Technical failures in PV projects

Risk assessment | The aim of the Solar Bankability project is to establish a common practice for professional risk assessment, which will serve to reduce the risks associated with investments in PV projects. In this article the project team discusses a key aspect of this work: the development of a methodology for the assessment of the economic impact of failures occurring during operation but which might have originated in previous phases

Historical performance data for PV systems on which to base technical risk assessments and investment decisions are not easily accessible by some market players, such as investors, PV plant owners, EPC contractors and insurance companies. The reasons for this difficulty are that most PV systems have been operational for only a few years (GW-level cumulative installations in many countries were only reached after 2010), and that there is a tendency among system operators and component manufacturers to keep available performance data confidential. In addition, performance data are in most cases not available for PV plants with low nominal power (e.g. residential/commercial market segments up to 250kWp), 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 (at least in paper form), this is not often carried out with a sufficient level of detail in order to derive meaningful statistical analysis because of missing cost information and the lack of a common approach in the assignment of failures to a specific category. For the PV industry to reach a mature market level, a better understanding of technical risks, risk management practices and the related economic impact is thus essential to ensure investor confidence.

One objective of solar bankability is to improve the current understanding of several key aspects of risk management during the project life cycle, from the identification of technical risks and their economic impact, through the process of mitigating and allocating those risks among project parties, to transferring those risks through insurance, warranties, preventive maintenance, etc. To achieve this, the Solar Bankability project team has started building upon existing studies and collecting available statistical data of failures with the following aims: 1) to suggest a guideline for the categorisation of failures; 2) to introduce a framework for the calculation of uncertainties in PV project planning and how this is linked to financial figures; and 3) to develop a methodology for the assessment of the economic impact of failures occurring during operation but which might have originated in previous phases. The focus of this article will mainly be on the third aspect.

Failures of PV system components

A description of the typical failures at the PV module level was the subject of extensive studies within the first phase of the IEA PVPS Task 13 "Performance and Reliability", and the results were presented in the deliverable review of PV module failures [1]. In that document the most common failures of PV modules are described along with the measurement methods in order to assess the impact on performance and safety, with a particular emphasis on visual inspection. Other studies [2] have found that the typical reasons for module returns are linked to problems with laminate cell/ribbon/solder failures (primarily cell interconnections), and to problems with the backsheet or encapsulant (e.g. delamination). Thus, the vast majority of the returns are associated with failures that can usually be identified visually.

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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. The literature on the subject of degradation rates for crystalline silicon modules shows that the degradation is dominated by a loss of short-circuit current [3,4]. In most cases this decrease in short-circuit current is associated with discoloration and/or delamination of the encapsulant material. Thus, statistics that relate both to returns of modules and to slow degradation appear to be correlated to mechanisms that can be observed visually. The systematic use of visual inspection would enable the collection of a large dataset of failures. However, other types of failure with low detectability by visual inspection (e.g. hotspots, cracked cells, PID, etc.) might then be under-represented, leading to biased conclusions.

The failure modes that mostly affect PV inverters are related to units that have been exposed to high thermal and electrical stress, as well as to the thermal management system itself [5]. Electronic components – such as bus capacitors, electronic switches and printed circuit boards – have been found to be responsible for the majority of PV inverter failures reported in the literature. Furthermore, maximum power point tracking (MPPT) schemes have also been identified as an important factor impacting the overall reliability of PV inverters. A fan failure could cause the inverter to overheat, affecting its overall lifetime and reliability. Nevertheless, it has been reported in the literature that even under extreme operating conditions, state-of-the-art fans used in PV inverters may work without failing over a period of more than ten years. The typical estimated life expectancy of integrated circuits and optical components is around ten years; however, this will to a large extent depend on the quality of the materials used and on the design topology.

The examples of failures detected in the field as described above only relate to modules and inverters, but each component of a PV system can be affected by failures. Within the Solar Bankability project (a project funded by the EC under the H2020 scheme), typical technical risks for all components of a PV plant and for

		I	II	III	IV	V
	Components / Project phase	Product testing	PV plant planning / development	Installation / Transportation	Operation / Maintenance	Decommissioning
A	Modules					
B	Inverter					
C	Mounting structure					
D	Connection & Distribution boxes					
E	Cabling					
F	Potential equalisation & Grounding, LPS					
G	Weather station & Communication & Monitoring					
H	Transformer station & MV/HV					
I	Infrastructure & Environmental influence					
J	Storage system					
K	Miscellaneous					

Figure 1. The risk matrix as implemented in the Solar Bankability project

various project phases (e.g. product testing, planning, transportation/installation, O&M, decommissioning) have been included in a risk matrix (Fig. 1), and a methodology has been developed to assess the economic impact of failures on the calculation of the levelised cost of electricity (LCOE) and on business models. This represents an initial attempt to apply a cost-based failure modes and effects analysis (FMEA) as an important step towards increased confidence in the operation of PV systems based on a large-scale failure analysis. More-detailed results of this work are presented in the Solar Bankability's public project report "Technical risks in PV projects" [6].

