Failure Risk Analysis of Photovoltaic Systems Based on Literature Review

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Abstract

In the context of the quick expansion of photovoltaic (PV) capacity, monitoring and correcting system failures are crucial to maximize performance. To reduce these sources of underperformance, a well-rounded knowledge of failures becomes essential. This paper highlights the most critical photovoltaic failure modes using the Failure Mode Effect and Criticality Analysis (FMECA) methodology. A review of the current knowledge of failures in PV systems, their detection methods, and their relationships is first performed. Then, this study ranks the failures based on their Risk Priority Number (RPN) deducted from their severity, occurrence, and detection score. The novelty of the approach relies on the adaptation and combination of assigned scores from different literature sources. The failure risk analysis especially outlines that critical failure modes occur in any component of the PV installation and every single part of the system needs special attention to manage underperformances.

Keywords: PV system, Failure risk analysis, FMECA

1. Introduction

Acknowledging the devastating consequences of climate change such as the dramatic increase in temperature, the rising water levels, and the intensification of extreme meteorological events (Pachauri, 2014) strong incentives at the European level have led to a massive deployment of renewable energies to mitigate energy-related environmental impact. The International Renewable Energy Agency forecasts a striking expansion of the photovoltaic capacity to 14 TW in 2050 in the 1.5°C scenario (International Renewable Energy Agency, 2021) which would correspond to 15 times more than in 2020 (Masson and Kaizuka, 2021). At the dawn of an energy paradigm shift, developing a PV performance guarantee becomes crucial to meet the objectives of climate plans and European directives such as the Energy Performance of Building Directive, EPBD (European Union, 2018).

In recent decades, the photovoltaic (PV) market has grown rapidly but the operation of PV installations continues to face significant challenges. With a 23% increase in capacity in 2020 (Masson and Kaizuka, 2021), the global photovoltaic market is experiencing unprecedented growth. On the other hand, substantial production losses subsist and around 5% of the total theoretical production could be recoverable (Leloux et al., 2011; Raycatch, 2021) if adequate operation and maintenance are ensured. Therefore, the investigation and alleviation of underperformance sources become essential to optimize the production of solar installations.

Mitigating failures reduce the Levelized Cost of Energy (LCOE) by increasing the operating lifetime of PV systems (Aghaei et al., 2022) and making power plants financially more viable. As mentioned by Catelani (Catelani et al., 2013), failures and their maintenance are rarely taken into account in the initial phases of PV projects. However, reducing underperformance effects would significantly improve the overall business cases of PV plants.

This study aims to map PV failures and rank them based on risk. Inspired by (Catelani et al., 2013; Colli, 2015; Collins et al., 2009; Milic et al., 2018; Rajput et al., 2019; Rongbin et al., 2015; Villarini et al., 2017), the failures Risk Priority Numbers (RPN) are computed from its performance reduction, occurrence, and detection ability as in a Failure Modes, Effects and Criticality Analysis (FMECA) process. A sampling method taking scores according to several data sources is then established to alleviate knowledge bias and take full benefit of the available information. Finally, the most critical failures are short-listed and described extensively.

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2. State of the art on photovoltaic failure modes and detection methods

In this section, the failure scope is defined to further list failure modes. Then, failure losses are dissociated from normal photovoltaic losses, and detection methods are collected to identify and avoid significant power losses. Finally, the inhomogeneous relationship between failures and detection methods is highlighted.

1. Failure Scope

This study focuses on failure modes that directly impact system performance on the following components: PV array, cables, and inverter. Even though PV systems are defined by their integration, even sometimes on buildings, failure modes specific to these features are accounted for as changes to PV array performance. This choice keeps the failure list generic and exploitable to any photovoltaic installation. Similarly, auxiliary systems are excluded from consideration as in most cases they do not affect the production generation itself (Bun, 2011; Villarini et al., 2017), and the failure of protection systems may be assumed negligible (Miquel et al., 2018) except for fuse faults that can be included in the “Combiner box failure” and “Inverter defect” category.

Each of those system sub-components is subject to failures along its life and might impact the system performance at different levels.

2. Power photovoltaic underperformances: expected losses vs failure

All photovoltaic systems are affected by underperformance which results from expected losses. Those can be estimated at the design phase and should not be considered as failures. These can be divided into six categories (Bun, 2011):

- **Module temperature losses**: the efficiency of PV cells varies with temperature, and temperature coefficients are commonly specified on manufacturer datasheets.
- **Non-optimal irradiance collection:** effects including spectral response (Lindsay et al., 2020) and shading.
- **Non-optimal array production extraction:** Mismatches between PV modules and strings due to the slight differences in electrical characteristics cause some inevitable losses.
- **Natural system aging:** materials and components naturally degrade over time and induce a degradation rate in the order of percentages per year. Regarding the PV modules themselves, the manufacturer warranty usually conforms with a 20 % reduction in 25 years.
- **Joule losses in the cables:** The intrinsic resistive nature of the cables leads to power being cleared up into joule losses.
- **Inverter losses:** The conversion from DC to AC in the inverter unavoidably involves some power losses.

