optimisers to prevent PV module damage and optimise power production.

Partial shading may also arise from soiling. In areas where soiling is expected, one may choose to mitigate power production with a regular cleaning cycle or to increase the tilt angle to increase the effectiveness of rain events. The system design should allow for cleaning crews to perform their work without walking on the PV modules. In addition, the PV modules' back sheet and encapsulant should be able to resist additional stress due to transient partial shading (e.g. delamination, cracking, burning, etc). One should not rely on the PV module to cope with a permanent partial shading without extra protection.

The maintenance of the PV system during operation should not be made according to the design of the installation but rather the design should enable the maintenance. For example, the inverters will require annual maintenance and should therefore be placed where they can easily be accessed. Similarly, as mentioned before, one may need to clean the PV modules. Such maintenance procedures cannot be performed on roof installations without dedicated walkways.

Finally, a PV system does not just operate itself. The production should be monitored and regular inspections performed. The design will command the monitoring system and should allow for offsite monitoring as well as data archive. The monitoring of the installation should be done by comparison to a reference system. Small weather stations are usually fitted on larger ground mounted installations allowing comparisons between the amount of sunlight received and the production. Due to higher relative costs, smaller roof mounted installations do not usually feature such systems, however, monitoring the performance of an installation serves no purpose without comparison to a reference. In this case, it may be beneficial to compare the production to other installations in the vicinity. The system design should define the reference to which the system will be compared to enable the monitoring of adequate operation.

1.3. Impact of cost pressures

Often, what may compromise the quality of an installation is the existence of conflicting priorities which is particularly dominant in larger ground mounted installations. The investors may push to have the best prices without considering the technical requirements. Similarly, Engineering Procurement and Construction (EPCs) companies participating to a tender process will be largely assessed on price to the detriment of the technical aspects. Only the best ratio of "price to quality" should be considered if an installation is expected to last 25 years. Where EPCs are expected to fulfil only 2 years of operation and maintenance without a third-party due diligence, emphasis will only ever be on short term outcomes [Figure 3].

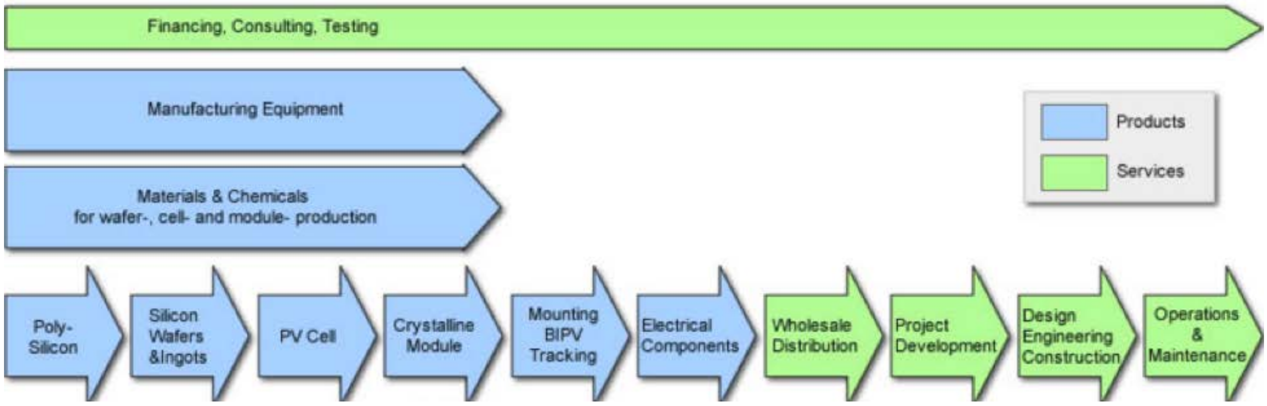


Figure 7: Phases involved in a PV projects (Source:

Integration of quality aspects through the value chain may help resolve some of the conflicts and promote quality as an overarching concept which is paramount to durability aspects [Figure 7].

A mitigation option, especially in large projects, is to consider the use of 3rd party consultants to evaluate the quality from upstream to downstream. As independent 3rd party does not have conflict of interest, they can really stand on the investors' side and protect the investment.

1.4. IEC certification

For an exhaustive list of standards of various standardisation organisations related to PV design, performance and characterization we refer to [3].

International Electronical Commission (IEC) certification is often retained by investors, EPCs and installers as a guarantee of performance in the field. In reality, IEC certification is supposed to be a design screening test which helps the designer to verify the material and module production process, and it is not strongly related to the lifetime of the PV module and other components, let alone the guarantee of performance.

In order to get more knowledge about the lifetime evaluation, many research institutes and product manufacturers worked on developing accelerated tests to simulate the failure modes occurring in the field. Great progress has been made in recent years, some tests are now able to replicate the failures that have been seen in the field. Field data collection can also serve as a calibration process to enable better material testing and design. Any accelerated test sequence that is correlated to field experience can then provide adequate confidence in the materials and design of components.

However, the acceleration factor is still eluding, so the lifetime of a PV module cannot be predicted simply by accelerated testing. It is natural that not all materials fail in the same way, but it depends on the inherent material weakness and module production process errors. If an acceleration factor can be derived for one type of material, it does not automatically apply to all the alternative materials, and not even the same material with different process parameters like temperature and pressure settings. In addition to this, new product might exhibit new failures once installed in the field.

1.5. Warranties

As certifications and accelerated tests do not have a lifetime guarantee, the warranty from the component supplier states an alternative means to mitigate the risk for investors. The typical warranty lasts 10 years for workmanship, covers 10 % power loss within 10 years and 20 % power loss within 25 years. Recently, more and more manufacturers provide linear warranty (e.g. -0.8 % per year) which is more favourable to the investors. All these seem to be attractive to the investors until we give it more careful consideration.

First of all, there is no standardized methodology to calculate the degradation of performance at system level and in most cases, uncertainty is not provided. Typically, 5-year data is needed to be able to calculate a degradation rate to indicate a certain degree of confidence [3], [4].

Second of all, there are many exclusion clauses that make it difficult to receive the compensation from the manufacturer in case of quality issues. The system owner needs to prove that the problem comes from the inherent defect of the module, which it is usually difficult as most the problems have various and complicated root causes. Also, it is difficult for the owners to investigate the technical problems since it requires advanced knowledge about the design of PV modules and systems as well as high-end equipment to measure the defects.

Figure 8 shows an example of exclusion of guarantees in the warranty conditions. In addition to the exclusion items, the most difficult passage in the document is: ‘The customer bears the burden of proof that the guarantees are not voided’. This example appears very often in warranties provided by the manufacturers.

E Exclusion of guarantees

1. The guarantees do not extend to solar modules that are impaired, damaged or destroyed as a result of

   a) being improperly stored or transported by the customer or a third party,
   b) not being installed or, if applicable, uninstalled or reinstalled, in accordance with the [redacted] assembly manual and the recognized good engineering practices,
   c) being operated in a manner inconsistent with the intended purpose and especially the instructions for operation in the assembly manual,
   d) not being maintained properly, in particular not in accordance with the maintenance instructions in the assembly manual,
   e) being improperly modified by the customer or a third party or being otherwise improperly manipulated, or
   f) as a result of *force majeure* (in particular lightning, fire or natural disaster). The insurance performance pursuant to the [redacted] Complete Cover remains unaffected in this respect.

2. Excluded from the guarantees according to section B are insignificant or changes or changes in appearance, in particular bleaching and discoloration of cells. The performance guarantee pursuant to section C remains unaffected in this respect.

3. The guarantees are also rendered void if the serial number or type plate of the solar module was manipulated or removed, or if the solar module can no longer be uniquely identified for other reasons.

4. Insofar as a warranty case is not provided in accordance with these warranty conditions, [redacted] reserves the right to bill the customer for the costs accrued for services provided (material and labor costs).

5. The customer bears the burden of proof that the guarantees are not voided on the aforementioned grounds. This does not apply for circumstances for which [redacted] or vicarious agents of [redacted] are responsible.

6. With the lapse of the period of notification pursuant to section H.3, the customer's warranty claims are rendered void unless the customer is not responsible for the lapse of said period of notification.

Figure 8: Exclusions in the warranty condition of a module supplier (Source: PV Guider)

Even if the customer is able to prove the manufacturer's liability, it is still difficult for him to be fully compensated for the quality issue. The warranty usually only covers the PV module replacement. The transportation and labour cost are usually not included. Additionally, the financial loss during the system shutdown is also not included in most cases, and it often takes months to finish the investigation and replacement of the PV modules. Moreover, the warranty does not outlive the manufacturer unless it is insurance backed. Many manufacturers have gone bankrupted, including very well-known ones. Insurance backing in now used to ensure that the warranty will last beyond the manufacturer's lifetime, at least for large projects.

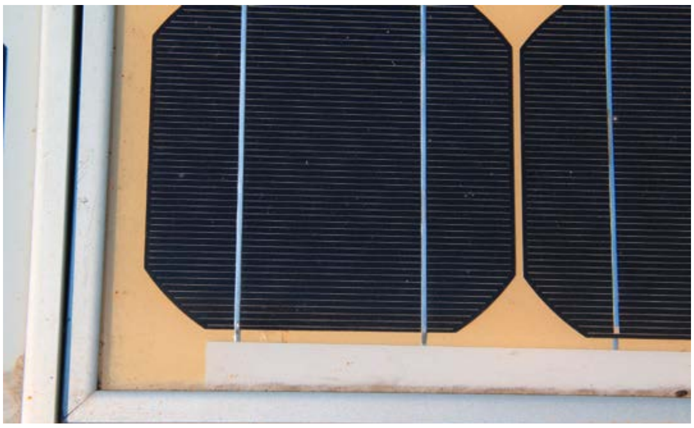
Therefore, investors should carefully check the details stated in the warranty condition. Although it is good to have warranty and power guarantee, it is not something investors can entirely rely on. It is thus even more important to confirm the component quality in advance, rather than rely on the warranty and certification.

1.6. Who is responsible?

The black sheep campaign launched by PV magazine in 2014 properly illustrates the intricate nature of the responsibilities. The module producer is ultimately responsible for making the PV modules with adequate materials. The EPC is ultimately responsible for ensuring the right components work together and are installed so as to minimise damage to the PV modules and other elements of the installation. The O&M contractor is responsible for ensuring the good operation of the PV system and minimising production losses and damage to the installation through maintenance operation both preventive and corrective and surveillance.

If we take hotspots as an example, we can easily understand how the responsibility for damage to the installation can come from various actors in the value chain. A hot spot develops when a solar cell is not capable of producing the same current as its neighbouring cells. The cell is said to be in reverse bias. In this case, it has to dissipate the current in excess by heating up. Bypass diodes are used to prevent damage to the PV module by isolating strings of cells connected in series if a reverse bias is detected. In this case, the diode is said to be triggered. A hotspot has the potential of damaging a PV module, and there are two ways in which such damage can take place:

1. The bypass diode is not triggered (it may be defective or it may not have adequate electrical characteristics to trigger, i.e. undersized). The heat may contribute to the degradation of the PV module in 3 ways:
   a. Prolonged exposure to temperatures 20°C above the baseline may accelerate the aging reaction kinetics of the polymers 4 times (according to Arrhenius law). Some of the backsheets which are most prone to aging may start to yellow (not always) and crack [5], [6].



   b. *Figure 9: Backsheet yellowed after 2 years installation (Source: PV Guider)*

c. Exposure of some backsheets constructions to temperatures at about 100 °C and above can lead to softening of the adhesion layer of the backsheet. This effect, coupled with differences in thermal expansion coefficient may lead to delamination of the backsheet from the hot area. Such delamination can promote condensation in the air pocket and create shunts by water accumulation.
d. A prolonged exposure of the cell to temperature above 100°C will eventually lower the shunt resistance of the cell. Long term temperature exposure may lead to shunts which are very localised very high temperature hotspots to which no polymer can resist (resulting in bubbling and/or burning of the polymers).

2. The bypass diode is triggered. The bypass diode is often presented as the solution to hotspots although it rarely has the electrical characteristics which will enable its operation. When it does trigger, it will heat up. Such heating can get out of control if the heat is not dissipated properly out of the PV module's junction box. In this case, it is fair to consider that the risk is not actually eliminated by the use of a bypass diode, it is merely shifted from the laminate to the junction box. There have been many examples of junction box damage by diode overheating. Examples will be shown later in the section related to defects (3.1).

We have considered the effects hotspots may have on the PV module. Let us now consider the circumstances which may lead to such a situation:

1. The underperforming cell may be broken.
   In this case, it is usually very difficult to establish when the cell was broken and therefore with whom the responsibility lies unless tests are performed at each stage of manufacturing, transport, installation and operation. Many companies now offer 100 % auditing services which are used for very large investments. In this case, every PV module electrical characteristics and electro-luminescence picture out of the production line are examined according to a set of quality criteria. It should be kept in mind that PV modules which are rejected according to this process could be demoted to a lower sellable power class and thus find their way to the field (often smaller installations such as roof mounted installation which operate in harsher conditions). Additionally, the solar cell may break more easily during the manufacturing process because of a more challenging soldering process inducing higher soldering temperature and built in stresses. The auditors can thereafter propose sample testing after each post manufacturing stage. This sampling will highlight systematic damage caused to the PV modules. In this case, responsibility could be attributed to either the cell manufacturer, PV module manufacturer, transporter, installer or O&M company, etc.
2. The cell may be in a partial shading condition as it is sometimes the case with roof mounted installations where roof features may cast shadows on some of the PV modules at specific times of the day. In this case, if the backsheet delaminates, one could argue that the fault should be assigned to the design of the installation permitting partial shading. However, some backsheets can easily resist partial shading and hotspot condition up to 160°C [7]. The use of more robust materials would minimise damage caused by a transient hot spot. Similarly, a bypass diode with the appropriate electrical characteristics should mitigate the risk of hotspot providing the junction box dissipates the right amount of heat to prevent melting. In this case, the responsibility may be attributed to the backsheet manufacturer, the junction box manufacturer, the PV module maker, the designer of the installation.

3. The cell may be dirty or shaded by growing vegetation.
   This case seems to clearly point to an operation and maintenance problem. However, if the system was designed so as not to enable proper maintenance (no walkways to allow a cleaning crew to operate without walking on the PV modules), then the root cause of the failure can be traced back to the design phase. Similarly, PV modules can get dirty between cleaning cycles (0.5 % power can be lost per day due to sand/dust deposition in the Qatar [8]). In this case, the risk of damage should be mitigated by using more robust materials both concerning backsheet, bypass diode characteristics and junction box design. In this case, the responsibility may be attributed to the choice of backsheet, junction box, module manufacturer, the designer of the installation, the operation and maintenance company.

