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A Reliability and Risk Assessment of Solar Photovoltaic Panels Using a Failure Mode and Effects Analysis Approach: A Case Study

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Abstract: Solar photovoltaic (PV) systems are becoming increasingly popular because they offer a sustainable and cost-effective solution for generating electricity. PV panels are the most critical components of PV systems as they convert solar energy into electric energy. Therefore, analyzing their reliability, risk, safety, and degradation is crucial to ensuring continuous electricity generation based on its intended capacity. This paper develops a failure mode and effects analysis (FMEA) methodology to assess the reliability of and risk associated with polycrystalline PV panels. Generalized severity, occurrence, and detection rating criteria are developed that can be used to analyze various solar PV systems as they are or with few modifications. The analysis is based on various data sources, including field failures, literature reviews, testing, and expert evaluations. Generalized severity, occurrence, and detection rating tables are developed and applied to solar panels to estimate the risk priority number (RPN) and the overall risk value. The results show that the encapsulant, junction box, and failures due to external events are the most critical components from both the RPN and risk perspectives. Delamination and soiling are the panels' most critical FMs, with RPN values of 224 and 140, respectively, contributing 16.2% to the total RPN. Further, moderately critical FMs are also identified which contribute 56.3% to the RPN. The encapsulant is the most critical component, with RPN and risk values of 940 (40.30%) and 145 (23.40%), respectively. This work crucially contributes to sustainable energy practices by enhancing the reliability of solar PV systems, thus reducing potential operational inefficiencies. Additionally, recommendations are provided to enhance system reliability and minimize the likelihood and severity of consequences.

Keywords: failure mode and effects analysis; solar photovoltaic panels; risk priority number; risk assessment; reliability analysis

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1. Introduction

Solar photovoltaic (PV) systems are considered some of the most reliable and sustainable power sources [1]. Solar energy is abundant and widely available for free globally [2]. Solar PV systems have a lower impact on the environment than other forms of energy generation since they do not emit greenhouse gases or pollutants that can harm the environment.

Moreover, these systems do not require water for their operation [1,3,4]. Solar PV systems have long lifespans (at least 25 years), significantly reducing the need for fossil fuels and other non-renewable resources [1,5]. Solar PV systems can be installed in many locations from remote areas without access to the grid to urban areas with a high electricity demand. These systems can be installed on rooftops, ground-mounted, or integrated into building facades, making them a flexible and versatile option for power generation [2,6]. Solar PV systems can provide significant economic benefits (including job creation, reducing electricity costs, and increasing energy independence). They can also provide a reliable source of electricity that is not subject to price volatility or supply interruptions [7].

A solar PV system's reliability is defined as the probability that the solar PV system can produce energy at its rated capacity for its intended lifespan when used under specified environmental conditions [8]. Reliability analyses of solar PV systems are crucial for ensuring their long-term performance, economic viability, safety, and effective maintenance planning [9]. A reliability analysis is essential in a successful solar PV system's product lifecycle, design, manufacturing, installation, and operation. A reliability analysis can estimate a solar PV system's expected performance over its lifetime. It can help determine whether the system performs optimally or if any potential issues may affect its long-term reliability. A solar PV system's reliability is directly linked to its economic viability. A reliability analysis can help identify potential sources of failure and determine the expected maintenance and repair costs over a system's lifetime. This information can be used to calculate the levelized cost of energy and determine the system's overall economic feasibility. A reliability analysis can help ensure that a solar PV system is safe to operate and that potential safety hazards associated with the system do not exist. A reliability analysis can help identify potential sources of failure in a solar PV system and determine an expected maintenance schedule and cost. This information can be used to plan for routine maintenance and to prepare for any unexpected repairs that may be needed.

Solar panels are the most crucial components in a solar PV system since they capture the sun's energy and convert it into electricity. Solar panels are made up of PV cells; these cells absorb sunlight and generate a flow of electrons, which can be harnessed to produce electrical power. Solar panels' efficiency and performance determine a solar PV system's effectiveness. A higher-efficiency panel will produce more power per unit area, meaning that fewer panels are needed to generate a given amount of electricity. This is important because solar PV systems are often installed on limited spaces, such as rooftops or small parcels of land. Additionally, solar panel quality and durability are essential to ensuring that the panels can withstand harsh weather conditions and maintain their performance over time. This is especially important in regions with extreme temperatures, heavy snowfall, or high winds.

The primary focus in solar PV development has been on significantly reducing the cost of solar panels and related components [7]. Many countries are developing and implementing policies and incentives, such as feed-in tariffs, tax credits, renewable energy mandates, and net metering programs, to encourage the adoption of solar energy. Growing awareness of climate change and the need to reduce greenhouse gas emissions has led to increased interest in solar energy [10]. Ongoing research and development efforts have led to continuous improvements in solar PV technology, including higher-efficiency solar panels, better energy storage solutions, and system design and integration innovations. As solar PV penetration increases, grid integration and management become more complex. Challenges such as intermittency, grid stability, and energy storage must be addressed to ensure solar PV systems' reliable and efficient operation [11].

A failure mode and effects analysis (FMEA) is a systematic approach to identifying and analyzing potential failure modes in a system, process, or product, assessing their potential impact on the system's performance and implementing preventative measures to mitigate the risk of these failures [12]. FMEAs are generally used in automotive, aerospace, and manufacturing industries to improve product reliability, reduce costs associated with product failures, and improve overall customer satisfaction [13–18]. When organizations perform FMEAs, they can identify potential failures before they occur, prioritize risks, and take proactive measures to reduce the likelihood and severity of failures, resulting in improved product quality and customer satisfaction. A failure mode, effects, and criticality analysis (FMECA) is sometimes used as an alternative approach to an FMEA. An FMECA is a more comprehensive and detailed version of an FMEA that also considers each potential failure mode's criticality [17]. It involves assessing the severity of each failure mode's impact and its likelihood of occurrence, allowing for the prioritization of mitigative actions. These criticality assessments often involve assigning numerical values to severity, occurrence, and detection ratings, enabling a more precise prioritization of actions. It helps organizations address the most critical failure modes first, reducing the overall risk more effectively.

This paper presents a reliability analysis of solar PV systems using the FMEA approach. A methodology for the FMEA of solar PV systems is developed and applied to analyze solar panels. The potential failure modes of solar panels are identified along with their effects on performance, reliability, safety, and degradation. The panels' failure modes are prioritized for their criticality (i.e., most, moderately, and least critical) based on their risk priority numbers (RPNs) [17,19]. A risk assessment is also carried out to categorize the failure modes. This paper provides recommendations for maintenance management, optimization, and design improvements.