All losses that come in addition to the previous ones are then considered as failure losses. For instance, unexpected shading or module under-ventilation leads to additional losses compared to the estimation and falls in the failure category.

Several projects (Aghaei et al., 2022; Bansal et al., 2021; Bun, 2011; Colli, 2015; Köntges et al., 2017, 2014; Miquel et al., 2018; Rongbin et al., 2015) aim at listing and describing failures. For the Agence Qualité Construction (AQC), which lists 37 faults (Miquel et al., 2018), a failure is characterized by its phase of appearance (design, installation, operation) and its target component (module/field, inverter, system, connectors, protection system, sensor). The frequency (low/high) and the risk (electric shock, fire) must also be considered when it comes to prioritizing failures. The causes of failures are very diverse and complex to anticipate from environmental stress, poor quality in commissioning, unexpected events to accelerated aging.

A total of 26 failure modes was identified and Table 1 collects the failures per system component. The failure modes have been initially collected from the AQC report (Miquel et al., 2018) and, then, rearranged to find intersections with the failure lists from IEA (Herz et al., 2022) and Long Bun (Bun, 2011) in order to complete information and counter-check the relevance of the given occurrence and performance scores.

Table 1: PV failure modes

Failure mode	Component	Failure mode	Component
Insulation failure and ground connection defect	**System**	Corrosion	**Module/Array**
Inverter defect	**Inverter**	Delamination	**Module/Array**
Inverter overheating	**Inverter**	Encapsulant degradation	**Module/Array**
Unexpected inverter voltage input	**Inverter**	Frame/Mounting structure defect	**Module/Array**
Combiner box defect	**Wiring**	Glass breakage	**Module/Array**
Connector defect	**Wiring**	Hot spot	**Module/Array**
DC cable defect	**Wiring**	Junction box defect	**Module/Array**
Anti-reflective coating degradation	**Module/Array**	Light Induced Degradation (LID) and Light and elevated Temperature Induced Degradation (LETID)	**Module/Array**
Backsheet degradation	**Module/Array**	Module under-ventilation	**Module/Array**
Burn marks	**Module/Array**	Not conform power rating	**Module/Array**
Bypass diode defect	**Module/Array**	Potential Induced Degradation (PID)	**Module/Array**
Cell cracks	**Module/Array**	Shading	**Module/Array**
Cell interconnection defect	**Module/Array**	Soiling	**Module/Array**

Most of the failures are related to “Module/Array” because of its sophisticated photoelectric phenomenon. Then, the wiring category is comprised of three failure modes accounting for each of its elements. Inverters are at the crossroads of important PV array segments which might induce significant performance losses in case of failures. Finally, “Insulation failure and ground connection defect” can appear in any location of the installation.

Active research is undertaken to avoid the apparition of failures and the first step towards risk mitigations is the implementation of detection methods.

3. Detection methods

A detection method is defined as follows according to the AQC report (Miquel et al., 2019): “Method that is manual or automated, enabling the detection of one or more dysfunctions of a system, and alerting the user”. In Table 2, the detection method list has been inspired by the AQC report.

Table 2: PV detection method characteristics

Category	Detection method	Maturity	Cost	Accessibility
Electrical test	Insulation test	Mature	€€	On-site
Electrical test	Isc measurement	Mature	€€	On-site
Electrical test	IV tracer	First prototypes/Mature	€€	On-site
Electrical test	Signal transmission method	Mature	€/€€	On-site
Electrical test	Voc measurement	Mature	€€	On-site
Imaging method	Electroluminescence	Mature	€€/€€€	On-site
Imaging method	Infrared thermography	Mature	€€	On-site
Imaging method	UV fluorescence imaging	First prototypes/Mature	€€	On-site
Monitoring	Inverter monitoring	Mature	€	Remote
Monitoring	IV monitoring	First prototypes	€€	Remote

Monitoring	Monthly net-metering	Mature	€	Remote
Monitoring	Platform monitoring	Mature	€€	Remote
Visual inspection	Visual inspection	Mature	€/€€	On-site

The “Visual inspection” category depicts the simple observation, ideally, of a specialist on the installation sub-components. The “Imaging method” covers all methods processing images of PV modules under stressed or normal operating conditions. The “Electrical tests” are all measurements that can be performed during a maintenance visit where measured values are compared to theoretical ones. Finally, “Monitoring” methods track the performance of the system from a remote location. Each method detects a specific spectrum of failures according to its methodology and its area of operation (Aghaei et al., 2022; Herz et al., 2022; Köntges et al., 2014).

4. Failure mode - detection method correspondence

A detection method can notice underperformances from several failures and a failure can usually be noticed from several detection methods. More specifically, Figure 1 displays the relationships between all failures and detection methods of the datasets previously developed.

A disparity in the associations between the 26 failure modes (red squares) and 13 detection methods (blue dots) is brought to light. There are failures such as “Shading” or “Cell interconnection defect” that can be detected with up to 9 detection methods but “Anti-reflective coating degradation” can only be discovered with “Visual inspection”. On the other hand, some detection methods like “Visual inspection” have a wide spectrum of detection with 21 detectable failures while some others such as “Isc measurement” detect only 4 failures.