The complexity of the problem is now evident. Actors all along the value chain need to understand their responsibility and provide some evidence of due diligence with regards to the design of their products and/or services. All the whilst, robust solutions cannot be provided at extreme low prices. The final responsibility for understanding the balance of price and quality ultimately also belongs to investors who have to become more aware about the issue either by internalising technical competences or by relying on third parties.

Regarding the effectiveness of IEC tests, the prescription of separate challenges on different PV modules do not help to follow the appropriate course of action in case of failures. Extra-long tests have been presented as an adequate counter measure extending the IEC tests by a factor 2 or 3. However, the inadequacy of the tests might not reside in the length of the test but very much in its single stress nature where each PV module will either undergo damp heat or thermal cycle (on another branch, humid freeze and thermal cycle). None of the PV modules are actually challenged with combined stress factors including UV exposure.

Materials suppliers must carry some responsibility in the quality of their components, however in the absence of adequate tests, due diligence (and good faith) cannot be demonstrated. Therefore, until then, one may want to rely on field performance where more data is still needed despite some good attempts. In the next chapter, the experience from the field is presented.

2. DOES PERFORMANCE OF PV SYSTEMS REACH EXPECTATIONS?

Business plans of PV systems are built on performance expectations and foreseen degradation rates. However, is the quality of the components and installations sufficient to guarantee the expected long-term performance? These questions are at the core of the PV market development, and individual supplier responses appear to be insufficient in improving the confidence of the solar investment community.

As previously stated, achieving the expected level of quality should involve the entire PV value-chain, from the material and equipment manufacturers to the installers, and ultimately PV systems operators.

From materials to PV plants producing electricity, the PV value chain is long and very often split between numerous actors. The components (modules, BoS, inverters) are in most cases produced by different companies, shipped, stored, sold, assembled and maintained by a range of companies that are not always equipped to communicate in the most efficient way. Of course, vertically integrated companies reduce the number of players, and developers / asset managers which internalise O&M are simplifying the transmission of information between all segments of the PV value chain.

The contribution included in this section is built on existing studies on PV performance and especially the following ones:

- Analysis of long-term performances of PV systems, IEA PVPS Task 13 [9];
- Review of failures of PV modules, IEA PVPS Task 13 [10];
- Report on technical risks in PV project development and PV plant operations. Solar Bankability project [11], [12];
- Assessment of PV Module Failures, IEA PVPS Task 13 [13] .

2.1. The impact of uncertainties on yield assessments

Technical risks identified before the operational phase (i.e. originated during the design phase) can have an impact on the levelized cost of electricity (LCOE) and on the cash flow of a business model. For each of these risks it is important to understand how the variability and associated uncertainty are calculated and how the values are distributed in terms of probability. These aspects are essential for the calculation of the exceedance probability of the energy yield and how this is influenced by the overall uncertainty. Figure 10 shows the exceedance probability of the energy yield with an uncertainty of 5 % and 10 % calculated based on a normal distribution of the energy yield. A reduction in the uncertainties can lead to a higher value of energy yield for a given exceedance probability and hence a stronger business case. Reich et al [14] estimated the combined overall uncertainty of the energy yield to fall in a range between 5 % and 11 %; in the study, the uncertainty on various effects such as irradiation, shading, soiling, inverter losses, etc. were taken into account. In another study [15], the authors have calculated the variation of the overall uncertainty of the energy yield over the lifetime of a PV plant and compared the findings with data from a portfolio of 26 systems located in Germany and Spain. These efforts show the importance of having a common framework that can assess the impact of technical risks on the economic performance of a PV project.

In the coming years, as the availability of measured data will exponentially increase, it will be important to build large databases which connect manufacturing data with experiences with installed PV modules and systems. Referring to a harmonized method, the database can increase the confidence level of the statistical analysis and thus reduce the perceived risk from investors related to the initial yield assessment.

The uncertainty contribution on the energy yield (or on the specific parameter when specified) of each identified effect can be taken for example from the literature and as given by “Technical Risks in PV Projects” [16]. Müller reported an analysis based on 26 systems located in Germany and Spain where the measured energy yield was 4 % higher than initially estimated. This was mainly due to an overestimation of the annual insolation for the selected location of a +4.9 % and an underestimation of the Performance Ratio (PR) of -0.9 %. This is of particular importance for systems where a guaranteed yield is requested together with a PR. The report “Identification of technical risks in the photovoltaic value chain and quantification of the economic impact” gives an overall uncertainty on the energy yield due to various effects in the range of ±5-11 %. “Uncertainties in PV Modelling and Monitoring” [17] gives a value of ±6-8 % for the energy yield and ±2-6 % in PR.

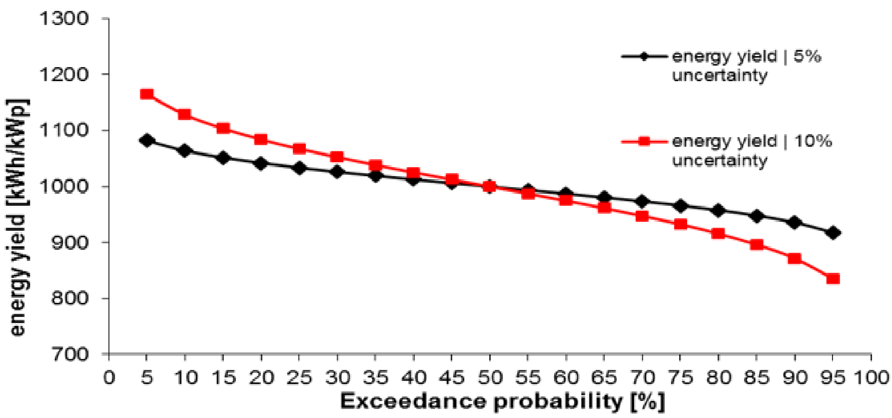


Figure 10: Exceedance probability for energy yield assuming different uncertainties calculated with a normal probability distribution function (Source: EURAC Research)

In Figure 10 the impact of the energy yield uncertainty on the exceedance probability was shown with a difference of around 60 kWh/kWp at P90 (exceedance probability of 90 %) assuming a P50 (exceedance probability of 50 %) value of 1000 kWh/kWp (> 5 % difference at P90). The curve was created based on a normal distribution of the energy yield where the median is equal to the mean value. Positively or negatively skewed distribution will also have an impact on the exceedance probability. The tail of the degradation rate distribution towards more negative values could lead for example to this result [4].

In the report of the Project Solar Bankability [18], different uncertainty scenarios were created to study the impact on the yield assessment. The group of cases assuring a low level of uncertainty (< 10 %) all refer to the use of long time-series of either ground measurements or satellite estimates of insolation.

The temporal range of the available insolation data seem therefore to be the most important factor affecting the uncertainty of the yield estimation. The report also showed that a lower uncertainty is assured when a) ground measurements are used in place of satellite estimates and b) time series of plane-of-array irradiance is available without the need to apply transposition models. Results show also that using a combination of long time series of satellite data with a short series of measured data is recommended than just using satellite data. This technique is known as site adaptation technique and it is not commonly used in yield assessment [19].

In the case a PV plant is to be installed in a location with high insolation variability, the uncertainty of the yield estimation is also negatively affected. Besides the insolation variability and the solar resource quantification uncertainty, the uncertainties related to shading and soiling effects and to the use of transposition models play also a role in the overall uncertainty of the final yield.

An alternative to the normal distribution of the energy yield is to compute the empirical cumulative distribution function from which the exceedance probabilities can be interpolated by using Monte Carlo methods.

The use of empirical methods can thus be regarded as the most advanced mitigation measure in reducing the risks in the initial yield assessment as it allows the inclusion of data which might not be normally distributed.

Unfortunately, there is not always a sufficiently large dataset available to establish the Cumulative Distribution Function (CDF) from which to interpolate exceedance probabilities. Nevertheless, for some elements involved in the calculation of the long-term expected yield as, e.g. the solar resource, this method can be applied. With the availability of more data for other elements, also other secondary effects can be included in the methodology as not normally distributed.

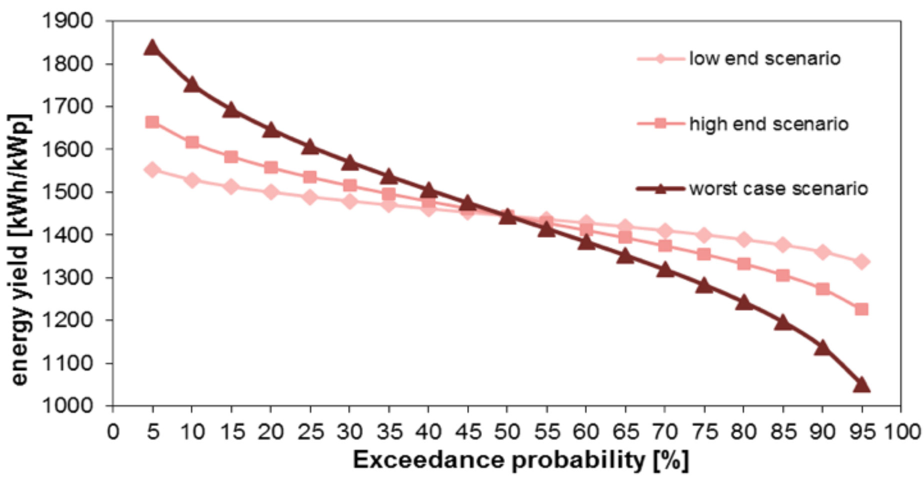


Figure 11: Comparison of the three scenarios assuming a normal distribution (Source: EURAC Research)

If we look at the effect of the results obtained for the selected case studies the uncertainty varies between 4.6 % (here defined as the low-end scenario) and 16.6 % (here defined as the worst-case scenario). A high-end scenario was defined as the average without the outliers resulting in a σ=9.3 %. The low end and high end scenarios are thus representative for the range given in [16], [20] of 5-10 % overall uncertainty of the energy yield. Here the impact of the uncertainty on the CDF is evident and the resulting P50, P90 and P90/P50 values are summarised in Table 1 and shown in Figure 11. The P90 values decrease respectively by -6 % and -15 % when compared to the low-end scenario.

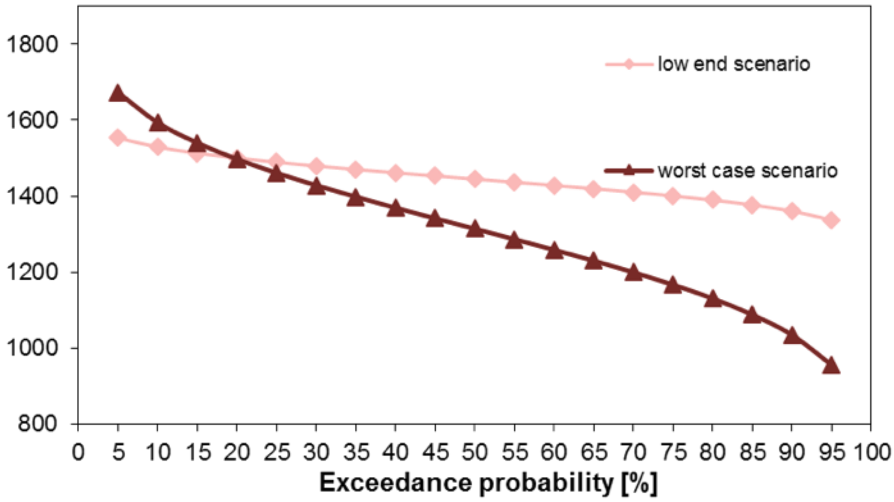


Figure 12: Comparison of the worst case scenario with different mean values of the normal distribution with =16.6 % (Source: EURAC Research)

Another important parameter which affects the overall analysis is the mean value of the energy yield (P50 if normally distributed). The main source of error is related to the solar resource assessment. Figure 12 shows the results for the worst-case scensario with a mean value of 1314 kWh/kWp instead of 1445 kWh/kWp. These values come from a solar resources assessment based on 5-year-measured data and 20-year-satellite-derived data, respectively. The use of shorter time series can clearly lead to an underestimation (or overestimation) of the mean value depending if the tails of the distribution are present or not. When compared to the low-end scenario, the reduction in P90 for this specific case is 22 %.

	(k=1)	P50 (kWh/kWp)	P90 (kWh/kWp)	P50/P90 (P50 reference case)
Low end scenario	4.6 %	1445	1365	94 %
High end scenario	9.3 %	1445	1273	88 %
Worst case scenario	16.6 %	1445	1138	79 %
Worst case scenario (different mean value)	16.6 %	1314	1034	72 %

Table 1: Summary of the exceedance probability values for variousw scenarios

To deepen the analysis and understand how initial yield assessments relates with actual data during operation, the Solar Bankability project compared the initial long-term yield estimates against the actual production over a portfolio of 41 PV plants at sites in mainland France, French oversea departments and territories (DOM-TOM) and Italy. Rooftop and ground mounted systems, covering a wide range of installed capacity from 10 kWp up to 12 MWp were analyzed. This analysis is presented in [21]. The initial long-term yield estimates were compared against the actual yields of the PV plants across the portfolio. The results of a first exercise without any correction for the actual unavailability are presented in Figure 13. The initial long-term yield estimate for the first year of operation (P50) is represented as the zero line. The red and green background colors represent the P90 and P10 estimates respectively, being typically between ±7 and ±9 % away from the P50. The difference with the actual production during the first year of operation is represented with the blue bars. In this case, a negative blue bar means that the actual production was lower than the initial estimate (i.e. over-estimation in the initial long-term yield assessment study). Ideally all bars should lie within the red (P90) and green (P10) regions.

The main purpose of this exercise is not to analyze each individual case but rather to understand the level of agreement, not only with the initial estimated yield (P50 values), but also with the related uncertainties leading to e.g. the P90 values. Figure 13 shows that for most of the analyzed PV plants, the actual production during the first year of operation (blue bars) lies within the expected uncertainty margins (±σ) calculated during the initial long-term yield assessment study. However, there are some PV plants within the analyzed portfolio of which the actual production is below the expected worst case scenario (i.e. P90). These deviations for some plants are further analyzed to understand the gaps.