Assessment of the economic impact of technical risks: CPN methodology

The typical approach in risk analysis for technical projects is to apply a classic FMEA in which the various risks, associated with a certain phase and component, can be prioritised through their risk priority number (RPN). In the FMEA each identified risk is evaluated for its severity (S), occurrence (O) and detectability (D); numbers are used to score each of these evaluation parameters. The RPN is then usually obtained by multiplying these three factors.

The classic FMEA with RPNs, although important, is incomplete and needs to be enhanced to include a method for assessing the cost impact of each risk. A classic FMEA is thus deemed inadequate for this specific objective when the technical risk analysis needs to provide a framework for the calculation of the economic impact.

Regarding the application of cost priority FMEA to other fields, many studies have been reported that involve the introduction of a special coefficient called the *cost priority number* (CPN). To the best of the authors' knowledge, there has not been any analysis documented in the literature relating to photovoltaic plants.

A CPN ranking prioritises risks which have a higher economic impact; however, this might not be applicable to each type of risk. To this extent, technical risks were first listed in the risk matrix. The inclusion of the risks in a risk matrix is considered a fundamental step to allow the possibility of failure data, based on an agreed nomenclature and definition, being shared by all the different stakeholders. For the calculation of the economic impact of risks, which are likely to occur during the implementation phase (i.e. during operation and maintenance), it is important to separate this into loss of income due to downtime, and the costs related to fixing the failure (e.g. repairing or replacing a component).

Loss of income due to downtime

For the calculation of the missing income due to downtime, the occurrence and severity were calculated following a well-defined procedure. This procedure is designed to allow generalisation and flexibility in order to maximise the use of the methodology. The severity, S, is defined as the total plant(s) production over one year in the absence of failures. The occurrence, O, is calculated on the basis of the downtime of a specific failure, normalised over the number of components and the total hours.

For the calculation of the costs due to downtime, it is important to consider the lost income as a result of reduced energy production. This can be related to feed-in tariffs (FiTs), to the missing income from power purchasing agreements (PPA), or to the missing savings generated by PV plants installed on roofs/facades which are linked, for example, to the retail cost of electricity. Specifically, the downtime costs are calculated considering the time to detection of the failure, the time leading to the repair/replacement, and the time to fix the problem.

Costs related to fixing the failure

The costs related to fixing the failure derive from the sum of the costs of repair/replacement, detection, staff, transport and labour; the calculation is carried out for failures affecting various components. The overall sum of this type of cost is then equal to the cost of monitoring/detection and corrective maintenance. Preventive maintenance can be included as a detection cost, and its impact can be assessed using the methodology, as it effectively reduces the time to detection.

As a final step, the calculation of the CPN is then given by the sum of the costs due to downtime and the costs due to fixing the failure.

Results from the CPN analysis

The division into the various categories allows the calculation of CPNs for very

Figure 2. Database used in the Solar Bankability project

	Total no. plants	Total power [kWp]	Average no. years
Total	772	441676	2.7
Components	**No. tickets**	**No. cases**	**No. components**
Modules	473	678801	2058721
Inverters	476	2548	11967
Mounting structures	420	15809	43057
Connection & Distribution boxes	221	12343	20372
Cabling	614	367724	238546
Transformer station & MV/HV	53	220	558
Total	2257	1077445	2373222

Module failure	Failure share
Soiling	23.4%
Shading	16.8%
EVA discoloration	11.6%
Glass breakage	6.5%
PID	5.0%

Table 1. Share of specific technical risks over all failures: PV modules.

Inverter failure	Failure share
Fan failure and overheating	21.8%
Fault due to grounding issues	4.9%
Inverter firmware issue	3.8%
Burned supply cable and/or socket	2.2%
Polluted air filter	3.3%
Inverter pollution	1.5%

Table 2. Share of specific technical risks over all failures: inverters.

generic cases or for plant-specific scenarios, depending on the type of input data available (statistical analysis of failures or specific plant-related figures). The parameters used for the calculation of the CPN can also be specified as country dependent by applying country-based coefficients to take into account different FiT schemes, retail cost of electricity, annual insolation, cost of labour, etc.