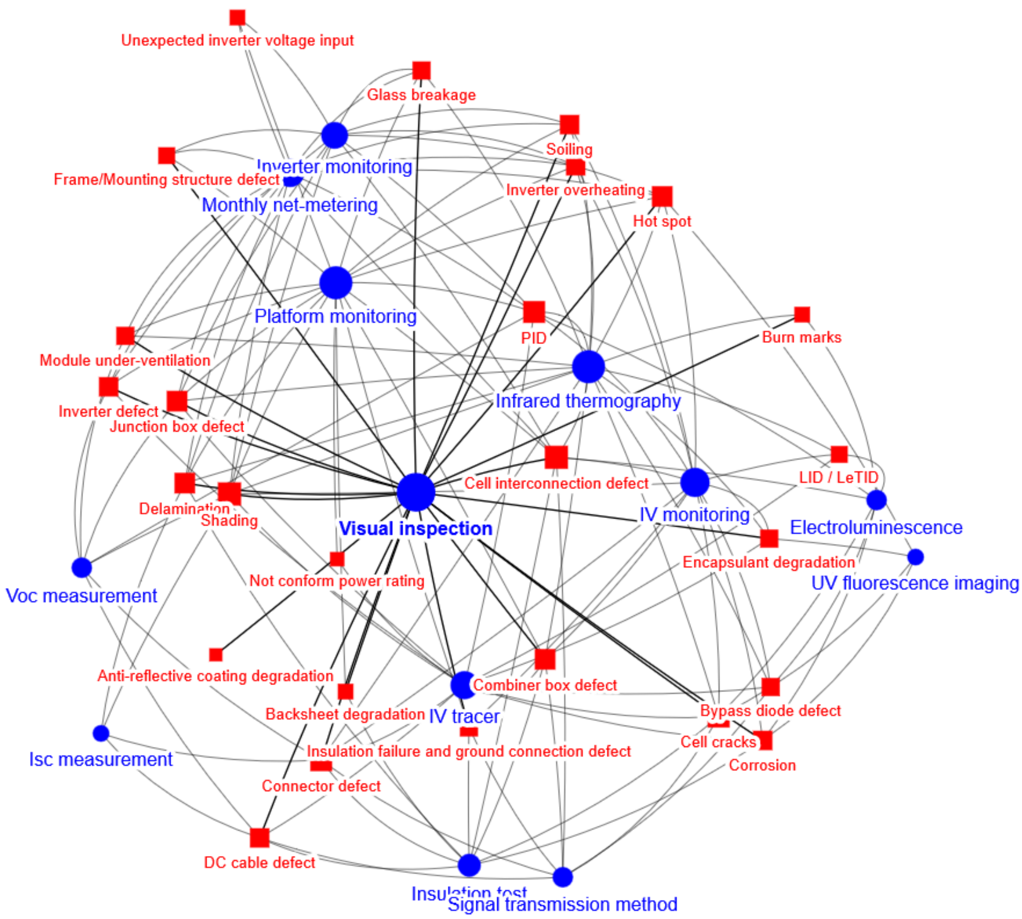

Figure 1: Network maps of failure and detection method

Figure 1 shows the relationship between "detection methods" and failure modes only with the "detection" signification that actually differs from "identification". A "detection method" notices underperformances without being able to associate them with a specific failure. It is usually the case with monitoring methods where a drop in performance can be easily observed, accounting for a failure although identifying the exact cause of the failure might require some more developed techniques. On the other hand, an "identification method" can locate exactly the failure and characterize it fully in detail for further correction purposes. In the rest of the paper, the "identification" signification is retained since those methods are mandatory to identify the exact root of the failure and suggest a correction. Each failure will be associated with at least one "identification" method.

3. Methodology to rank failures via FMECA based on different data sources

This paper introduces a new way to adapt score scales from different literature data sources. Compared to other PV FMECAs (Catelani et al., 2013; Colli, 2015; Collins et al., 2009; Milic et al., 2018; Rajput et al., 2019; Rongbin et al., 2015; Villarini et al., 2017), the detection score also takes into account the maturity of the associated identification method. Then, a new methodology to combine different literature sources through a random score generation is investigated.

In this section, the Failure Modes, Effects, and Criticality Analysis (FMECA) is first introduced and the score-sampling methodology for each failure is then explained.

1. Failure Modes, Effects, and Criticality Analysis

Failure Modes and Effects Analysis (FMEA) is based on expert opinions and would coincide during the early phase of strategy implementation (Herz et al., 2022) such as failure mitigation. FMEA is particularly suited since operational data is limited due to the relatively recent uprise of the photovoltaic sector, the lack of systematic failure reporting (Moser et al., 2017), and the large diversity of technologies and climates.