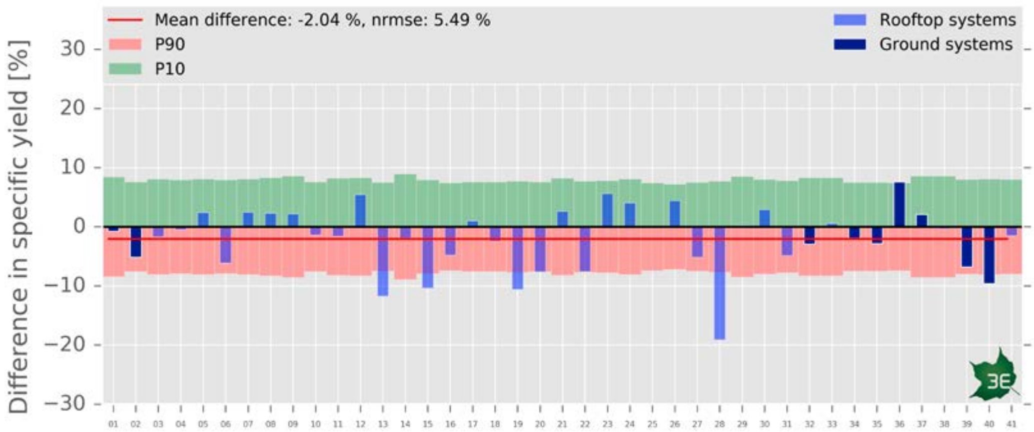


Figure 13: Difference in specific yield between initial estimated values and actual production data from 41 PV plants in FR, DOM-TOM region and IT (Source: 3E)

To understand better such deviations observed on some PV plants [Figure 13], the availability of each individual plant has been analyzed. Figure 14 shows the actual percentage unavailability (downtime) for most of the analyzed PV plants. For most cases, the unavailability data comes directly from the detailed O&M reports. Moreover, when possible, the unavailability was calculated from the high-resolution data (15-minute data). However, unfortunately it was not possible to determine the unavailability for all 41 PV plants since the detailed O&M report is not available for some plants and often only monthly data is available.

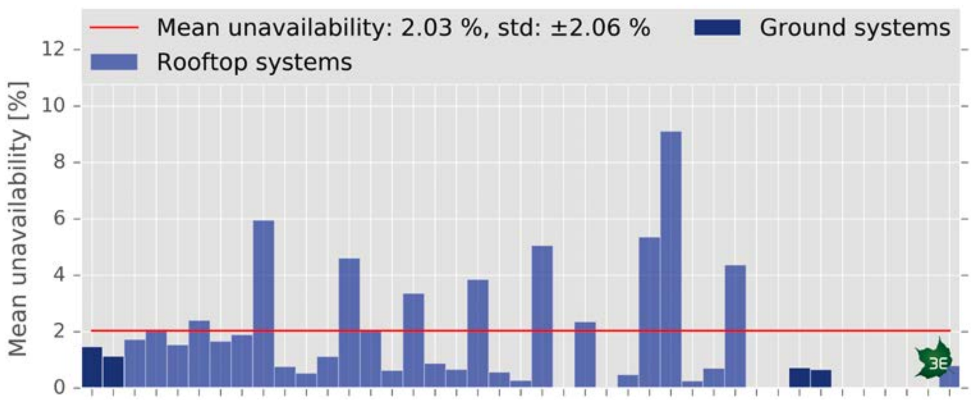


Figure 14: Actual unavailability data from most of the PV plants. (Source: 3E)

Figure 14 highlights that for some PV plants in the portfolio, the actual unavailability is very high compared with the initial expectations (e.g. PV plant number 28). Moreover, the mean yearly unavailability of the analyzed portfolio is around 2 %. As observed in a review of current industry practices, a typical assumption of unavailability taken in initial Long Term Yield Assessment (LTYA) studies and O&M contracts is around 1 %. However, the unavailability values in the LTYA studies and in the O&M contracts are not necessarily the same as the O&M operators are only liable for plant outages caused by their negligence. Therefore, the unavailability used in the LTYA studies, which in turn will be used to assess the energy production income, are usually higher and should be adapted with the actual availability once representative operational data become available.

For this use case, the updated results of the comparison between the initial estimates and actual production taking into account the actual unavailability are presented in Figure 15. The effect of the actual unavailability correction is highlighted for some example cases with the orange arrows in Figure 16. Results show clearly that the gap is significantly reduced. Moreover, the deviations below the confidence margin (P90) disappear after the corrections as highlighted by the orange arrows in Figure 15 for some examples (e.g. PV plants numbers 13, 19 and 28).

The overall results taking into account actual unavailability show that in general there is a good agreement between the initial estimates and the actual production. The overall mean difference after correction is -1.15 %. This means that over the analyzed portfolio the actual yield is, on average, slightly lower than the initial estimates done during the PV plant planning (design) phase. Furthermore, as shown in Figure 15, the dispersion (nRMSE) is around 4.4 % for the analyzed portfolio. These variations lie within the normal expected ranges and are similar than the values reported in e.g. [20]. Such variations are typically expected mainly due to the variability of the solar resource and other on-site specific losses that are not precisely modelled during the design phase [11].

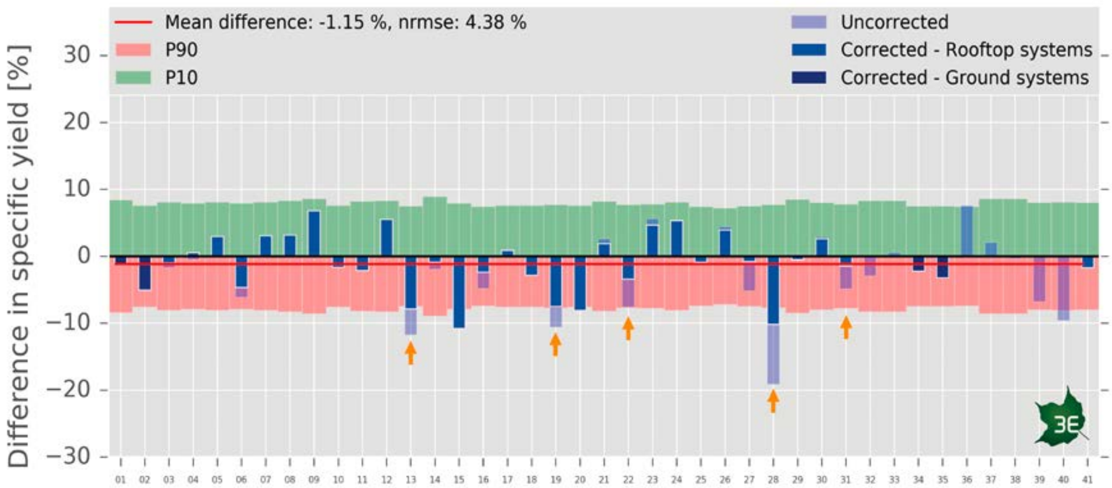


Figure 15: Difference in specific yield corrected for actual unavailability (orange arrows highlight the effect of the unavailability correction for some examples). (Source: 3E)

Finally, the difference between the initial estimates from the LTYA study done during the design phase and the actual values during the first year of operation for Plane of Array (POA) irradiation and PR are shown next to the final specific yield in Figure 16. As it can be seen, the largest gap comes from the performance ratio estimates. The initial estimates of system losses depend on several factors. In addition to the PV software modelling accuracy, several user estimates and assumptions affect the yield estimates. One should note that the results for the POA irradiation shown in Figure 16 are the outcome of comparing the initial estimate done during the LTYA against the satellite-derived irradiation from Cloud Physical Properties algorithm (CPP) for the first year of operation.

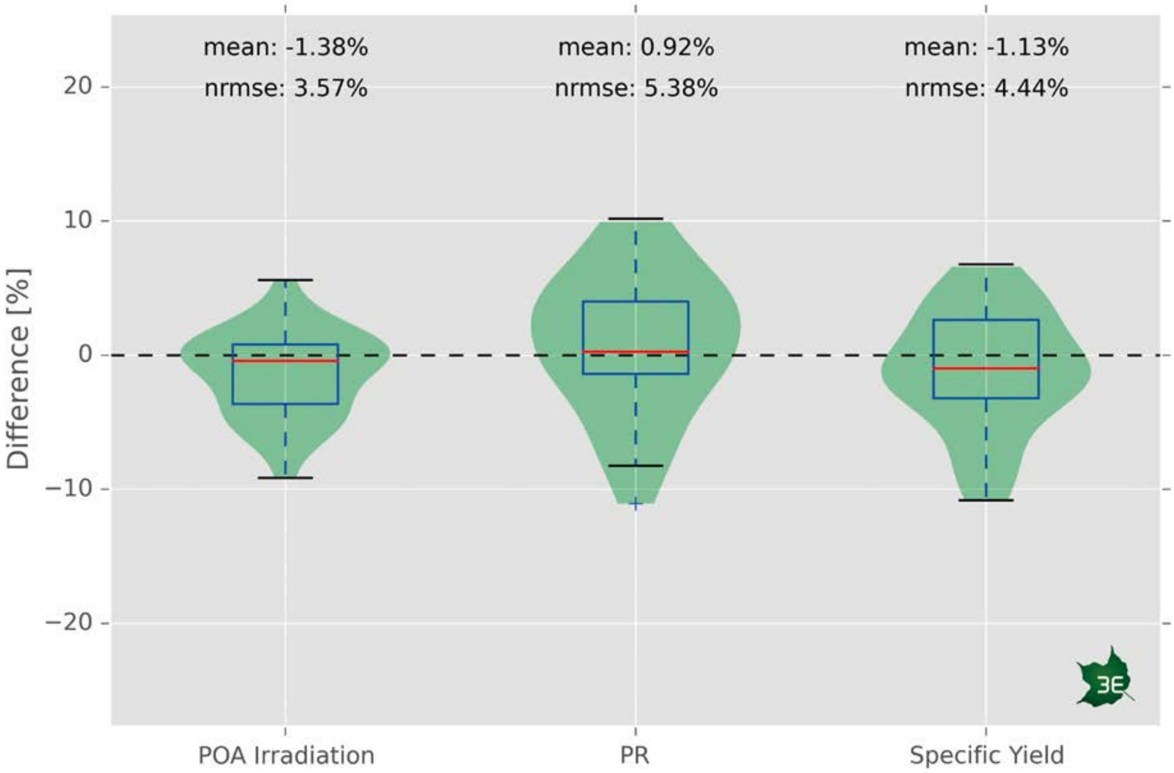


Figure 16: Violin plots for the difference in POA irradiation, PR and resulting specific yield between initial expected yield and actual yield for the analyzed portfolio of 41 PV plants (Source: 3E)

Investing in a big portfolio of PV plants may be a risk mitigation strategy for investors through diversification of risks. As observed in this example, the overall risk of not achieving the expected energy yield decreases when comparing a portfolio of PV systems with a single site. This is valid for a portfolio that consists of a reasonable large number of systems which are spread over a large region. Similar results were presented e.g. by [22]. Several variables such as the number of systems, their geographical distribution, PV module technologies, the type of installations, system configuration, etc. will influence the resulting overall uncertainty [11].

2.2. How frequent are failures in the field?

In the IEA PVPS Task 13 report "Assessment of Photovoltaic Module Failures in the field" [13] the authors presented the current status in terms of determining the power loss of PV modules for specific failure modes and intended to estimate their frequency in the field. In most cases the encapsulant and backsheet films seem to play a major role in PV module degradation. Some failure modes like browning of encapsulants are directly related to the encapsulant film. But in most cases material interactions are the main root cause for PV module degradation. For example acetic acid, which is a degradation product of ethylene vinyl acetate (EVA) encapsulants, not only causes corrosion of the PV stringing and tabbing ribbons and the PV cell gridlines or fingers, but also promotes potential induced degradation and/or delamination. Furthermore, it accelerates the oxidation process of EVA itself. Also, the type of backsheet used in the PV module influences many degradation mechanisms by its barrier properties against water vapour, oxygen, and acetic acid. High concentrations of water vapour and acetic acid in the PV module accelerate nearly all degradation modes.

The literature review shows that PV module failure modes are well described in the literature, including their main driving factors. The review also shows that the right combination of the encapsulant and backsheet films can be beneficial in reducing failures. Nevertheless, the studies also show that there are no common rules or acceleration factors which apply generally for all PV modules and can be used for modelling. On the one hand, the degradation modes depend on the bill of materials and components and are unique for each single PV module brand and model. On the other hand, there are typically several degradation modes and pathways activated simultaneously and these may have synergistic or antagonistic effects, making it challenging to correlate observed effects with single mechanisms.

In the report, a survey on the impact of PV system failures in various climatic zones was conducted to identify the impact of the various failures. The results do not show a strong correlation of the observed failure occurrences and impacts with the Köppen and Geiger climatic zones. In the future, larger datasets of observations may enable these insights, while additional factors which need to be considered for PV module failures may be identified. Independent of climatic zones, some PV module failures stand out with a high power loss if a PV system is affected by the failure. In the rank order of impact, these failures are potential induced degradation, failure of bypass diodes, cell cracks, and discolouration of the encapsulant (or pottant) material.

This rank order of failure modes may be a result of the fact that for potential induced degradation, bypass diodes, and discolouration of the pottant material, no appropriate tests exist in the standard IEC61215 design qualification and type approval test. Currently for all these failure type tests are in development, but they are not even included in the current revision of the IEC61215. Therefore, the authors recommend PV plant designers not only to check for an approved IEC61215 test for the PV module brands/models considered for use, but also for additional tests for PID (IEC/TS 62804 series), bypass diode test (IEC 62979, IEC/TS 62916). The UV degradation test is slightly tightened in the current IEC 61215 compared to the former one, but there is still no pass/fail criterion for discolouration. However, it is recommended to read the full protocol of an IEC 61215 test and look for discolouration remarks.

Besides PV module failures, the failure with the highest impact on the PV system is the soiling of PV modules in specific outdoor regions. The soiling also does not strongly correlate with the climate zones of Köppen and Geiger. Therefore, a special stressor classification for PV modules for soiling in the Middle East and North Africa regions is introduced. These classifications are derived by geographic information systems to allow a worldwide mapping of relevant stress factors for PV systems. In the future this stress factor mapping has to be expanded to other regions worldwide and for other stress factors than soiling.

3. UNDERSTANDING THE FAILURES AND PERFORMANCE LOSSES

Failures and performance losses can be associated with different kind of events, which cannot all be attributed to the technology and its implementation. This paper intends to focus on the events having a technical root cause that could be solved by technical improvements at the planning, or at production stages, or that can be solved by a better use of procedures for installation, visual inspections, and maintenance linked to specific material or components use. It excludes all events related to failures and performances losses which cannot be solved by the upstream part of the PV value chain.

However, Before one starts digging into the different type of failures and the related performance loss, there is a need for the industry and the experts involved to move all together towards a common nomenclature of failures found in the field.

Efforts in this direction have been reported for example by Köntges et al [10] within the framework of IEA PVPS Task 13 with a review of PV module failures found in the field and by Moser et al. within the framework of the Solar Bankability - H2020 project [16], [12] with a list of definition of common technical risks per component along the value chain (included in a so called Risk Matrix).