This paper is divided into five sections. Section 1 provides the background and need for the reliability analysis of solar PV systems and panels. Section 2 presents the relevant literature on solar PV systems' reliability, applications of FMEAs in solar PV systems, and allied systems. Section 3 provides a novel FMEA-based methodology for conducting solar panel reliability analyses. Section 4 presents and discusses the results obtained from the FMEA of solar PV panels. Finally, Section 5 concludes this paper with key contributions, conclusions, and observations.

2. Literature Review

This section presents a survey of the reliability, availability, and maintainability (RAM) of solar PV systems and the data, tools, techniques, and approaches to be used for the analysis. This section is subdivided into six subsections: Section 2.1 presents the types of data to be used for a practical RAM analysis. Section 2.2 compares different tools and techniques for the RAM analysis and describes how to select a suitable approach for solar PV panels. Section 2.3 presents the historical development of the FMEA approach and the standards used for the analysis and the selection of the appropriate standard for this study. Sections 2.4 and 2.5 describe when to use an FMEA and how to select a suitable FMEA method to conduct an effective FMEA, and Section 2.6 presents the approaches, outcomes, and limitations of existing studies on the FMEA of solar PV systems and panels; finally, the need for further work on the FMEA of solar panels is presented.

2.1. Data Collection Approach

Table 1 summarizes the different types of data used for conducting reliability analyses of solar PV systems. Data from the published literature (50%) and data collected from the field (32.5%) are often used for reliability analyses. The data collected from the literature are relatively older (published in the last 10 to 15 years) and apply solely to old solar PV system technologies; they may have little relevance for recent technologies. The reliability analysis and prediction accuracy depend on the quality and quantity of the data used. Therefore, the accuracy of a solar PV system FMEA can be enhanced by using hybrid data (i.e., data from the literature, field, reliability tests, and expert evaluations). Looking at Table 1, one can recognize that studies on the FMEA of solar PV systems using hybrid data have yet to be available in the literature.

Table 1. Data used to analyze the reliability of solar PV systems.

Data Used for Reliability Analyses	References	No. of Papers
Data from the literature	[19–36]	20 (50%)
Field failure data	[37–49]	13 (32.5%)
Reliability testing data	[8,50,51]	3 (7.5%)
Expert evaluations	[52]	1 (2.5%)
Data from the literature and expert evaluations	[53]	1 (2.5%)
Field failure data and reliability testing data	[54]	1 (2.5%)
Field failure data and data from the literature	[55,56]	1 (2.5%)
Field failure data, data from the literature, reliability testing data, and expert evaluations	-	0

2.2. Selection of RAM Analysis Approach

Table 2 presents methods used for the system reliability modeling and analysis of solar PV systems. Fault tree analysis (FTA), FMEA, probability distribution, reliability block diagram (RBD), Markov chain, and hybrid FTA methods are widely used for these studies. It is imperative to note that different reliability analysis techniques each have their own strengths and applications. The choice of technique depends on the specific context, objectives, and available resources for the analysis. Combining multiple techniques can provide a more comprehensive and robust understanding of system reliability. FMEA is a method that identifies the possible failure modes of a system/component, the potential causes of the failure modes, their effect on the component/system, and methods used to detect the failure modes. At the design and operations stage, an FMEA allows for the early detection and mitigation of failure risks before implementation, reducing the likelihood of costly failures in the future. The FMEA approach can be applied at various product lifecycle stages and is often used at the design and operations stages. Considering the Indian context, solar PV design, development, operation, and maintenance are the dominant phases. The results of FMEAs allow us to work on critical areas and components of solar PV systems. Therefore, this paper uses the FMEA approach to analyze solar PV systems.

In contrast, RBD, FTA, Markov chain, and Monte Carlo simulations are typically used to analyze existing systems rather than to predict failures in the design phase. FMEAs provide a systematic approach to understanding the root causes of failures, enabling the design/operation team to implement necessary design changes or improvements to prevent those failures from occurring altogether. This proactive approach sets the FMEA apart from techniques such as Markov chain and Monte Carlo simulations, which focus more on modeling and analyzing failure probabilities rather than prevention. An FMEA provides a comprehensive understanding of potential risks and enables the prioritization of mitigation efforts. In contrast, techniques such as RBD and FTA focus more on interdependencies between system components or events leading to failures. Still, they may need to provide a different level of granularity when assessing the consequences of a failure or preventive measures. An FMEA encourages cross-functional collaboration among different stakeholders.

It is worth mentioning that the failure mode, mechanisms, and effects analysis (FMMEA) is a recently developed methodology that originated from the FMEA [57]. It is a systematic approach used to identify potential failure mechanisms and models for all possible failure modes and to prioritize these mechanisms. Its effectiveness has been proven in various industrial applications, such as lithium-ion batteries [58,59], printed circuit boards (PCBs) used in the automotive industry [60], the redundant architecture of temperature sensors used in oil and gas applications [61], the evaluation of medical devices [62], LED backlight systems used in LCD TVs [63], high-voltage DC arcs in electric vehicle cables [64], single-board computers [65], and prognostics and health management (PHM) [66,67]. This technique is a valuable tool that can be explored and investigated for analyzing systems, including solar PV systems. However, effectively implementing an FMMEA for this specific study requires collecting sufficient data, so it will be left as a future objective.

Table 2. Methods used for the RAM analysis of solar PV systems.

Sr. No.	Methods Used for Reliability Analyses	References
1	Fault Tree Analysis (FTA)	[18,21,26,29,34,36,42,55,68,69]
2	Failure Mode and Effects Analysis (FMEA)	[19,27,42,44,48,54,70,71]
3	Probability Distributions	[20,31,32,39,40,72,73]
4	Reliability Block Diagram (RBD)	[8,31,33,51,54]
5	Markov Chain	[22,26,50,52]
6	Hybrid FTA	[9,23,30,53,74]
7	Monte Carlo Simulation	[28,37,41]
8	Petri Networks	[24,46]
9	FMECA and Markov Process	[69,75]
10	State Enumeration Method	[25]
11	Dynamic Bayesian Networks	[52]
12	Multi-State Model	[48]
13	Optimization Model	[76]
14	Control Chart	[43]
15	Performance Ratios	[38]

2.3. History of FMEA

The origins of the FMEA can be traced back to the 1940s when the US military and aerospace industries began using various forms of reliability analyses to improve the safety and reliability of their products and systems [77]. The US military used an FMEA in "pilot plant testing" to identify and eliminate potential failure modes in its industrial processes. In the late 1950s, the US Air Force developed one of the earliest forms of an FMEA to identify and analyze potential failure modes in the Atlas missile program. In the 1960s and 1970s, the FMEA became widely used in both military and commercial applications. In the 1980s, the automotive industry adopted the FMEA as a key part of its quality control process, and it has since been widely used in other sectors, such as healthcare, manufacturing, and electronics.