Failure modes may be prioritized according to their importance and this process is referred to as Failure Modes, Effects, and Criticality Analysis (FMECA). As defined by Milic (Milic et al., 2018) in Figure 2, the FMECA starts with defining the scope of the PV system, identifying the failures modes, characterizing its causes as well as effects, and assigning severity/occurrence/detection scores to calculate the Risk Priority Number (RPN) in order to diagnose corrective measures.

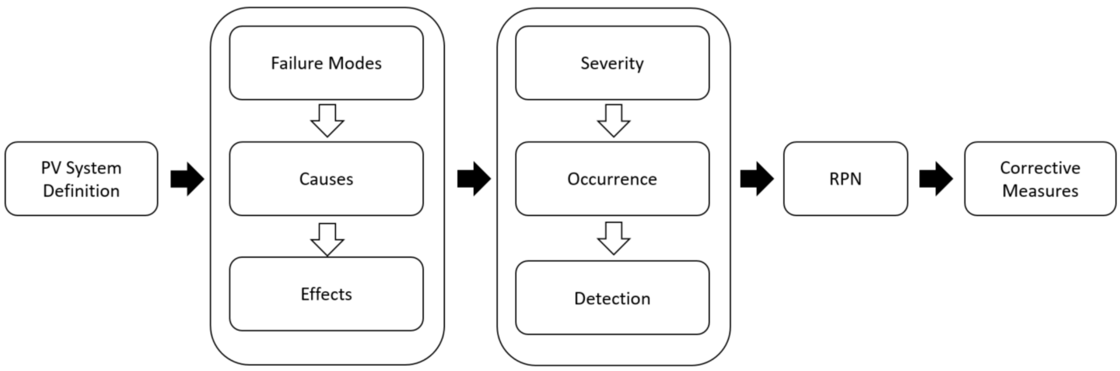

Figure 2: FMECA flow chart (Milic et al., 2018)

The Risk Priority Number (RPN) in Equation 1 reveals the criticality of each failure and is calculated with the product of three decision criteria: severity, occurrence, and detection. The severity (S) is an estimate of how strongly the failure will affect the system (Milic et al., 2018). The effect on the performance raised by that failure mode is specific to each site. The occurrence (O) represents the likelihood that the failure mode might occur and lead to the indicated severity of the consequence. It may be defined according to the computed frequency of each failure mode. Detection (D) approximates the ability to identify and prevent the failure before the system is impacted.

$$RPN = S * O * D \quad \text{(eq. 1)}$$

Table 3: Severity, Occurrence, and Detection scoring systems partially from (Milic et al., 2018)

Score	Severity (S)	Occurrence (O)	Detection (D)
1	**Insignificant**, no effect on the performance	**Remote**, unlikely	**Undemanding**, mature identification method with low costs
2	**Low**, slight impact on the system performance	**Low**, rare apparition	**Straightforward,** detection with low requirements
3	**Moderate**, noticeable degradation of parts of the system performance	**Moderate**, occasional downtime	**Intermediate**, identification method with moderate cost and maturity
4	**High**, high degradation, non-functionality/loss of performance	**Hig**h, frequent apparition	**Complex detection** with high requirements
5	**Hazardous**, system interruption or severe loss of performance	**Very High**, almost certain apparition	**Highly complex**, not mature, and high costs

The performance and occurrence scores from the AQC (Miquel et al., 2018), IEA (Herz et al., 2022), and (Bun, 2011) have been adapted to fit the presented scoring system in Table 3. The AQC performance scoring includes five possible categories comparable to the chosen ones and then, the scores have been moved up by 1 additional point from the AQC's 0-4 scale to fits the 1-5 given performance scoring range. Regarding the AQC's occurrence scores, they have been updated from "+"," ++"," +++" to 1,3,5 respectively to fill the whole score range. Similarly, L. Bun's occurrence and severity scores got revised from 1,2,3 to 1,3,5.

In the aim of following the same systematic method, the qualitative costs and maturity levels given from another AQC report (Miquel et al., 2019) are used to compute scores for all identification methods. The qualitative costs given by the AQC are translated from (€, €€, €€€) to (1,2,3). Then some points are added depending on the maturity level: 2 points are added if the maturity is at "First prototypes", 1 point is added if the identification method is in between "First prototypes" and no point is added if the method is "Mature". The detection score D of each failure is then set by the lowest score of its associated "identification" methods.

$$D = M + C \quad \text{(eq. 2)}$$

Where:

- **D**: detection score of the identification method, between 1 and 5
- **M:** Market maturity of the method, between 0 and 2
- **C:** Identification method intervention cost, between 1 and 3

Regarding the adopted identification method for each failure, the correspondence with failure has been inspired and completed thanks to the AQC (Miquel et al., 2019) and IEA report (Herz et al., 2022).

In some cases, multiple severity and occurrence scores can be assigned to a failure from Table 1. The IEA report generally lists several score "options" out of five for the same failure mode. Also, several sub-"associated" failure modes from a data source can sometimes match only one failure from Table 1 and would correspond to variants or alternatives. All those failures were retained to randomly generate scores in the sampling methodology presented later.