3.1. Types of defects

Defects can happen at every stage of PV installation, it can be an inherent defect results from module production, a design error of the module or system, the mishandling during installation, or the improper maintenance efforts. Some defects only result in power loss and subsequently influence the return of the investment (financial risk); while some other defects have an impact on safety issues and result in even more serious problems like electric shock or fire hazard. In this section, we introduce several

types of defects that are frequently seen in PV systems, and hope they help the readers get an idea about the risks in PV investment and what action should be taken to prevent the risk.
Please be noted that there are too many types of defects that we cannot show them all in this report, so these are only examples to exhibit the defects of different root causes. There are still many other problems in the field, investors should carefully control the quality of the system.

3.1.1. Inherent defects

Inherent defect means the defect exists when the module is produced, it may appear immediately after production, or present few years after installation. The root cause can be inappropriate production process, wrong material used, human errors or any other mistakes during production.

I. Delamination

Delamination is a frequently seen defect and it can be a very serious impact to the PV system. It is the adhesion failure at the interface of laminated materials, for example failure at the interface EVA/glass, EVA/cell or EVA/backsheet. EVA is the material to bond all materials together, and it also provides sealing and insulation to protect the electrical circuit in the module. When delamination happens, the first influence is that it reduces the light transmitted to the cells and subsequently reduces the power output. But the more serious problem is that edge delamination allows water ingress in the module, and results in leakage current and the potential risk of electric shock. The inverter might also shut down due to the leakage current.

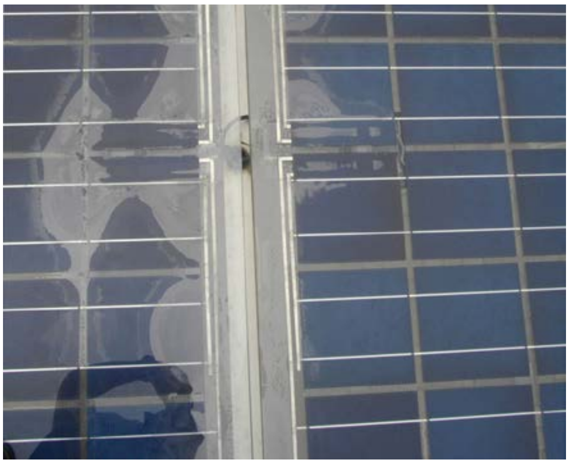


Figure 17: Delamination in PV modules (Photo by PV Guider)

Figure 17 shows PV modules with serious delamination: the big bubbles are the delamination between glass and EVA. Delamination usually happens batch wise, that means 90 % of the modules in the same batch will have the same problem. Delamination mainly results from the failure of bonding between materials, and there are many reasons for it. For example it can be the raw material problem, wrong material preservation condition (EVA needs to be stored in low temperature and low humidity condition), improper lamination parameters (temperature, cycle time), or defect of laminator (non-uniform temperature, inaccurate temperature sensor, etc.). PV module manufacturers should control lamination quality by monitoring the peel strength and the degree of cross-linking of the EVA; this is not always well executed by all manufacturers.

II. Potential Induced Degradation (PID)

PV modules are usually string connected in the system, and the voltage can be as high as 1500 V (and even higher for newer PV system designs) at the end of the string with a tendency to go even higher in voltage in newer PV system design. The frame of the module has to be grounded to earth, which means the potential level of the frame is at 0 V. Therefore, the potential difference between the frame and internal circuit will be up to 1500 V, and the high potential difference results in the damage of the PN junction in the solar cells. Since the defect is generated by high potential difference, it is called potential induced degradation (PID).

Typical PID affected cells have lower shunt resistance (Rsh), and the power decay can be 10 to 100 % depends on the field condition and module materials. PID defect is invisible with naked eyes, but it can be shown by Infra-red imaging and electroluminescence (EL) image. Figure 18 shows an example of PID affected modules, in which the dark cells are PID affected.

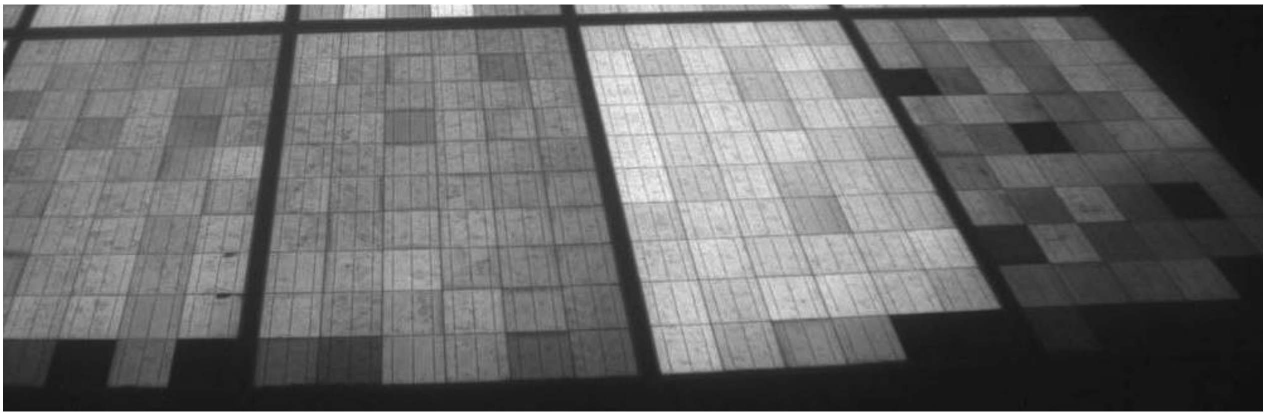


Figure 18: EL image of a PID affected string (Photo by PV Guider)

PID can be prevented at system, module and cell level:

- System level: avoid high negative bias of cells in modules. For example connect the negative pole to the ground, so the cells are in positive bias against the grounded frame. However, grounding the negative pole is only applicable for special types of inverters, and the cost is higher than those without negative grounding. So the EPC and system owners tend to ask the module supplier to prevent the PID problem.

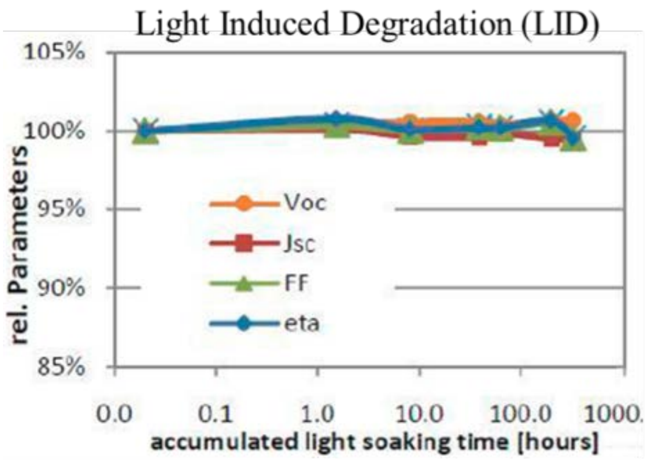
- Module level: PV module suppliers can choose the materials that prevent the ions from damaging the cells. For example, use "PID resistant encapsulants like Polyolefins or Ionomers" to reduce the mobility of ions, or use special glass with less mobile ions.
- Cell level: cell manufacturers can change the anti-reflection (AR) coating or modify the wafer surface to prevent the ions from damaging the PN junction.
- In general, the PID problem can be solved by choosing right materials and cells, however it still happens because some materials are not stable, or the supplier does not use the correct material. For better quality control, PV module manufacturers should regularly carry out a PID test, and stick to the verified material combination.

III. Light Induced Degradation (LID)

The Light Induced Degradation (LID) is a different kind of induced degradation phenomenon effecting solar cell and module efficiency with respect to PID: the LID is conducted by sunlight (real or simulated), and, it can permanently reduce the efficiency of modules by up to 15 %rel .
This degradation effect can be reduced or even avoided by optimizing the cell process or passivating the LID defects.

As analyzed in the report [23] , LID can be mitigated through:

- The selection of proper wafer material: Since most LID defects can be traced back to the wafer material, a proper choice of wafers can minimise LID. For example, to mitigate B–O-related degradation, it's important to choose wafers with reduced boron and/or oxygen concentrations. Degradation effects in multi-crystalline silicon solar cells (FeB-LID or mc-LID) can be reduced using wafer material with fewer metal contaminations.
- The optimization of solar cell and module production: Adaption of the solar cell process can lead to a reduction of various LID types. For example, optimisation of firing conditions reduces the extent of degradation on mc-Si PERC cells. Subsequent treatments can also be carried out, such as illuminated annealing or a second firing step. However, these approaches are lavish and have several disadvantages i.e. no complete avoidance or avoidance to an unknown extent and negative influences on the solar cell efficiency and other parameters.
- The introduction of a production step to avoid LID: A promising technique is so-called regeneration; a subsequent process step within the solar cell production that passivates the LID defects. The passivated defects are stable under field conditions. Generally, light and elevated temperature is used to perform regeneration. On the other hand, within the regeneration process individual cell treatments and in-situ processes are not possible.



Light-and-elevated-temperature-induced degradation (LeTID)
mc-LID or LeTID is a specific degradation process connected to PERC modules (n-PERT is apparently not affected). In contrast to other LID mechanisms, it occurs at elevated temperatures above 50°C only. Therefore, this phenomenon is named light-and-elevated-temperature-induced degradation (LeTID). It is currently begin studied and seems to be linked to several different degradation phenomenon; It affects both mono and multi PERC but it doesn't affect HJT.

IV. Interconnection failure
String interconnection is a simple process in module production. The ribbons are soldered on a wide ribbon to connect the cell strings. Although equipment is available for automated string interconnection, this process is often still performed manually because it is very simple and easy to be handled by the operator. However, manual processes are prone to mistakes.

Figure 19 shows a connection failure found in a pre-shipment inspection. The connection was not strong enough, so the thin ribbon was moved by EVA flow in the lamination process and it mainly results from insufficient or over soldering. The inspection allowed the buyer to find it before delivery in this example, but in most cases the defect is not detected. _Even if the connection may look ok in the factory, temperature cycles under outdoor conditions, will damage the weak soldering with ribbons disconnection as result.

Figure 19 shows an example of ribbon disconnection. The current flow through the disconnected ribbon is interrupted, so the areas become darker in the EL image. On the other hand, the current in the remaining connected ribbon makes the area brighter in the EL image; the temperature is also higher at this ribbon. This defect does not only reduce the power but also generates hot spots in the cell and has an impact on the lifetime of the PV module.

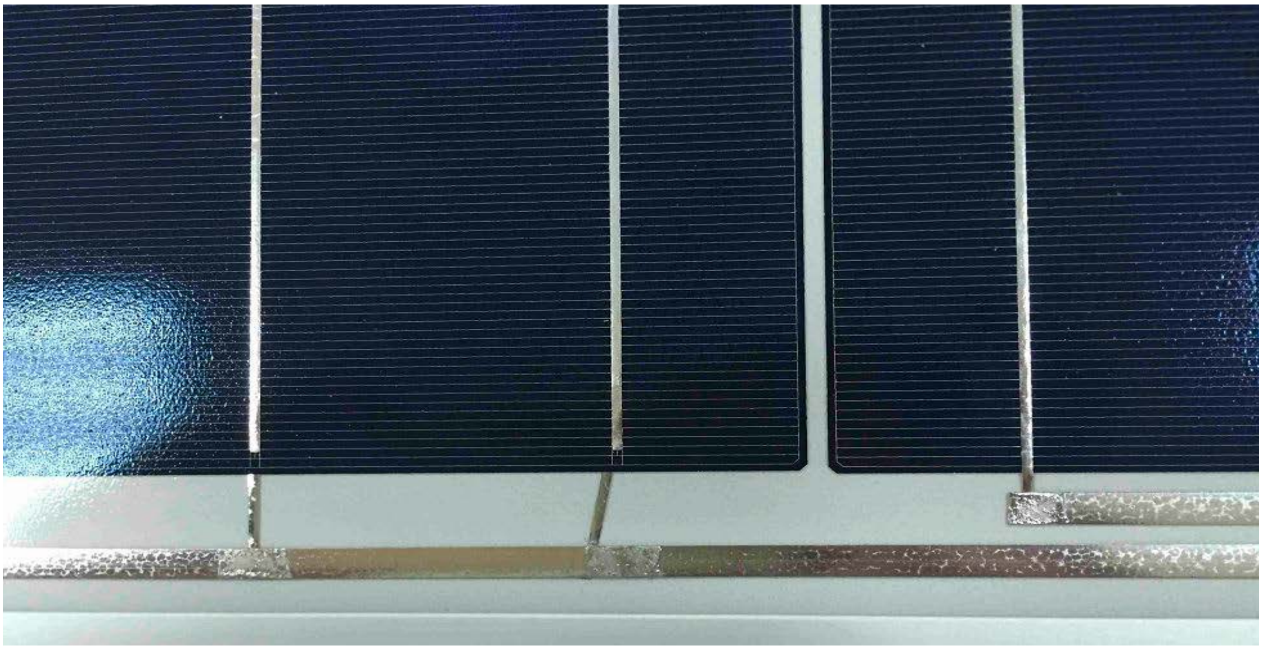


Figure 19: Interconnection failure (Photo by PV Guider)

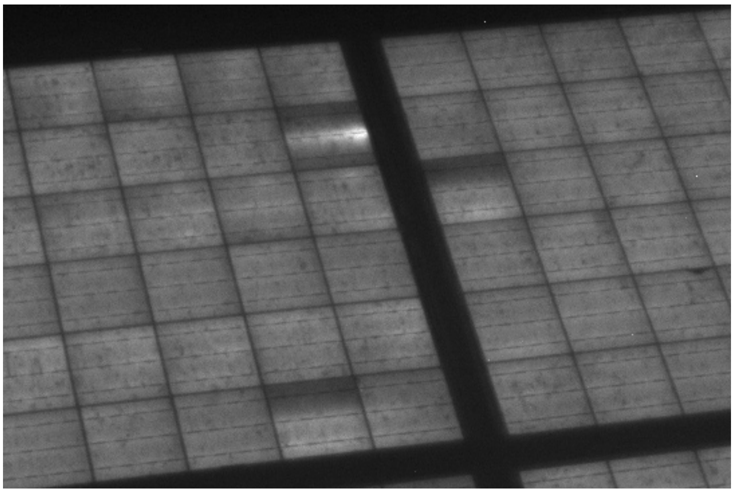


Figure 20: EL image of disconnected ribbons (Photo by PV Guider)

The training of the operator is very important to prevent this kind of defect, PV module manufacturers also need to control the soldering quality carefully in order to prevent the inevitable human errors.