CPNs are given in €/kWp or in €/kWp/year and can thus directly give an estimation of the economic impact of a technical risk. The methodology also considers the year of installation, the year of failure and the nominal power in order to be able to run analyses for different market segments and to evaluate the distribution of failure probability once the available data in the database reaches statistical relevance to this type of data granularity. The methodology also considers other statistical parameters, such 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 entire PV plant portfolio.

The database used for the calculation of the CPN for various technical risks includes so far 772 plants, for a total of around 450MWp and with an average operating period of around three years (Fig. 2). The number of components totals 2.4 million (including 2 million modules and 12,000 inverters).

If all market segments are considered, the most important failures (in terms of occurrence) for PV modules are: soiling, shading, EVA discoloration, glass breakage and potential-induced degradation (PID) (Table 1). In the case of inverters, the failures are: fan failure and overheating, fault due to grounding issues, inverter firmware issues, burned supply cable and/or socket, polluted air filter and inverter pollution (Table 2). Overall, the occurrence per year for affected components is around 12% for PV modules (including shading and soiling) and 8% for PV inverters.

To be able to translate the information about failure occurrence into a CPN, two scenarios were established: 1) a scenario in which the failure was never detected over a one-year period; and 2) a scenario in which the failure, once identified, was fixed within a month. The sum of the CPNs calculated for the two scenarios was defined as the base-case scenario for the analysis. In terms of CPN, the most significant failures for PV modules turn out to be glass breakage followed by PID, snail tracks, defective backsheet, delamination, and hotspots, equating to total costs of €60/kW/year. The analysis also shows that it is important to consider the evolution of the impact of failures on the performance loss over the course of several years. The contribution to the overall CPN of the first scenario (no detection) alone can in fact double or triple over the years (Fig. 3).

It is important to highlight that a lower CPN value for the 'never detected' scenario (solely due to downtime) does not mean that this strategy is more cost-effective than fixing the problem. Power losses will increase over the years, and the existing or impending failure could also pose safety risks!

Another important aspect is represented by the spread of the failures over the PV plant portfolio included in the database. If only the PV plants where the failures occur are considered, the results are remarkable: the overall occurrence might be low but when the failure occurs it can have an important economic impact on the affected plants. The costs relating to theft of modules can then increase from €0.08/kW/year when considered over the whole portfolio, to €34/kWp/year for the affected plants; similarly, the PID-related costs can increase from €6 to €114/kWp/year.

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Mitigation measures

Once the base-case scenario has been defined and the overall CPN calculated, the next step is to assess the effectiveness of the combination of various mitigation measures in terms of CPN reduction, and to understand who bears the risks and who ultimately bears the costs of PV component failures.

The most significant mitigation

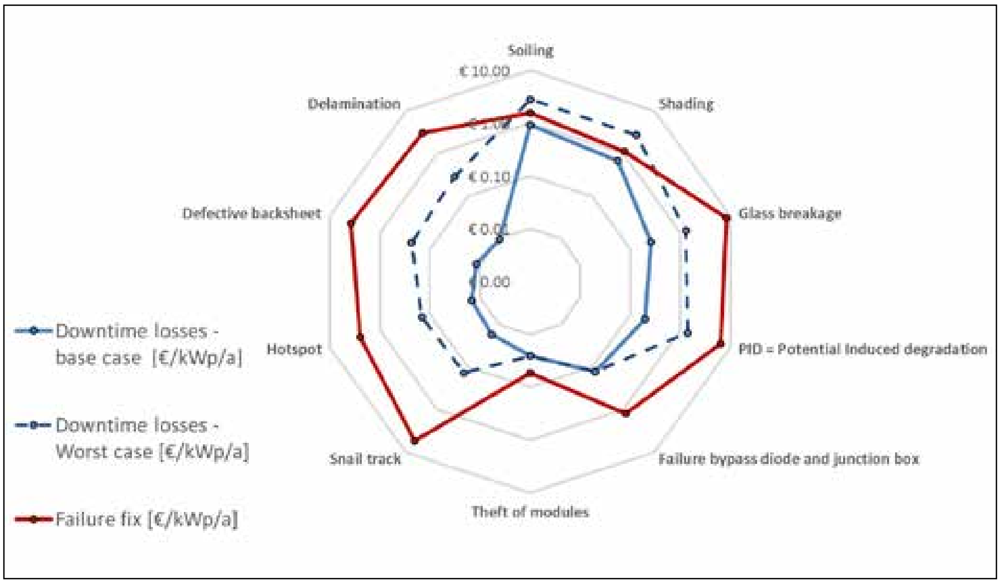

Figure 3. CPN values resulting from the statistical analysis for the top ten technical risks for PV modules. The red line represents the cost/kWp/year of fixing the specific failure. The dashed and solid blue lines represent the cost/kWp/year due to downtime in the worst and base case scenarios respectively

measures are related to component testing, design review and construction monitoring, qualification of EPC contractors, the use of basic or advanced monitoring systems, the use of visual or advanced inspection, and spare part management. Each of these mitigation measures has an associated cost and impact. Starting from a value of around €100/kWp/year as the overall CPN when all components are considered over the entire PV portfolio included in the database, the best combination of mitigation measures can reduce this value to under €20/kWp/year. This value can now be compared with the current costs of O&M in Germany, which is around €8/kWp/year.