Today, the FMEA is a widely recognized and standardized method for identifying and analyzing potential failure modes and their effects which organizations worldwide use to improve product quality, reliability, and safety. Hybrid FMEA approaches that combine the FMEA parameters (severity, occurrence, and detection) with other significant parameters, such as maintenance time and the cost of maintenance and operations, have also been proposed in the last one to two decades. Several standards, summarized in Table 3, have been developed to guide how to use FMEAs and related methods. These standards are often used to ensure consistency and standardization in FMEA practices across industries and organizations.

Table 3. FMEA standards used in various sectors.

Standard	Developed by	Applications
MIL-STD-1629A	Department of Defense, USA	Military systems and equipment
AIAG FMEA Manual	Automotive Industry Action Group (AIAG)	Automotive industry
ISO 9001	International Organization for Standardization (ISO)	Quality management systems
VDA Volume 4	Verband der Automobilindustrie (VDA)	Manual for the automotive industry that provides guidance on FMEA methodology, documentation, and reporting.
SAE J1739	Society of Automotive Engineers (SAE)	Automotive industry
IEC 60812	International Electrotechnical Commission (IEC)	Hazard analysis of systems, equipment, and facilities

2.4. When to Conduct an FMEA

An FMEA can be used in various product, process, or service lifecycles (e.g., the design stage, manufacturing, and testing) to identify and mitigate potential failure modes. An FMEA can be conducted during a product's design phase to identify and mitigate potential failure modes before the product is manufactured. This helps to reduce the likelihood of expensive design changes or future product recalls. An FMEA can be used to assess the risks associated with a new process before it is implemented. This can help identify potential failure modes, reduce the risk of errors, and improve the efficiency of the process. An FMEA can be used to analyze a product or process that has experienced failures in the field. This can help identify the failures' root causes, develop corrective actions, and prevent similar failures. An FMEA can be used to analyze a product or process that is being improved. This can help to identify potential failure modes and ensure that the improvements do not introduce new risks.

2.5. Types of FMEA

Figure 1 depicts the types of FMEA which are used to identify and assess potential failure modes in different areas of the product or process development cycle. A design-FMEA (D-FMEA) is used to identify and assess potential failure modes in the design phase of product development. A D-FMEA is typically used to analyze the effects of design features on a product's functionality, reliability, and safety. A process-FMEA (P-FMEA) is used to identify and assess potential failure modes in the process phase of product development. A P-FMEA is typically used to analyze the effects of manufacturing, assembly, or testing processes on a product's functionality, reliability, and safety. A system-FMEA (S-FMEA) is used to identify and assess potential failure modes in system-level interactions between components or subsystems of a product. An S-FMEA is typically used to analyze the effects of these interactions on the product's functionality, reliability, and safety. A service-FMEA (Ser-FMEA) identifies and assesses potential failure modes in the service phase of a product's life cycle. An SerFMEA is typically used to analyze the effects of service, maintenance, or repair processes on the product's functionality, reliability, and safety. A software-FMEA (SW-FMEA) identifies and assesses potential failure modes in software development. An SW-FMEA is typically used to analyze the effects of software design, coding, and testing on a product's functionality, reliability, and safety.

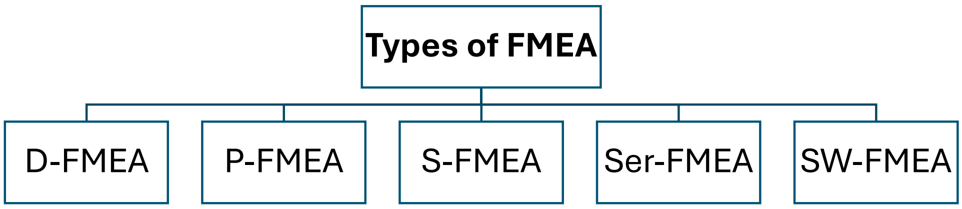


Figure 1. Types of FMEA.

2.6. Existing Work on FMEAs of Solar PV Systems

Table 4 shows the application of the FMEA methodology for analyzing solar PV systems. The primary objectives of these studies were to identify solar PV systems' failure modes. The severity rating (SR), occurrence rating (OR), and detection rating (DR) tables were also developed using the published literature. There are no specific severity, occurrence, and detection tables developed only for the solar panel as it is the most critical component of a solar PV system and its performance determines a PV plant's efficiency and performance. Therefore, it is necessary to develop an FMEA methodology to analyze solar panels. Furthermore, from Tables 1 and 4, it can be inferred that most FMEA studies used data (failure modes and their effects, causes, and detection techniques) from the literature, and very few studies used data from the field or expert evaluations. Thus, hybrid data can be used to identify the critical failure modes of solar panels and their critical components and optimal methods of detecting failure modes more effectively.

Table 4. Application of FMEAs for solar PV systems.

Reference	SR	OR	DR	Key Findings
[19,44,78–81]	✓	✓	✓	• Hotspots, encapsulant EVA discoloration, corrosion in solder bond, bubbles in back sheet, scratches in solar cells, insulation resistance, chalking of back sheet, defect in finger/gridline, distorted module frame junction box corroded, glass soiling/cracked, and partial shading were noted. • Inverter, modules, and grounding/lightning protection system showed high RPNs.
[82]	✓	✓	✓	• Encapsulation in CIGS.
[83]	✓	✓	✓	• Voltage, current, temperature, and irradiance sensors are sufficient to detect, diagnose, and classify faults in PV systems.
[84]	✓	✓	✓	• High-risk fault identified for PV design improvement.
[27]	✓	✓	✓	• Traditional reliability, hazard analysis, and risk analysis techniques can be useful for PV reliability studies.
[85]	✓	✓	✓	• Solder bond failures and encapsulant discoloration were found to be critical in hot, dry climate conditions.
[86]	✓	✓	✓	• Information scoring to construct a surprise index for use within FMEA worksheets.
[87]	✓	✓	✓	• Higher RPN value is related to pollution and dust on panel surface.
[88]	✓	✓	✓	• PaM (proactive maintenance) strategy can enhance maintenance performance.
[89]	✓	✓	✓	• Matrix FMEA is introduced.
[15]	✓	✓	✓	• FMEA-IPA-DEMATEL research methods integration proposed.
[90]	✓	✓	✓	• RCM assessment using FMEA was carried out.
[91]	✓	✓	✓	• Preventive and corrective measures and important recommendations were enlisted for mitigating failures and improving system performance.