3.1.2. Defects in installation and maintenance

Some of the failures are not from the module manufacturer but are generated during the installation or maintenance phase. Here we list some examples to show the readers that module problems arise not always during the manufacturing phase; installation and low quality operation and maintenance practices also lead to technical risks and eventually failures and need good quality control at system level as well.

I. Cell breakage

Silicon cell is extremely brittle and easy to break in handling, soldering, lamination, transportation, installation and maintenance. Nowadays, most module manufacturers perform 100 % EL inspection before the modules are delivered, so the cell breakage found in the field is most likely not linked to the manufacturing process. It is usually related to the transportation, delivery, and installation process: for example installers mishandling and/or standing on the PV module, or cleaning workers standing on the PV modules. Figure 21 shows EL imaging of PV modules with cell breakage, when the module EL images taken in the production line showed no cracks. These cracks do not only reduce the power of the module, but also generate hot spots and therefore reduce the lifetime of the PV module.

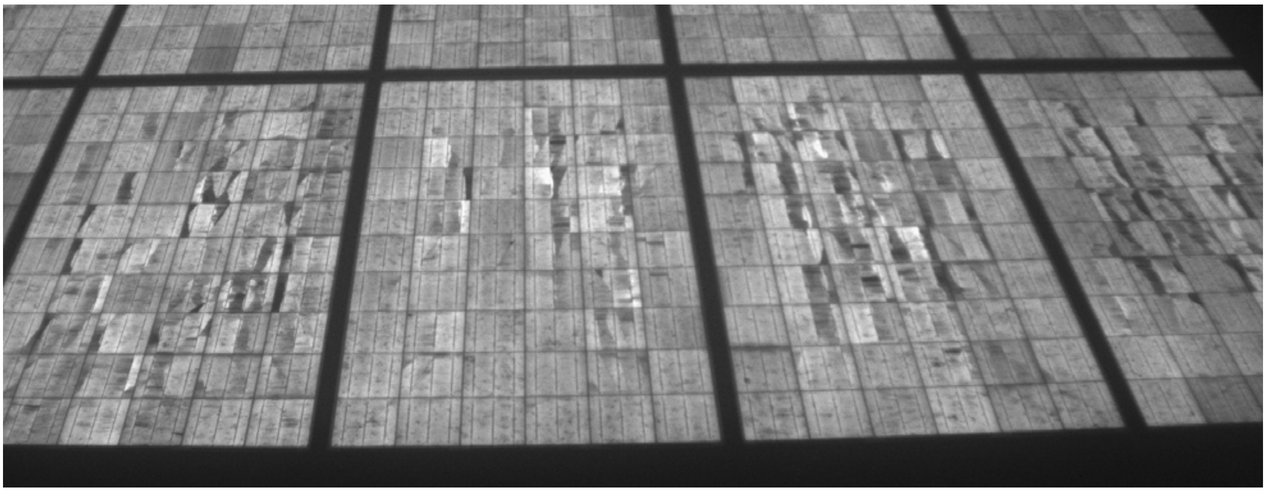


Figure 21: EL image of cell breakage in installed modules (Photo by PV Guider)

Most PV modules can stand a uniform load of 5400 Pa, corresponding to around 900 kg loading uniformly distributed over the surface of the module. Although the PV module can easily bear the weight of a person, when people stand on it the cells inside could break. The concentration load on the feet creates serious local deformation. Before EL technology was introduced in PV inspections, people were not aware of the risk of standing on PV modules. Nowadays workers are not allowed to walk or stand on the PV modules anymore. However, in reality, especially for small/medium size systems without a professional O&M operator in place, it is not uncommon to see workers stepping on the modules during maintenance efforts such as cleaning, weed removal, removal of defected modules, etc.

In order to clarify the responsibility of cell breakage, it is recommended to check with electroluminescence (EL) images the modules before installation. After the installation is completed, string EL inspection is also recommended in the acceptance tests, so the investor can assure the system is in healthy operational conditions.

II. Shading

Shading is recognized as a serious problem that should be avoided. People know that shading can reduce the power output, but it is actually much more than simply power reduction. In crystalline silicon PV modules, since the cells are connected in series, one cell shaded in a 60-cell module will reduce by 1/3 (if bypass diodes are present and properly working) the output power, and, even worse, the shaded cell is in reverse bias and it generates high temperature.

Figure 22 shows a PV module shaded by a small plant where the shaded cell had very high temperature up to 120 oC. The temperature is above the Relative Thermal Index (RTI) of the EVA and backsheet material, which means the insulation and mechanical property of the material degrades more than 50 % at this temperature. Furthermore, the EVA and backsheet will deteriorate and become browning under continuous high temperature. All these results are extremely decremental for the lifetime and reliability of the PV module.

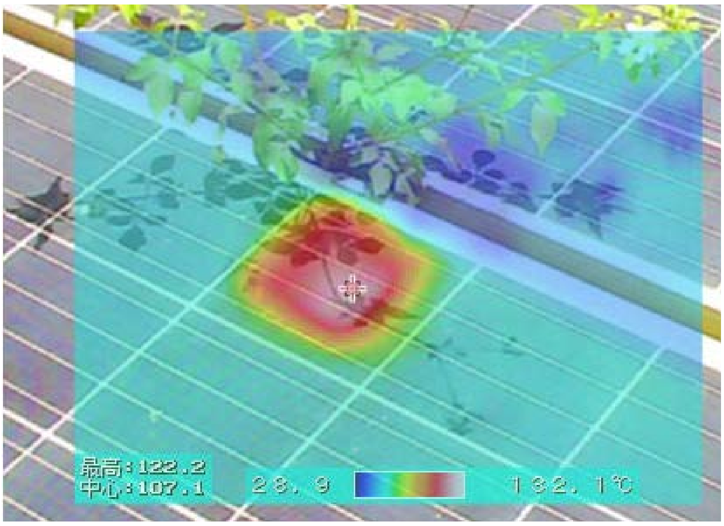


Figure 22: Hotspot generated by shading from vegetation (Photo by PV Guider)

In order to prevent the shading problem, every PV plant should have suitable maintenance plan. For example, in the area where grass grows fast the weeding frequency should be increased. Investors should be aware that a poor maintenance plan not only reduces the power output, but also causes irreversible damage.

4. TRACKING FAILURES IN THE FIELD: "HOW PV PLANTS CAN PERFORM BETTER – FAILURE ANALYSIS AND DERIVED RECOMMENDATIONS FOR IMPROVEMENTS"

4.1. Past experiences with underperforming PV plants and tracking failures in the field

4.1.1 Context

In the following sections we will evaluate past and existing experiences with failure detection and analysis of these impairments in PV plants. As for end of 2017 [24], with 109 GW of PV systems installed so far in Europe, 45 GW in North America and 211 GW in Asia, and a continued growth of the total cumulative PV power installed worldwide, tracking defects in the field is and will remain an enormous challenge. This cumulative power is translated into millions of PV systems worldwide.

Historical data of the performance and failure modes of PV systems are not easily accessible by all market players. These stakeholders have a diverse background and can be categorized as investors (private and public), PV plant owners, EPCs, O&M operators, and insurance companies. The reasons for the difficulty to have access to historical data of PV plants is to be found in the short time that most PV systems have been operational so far. Furthermore a tendency exists among system operators and component manufacturers to keep performance and failure data confidential. This situation should improve because many technical risks assessments and investment decisions regarding the installation of PV plants are based on available information about PV system performance and possible defect rates.

In addition, detailed performance data are in most cases not available for PV plants of residential and commercial market segment as the cost of monitoring is still perceived as an added cost. Finally, although the description of failure and corrective measures is common practice in the field of operation and maintenance, this is not often carried out at a sufficient level of detail for PV systems. However, for the PV industry these performance and failure data are required to have a better understanding of technical risks, risk management practices and the related economic impacts. This information is also essential to ensure investor's confidence and hence to develop a mature and bankable market.

4.1.2 Tracking failures in PV modules

PV modules with c-Si technologies show median degradation rates in the 0.5–0.6 %/a range with the mean in the 0.8–0.9 %/a range [4]. Other technologies like Hetero-interface technology and micro-crystalline silicon technologies, exhibit degradation around 1 %/a and thin-film products are similar to c-Si, but with a high variation of the degradation rate in different products and various reported studies.

In 2013 Hasselbrink et al. summarized data for returns from a fleet of >3 million module-years [25]. The study found that 0.44 % of front contact modules were returned after an average deployment of 5 years, with the majority (~66 %) of these returned because of problems with laminate cell/ribbon/solder failures (primarily cell interconnections). The second most common reason (~20 %) for returns was because of problems with the backsheet or encapsulant (e.g. delamination). Thus, the vast majority of the returns were associated with failures that can usually be identified visually. More analyses are needed to understand if the lower rate of return associated with other types of failures are due to the low detectability by visual inspections (e.g. hotspots, cracked cells, PID, etc.) leading to a biased conclusion. Other bias could be introduced by the number of modules which had defects but were not included in the statistics as the module manufacturers did not accept the warranty claim. Modules that have failed and been returned to the manufacturers are not the only factor to be considered; modules are usually observed to degrade slowly in the field. In 2012 Jordan et al. have summarized ~400 reports in the literature on the subject of the degradation rates for crystalline silicon modules [26]. The degradation is dominated by a loss of short-circuit current. In most cases, the researchers observed that this decrease in short-circuit current is associated with discolouration and/or delamination of the encapsulant material. Thus, both statistics on returns of modules and statistics on slow degradation appear to be correlated to mechanisms that can be observed visually.

Task 13 experience

The description of typical failures at the PV module level was subject to extensive studies within the IEA PVPS Task 13 “Performance and Reliability” and the results were presented in the deliverable “Review of Failures of PV Modules” [27] which was published in 2014 and “Assessment of PV module failures in the field” [13] from 2017. In these two documents, the most common failures of PV modules are described together with the measurement methods to assess impact on the performance and safety and the importance of visual inspection is highlighted. While the types of failures are highly dependent on the design (or failure of the design) of the PV module and on the environment in which the module is deployed, statistical evaluation of what has been reported can help to understand some of the most common failures. The literature review carried out in [27] showed that in most cases interactions between materials in the PV module are the main root cause for PV module degradation.

For this reason, the permeation properties of the particular encapsulation and backsheet films used are of prime importance for the reliability of PV modules. For example, in order to avoid or reduce potential induced degradation, it is desirable to combine an encapsulant film with reduced water vapour transmission rate and higher volume resistivity with a backsheet films that shows selective permeability, i.e. high resistance to water vapour transmission and low resistance to acetic acid transmission.

Next to the critical role of the correct choice of materials and components for the PV module, also the PV module lamination process can have an influence on long-term reliability. Here poorly cross-linked EVA encapsulant, but also too long lamination times are mentionable, which can lead to accelerated degradation or increased delamination.

Forecasting or predicting the degradation of a specific PV module failure is still a challenging task. For some failure types, such as potential induced degradation or silver finger corrosion, predictive models with highly predictive accuracy on a heuristic level are under development. For the cell cracking failure type, some assessment can be done to estimate the maximum power loss due to this failure, but no model, which calculates the power loss considering its dependence on local loads, is yet available. Cell cracking is less harmful for modules with more busbars, but more harmful for modules with higher fill factor. For other failure types (like EVA browning and delamination) the basic mechanisms of the failure are understood, but no models are currently available. Dust and biological soiling are not in fact a module failure, but they still causes serious power degradation and yield loss in the field. It is one very important cause of power loss of PV systems all over in the world.

To identify the relevance of the different failure types, in [27] they conducted a survey of PV module failures and a survey on visual PV module conditions in the field. Potential induced degradation is the most often found module failure in the field and results in a high mean degradation rate of ca. 15 %/a for the affected modules. The PV community should take additional efforts to include a PID test procedure into the IEC 61215 standard so as to avoid further module failures in the field. Cell cracks are also found to be a common problem, but this type of failure does not harm the module power too much (below 3 %/a). However, in cold and snow climate zones (D&E in Köppen and Geiger classification) cell cracks seem to have a more pronounced impact. Here relatively high mean degradation rates of ca. 7 %/a can be found. Therefore, in regions with high snow loads and long periods below 0°C PV modules that are more resistant to cell cracking should be chosen. A relative high impact on the performance of the modules has a failure caused by defective bypass diodes. For the most common modules with 3 bypass diodes already one shunted bypass diode reduces the module's output power by. This failure type is quite common. This failure may be caused by wrong specification and choice of the bypass diodes or by a high voltage event. A bypass diode which changes into open-circuit failure mode causes yield loss during shading of the module and may also cause hot spots, and a fire risk arise. Without shading, these modules show no power loss. Therefore, a wide range of power loss levels are found for this failure in the survey. For bypass diode failures more appropriate tests should be added to the IEC 61215.

One of the most important wear-out failures is the browning of the encapsulant material and module delamination especially for thin-film solar modules. Encapsulant browning becomes relevant in the wear-out phase of the module, because its degradation rate is typically about 1 %/a for affected modules. This determines how much energy the module will produce over the nominal service life. This failure cannot be prevented by the design qualification and type approval test, because it is a wear-out failure. But it is recommended that a test is performed to assess encapsulant browning. The test IEC 61345 describes a UV test procedure for UV exposure. However, this standard is already old and will be withdrawn in the near future. There is no replacement test in sight.

The UV degradation procedure used in the current IEC 61215 is slightly intensified compared to the previous standard. However, a pass/fail criterion is still missing. But a remark in the test report about browning of the laminate may be a first hint on fast browning of the tested module.

There are new procedures defined for material testing in IEC 62788, but this does not help to assess the browning resistance of modules. Therefore, some new efforts must be taken to allow the assessment of the most important wear-out failure browning of encapsulation materials.

No clear picture was found for failure occurrence or degradation in different climate zones. Even though no clear correlation between soiling and climate zones can be found. Therefore, additional new classification on local stressors (dust, UV radiation, irradiance, wind, etc.) and stress levels are needed. The Köppen-Geiger (KG) classification, since it is developed for agriculture and plant growth in different regions, may not consider all particular factors that play an important role for PV systems. As more PV systems are operating in diverse climatic zones, stronger correlations between KG climatic zones and failure modes may arise. New efforts to establish cross-correlations between lab-based testing and out-door real-world PV module performance and failures, coupled with studies of systems in diverse climatic zones will help identify new stressors that play critical roles in PV module degradation and failures [27].

The systematic use of visual inspection enables the collection of a large dataset of failures. Care must be taken in understanding the frequency and statistics of failures as the dataset will be biased by failures which are detectable with visual inspection.