Future development and other aspects

In the coming years, as the availability of measured data exponentially increases, it will be important to build large databases along with potentially a uniform method for increasing the confidence level of the statistical analysis and thereby reducing the perceived risks by investors. With the availability of these large databases, the necessary information (minimum requirement) can be filtered out in order to perform tailored analyses in a uniform way, i.e. using the same granularity, data and formulas. The Solar Bankability methodology based on CPNs attempts to provide such a benchmark.

This particular methodology can only be applied to the failures that have a direct economic impact on the business plan, in terms either of the reduced income due to downtime or of the costs associated with repair or replacement. The technical risks included in the risk matrix which cannot be described using a CPN are very important and have to be taken into account, as they might have an impact on the CPN value of other component failures. For example, the technical risks related to the monitoring system, spare parts, norms and documentation, insurance reaction time, O&M contract, video surveillance and detailed field inspection (IR, EL, etc.), just to name a few, can reduce or increase the time to detection or the time to repair/replacement and might have an impact on the detection costs. To other technical risks, for example during planning, it is possible to assign an uncertainty (e.g. irradiance variability, soiling, shading, etc.) in terms of impact on the initial yield assessment. These risks can have an effect on the overall uncertainty during the initial energy yield calculation and assessment. A reduced uncertainty can in fact correspond to a higher level of energy yield for a given exceedance probability value (given as P50/P75/P90/P99/etc.) and thus directly impact the business model. Typical values of the overall uncertainty for the initial energy yield lie in the range 5–10%. In the case of the scenario in which non-optimised models are used in the calculation, and the overall solar resource assessment is characterised by high uncertainty, this value can be as much as 15% or even higher. The reduction in the energy yield at P90 can be greater than 22% when the worst-case scenario is compared with the base-case scenario.

From all these considerations, the general recommendations laid out in Table 3 can be formulated in terms of PV plant design, commissioning and O&M (these recommendations were defined in the project report "Review and gap analyses of technical assumptions in PV electricity cost" [7]).

Risk	Phase/field	Identified critical technical gaps
Year 0	Procurement/product selection and testing	EPC technical specifications that are insufficient to ensure that selected components are suitable for use in the specific PV plant environment of application.
		Inadequate component testing to check for product manufacturing deviations.
		Absence of adequate independent product delivery acceptance test and criteria.
	Planning/lifetime energy yield estimation	Effect of long-term trends in the solar resource is not fully accounted for.
		Exceedance probabilities (e.g. P90) are often calculated for risk assessment under the assumption of a normal distribution for all elements contributing to the overall uncertainty.
		Incorrect assumption of degradation rate and behaviour over time in the yield estimation.
		Incorrect availability assumption in calculating the initial yield for the project investment financial model (vs. O&M plant availability guarantee).
	Transportation	Absence of standardised transportation and handling protocols.
	Installation/construction	Inadequate quality procedures in component unpacking and handling by workers during construction.
		Missing intermediate construction monitoring.
	Installation/provisional and final acceptance	Inadequate protocol or equipment for plant acceptance visual inspection.
		Missing short-term performance (e.g. performance ratio – PR) check at provisional acceptance test, including proper correction for temperature and other losses.
		Missing final performance check and guaranteed performance.
		Incorrect or missing specification for collecting data for PR or availability evaluations: incorrect measurement sensor specification, or incorrect irradiance threshold to define the time window of PV operation for PR/availability calculation.
Risks during operation	Operation	Selected monitoring system is not capable of advanced fault detection and identification.
		Inadequate or missing devices for visual inspection to catch invisible defects/faults.
		Missing guaranteed key performance indicators (PR, availability or energy yield).
		Incorrect or missing specification for collecting data for PR or availability evaluations: incorrect measurement sensor specification, or incorrect irradiance threshold to define the time window of PV operation for PR/availability calculation.
	Maintenance	Missing or inadequate maintenance of the monitoring system.
		Module cleaning absent, or cleaning too infrequent.

Table 3. General recommendations.

References

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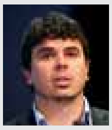

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