Several reliability studies of solar PV systems were carried out using data (failure and repair) available in the literature which are not current and represent outdated technology. Further, significant advancements in materials, manufacturing processes, operations, and maintenance strategies are observed. Therefore, a reliability analysis of solar PV systems should be carried out using four types of data sets: field failure data, expert evaluations, reliability tests, and relevant data available in the literature. Furthermore, the accuracy of the reliability analysis largely depends on the careful analysis of the data by removing anomalies present in the data and prioritizing failure modes observed in the field. The accuracy of the reliability analysis also determines the effectiveness of the strategies to be implemented to enhance the system's reliability. The FMEA is one of the most effective reliability analysis tools for identifying solar panels' critical failure modes. In this regard, it is necessary to develop an FMEA-based methodology for the reliability analysis of solar panels. Furthermore, it is necessary to develop severity, occurrence, and detection rating criteria and tables for solar panels to calculate the RPN accurately.

3. FMEA Methodology

A generalized methodology for the FMEA is developed and presented in Figure 2. The developed methodology comprises several steps, explained one by one, as follows:

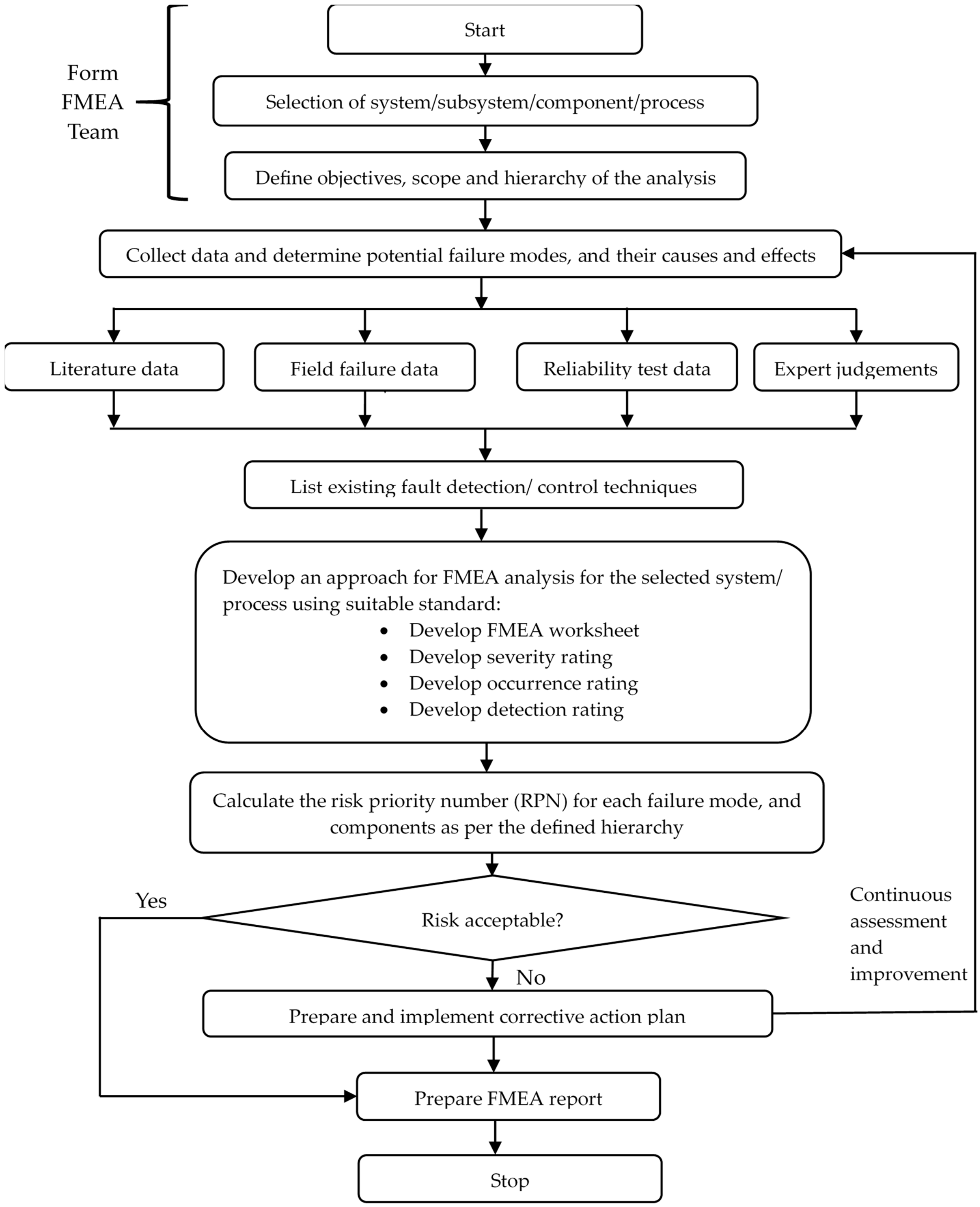


Figure 2. A generalized approach for FMEA.

3.1. Formation of FMEA Team

An FMEA is typically conducted as a team activity because it requires input from different areas of expertise and perspectives to identify and analyze potential failure modes. The FMEA team comprises design engineers, operators, process engineers, reliability engineers, materials suppliers, maintenance engineers, and customers. By involving a team with diverse knowledge and experience, it is more likely that all potential failure modes will be identified and assessed. If a team is involved in the FMEA process, each team member has a stake in the outcome and is more likely to be invested in the project's success. Collaboration also promotes transparency and knowledge sharing, leading to better decision making. A team-based approach to FMEA can help identify potential failure modes earlier in the product or process development cycle, leading to improved quality and reduced costs associated with failure modes discovered later in the development cycle. Organizations can prioritize risk-mitigation efforts by involving a team and allocating resources accordingly. The person who leads the FMEA team should have the necessary skills and experience to facilitate the process effectively. This includes knowledge of the product or process being analyzed, facilitation skills, technical expertise, leadership and communication skills, and experience with FMEAs.

3.2. Defining the Scope and Objectives of the Analysis

Table 5 shows the subsystems and components of a solar PV system. Solar panels are the most significant component of solar PV systems; therefore, this study focuses on developing an FMEA method for solar PV panels. The objectives of the FMEA of solar PV panels include the identification of the potential failure modes of the solar PV panel that could occur during its lifecycle along with their effects and causes; the evaluation of their severity their prioritization based on their potential impact on the system's performance; the analysis of their causes while linking them with various solar PV life cycle stages (e.g., design flaws, manufacturing defects, and environmental conditions (e.g., ambient temperature, relative humidity)); the determination of their likelihood using a combination of field failure data, literature reviews, expert evaluations, and reliability testing and their prioritization based on their probability of occurrence; and the identification of preventative measures that can be taken to mitigate potential failure modes, such as design changes, improved manufacturing processes, or enhanced maintenance procedures.