4.1.3 Tracking failures in Inverters

Regarding the determination of reliability at inverter level, it involves taking a look at the failure rate (including the bathtub curve of failure), the infant mortality rate, the useful life of a solar inverter and the meantime between failures (MTBF). The vast majority of PV system failures are believed to be inverter-related [28]. Interestingly, a 1994-1997 study on 126 PV systems found that 75 % of the failures were due to inverters with an MTBF of 1.65 years. Module MTBF was 552 years for residential and 6666 years for utility scale system, i.e. one would expect one module of every 552 or 6666 to fail every year, respectively. Another study between 1996-1997 (SMUD's PV Pioneer Program, 332 PV systems) found that 90 % of the failures were due to inverters [29]. The MTBF of inverters are thus not comparable with the values for modules and inverters must be replaced one or more times during the course of the PV system service life.

The failure modes that mostly affect PV inverters are related to units exposed to high thermal and electrical stress as well as the thermal management system itself (e.g. a fan failure could cause the inverter to overheat affecting its overall lifetime and reliability). Electronic components such as bus capacitors, electronic switches (e.g. IGBTs) and printed circuit boards (PCBs) are found to be responsible for the majority of PV inverter failures reported in literature. Furthermore, maximum power point tracking (MPPT) schemes are also identified as an important factor impacting the overall reliability of PV inverters [30]. Typical estimated life expectancy of integrated circuits (ICs) and optical components is around ten years [31]. However, this will strongly depend on the quality of the materials used and on the design topology. For example, new developments with high quality materials used for special applications like, for e.g. micro-inverters, are designed to work under extreme conditions and are claimed to have longer lifetimes.

Over the last years, significant improvements on PV inverters reliability have been made. Amongst others, reliability of capacitors has improved significantly by replacing electrolytic capacitors by metal film or foil capacitors. However, the current trends in PV industry keep pushing forward the limits of inverter reliability: the higher kWp/kWac ratios, higher DC operating voltages, the micro-inverters and continuous pressure to reduce unit costs are seen as the main challenges for future of inverter reliability [32], [33]. Based on past due-diligence it is found that many failures occurring in the field are related to non-electronic parts of the PV inverter, e.g. failure of contactors, the malfunction of protective equipment under demanding environmental conditions, such as very high and very low ambient temperatures, high humidity, water (or snow) ingress, excessive soiling and lightning strikes. Many failures are associated with new technologies, still lacking an extended track record in the field and often suffering from unexpected failures.

Most of the commercial PV systems have monitoring equipment installed to continuously measure and store different plant operation parameters throughout the lifetime of the PV system. The data collected encompass, among others powers, voltages and currents measured at different stages of the system. Often, other parameters such as solar irradiance, ambient temperature, wind speed, module temperature, inverter events, and insulation resistance are also monitored. These data are typically logged with a time resolution of 15 min or higher and should be stored for the rest of the project lifetime.

In the report from the H2020 Solar Bankability project [12], 3E statistically evaluated the inverter lifetime based on monitoring data coming from more than 2000 plants starting from 2010. The population consists of all inverters that are installed since 2010 and that are smaller than 100 kW.

In Figure 23 ([16]), the yearly inverter replacement rates are shown as a function of installation dates. As the figure illustrates, there appears to be large variations in the inverter replacements depending on the installation dates. Especially, 2011 turned out to be a bad year – already more than 20 % of inverters installed during that year have been replaced by now.

The inverter replacement records were used to generate (part of) a bathtub curve. Figure 24 (taken from [16]) shows the average inverter replacement rate as a function of operational lifetime for the nverters. The first phase of the bathtub curve is clearly visible with the replacement rate decreasing from more than 3.5 % during the first three years to less than 1 % in the fifth year. Thus, it seems that most replacements are due to early failures. Though data of older inverters are missing, there are indications that the onset of the second phase occurs approximately in the fifth year and that the constant replacement rate during the second phase is around 0.5 %. Finally, the onset of the third phase could not yet be derived from the data, but in any case, it does not occur in the first seven years of operation.

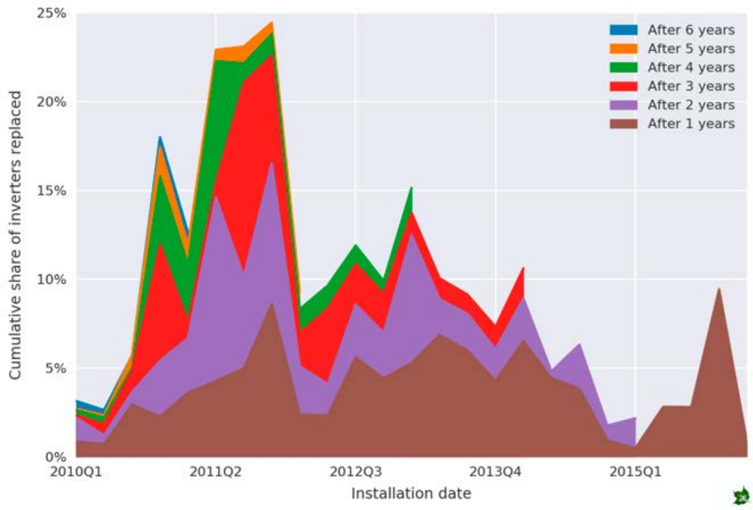


Figure 23: Cumulative share of inverters replaced as a function of installation date and age (total population: 40955 inverters) (source: 3E)

In addition to the investigation of the failure trends with respect to the inverter age, in the Project Solar Bankability the influence of inverter brand and model on the inverter replacement were analyzed. More than 30 brands were studied and there are multiple models in one brand. The following observation were gathered:

- New inverter models typically suffer the most from early failures.
- Iverter failure rates are rarely disclosed by inverter manufacturers, and if they do, the claimed failure rates are typically much lower than the actual replacement rates found in the analysis. This discrepancy may be due to early failures which are typically not accounted for in claims made by manufacturers. Nevertheless, the observations of this analysis are more or less in line with the limited independent literature where inverter failure rates have been found to vary greatly from 0 % to 15 % per inverter year for inverters installed between 1990-2001 ([30], [34]). It is however remarkable that failure rates appear to not have improved significantly since.

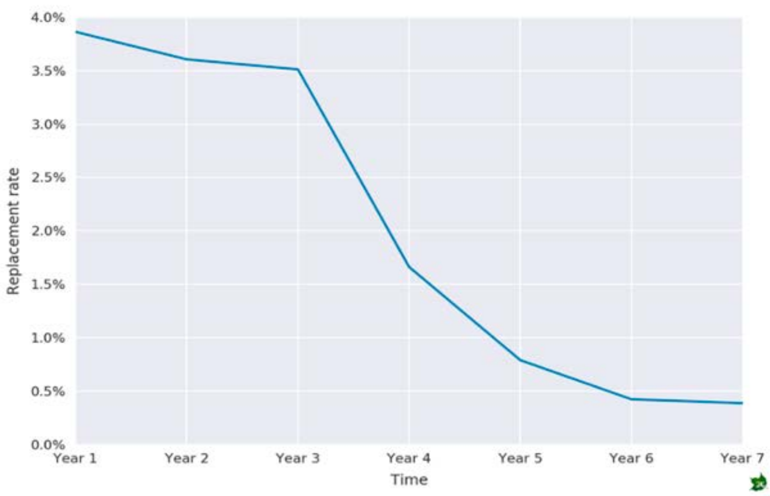


Figure 24: Inverter replacement rate as a function of operational lifetime, showing the initial phase of the so-called ‘bathtub curve’. (Source: 3E)

4.1.4 Tracking failures in PV systems

Extensive work was also carried out in the USA in the framework of the PVROM project [33] where a rigorous data collection, analysis and feedback mechanism is developed and considered a best practice for PV plant owners and operators looking to go beyond simple data collection and immediate incident response. The PVROM project was formally launched in 2013 with the aim of increasing the data sample collected from and shared by industry partners. The database allows for detailed analysis of component failures and indicators such as the average active repair time, mean downtime and maintenance actions. The database builds on the commercially available software tool XFRACAS for failure reporting and corrective actions [35]. Collins et al. described [36], [37] the minimum data necessary for reliability and availability analyses of PV systems as: incident occurrence date/time, Bill of Material part number, part serial number, part commissioning date (in-service date), incident description, incident category, service response date/time, service completion date/time, restoration to service duty date/time, and estimated energy lost (kWh), and also reported how an incident tracking utility can be used for real time data entry.

In Europe, a large scale collection of failure data (representative of around 450 MWp, more than 2 million modules and 12000 inverters) was collected in [12]. The most important technical risks related to PV projects were identified and included in a risk matrix organised by components and divided into five categories to cover the whole PV value chain: product testing/development, PV plants planning/development, transportation/installation, PV plant operation and maintenance, and decommissioning.

The inclusion of the risks into a risk matrix is considered a fundamental step to enable the possibility to share failure data based on an agreed nomenclature and definition by all different stakeholders.

The prioritisation of the risks was not estimated by following a classical Failure Mode and Effects nalysis (FMEA) approach by assigning a Risk Priority Number (RPN) value, but by developing a methodology that was never previously applied to PV systems, a cost-based FMEA with Cost Priority Numbers (CPNs). CPNs are given in €/kWp or in €/kWp/year and can thus directly give an estimation of the economic impact of a technical risk.

Example: Impact of extreme weather conditions on PV systems in Latin America and the Caribbean (LAC) (Source: [38])

Latin America and The Caribbean is generally characterized by a very diverse climate. The continent is located between latitudes of 32° N and 55° S, polar, cold, temperate, dry and tropic climates are prevalent.

The efficiency of a whole PV system depends on the temperature, irradiation, wind (which has an effect on the temperature of the PV module, and may lead to soiling), humidity, rain, snow, hail, and other weather variables. Thus, weather does have an impact on all parts of PV systems and it is crucial to consider in standards and testing methods the influence of different climatic conditions [Table 2].

Climatic Condition	Related Impact
Extreme Temperature	Reduced efficiency, induces PID
High Temperature Variations	Broken interconnects, broken cells, solder bond failures, junction box adhesion problems, open circuits leading to arcing, open circuits of the module connection
Dust Storms	Abrasion, soiling, cementation, hot spots.
Wind / Storm / Hurricane	Mechanical stress
Rainfall	Impacting only when combined with corrosion or UV degradation
Humidity and Salt (Corrosion)	Affecting solder joints, interconnects and other (metallic) parts like the structure, can cause DC arcing, induces PID
Drought	Affects ventilation systems (transformer)
Irradiation	EVA-browning, encapsulant adhesion or delamination; Damages to cable isolation
Hail	Mechanical stress
Snow	Mechanical stress

Table 2: Impact caused in PV systems due to climatic conditions (Source: IRENA)

Tests in standards, such as the damp heat test, UV defined dose, stress test, and guidelines related to ventilation systems for inverters and dry type transformers; can be further improved and customized to the local climatic conditions. Some standardization committees, especially TC82 of the IEC, have these items on their agenda and they are starting to address the inclusion of climatic conditions in existing or new standards.

4.1.5 The economic impact of failures during the operational phase

The CPN methodology developed within the framework of the project Solar Bankability was defined in order to assess two main economic impacts of a specific failure: impact due to downtime and impact due to repair/substitution cost. For the calculation of the economic impact due to downtime, parameters such as time to detection, time to repair and repair time were considered (values for the occurrence for the whole portfolio in the database are of the order of 1 % and 2.7 % for PV modules and inverters, respectively, which means that there is a drop in equivalent hours due to performance losses of around 3.7% in the considered portfolio due to failures in modules and inverters), while for the cost due to repair/substitution, cost for detection, labour cost, cost of repair/substitution and cost of transportation were included. The methodology also considered other statistical parameters such

[8] On the other hand, It is also important to highlight that the UK shows high occurrence of PID, mostly linked to rainfall occurrence rather than temperature.

as the number of affected plants and the number of components in affected plants; in this way it is possible to understand if a specific failure is PV plant dependent or if it is equally present over the whole PV plant portfolio. The analysis showed that high ranking failures for PV modules are glass breakage, potential induced degradation, snail tracks and defective backsheet. Most of these failures can be detected by simple visual inspection. For the inverters, the most important specific failure is related to fan failure and overheating. If only affected plants are considered, safety-related failures become predominant, for example, theft of modules and fire.

In a PV project, costs for correction of defects increase exponentially with a factor of 10 by each step along the value chain from the product idea to the handover to the customer [39]. Defect prevention instead of defect correction should thus be considered as a first mitigation option with an effective risk management strategy during system design and planning. The reduction in occurrence of failures during the planning phase has in fact a direct positive consequence in terms of reduction in occurrence of failures during the operational phase, resulting in a lower CPN. Mitigation measures as defect correction will also have a cost. Therefore, the balance between the increased capital expenditure during planning must be countered by an effective decrease of operational (monetary) losses caused by downtime, component replacement or repair. As already introduced in the previous chapter, it is important to this extent to analyse how risks propagate from one step of the value chain to the next: this allows the identification of mitigation measures and to understand if, for some specific failures, an effective mitigation measure is already in place. For the latter, it means that a failure present during an early step of the value chain is not detected during the operational phase.

In a PV project with a risk management framework in place, typically, during the design phase, a component qualification process is put in place. This is applicable for the main components (module, inverter, mounting structure) and contains compatibility check, risk analysis, supplier audit, and lessons learnt. It entails different complexity according to the project configuration (e.g. technology, country, region, climate).

The cost of mitigation measures needs to be included in a cost benefit analysis, which has to consider the expectations of the stakeholders that are involved in a PV project [40]. Investors are seeking for long defect warranty periods, performance guarantees, reasonable low CAPEX and OPEX, high long-term plant performance and lifetime (ideally above the initial prediction). Banks have requirements similar to those of the investors which are looking for projects with a 10-15 years financing period and PV plant performance which can also be slightly below prediction. Insurers try to limit their liability to failures with an external root cause based on PV plants, which meet technical market standards and are maintained on a regular basis. On the contrary, EPC contractors will look for short defect warranty periods, minimum of additional guarantees and warranties, high sale price with low OPEX showing a very different time horizon compared to the investors.

4.1.6 The role of operation and maintenance in mitigating failures in the field

As a consequence of the different needs between the key actors, O&M operators are in a difficult position to manage all these conflicting requirements for a long period of time. The best condition for O&M operators is in fact in the presence of long defect warranty period and low sale price to allow for higher OPEX. Recent trends in the PV market have put a lot of pressure on the O&M price which is reported to be as low as 8 Euros/kWp/year in Germany in 2016 [40]. A large share of these costs is labour intensive (i.e. site keeping and inspection, preventive maintenance, monitoring and reporting). It is therefore of extreme importance to identify what O&M scope is obligatory vs what is optional and the required reaction time depending on the severity of the failure by assessing the cost of various mitigation options during the operational phase which can be part of an effective O&M strategy.