All severity, occurrence, and detection scores are collected and a sample of five failures is shown in Table 4. If there are several sub-"associated" failures from a data source to a failure "k" from Table 1, the scores are listed with a comma separator. In the case a data source gives a range of different score "options" for the same sub-"associated" failure, those are all informed with a semicolon separator. When the data source does not contain any info about severity or occurrence, no score is shown.

Table 4: Five PV failures with performance, occurrence, and detection scores

Failure mode	Severity (S)			Occurrence (O)		Associated identification methods	Detection score (D)
	AQC (Miquel et al., 2018)	IEA (Herz et al., 2022)	(Bun, 2011)	AQC (Miquel et al., 2018)	(Bun, 2011)		
Inverter defect	5	1;2;3;4;5	[5, 5, 5, 5, 5, 3, 1, 1, 1, 1]	3	3	Visual inspection	1.5
Inverter overheating	5	[3;4;5, 1;2;3;4;5]	[5, 5]	3	3	Platform monitoring	2.0
Unexpected inverter voltage input	2		[5, 5, 5, 3, 3, 3]	3	5	Platform monitoring	2.0
Anti-reflective coating degradation	1		3	1	1	Visual inspection	1.5
Backsheet degradation	4	[1;2;3;4;5, 1]		1	1	Visual inspection	1.5

2. Random FMECA score-sampling

To fully take advantage of the available information from the diverse data sources, a methodology has been developed to randomly generate scenarios. Each scenario especially represents a point of view on the failure risk at three different levels: data source, sub-“associated” failures, and score options. Since there is not any valuable argument to trust more any data source, any sub-“associated” failure, or score options, an even distribution is applied to pick each of the levels starting from the data source, through the sub-“associated” failures to the score options.

For each scenario of each failure, the severity and occurrence scores are randomly picked separately with the following steps:

i. The data source is randomly picked with uniform weights.

ii. Since, sometimes, several sub-“associated” failures from a data source are associated with only one failure from the list from Table 1. An “associated” failure is uniformly randomly picked.

iii. If the IEA source has been picked, the final score is randomly picked among the failure score options from IEA.

The example below illustrates the random pick of the severity score for the delamination case.

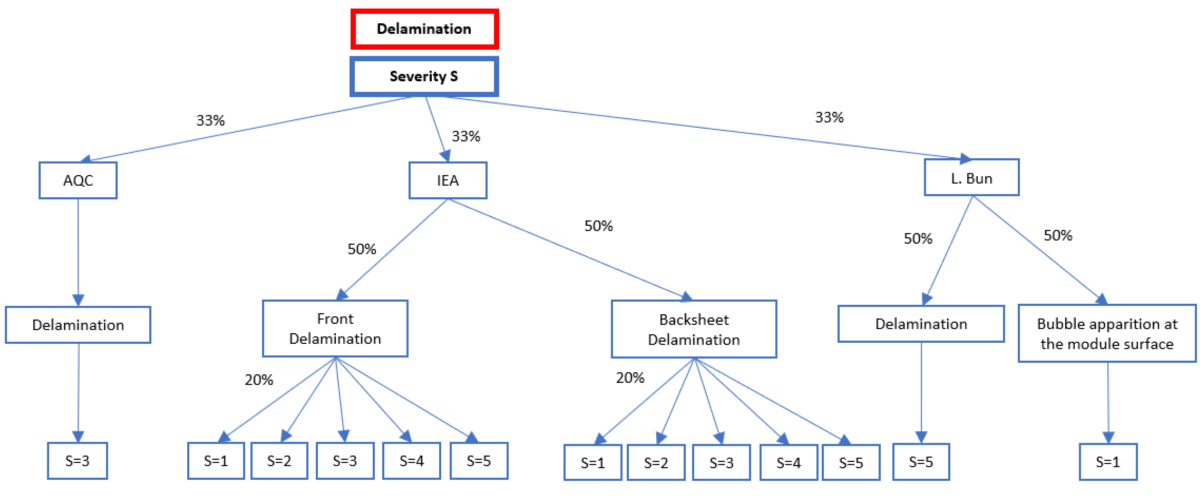

Figure 3: Severity random sampling, "delamination" case

A total of N_s = 5000 scenarios are further generated with the severity and occurrence score picked distinctly for each scenario. The severity, occurrence, and detection scores are then combined to get the RPN score for each scenario "n" as in Equation 3 which enables to create a RPN distribution for each failure "k".

$$RPN_{k,n} = S_{k,n} * O_{k,n} * D_k \quad \text{(eq. 3)}$$

In order to compare failures to each other from their RPN distribution, a final score indicator $RPN_{RMS,k}$ for each failure k, is defined in Equation 4. The Root Mean Square (RMS) method penalizes more significantly the failures containing $RPN_{k,n}$ with higher scores in their distributions.

$$RPN_{RMS,k} = \sqrt{\frac{1}{N_s} \sum_{n=1}^{N_s} RPN_{k,n}{}^2} \quad \text{(eq. 4)}$$

RMS has the advantage to grasp a whole distribution through one indicator. It assigns more weight to the highest scores and, ineluctably, is sensitive to any outlier. The regular mean of the distribution could have been instead applied but its uniform weights would not promote critical failures with distribution with a fat tail risk. The RMS indicator is thereafter applied to rank and shortlist the most critical failures.