Table 5. Subsystems/components of solar PV system.

System	Sub System/Component
PV array	Mounting structure, PV modules, PV cells/solar cells, junction box/bypass diode, interconnector, encapsulation, front glass, back sheet, solder bond, grounding, and lightning protection system
Balanced system	Connector, bypass diode, AC switch, AC CB, differential CB, grid protection, and DC combiner
String	Fuse and disconnect
Cables	Arial cables and underground cables
Storage system	Battery, charge controller, and control unit
Switching device	Fuse and circuit breakers
Power	Fuses and breakers, transformer, and protective relays
conditioning	Inverter—IGBT module, DC link, microcontroller, AC converter, DC converter, Colling fans, and PCB

The hierarchy for the FMEA of solar panels is shown in Figure 3 and has three levels: solar panels, their components, and failure modes. First, the RPN value of each failure mode is calculated, and then the component's RPN is calculated.

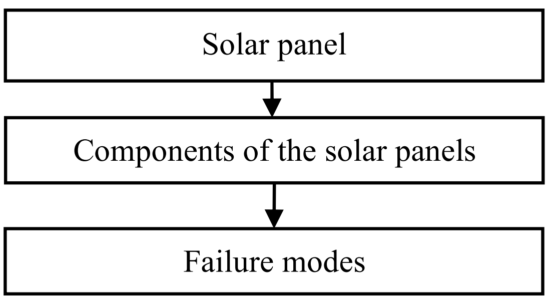


Figure 3. Hierarchy for FMEA of solar panels.

3.3. Data Collection, Sorting and Preprocessing

The FMEA requires data on failure modes and their effects, the causes of failures, and failure detection techniques. The required data should generally be collected from the following four sources: (1) the literature, (2) field failures, (3) expert evaluations, and (4) reliability tests conducted in laboratories. Solar panel and component manufacturers often collect data on failures and repairs during the manufacturing and testing processes and data on how the panels perform over time. Field data, which include warranty claim records, service books, and operations and maintenance registers, etc., are collected from actual solar PV systems in operation and can provide valuable information about how panels perform in real-world conditions. These data are also obtained from monitoring systems (included in the inverter system) which track the performance of individual solar panels and systems over time. Maintenance and repair records provide detailed information on any repairs or replacements made to solar panels or other components and any issues identified during routine maintenance. In addition to field failure data, experts working in the field are identified, and experiential data are collected by conducting interviews, questionnaires, discussion sessions, etc.

Several industry databases, such as the National Renewable Energy Laboratory (NREL)'s Photovoltaic (PV) Reliability Performance Model and the Sandia National Laboratories Photovoltaic Reliability Database, collect data on solar PV system failures and repairs. Researchers may conduct studies on solar PV system failures and repairs, which can provide valuable information about the root causes of failures and potential solutions. This paper uses hybrid data to gain detailed insights into the common failure modes of solar panels and their components and develop strategies to improve their reliability and durability.

The all-potential failure modes that could occur in the solar panels that need to be analyzed are identified. This involves looking at how the solar panels work, how different factors affect the operations and performance of the solar panels, and areas in which problems could arise. The consequences that could result from a failure are determined for each failure mode. These consequences include safety hazards, a degradation in performance, a lower power output, quality issues, reliability problems, customer dissatisfaction, and other negative impacts. Current fault detection techniques are also identified along with their effectiveness in terms of the time required, cost, availability (in-house/outsourced), and expertise required.

3.4. FMEA Worksheet

Table 6 shows the FMEA worksheet used to document the FMEA process and capture the analysis results. The FMEA sheet provides a systematic approach to identifying, evaluating, and prioritizing potential failure modes and their effects. The product/process section of the worksheet identifies the component/failure mode/process being analyzed. It includes a description of the item or process, its function, and its location. The functions are usually listed in order of importance. The worksheet's failure mode section identifies each function's potential failure modes. The failure modes are listed in order of the likelihood of their occurrence. The potential effects section of the worksheet describes the likely effects of each failure mode, including its impact on safety, reliability, performance, and other factors. The severity section of the worksheet assigns a severity score to each potential effect.

Table 6. FMEA worksheet developed for solar panels.

Product/Process	**Failure Mode**	**Failure Effects**	**S (1–10)**	**Causes**	**O (1–10)**	**Control**	**D (1–10)**	**RPN**
Actions/Plans	**Responsibility and Target Completion Date**	**Improved/Post Severity**	**Improved/Post Occurrence**		**Improved/Post Detection**		**Improved/Post RPN**	

The severity, occurrence, and detection ratings criteria are defined and summarized in Table 7, Table 8, and Table 9, respectively. The FMEA standards, the opinions of experts in the field, the field failure database, and the published literature are taken into consideration to effectively implement solar panels. For instance, the severity score is typically based on a predefined severity scale which rates the severity of the effect on a scale from 1 to 10, where 1 represents a minor inconvenience and 10 represents a catastrophic failure with severe consequences.

Table 7. Severity rating developed for solar PV panels.

Rating	Severity	Effect
9	Hazardous	• The degradation rate of the PV panel is more than 3.0% per year. • The panels have the potential to catch fire unexpectedly, regardless of whether there is a warning, and should be discarded. • There is no power output, and it is unsafe for maintenance.
7	High	• The degradation rate of the PV panel is between 1.0 and 3.0% per year. • A reduction in power output of more than 50% results in customer dissatisfaction as there is no profit generation. • The panels should be discarded and no power output.
5	Moderate	• The degradation rate of the PV panel is between 0.5 and 1.0% per year. • A 10 to 20% reduction in the power output and a significant impact on profit.
3	Low	• The degradation rate of the PV panel is between 0.25 and 0.5% per year. • There is less than a 10% reduction in the power output and a moderate impact on profit. • There is no impact on safety and reliability.
1	Negligible	• The degradation rate is less than 0.25% per year. • There is no impact on safety, reliability, and power output.

Table 8. Occurrence rating developed for solar PV panels.

Rank	Occurrence	Description
10	High probability/frequent	The occurrence probability is once a week.
9		The occurrence probability is once a month.
8	Moderate probability	The occurrence probability is once in three months.
7		The occurrence probability is once in six months.
6	Occasional probability	The occurrence probability is once a year.
5		The occurrence probability is once in five years.
4	Remote probability	The occurrence probability is once in 10 years.
3		The occurrence probability is once in 15 years.
2	Unlikely/improbable	The occurrence probability is once in 20 years.
1		The occurrence probability is once in 25 years.