It is important to put an incentive based remuneration on the O&M rather than a penalty based remuneration. The latter tends to limit the performance at a specific performance ratio whereas the former will push for higher performance ratios.

Mitigation measures must be identified along the PV value chain and assigned to various technical risks. Typical mitigation measures during the design phase are linked to the component selection (e.g. standardised products, products with known track record), O&M friendly design (e.g. accessibility of the site, state of the art design of the monitoring system), LCOE optimised design (e.g. tracker vs. fixed tilt, central vs. string inverter, quality check of solar resource data). Mitigation during the transportation and installations are linked to the supply chain management (e.g. well organised logistics, quality assurance during transportation), quality assurance (e.g. predefined acceptance procedures), grid connection (e.g. knowledge of grid code) [41]. These mitigation measures positively affect the uncertainty of the overall energy yield, increase the initial energy yield and reduce the cost of O&M during the operational phase (e.g. faster replacement of components, lower cost of site maintenance, lower occurrence and severity of defect, etc.).

Mitigation measures during the O&M phase are linked to maintenance (e.g. preventive maintenance, visual inspection, spare parts management), monitoring and data quality (e.g. state of the art measurement equipment and software, performance evaluation, predictive monitoring), outsourcing (e.g. in-sourcing can reduce costs and dependency from suppliers), remote monitoring (e.g. video surveillance, defined workflow to reduce replacement time). These mitigation measures directly affect the CPN of failures occurring during the operational phase by reducing the time to detect defects, the time to repair/substitute defects, etc.

A continuous O&M programme is essential to optimise energy yield and maximise the lifetime and viability of the entire plant and its individual components. Many aspects of O&M practices are interrelated and significantly affect the performance of all the components in the generation chain and project lifecycle. The PV technical risks were defined in the Solar Bankability Project Report “Technical Risks in PV Projects” [16] in terms of downtime, production performance, operational costs and time to complete the required activities. It is important that risk ownership is also considered to better understand which key actor is responsible for the action of mitigating the risk. These risks can then be turned in opportunities to meet or even exceed the expectations of the developers and owners in terms of return on the investment. In particular, suitable planning, supervision and quality assurance actions are critical at all stages of a PV project in order to minimise the risk of damages and outages, optimise the use of warranties, avoid non-optimal use of resources and ultimately optimise the overall performance of the PV plant.

The scientific PV community has thoroughly investigated some specific failures and drawn recommendations on how to mitigate the economic impact for, e.g. soiling [42], [43], grid integration [44], PID [45]. General recommendations on the mitigation measures to reduce the impact of echnical risks are also found in more general publications given by companies active in the field as EPC contractors, consultants, and O&M operators [46], [47]. Some failures can be prevented or mitigated through specific actions at different project phases (e.g. for PID, a different encapsulant or glass during product manufacturing phase, a PID box in case of reversible PID during the operation/ maintenance phase); others can be prevented or mitigated through a more generic action. For example, the monitoring of performance or visual inspection can be considered as generic mitigation measures that can have a positive impact on the reduction of the CPN of many failures. In practice, it is important to understand how mitigation measures can be considered as a whole to be able to calculate their impact and thus assess their effectiveness.

From an LCOE perspective, from the review of the current industry practices, the EPC costs dominate the CAPEX while the O&M costs are the major contributor to the OPEX. The technical aspects in the EPC and O&M contracts are therefore important in managing the technical risks in PV project investment. Since the root-causes of technical risks and failures could be introduced either during project development (procurement and product testing, planning, transportation and construction) or during PV operation (O&M), the EPC and O&M contract terms should therefore account for these risks as much as possible. Whether to place the different mitigation measures in the hands of the EPC contractor or the O&M operator (or other parties) is a decision to be made with a goal to minimize the LCOE by optimizing the balance between the CAPEX and OPEX.

The technical aspects in the EPC and O&M contracts at present day are not sufficiently comprehensive and [11] identified the top 20 gaps found to be either missing from or inadequately defined in the EPC or O&M contracts. Using the results from this gap analysis, recommendations were made to be included in the EPC or O&M contracts that could eventually address the important identified gaps.

In the project Solar Bankability, mitigation measures with an impact on the overall CPN were identified as: component testing, design review and construction monitoring, qualification of EPC, basic and advanced monitoring system, visual and advanced inspection, and spare part management [18]. The total CPN without mitigation measures was found to be 104.75 €/kWp/year for the defined scenario, where the components with failures were substituted. The impact of mitigation measures massively reduces this figure and it is possible to significantly reduce the risks and to obtain values of CPN in the order of 15 to 20 €/kWp/year. The value includes the economic impacts of the mitigation measures, their cost and the economic impact of the identified technical risks for all components after mitigation. Depending on when the failure occurs the ownership of the risk (and consequently, cost) will vary between the involved actors, i.e. PV plant owner, investor, EPC contractor, insurance company, O&M operator. It is thus important as a next step to be able to assign the risk to the relevant stakeholder along the lifetime of a PV project and to evaluate who will ultimately benefit in terms of cost reduction from mitigation measures, which are implemented [48].

4.1.7 The use of data collection in databases

In the next years, as the availability of measured data will exponentially increase, it will be important to build large databases with potentially a harmonised method to increase the confidence level of the statistical analysis and thus reduce the perceived risks from investors. With the availability of these large databases, the necessary information (minimum requirement) can be filtered out to perform tailored analysis in a uniform way, that is, same granularity, same data and same formulas.

4.2. Present situation regarding current initiatives and collaborations

The evaluation of the performance of PV systems, their degradation rates and failure modes, are the focus of several initiatives involving organizations, stakeholders, and other entities:

- Industry initiatives such as SOLARUNITED
- Projects such as PEARLPV, PVQAT
- Research collaborations such as ETIP PV, IEA PVPS, NEDO
- International cooperation platforms such as IRENA
- Standards organizations such as IEC and ASTM

This section will mention only some of the initiatives listed above, focusing on the latest activities and outcomes.

SOLARUNITED

As already mentioned, SOLARUNITED focuses on Quality, Reliability and PV technology addressing the interest of the complete PV value chain. The association aims at sharing best practices, providing international insights, and working with local and global partners. In this framework, SOLARUNITED sets up ad-hoc working groups (WGs) bringing the key stakeholders together to define best practices for the PV Industry to became truly sustainable . The WGs active so far are:

- WG1 – PV Quality & Reliability
- WG2 – PV Life Cycle and Circularity
- WG3 – PV Localized Manufacturing
- WG4 – Thin Film PV Manufacturing (TFPV). Focusing VIPV and Emerging PV Segments

The WG on Quality & Reliability is seeking to ground a data collection method to generate homogeneous data sets which will allow for large data gathering across the globe and subsequent analysis of the resulting trends. Drawing on previous studies brought together by IEA PVPS, the Solar Bankability Group and others, the WG aims at determining Drawing on previous studies brought the strength and weaknesses of the various data sets already available [49].

PEARLPV

The aim of PEARL PV is to improve the energy performance and reliability of photovoltaic (PV) solar energy systems in Europe leading to lower costs of electricity produced by PV systems by a higher energy yield, a longer life time eventually beyond the guaranteed 20 years as specified by manufacturers, and a reduction in the perceived risk in investments in PV projects [50].

The COST Action is organized in 5 working groups (WGs):

- WG1 - PV monitoring
- WG2 – Reliability and durability of PV
- WG3 – PV simulation
- WG4 – PV in the built environment
- WG5 – PV in grids

COST Action PEARL PV has started with developing a data bank for monitored PV systems and PV modules.

The International PV Quality Assurance (PVQAT) Task Force

The International PV Quality Assurance Task Force leads global efforts to craft quality and reliability standards for solar energy technologies. These standards will allow stakeholders to quickly assess a solar photovoltaic (PV) module‘s performance and ability to withstand local weather stresses, thereby reducing risk and adding confidence for those developing products, designing incentive programs, and determining private investments. The PVQAT can be grouped in three broad categories; here below are listed the concrete actions and the latest results achieved for each category.

- Module Durability: PVQAT has ongoing research projects to guide the writing of IEC 62892-1, „Testing of PV modules to differentiate performance in multiple climates and applications – Part 1: Requirements for testing.“

- Manufacturing Consistency: Task group 1 completed a guideline that has been published as IEC 62941.The guideline is focused on PV manufacturing processes and procedures aiming to ensure manufacturing quality and the consistency of the produced PV modules to the warranties given by the producer. The ISO 9001-2008 standard is considered a starting point for compliance with the new requirements.
- System Verification: PVQAT supports the IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE) providing a mechanism for communication between the separate efforts [51].

European Technology and Innovation Platform (ETIP) PV

The European Technology & Innovation Platform (ETIP) PV provides advice on photovoltaic solar energy policy. It is an independent body recognised by the European Commission and the SET Plan Steering Group as representative of the photovoltaic sector. Its recommendations may cover the areas of research and innovation, market development including competitiveness, education and industrial policy. Among other activities, ad-hoc working groups for specific tasks are proposed by the Steering committee.

In this regards, the platform published in November 2018 a white paper on “PV Quality and Economy” as the first outcome of the WG on PV Quality Assurance and Reliability. The WG aims at supporting the European manufacturing, strengthening confidence in PV system quality and public acceptance of PV technology, raising quality in construction and maintenance of systems, showing associated demand for research and regulations. To achieve these goals, the recently published white paper aims at creating synergies with European and national policy makers, evaluating the most relevant and recent studies in coordination with related activities (e.g. PVQAT, IEA PVPS Task 13).

The strong growth of the PV sector is accompanied by high cost pressure, accelerated innovation cycles and dynamic deployment, clearly indicating that the quality of PV products and the holistic economy of PV electricity deserve special attention. PV is expected to deliver electricity at low LCOE, Energy Pay-Back Time (EPBT) and Product Environmental Footprint (PEF). The ETIP PV WG report defines quality as the ability of a product to meet demanding customer expectations while focusing on the impact of quality parameters on monetary, energy and environmental cost.

IEA Photovoltaic Power Systems Programme (PVPS)

The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R&D Agreements established within the IEA and, since its establishment in 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 Technology Collaboration 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.

Currently seven research projects (Tasks), are established within the IEA PVPS Programme [52]. Among these, IEA PVPS Task 13 –- Performance, Operation and Reliability of Photovoltaic Systems – engages in focusing the international collaboration in improving the reliability of photovoltaic systems and subsystems by collecting, analysing and disseminating information on their technical performance and failures, providing a basis for their technical assessment, and developing practical recommendations for improving their electrical and economic output.

The IEA Photovoltaic Power Systems Programme (PVPS) Task 13 report on PV module failure assessments published in May 2017 gives a very comprehensive description of observed failure modes and associated mechanisms [13]. It further highlights the influence of materials and the manufacturing process on panel degradation. IEA PVPS has been active in this area since 1993. This report also compiles a review of field failure databases dividing the bulk of the existing data into two main sections including the expert (research groups, industry groups) surveys and data acquisition done through voluntary contributions. Long term outdoor studies are mentioned although they often concern a very small (but very detailed) data set. The report further mentions that many separate studies exist which are not yet compiled into a large data set. Whilst this could be technically interesting, it pauses several challenges:

a. Defect categorisation. NREL has published visual inspection sheets. Whilst these are very comprehensive, they are difficult to apply in a practical environment. The NREL checklist published in 2012 comprises 6 pages of a comprehensive checklist of all possible defects known in 2012. All six pages cannot be used for each panel inspection in the context of a large solar park inspection (more than several hundred panels). The inspection checklist also precludes of a common understanding of the failure mechanism allowing for appropriate categorisation. However, intricate interaction mechanisms do not necessarily render this task as straightforward as anticipated. As an example, certain types of backsheets may yellow on the sunny side but this failure could easily be wrongly attributed to encapsulant yellowing without prior understanding.
b. Data inconsistencies. A survey performed by one organisation is rarely done in the same way by another organisation. Consolidating data with large discrepancies can be very challenging.
c. Climate classifications are also rarely in agreement. The IEA PVPS report [13] states that defects do not tend to follow the Köppen & Geiger (KG) classification. IEA PVPS Task [13] suggests to regroup climates into 4 main zones such as Hot and Humid, Hot and Dry, Moderate, Cold and Snow. Such classification has the advantage to separating two main potential drivers for failure. It is believed that the temperature is one major driver for failure although technically, it is in fact an accelerator in all degradation modes involving chemical processes from chemical reactions to migration of species. The work performed by the Sophia project demonstrates clearly enough that an increase in temperature (20°C) is more detrimental to UV aging than doubling the UV dose (given a baseline UV exposure) [53]. Work performed by Fraunhofer ISE further highlights this effect using the long know Arrhenius equation detailing activation energies.

The link between failure and humidity is believed to exist but appears tenuous compared to the overwhelming impact of temperature. Other work by DuPont has divided the "climate" stresses into a simpler 3 zone system solely based on zones of similar defect proportion [54]. These zones highlight temperature as the main differentiator for polymer aging.

Based on the criteria prescribed by IEA PVPS, a database was put in place with reasonable harmony which allowed an analysis of failures. Contributors were mostly expert contributors (as defined earlier: research and industry groups) to the level of about 430 MWp. Other sources included system owners, installers, manufacturers, publications, survey amounted for 13.5 MW. 45 % of the data was collected in the moderate zone, 26 % in the hot and dry, 10 % in the hot and humid and finally, 19 % in the cold and snow. 45 % of systems were ground mounted with an additional 11% ground mounted test parks and 21 % were roof mounted with an additional 4 % roof mounted test installations. The balance involved special configurations such as facades, tracking, etc. It is crucial to differentiate both ground and roof mounted due to the very different ambient temperatures. Similarly, it is crucial to differentiate commercial installations from test installations which tend to differ greatly in terms of selection of the components. Although it has been reported in the past that panels account only for a small proportion of failures, data reported by the participants of the IEA PVPS database only reported panel failures. A broad analysis could therefore not be performed all of the components of the system [54], [13].

In order to analyse potential improvements to the data collection system, one has to attach himself to analysing the data for potential bias which was not foreseen in the collection plan. One of the main findings is that most failure occur within 7 years of the system with occasional spikes in later years. This deviation from the expected bathtub curve is not so surprising considering two main effects:

1. Components have changed greatly to optimise the cost positions of systems, often with little understanding of the aging mechanisms involved and tenuous consensus on what made an adequate accelerated testing.
2. Installations rushes contribute greatly to failure rates. When Feed in Tariffs were implemented in Spain and Italy, they triggered an installation rush in both countries at different times (about 2 years apart) which correlates well with higher defect periods. These defects may be influenced by sourcing poor quality components, poor workmanship due to rushed timetables, bodged installations and grid connections tied to unattainable deadlines.