4. Results of the FMECA applied to photovoltaic failures

Sample generation has been performed according to the presented methodology and the first noteworthy observations come from the Severity (S) and Occurrence (O) scores. In Figure 4, the S and O means have been collected for all failures.

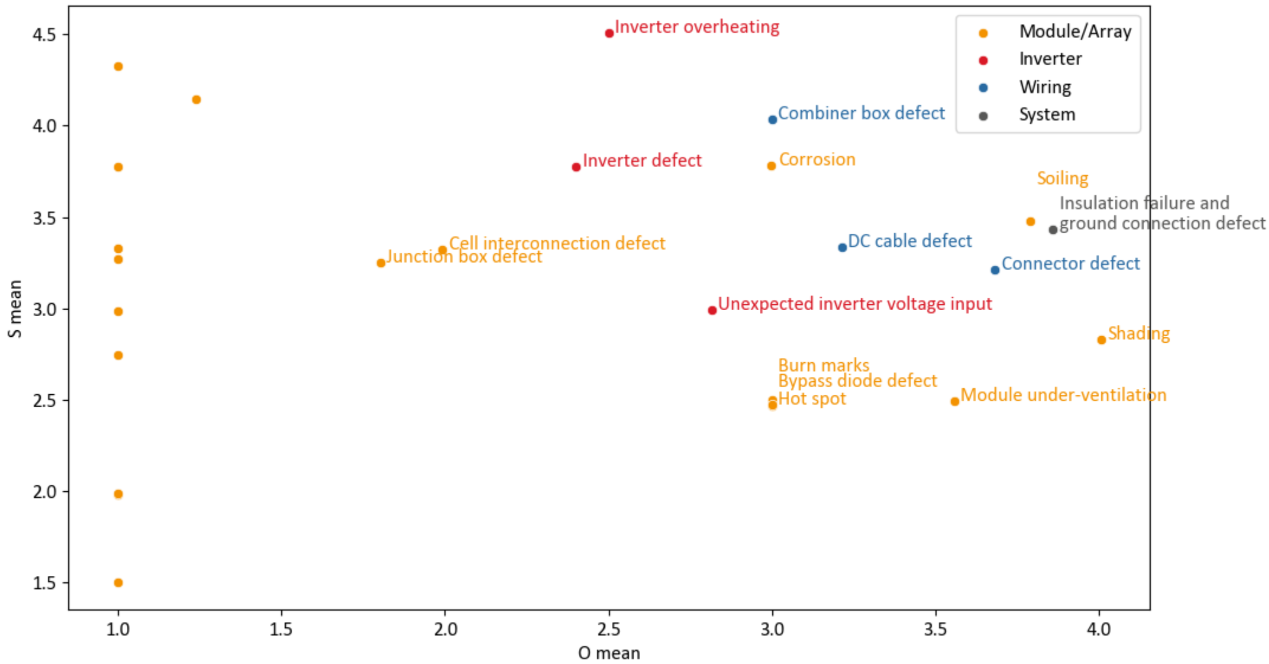

Figure 4: Severity (S) and Occurrence (O) mean scores from the sample generation

The focal position of the inverter conveys the consequences of any failure mode on a large section of the PV array and includes the most dangerous financial repercussions according to Tjengradwira (Tjengdrawira et al., 2017). Legitimately getting severity scores over 3 and coupled with steady occurrence scores, the "Inverter" component needs to actively be supervised to mitigate risks.

Similarly crucial to the architecture, the "Wiring" category bundles high severity and occurrence results. "Insulation failures and ground connection defect" has also the potential to lead to serious consequences. The wiring and insulation failures have the highest safety-risk scores in (Miquel et al., 2018) and, from a safety and performance perspectives, are definitely to prioritize

The number of failures related to “Module/array”, 19, does not necessarily reflect more severe consequences compared to other components but highlights rather the complexity of the PV technology. 12 out of 19 of the failures obtain a mean occurrence score lower than 2 and are rather negligible in terms of technical risks. On the other hand, still some failures such as “Corrosion”, “Soiling” and “Shading” remain with very high scores and need special care during maintenance visits.