Table 7 reports the severity rating criteria for the solar panels. These were developed considering the effect of failures on safety and reliability, reductions in power output, the degradation rate of the solar panels, the maintenance cost, and profit. The severity rating scale values are 1, 3, 5, 7, and 9 as it assigns the severity rank and differentiates the impact of failure without the low probability of confusion. Severity rating 9 is the highest rating that indicates the hazardous impact of a failure on the solar panel; for example, the panels may catch fire and be unsafe for operation and maintenance activities. Severity rating 1 is the lowest rating and indicates no impact of failure. The panel's degradation is within the acceptable limit and as per the design predictions. The intermediate severity ranks are then defined appropriately.

Table 9. Detection rating developed for solar PV panels.

Rank	Detection Level	Description
10	Very low	• The present control system cannot detect failure modes before they occur. • There is a need to develop an automatic fault detection system.
8	Low	• The present control system can detect a failure mode only if external experts are called and have specialized equipment, tools, and techniques. • The failure detection probability is less than 50%. • There is a need to develop an automatic fault detection system.
6	Moderate	• The present control system can detect the failure mode with the available equipment, tools, techniques, and expertise. • The failure detection probability is greater than 80%.
4	Very high	• The present control system can detect failures with a probability of detection greater than 90%. • The system's operator or user can detect a failure without any equipment. • Failures and automatic detection and warning systems may also indicate failure.
2	Almost certain	• The present control system can detect failures with a probability of 100%. • An automatic fault detection and warning system is in place.

On the other hand, the likelihood of occurrence section of the worksheet assigns a likelihood of occurrence score to each potential failure mode. The likelihood of occurrence score is typically based on a predefined scale which rates the likelihood of the failure mode occurring on a scale from 1 to 10, where 1 represents a highly unlikely occurrence and 10 represents a very likely occurrence. This involves looking at historical data, industry standards, and expert knowledge to assess each failure mode's probability. Table 8 depicts the occurrence rating for the solar panels, and it is defined based on the failure data collected from the published literature, maintenance registers, online database management systems, and experts in the field. A scale of 1 to 10 is selected for assigning the occurrence ranking to the failure modes. Occurrence rank 10 is the highest rating and indicates that the failure event occurs very frequently and the probability of its occurrence is once a week. Occurrence rank 1 is the lowest rating and means that the probability of failure of the given failure event is very rare and it rarely occurs in the entire lifespan of the solar panel (i.e., once in 25 years). The intermediate occurrence ranks are then defined appropriately, considering the effect of failure on maintenance activities, maintenance cost, and support/maintenance/operations team availability. The occurrence table is used as a tool for continuous improvement because it can identify trends and patterns in failures, track the effectiveness of corrective actions, and identify opportunities for further improvement.

Lastly, the detectability section of the worksheet assigns a detectability score to each potential failure mode. The detectability score is typically based on a predefined scale which rates the ease of the detection of the failure mode on a scale from 1 to 10, where 1 represents a highly effective detection method and 10 represents an ineffective detection method. This involves looking at the detection methods in place and assessing their effectiveness. The detection criteria and ratings are summarized in Table 9 and are based on how easily the present control system can detect failures. The detection rating scale values are taken as 2, 4, 6, 8, and 10 for simplicity and to improve allocation accuracy. It also considers all the present control mechanisms, fault detection, and diagnosis systems used in the field. Detection rank 10 is the highest rating and designates that the present control system cannot detect the failure modes before they occur and there is a need to develop control systems. Detection rank 1 is the lowest rating and depicts that the present control system can certainly detect failures easily and accurately.

Furthermore, fault detection and warning systems are also in place. Intermediate detection ranks are defined appropriately based on the availability of the control systems, tools, techniques, and equipment required to detect the fault and the desired level of expertise. The detection methods are prioritized based on their effectiveness, probability of detection, cost, and feasibility. Focusing on the highest-priority detection methods is important when developing corrective actions. Updating the detection table regularly is required to reflect changes in the system, process, or product. This will help ensure that your FMEA remains relevant and effective over time. The detection table is used as a tool for continuous improvement because it can identify opportunities for improving detection methods and reducing the risk of failure.

3.5. Calculating RPN

The RPN is a numerical value used in the FMEA to prioritize potential failure modes based on their severity, occurrence, and detectability. Severity, occurrence, and detection ratings are assigned to each failure mode. Each potential failure mode's RPN is calculated by multiplying the severity, likelihood of occurrence, and detection scores given in Equation (1) [92,93]. The failure modes are sorted by their RPN values in descending order, with the highest RPN values indicating the most critical failure modes that require immediate attention. The lowest RPN value indicates the least critical failure modes, and no special attention is required. The FMEA is also used to assess the risk of failure events. The multiplication of the severity and occurrence ratings provides the risk associated with the event, as given in Equation (2). The failure modes are also sorted by their risk values in descending order. The highest risk value indicates the riskiest failure mode, and the lowest risk value indicates the least risky failure mode. The values of the RPN and risk are used to develop reliability improvement plans, optimize maintenance, and so forth.

$$\mathrm{RPN} = \mathrm{Severity(S)} \times \mathrm{Occurrence(O)} \times \mathrm{Detection(D)} \tag{1}$$

$$\mathrm{Risk} = \mathrm{Severity(S)} \times \mathrm{Occurrence(O)} \tag{2}$$

3.6. Corrective Action Plan and Improved FMEA

The earlier FMEA refers to the FMEA that is conducted for existing systems either early in the product design development stages, before any actual production or implementation has begun, or during the operation and maintenance of the systems. The earlier FMEA of solar PV panels provides critical failure modes and their effects on the panels, in which corrective actions such as preventive maintenance measures and optimization can be taken for reliability and performance improvements. The actions may also include redesigns, process changes, testing, or other corrective actions. Corrective actions are developed to mitigate the risks associated with high-priority failure modes, starting with those with the highest RPN values. The improved FMEA refers to the FMEA conducted after implementing reliability improvement strategies for critical failure modes and assesses the effectiveness of the implemented methods. This may involve adding new failure modes or effects, updating the severity, occurrence, or detection ratings for existing failure modes, or modifying the recommended actions for high-priority failure modes. Overall, both the earlier and improved FMEAs are essential tools for identifying and mitigating potential risks in a product or process.