Furthermore, although the mechanisms for materials interactions are well described in the IEA PVPS report, they remain obscure in the database provided. For example, it is difficult to determine if the EVA is delaminated from the glass, the cell or the backsheet. Each layer of delamination may be triggered by very different mechanisms. The observer may not however be able to categorize the three types of delamination due to his limited knowledge of the panel manufacturing process.

DuPont references field studies on about 1GW across the world highlighting that 22 % of the panels surveyed show a visual change. Although this study is sizable, it lacks data in particular in the hot and humid zone (much as for the IEA PVPS data set). Although IEA PVPS did not find climate related degradation rates, DuPont highlighted that polymer degradation (backsheet and EVA) seemed to follow a clear temperature trend. This data set is gathered by a unique group of individuals from the same organisation which should contribute positively to its accuracy. It is however the painstaking work of 5 years of field surveys and remain a slow data gathering process.

The New energy and Industrial Technology Development Organization (NEDO) has establish a target of 14 yen/kWh in 2020 and 7 yen/kWh in 2030 by working simultaneously on efficiency and reliability and started the “development of high performance and reliable PV modules to reduce the levelized cost of electricity” project in 2015 [55].

Most contributions to consortium-like activities are often triggered by failure. Experts consultants are most often called to problematic installations. Organisations like TUV Rheinland also regularly publish failure rates (based on PV power plant inspections of several GWs) [55]. Whilst this type of data has a lot of value, it is not representative of the whole sample available. We therefore have to be aware in which category the dataset belongs: the random sampling or the defect based sampling. Thereafter, most systems will call attention if they exhibit operational problems leading to a loss of revenue. Much in contradiction of this though, systems which have led to settlement of claim (in or out of court) are often subject to a non-disclosure agreement, making the reporting never so totally defect based or random!

Where data is gathered by a large panel of contributors, accuracy may be lost due to lack of alignment which may arise from lack of knowledge and differing experience. Much to the opposite, if data is gathered by a well aligned but limited number of contributor, whilst accuracy may benefit, the volume of data then suffers. The challenge resides in marrying accuracy and volume with an unbiased sampling scheme.

IRENA

IRENA serves a platform of cooperation and dialogue, enabling a communication bridge between stakeholders involved in quality assurance and renewable energy fields, particularly policy-makers, industry and QA related institutions. IRENA publishes comprehensive reports in how to develop quality assurance frameworks following a step by step approach and it facilitates workshops in countries to assist in the development of quality assurance and standardisation. Furthermore, IRENA offers for free an online platform for International Standards and Patents in Renewable Energy (INSPIRE) , repository of an interactive standards database and multiple publications in quality assurance for renewable energy.

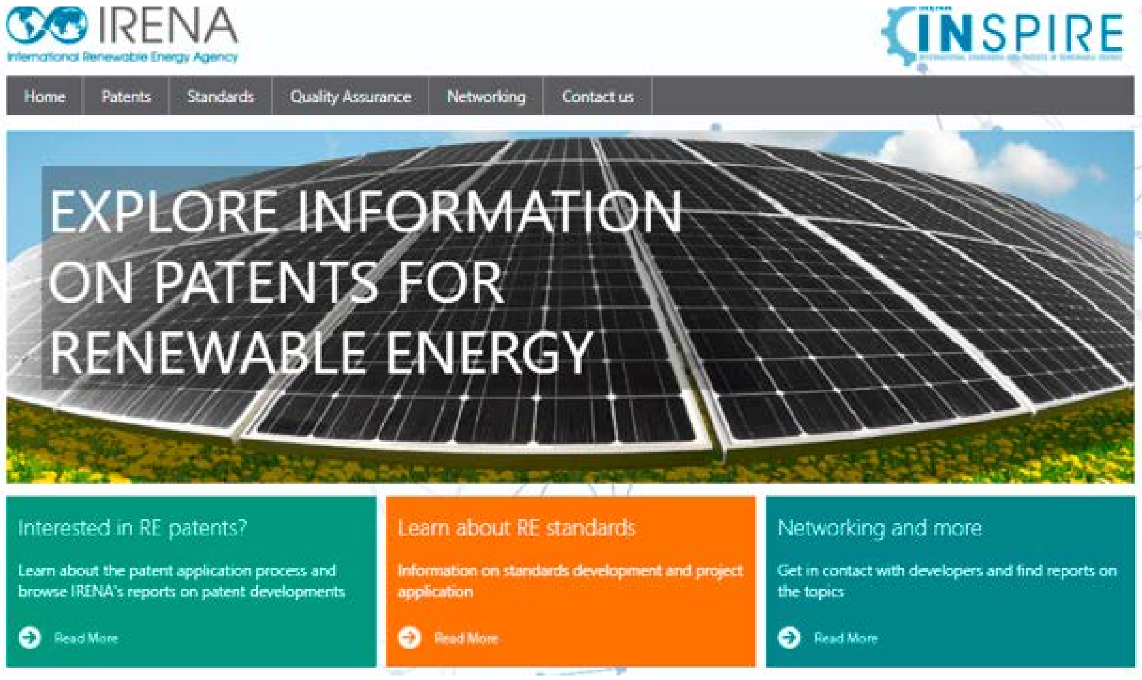


Figure 25: IRENA Platform INSPIRE

4.3. Desired future situation

It is always a challenge to look in the future, but as we know the future always seems to provide better solutions than we have nowadays. This also applies to failure analysis of PV plants. In this section it is therefore assumed that in the future both upstream and downstream PV quality and reliability will have significantly improved. Also it is assumed that the future is positioned in the year 2025 and beyond.

In order to archive this desired future situation for upstream situations, it will be necessary to streamline and further automate PV module production lines. Especially in the last production steps, the cell and the module production, mainly in Asian factories, need to upgrade. Production capacities of factories are meanwhile counted in Gigawatts, 5 to 10 GW per site are being built already. These amounts can only reliably be produced in high quality if production parameters are inspected steadily and kept in narrow tolerances.

Still most of the solar cells produced in Mainland China are eye-inspected and hand-sorted or sorted with low performance Automatic Optical Inspection (AOI). This means quite a significant amount of defects is not sorted out and can cause malfunction or degradation later on. State of the art AOI integrated in the Tester/Sorter can ensure the rejection of cells that would probably cause later degradation (e.g. bad firing, bad metallization, print interruptions, uneven coating, improper laser openings, missing rear side print, residues from chemicals, etc.). Human eye inspection will then be far exceeded.

Inline process control with AOI is even more powerful after most production steps (coating, front and rear side metallization). Drifts of quality relevant parameters can be observed before relevant defects occur and measures be taken to always stay within narrow tolerances (short feedback loop).
"Big Data" collected in Manufacturing Execution Systems (MESs) along the production line enables transparent production, quality control and quality optimization. Up to now effective MESs are established at only very few producers. For optimized quality an effective cell tracking is mandatory. It enables to track almost all defects and effects back to their root by reading the code on the faulty solar cell. Up to now it has only been applied at one major producer, Hanwha Q Cells (laser marking ID). Consequently such quality tracking also should be established and used in all module production lines. Some stringer machines already are equipped with effective optical quality inspection. Also before or in the final flasher (IV-tester) automatic visible light and electroluminescence inspection can ensure high and equal quality modules for the installation.

This is a call for all investors in PV to push producers to install and maintain state of the art wafer tracking and inline inspection and to prove their effective and continuous usage.

It is important to note that besides the inspection at the wafer, cell and module level, it is required to continuously monitor the material quality of the major process materials as well as the most important process parameters, which not only needs state of the art AOI in the Cell Tester/Sorter, but also after major production steps (especially after metallization). Ideally this data should automatically be linked to the device data (MES). This will help to identify the potential root cause of reliability or durability issues in the field significantly more effectively.

For the downstream situation, including installed PV systems, it can be assumed that:

- It will be possible to make use of the "internet of things" (IoT) to collect information of PV systems and their components and apply Artificial Intelligence / Machine Learning to gather insights;
- Data from PV systems and local distribution grids will be open data, available to various users;
- Most components such as PV modules, inverters and other power electronics, but also their interfaces with their users, will have smart features;
- Drones will be a common tool that will be applied for visual inspections of PV arrays;
- Simulation models will be even more accurate than nowadays models;
- Allowing reliable forecasting of the performance of PV systems on short and long time scales.
- This improved technical context will create a better access to diverse types of data to PV system experts - but also the owners of PV plants - leading to a better understanding of key factors influencing real-life relations between performance, reliability and durability.

As already mentioned in in the previous section key precondition for this advanced data evaluation is that all relevant data can be automatically linked and stored in an easily accessible database.

In the future, indicators used to quantify and compare the performance of PV modules and PV systems, will remain similar performance ratio (PR), final yield (Yf) and temperature-corrected efficiencies (25 oC). These indicators will be related to available irradiation (H) and modes of operation and eventual failures. Assumingly new indicators will be required for low concentrating PV technologies.

However, one should be aware that due to more rapid climate change the prediction of PV system performance based on historic climate data will face additional challenges.

For reliability and durability research, firstly performance data – as indicated above – will be used to determine the rate of degradation of PV module and systems, secondly failure modes will be collected, identified and statistically evaluated. This evaluation will happen in the context of, among others, location, hence irradiation, life time of the PV modules/systems, typical components and modes of installation, system operation and integration with the grid as well as maintenance schemes. Assuming a higher statistics of data collection of large amounts of PV systems in the future, it will also be possible to process these data and related indicators by statistical methods originating from the field of maintenance research, such as FMEA and Multi-variables Analysis.

As PV systems in the future will be more complex systems – due to integration of energy storage and grid stabilization functions – it is of outmost importance that, besides the existing quality control for the system components, an independent quality assurance for system design and engineering is established. This quality assurance needs to focus on the key aspects of system performance, reliability and safety.

5. RECOMMENDATIONS

The recommendations that can be drawn from the chapters above are the following:

General recommendations:

Comprehensive Quality Infrastructure should be in place to assure that PV technologies will deliver reliable and secure services. A well-established Quality Infrastructure frame-work that comprises metrology, standards, testing methods, inspections, certifications, accreditation, among others, can mitigate development and operational risks, decrease failure rates and improve overall performance of solar PV technologies.

As PV systems in the future will be more complex systems – due to integration of energy storage and grid stabilization functions -– it is of outmost importance that, besides the existing quality control for the system components, an independent quality assurance for system design and engineering is established. This quality assurance needs to focus on the key aspects of system performance, reliability and safety.

Recommendations for data collection:

*In the coming years, as the availability of measured data will exponentially increase, it will be important to build **large databases** which connect manufacturing data with experiences with installed PV modules and systems. Referring to a harmonized method, the database can increase the confidence level of the statistical analysis and thus reduce the perceived risk from investors related to the initial yield assessment. With the availability of these large databases, the necessary information (minimum requirement) can be filtered out to perform tailored analysis in a uniform way, that is, same granularity, same data and same formulas.*

Data acquisition is of fundamental importance not only for fast feedback within subsequent steps of the value chain but also between processes which are not directly linked (i.e. manufacturing and installation of components). Reliable, automatized and harmonized measurements and tools can improve quality and allow manufacturer of PV components to maintain a competitive level.

*Before one starts digging into the different type of failures and the related performance loss, there is a need for the industry and the experts involved to move all together towards a **common nomenclature** of failures found in the field.*

*The **inclusion of the risks into a risk matrix** is considered a fundamental step to enable the possibility to share failure data based on an agreed nomenclature and definition by all different stakeholders.*

Key precondition for the advanced data evaluation is that all relevant data can be automatically linked and stored in an easily accessible database.

Due to more rapid climate change the prediction of PV system performance based on historic climate data will face additional challenges.

Recommendations about inspections:

*It is important to put an **incentive based remuneration on the O&M** rather than a penalty based remuneration. The latter tends to limit the performance at a specific performance ratio whereas the former will push for higher performance ratios.*

Besides the inspection on wafer, cell and module level, it is required to continuously monitor the material quality of the major process materials as well as the most important process parameters which not only needs state of the art AOI in the Cell Tester/Sorter, but also after major production steps (especially after metallization). Ideally, these data should automatically be linked to the device data (MES). This will help to identify the potential root cause of reliability or durability issues in the field more effectively.

A mitigation option, especially in large projects, is to consider the use of 3rd party consultants to evaluate the quality from upstream to downstream. As independent 3rd party does not have conflict of interest, they can really stand on the investors' side and protect the investment.

In order to clarify the responsibility of cell breakage, it is recommended to check with electroluminescence (EL) images the modules before installation. After the installation is completed, string EL inspection is also recommended in the acceptance tests, so the investor can assure the system is in healthy operational conditions.

The systematic use of visual inspection enables the collection of a large dataset of failures. Care must be taken in understanding the frequency and statistics of failures as the dataset will be biased by failures which are detectable with visual inspection.

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Acronyms and Abbreviations

AOI:	Automatic Optical Inspection
BoS:	Balance of System
CDF:	Cumulative Distribution Function
CPNs:	Cost Priority Numbers
CPP:	Cloud Physical Properties algorithm
DC:	Direct Current
EL:	electroluminescence
EPCs:	Engineering Procurement and Construction
EVA:	Ethylene Vinyl Acetate
FMEA:	Failure Mode and Effects Analysis
ICs:	integrated Circuits
IEA PVPS:	International Energy Agency Photovoltaic Power Systems Programme
IEC:	International Electronical Commission Certification
IGBTs:	Insulated-Gate Bipolar Transistors
IRENA:	International Renewable Energy Agency
LCOE:	Levelized Cost of Electricity
LeTID:	Light and elevated Temperature Induced Degradation
LID:	Light Induced Degradation
LTYA:	Long Term Yield Assessment
MES:	Manufacturing Execution System
MPPT:	Maximum Power Point Tracking schemes
MTBF:	meantime between failures
NRMSE:	Normalized root-mean-square deviation
O&M:	Operation and Maintenance
PCBs:	Printed Circuit Boards
PID:	Potential Induced Degradation
POA:	Plane of Array
PR:	Performance Ratio
PV:	Photovoltaic
PVQAT:	International Photovoltaic Quality Assurance Task Force
QA:	Quality Assurance
QI:	Quality Infrastructure
RPN:	Risk Priority Number
Rsh:	shunt resistance
RTI:	Relative Thermal Index. The temperature index at which the material characteristic is seriously deteriorated
WG:	Working Group

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