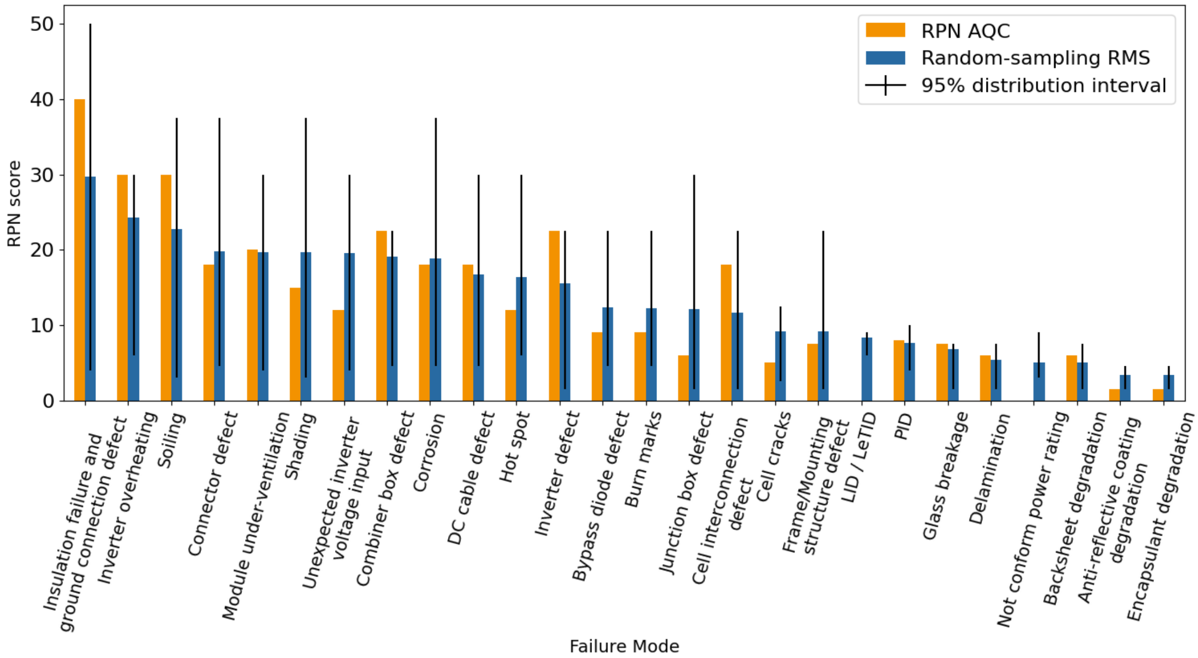

Figure 5: RPN scores from AQC and sampling RMS with 95% confidence interval

Appending the detection score in the random sampling, RPN scores have been calculated in Figure 5. The AQC dataset in orange is introduced as a benchmark. The RPN_{RMS} calculated for each failure with Equation 4 from the sampling distribution associated with the 95% confidence interval is displayed in blue and the failures are ordered according to their RPN_{RMS} score.

The variations in AQC and RMS scores globally follow each other although the latter has less amplitude since it gets flattened with the inclusion of different score sources. The RPN score distribution for each failure stays wide because the IEA report usually suggests large score intervals. Indeed, failure modes can impact the performance at different degrees such as soiling of which impact is a function of its homogeneity (Maghami et al., 2016).

Some of the failures with a low RPN score need special consideration. The “LID / LeTID” and “Not conform power rating” failure modes that were not considered in the AQC dataset stay at the low end of the ranking. For LID, this low score is particularly valid for all technologies except for amorphous silicon where the module power degradation can reach 10 – 30 % according to Gostein (Gostein and Dun, 2011). “PID” is also a well-identified failure mode with significant impact (Dhimish and Tyrrell, 2022; Luo et al., 2017) reaching sometimes 40 % of losses on real installations (Libby, 2014) but its low occurrence keeps the failure away from the top 15.

Regarding the changes from AQC to the RMS method, Table 5 highlights the respective scores and rankings.

Table 5: PV failure ranking

Failure mode	Score RPN_AQC	Ranking AQC	Score RPN_RMS	Ranking RMS
Insulation failure and ground connection defect	**40**	**1**	**29,8**	**1**
Inverter overheating	**30**	**2**	**24,6**	**2**
Soiling	**30**	**2**	**22,6**	**3**

Unexpected inverter voltage input	**12**	**12**	**19,9**	**4**
Module under-ventilation	**20**	**6**	**19,8**	**5**
Connector defect	**18**	**7**	**19,7**	**6**
Shading	**15**	**11**	**19,4**	**7**
Combiner box defect	**22,5**	**4**	**19,1**	**8**
Corrosion	**18**	**7**	**18,9**	**9**
DC cable defect	**18**	**7**	**16,9**	**10**
Hot spot	**12**	**12**	**16,4**	**11**
Inverter defect	**22,5**	**4**	**15,8**	**12**
Bypass diode defect	**9**	**14**	**12,3**	**13**
Cell interconnection defect	**18**	**7**	**11,6**	**16**

The retained failure modes to further establish risk mitigation strategies are the RMS top 12. Those are nearly the same as the AQC top 12 and capture the agreement between all data sources on the failure batch to mitigate. The RMS score also steps down by 3,5 significant points between the 12th and the 13th place which separates the top 12 from the rest of the failures.

The failures contained in the Top 12 almost do not change between the AQC and RMS methods but the internal ranking gets modified. The "Cell Interconnection defect" is ejected from the top 12 to the 16th place in the RMS ranking due to the IEA report and L. Bun assigning more moderate severity and occurrence scores. In addition, the IEA report and L. Bun consider realistically more different failure alternatives for "Inverter defect" compared to AQC which has high scores, and the RMS makes it drop from the 4th to the 12th place in the final ranking. Finally, L. Bun has more severe scores for "Unexpected inverter voltage input" and significantly increases its ranking to 4th place.