3.7. FMEA Report

The preparation of the FMEA report is the most significant step in the analysis since it is a continuous process needed to achieve short-term and long-term goals. It helps the user understand what has already been accomplished to improve the product/processes and what should be carried out in the future. It also provides all historical records to a new FMEA team member. A comprehensive report should include the following sections: introduction, methodology, results, recommendations, conclusions, and appendices. The introduction should provide an overview of the purpose and scope of the FMEA, including a description of the solar PV system or component being analyzed and the objectives of the analysis. The methodology section should describe the approach taken to conduct the FMEA, including the data sources used, the team members involved, and the analytical tools and techniques utilized. The results section should present the findings of the FMEA, including a summary of the potential failure modes identified, their severity rankings, the causes and effects of the failure modes, and the likelihood of occurrence. The recommendations should outline the preventative measures that can be taken to mitigate the potential failure modes identified in the FMEA. These recommendations may include design changes, improved manufacturing processes, enhanced maintenance procedures, or other solutions to improve reliability and durability. Finally, the conclusions should summarize the FMEA's key findings and recommendations, highlighting the importance of the analysis in improving the reliability and performance of the solar PV system or component. For completeness, when necessary, the appendices could include any supporting data or documentation used in the FMEA, including diagrams, charts, and tables, in addition to references to any relevant industry standards or guidelines.

4. A Case Study of Polycrystalline Solar Panels

This section presents an FMEA of solar panels using the developed methodology. The analysis is carried out using four types of data sets: field failure data, data from the literature, testing data, and expert evaluations.

4.1. Construction of a Solar Panel

The construction of a typical solar panel is shown in Figure 4. The construction of a solar panel involves several key components and layers that work together to convert sunlight into electricity. Solar panels are made up of individual solar cells, typically composed of crystalline silicon or thin-film materials. These cells are the primary component responsible for converting sunlight into electricity through the PV effect. The solar cells are encapsulated within protective layers to shield them from environmental factors and to ensure their durability. The encapsulation process typically involves using a top layer of transparent and anti-reflective material, such as tempered glass, to allow sunlight to reach the solar cells while protecting them from moisture, dust, and physical damage. The back sheet is a rear layer of the solar panel, which provides additional protection against moisture and acts as an electrical insulator. It is typically made of a polymer material with good electrical insulation properties.

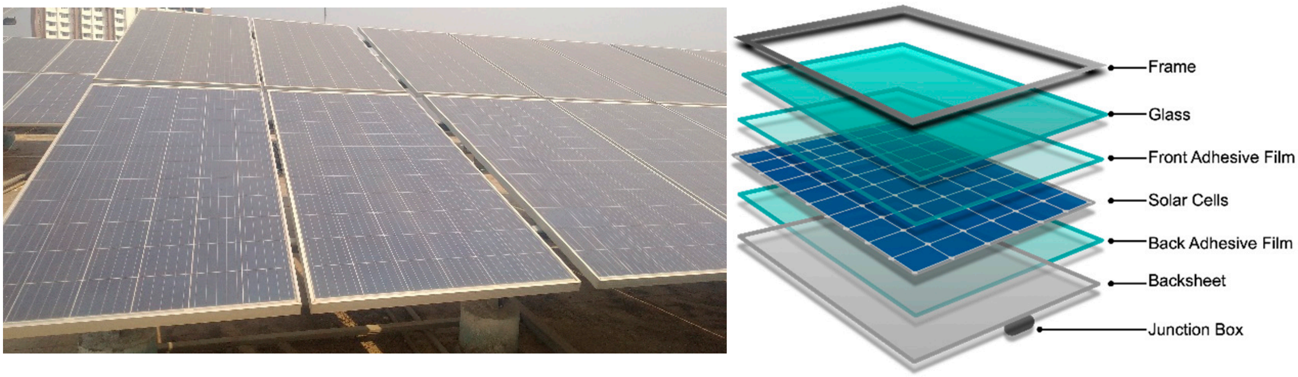


Figure 4. Construction of typical solar panel.

Metal conductive strips, known as busbars, are applied to the front surfaces of the solar cells to collect the generated electricity and transfer it out of the panel. These busbars are typically made of silver or other conductive metals. A layer of encapsulant is applied between the solar cells and the back sheet to provide adhesion, insulation, and further protection. The encapsulant is usually made of a polymer material, such as ethylene-vinyl acetate (EVA), which bonds the solar cells, busbars, and back sheet. Solar panels are often framed to provide structural support and protection. The frame is typically made of aluminum or another lightweight and corrosion-resistant material. It adds rigidity to the panel, protects the edges, and provides a mounting structure for installation.

A junction box is attached to the back of the solar panel, typically near the frame, to provide electrical connections. It houses bypass diodes and facilitates the connection of multiple panels in series or parallel configurations. Electrical wires connect the busbars of individual solar cells and the junction box, allowing the generated electricity to be collected and channeled out of the solar panel. It is important to note that solar panel construction can vary depending on the specific type of solar cells used, manufacturing processes, and intended applications. The above description provides a general overview of the components and construction principles commonly employed in producing solar panels.

4.2. FMEA of Solar Panel

A comprehensive FMEA sheet for the solar panel is shown in Table 10. The solar panels' failure modes are classified according to the components and external events: frame, glass, encapsulant, solar cells, back sheet, junction box, and other failures. The all-possible failure modes of the components and externally occurring events (other failures) are identified along with their failure effects, dominating causes, and commonly used detection techniques. A severity rating is allocated to the effects of the failure mode using ratings given in Table 7. An occurrence rating is then assigned based on Table 8. The allocation of the fault detection rating is a critical task since the approach used at different sites involves different techniques. This is because the expertise levels available at various sites are also different. Therefore, the severity rating is allocated by referring to Table 9, and a combination of the available expertise and the cost of the fault detection techniques and expert evaluations is considered. Finally, each failure mode's RPN is calculated by multiplying its severity, occurrence, and detection ratings. The RPNs of the components and externally occurring events (other failures) are calculated by taking the sum of the RPNs of the corresponding component's failure modes.

Table 10. FMEA sheet for solar panel.