The failures excluded from the top 12 are all categorized in the Module/Array category. It particularly underlines that any failure mode appearing in the inverter, wiring, or system component is considered critical. On the other hand, it also stresses that all components need attention when it comes to monitoring underperformances since they all contained at least one failure in the top 12.

5. Discussion

The outcome of the FMECA is confirmed by the literature. "Insulation failure and ground defect" is generally in the very top priorities (Catelani et al., 2013; Colli, 2015; Milic et al., 2018; Villarini et al., 2017). "Inverter defect" and "inverter overheating" are well advised, usually in the top 5 (Milic et al., 2018; Villarini et al., 2017). The "abnormal values of the voltage" (Villarini et al., 2017) and "improper function" (Milic et al., 2018) could reflect the "Unexpected inverter voltage input" and has a more versatile ranking but generally in the first half of the ranking. "Shading" and "Soiling", often combined, are frequently in the most critical failures (Basu, 2015; Catelani et al., 2013; Milic et al., 2018) and "Hot spot" in the top 10 (Catelani et al., 2013; Milic et al., 2018). "DC cable defect", "Connector defect" and "Corrosion" defect are never in the top priorities but maintain consistent scores (Basu, 2015; Milic et al., 2018; Villarini et al., 2017). "Module under-ventilation" has not been identified in the literature except by Basu (Basu, 2015) considering rooftop PV applications where its score is relatively low. However, when considering building-mounted installations, it might be relevant to account for it due to the complex integration. "Combiner box defect" has also not been found cited as such in the literature and represents one of the specificities of the analysis.

The presented study showcases the advantages of looking into a whole system with well-defined and counter-checked scores from different literature sources. Some studies have already looked into the FMECA but at the PV module level only (Catelani et al., 2013; Rajput et al., 2019; Rongbin et al., 2015). Some other studies analyze the whole system (Colli, 2015; Collins et al., 2009; Milic et al., 2018; Villarini et al., 2017) without analyzing the sensitivity of the RPN coefficients. Also, a thorough methodology is developed in this study to calculate detection scores as of the qualitative cost/maturity detection scores from the literature (Miquel et al., 2019). Finally, as mentioned by Villarini (Villarini et al., 2017) different climate conditions might affect the FMECA analysis, datasets, and using datasets from different sources would showcase a generic analysis covering most of the cases.

Moreover, some additional features might improve the presented methodology. As mentioned by (Villarini et al., 2017) the FMECA could eventually be updated with live data provided by reliability maintenance systems, and/or the occurrence score could be fed according to Mean Time Between Failure (MTBF) figures as examined in (Colli, 2015; Collins et al., 2009). A complete data-driven FMECA from (Filz et al., 2021) with a detection score based on forecasting model accuracies could eventually be extended to the severity and occurrence scores.

Additionally, FMECA scores could be improved to consider a higher level of detail. For instance, shading might lead to additional failures such as hot spot and bypass diode defects. Also, the concomitance of "Soiling" and "Potential Induced Degradation (PID)" could lead to more serious power reduction than when each phenomenon is considered separately (Luo et al., 2017). Modeling capabilities with empirical studies would additionally improve the understanding of performance impact such as the impact of PID (Annigoni et al., 2016) and LID as mentioned by (Woodhouse et al., 2020).

Having identified the most critical failures, the next steps would logically be to optimize the inspection methodology along the life of any PV installation in terms of frequency and content. Modeling more precisely the failure performance impact with their evolution in time and the interactions between them would give indications on how and when to perform diagnostics with which identification methods. From those simulations, a failure-correction decision support tool could also be envisioned to optimize the energetic, environmental, and financial value of the PV plant. All those suggestions together could come to fruition with a PV performance guarantee.

6. Conclusion

In this article, all photovoltaic failure modes are listed and associated with identification methods. The Failure Modes, Effects, and Criticality Analysis (FMECA) methodology assigns criticality scores to each failure based on its severity, occurrence, and detection ability. Based on the information from different data sources, score samples are randomly generated to take into account the different failure variants, eliminate knowledge bias, and obtain a generic overview. Those failures are finally ranked according to the Root Mean Square (RMS) of their respective score distribution.

Results demonstrate that all PV components from "Module/Array", "Wiring", "Inverter" to "System" contain critical failures in the top 12, and not any of those can be set aside to develop a strategy to decrease underperformances. In the first place, the "Insulation failure and ground defect" can occur in any part of the installation and has among the highest severity and occurrence scores because of its major safety and performance consequences. All failure modes collected in the inverter and wiring components are in the top 12 because of their central position in the PV architecture. Due to its technology complexity, "Module/Array" collects 19 failure modes while only 5 are in the top 12: "Hot spot", "Corrosion", "Shading", "Soiling" and "Module under-ventilation".

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