Failure Mode	Effect	SR	Cause	OR	Detection	DR	RPN
Frame							122
Deformation	Crack in module	5	Manufacturing quality; installation	5	Visual inspection	4	100
Corrosion	Reduced module efficiency	3	Corrosive environment	2	Visual inspection	2	12
Distorted frame	Reduced module efficiency	5	Manufacturing quality; installation	1	Visual inspection	2	10
Glass							146
Soiling	Reduced power output; activate various faults	5	Dust accumulation, bird droppings, vandalism	9	Visual inspection	2	90
Breakage	Reduced power output	7	Vandalism; environmental effect; external	4	Visual inspection	2	56
Encapsulant							940
Delamination	Increased degradation; reduced energy output/no energy output	7	Thermal and high-voltage (HV) stress; ultraviolet (UV) light; aging; extreme weather conditions; vandalism; animals; lightning; earthquakes	4	Visual inspection; I-R thermography	8	224
Metallization or busbar discoloration	Reduced power that impacts the lifespan of the panel	5	Overheating	4	Electrical maintenance	6	120
Loss of air tightness	Formation of water vapor inside the panel; water contamination; increased degradation; reduced energy output	7	Bad lamination; high voltage stress; hot spots; high cell temperature; corroded/damaged frame; cleaning actions; extreme wind snow load; animals	2	Operating/maintenance manual	8	112
Oxidation of front grid metal fingers	Power loss	7	Extreme weather conditions, aging, mechanical stresses	4	IR thermography	4	112

Table 10. *Cont.*

Failure Mode	Effect	SR	Cause	OR	Detection	DR	RPN
Hot spots	High power loss; increased degradation	7	Shading; localized dirt; broken cells; bad soldering; bypass diode failure; bird droppings and nest; operating current is greater than the short circuit current	4	IR imaging, EL imaging, and visual inspection	4	112
Corrosion in solder bonds	Reduced module efficiency	5	Moisture penetration	3	Visual inspection; infrared (IR) thermography; EL imaging; electrical performance test	6	90
Insulation resistance	Power loss; overheating; fire	9	Electrical stress; mechanical damage; vibrations; excessive heat or cold; dirt; oil; corrosive vapors; moisture from processes; humidity on a muggy day	1	Insulation tester	8	72
Discoloration	Reduced energy output; overcurrent; decrease in shunt resistance; degradation rate approx. up to 1% per year	3	Material defects; oxidation; aging; thermal/mechanical/electrical stress; material contamination; heat; and UV	2	Visual inspection; thermal imaging; electroluminescence (EL) imaging; UV light test	6	36
Corrosion in busbar	Electrical performance degradation; power output; series resistance	5	Moisture; atmospheric gas penetration; water; acetic acid from EVA degradation	3	Maintenance; visual inspection	2	30
Solder bond failure	Increased series resistance	5	Stresses induced by thermal cycling or vibration	1	Visual inspection	4	20
Defect in finger/gridline	Power loss; hotspot; reduced durability	3	Manufacturing error; mechanical stress; handling and installation	1	IR imaging; EL imaging; visual inspection; contact resistance test	4	12
Solar cells							76
Broken cells	Reduced power output	7	Mechanical stress	4	Visual inspection; EL imaging	2	56
Discoloration	Reduced power output	5	Uncontrolled chemical reaction	1	Visual inspection	4	20
Backsheet							178
Insulation compromise	Power loss; overheating; fire	9	Electrical and mechanical stress; vibration; excessive heat or cold, dirt; corrosive vapors; humidity on a muggy day	3	Insulation tester	2	54
Burnt back sheet	Damage to the back sheet	5	Hot spot in solar cell	4	Visual inspection	2	40
Delamination	No energy output; thermal damages; fire	7	Damages; improper installation; disconnections; animals; vandalism	2	Visual inspection; tap test; thermal imaging; EL imaging	2	28
Bubble formation	Reduced energy output; no energy output; thermal damage; reliability issue	3	Corrosion; improper installation; lightning damage	4	Visual inspection	2	24
Warping/detaching	Performance degradation; increased maintenance cost	3	Defective material; back sheet adhesion loss	3	Visual inspection	2	18
Chalking	Reduced power output; overcurrent	1	Defective material; aging; thermal stress	4	Visual inspection	2	8
Burn marks	No energy output	3	Damage; disconnection; animals; vandalism; strong wind; pulled cables	1	Visual inspection	2	6
Junction box							430
Open contact	No energy output	9	Defective material; corrosion; mechanical damage	2	Regular maintenance; U-I measurement	6	108
Short circuit	No energy output; safety; thermal damages; fire; damage to the system	9	Water contact; electricity overloading; loose connections; degradation of insulation; aging; animals; lightning	2	Regular maintenance; visual control; U-I measurement; no control; detected from the signs of burning; burning smell; flickering light	6	108

Table 10. *Cont.*

Failure Mode	Effect	SR	Cause	OR	Detection	DR	RPN
Poor contact	Reduced/no power output; thermal damage	7	Defective material; oxidation; aging	2	Regular maintenance; visual control; U-I measurement	6	84
Bypass diode parameter change	Reduced/no power output; thermal damage; over current; safety problems	7	Defective material; aging; thermal stress	2	Regular maintenance; visual control; U-I measurement	6	84
Diode failure	Leakage current drop	3	excessive forward current and a high reverse voltage	4	OC (open circuit) diode inspection with a portable device	2	24
Internal circuitry discoloration; series resistance increase	Reduced energy output; no energy output; thermal damage; over current; safety problems	1	Solder bond failure	4	I-V curve	4	16
Junction box corroded	Performance loss; leakage current	3	Moisture	1	Visual inspection	2	6
Other failures							300
Partial shading	Reduction in energy output	5	Improper installation; site selection	6	Visual inspection; output power data	4	120
Fading in the heat	Reduced open circuit voltage	7	Weak PV modules; charge controller failure	4	Selective shading test; charge controller field test	4	112
Increase in new shading element	Power output reduction	5	Proposed obstruction	6	Visual inspection	1	30
Snail trail effect	Reduction in energy output	3	Accumulation of dust, pollen, and debris on the panels	4	Visual inspection; I–V measurement; EL measurement	2	24
Improper tilt angle/improper orientation	Reduction in energy output	7	Geographical location data not available	1	Weather data use	2	14

4.3. Prioritizing the Failure Modes

The failure modes of the solar panel are prioritized based on their RPNs, as shown in Figure 5. It clearly shows that delamination and soiling are the solar panels' most critical failure modes, having RPNs of 224 (10%) and an RPN of 140 (6.2%), respectively, as their RPN values are greater than 125. Delamination and soiling contribute nearly 16.2% of the total RPN. Partial shading, metallization or busbar discoloration, fading in the heat, hot spots, the oxidation of front grid metal fingers, the loss of air tightness, short circuits, open contact, deformation, corrosion in solder bonds, bypass diode parameter changes, and poor contact are moderately critical failure modes as their RPN values are between 75 and 125 and their cumulative RPN percentage is nearly 56.3%. The remaining failure modes are considered the least critical as their RPN values are less than 75.

A failure mode's risk is calculated by multiplying its severity and occurrence ratings. A risk assessment of the failure modes is also carried out and summarized in Figure 6. The risk associated with soiling is very high, with a value of 70, and its contribution is 11.3%. Soiling also accelerates the corrosion rate, snail trailing rate, and the probability of the occurrence of several other failure modes; therefore, it should be addressed appropriately. Failure modes with risk values between 25 and 50 are considered moderately risky. Failure modes with a risk value of less than 25 are considered the least risky.

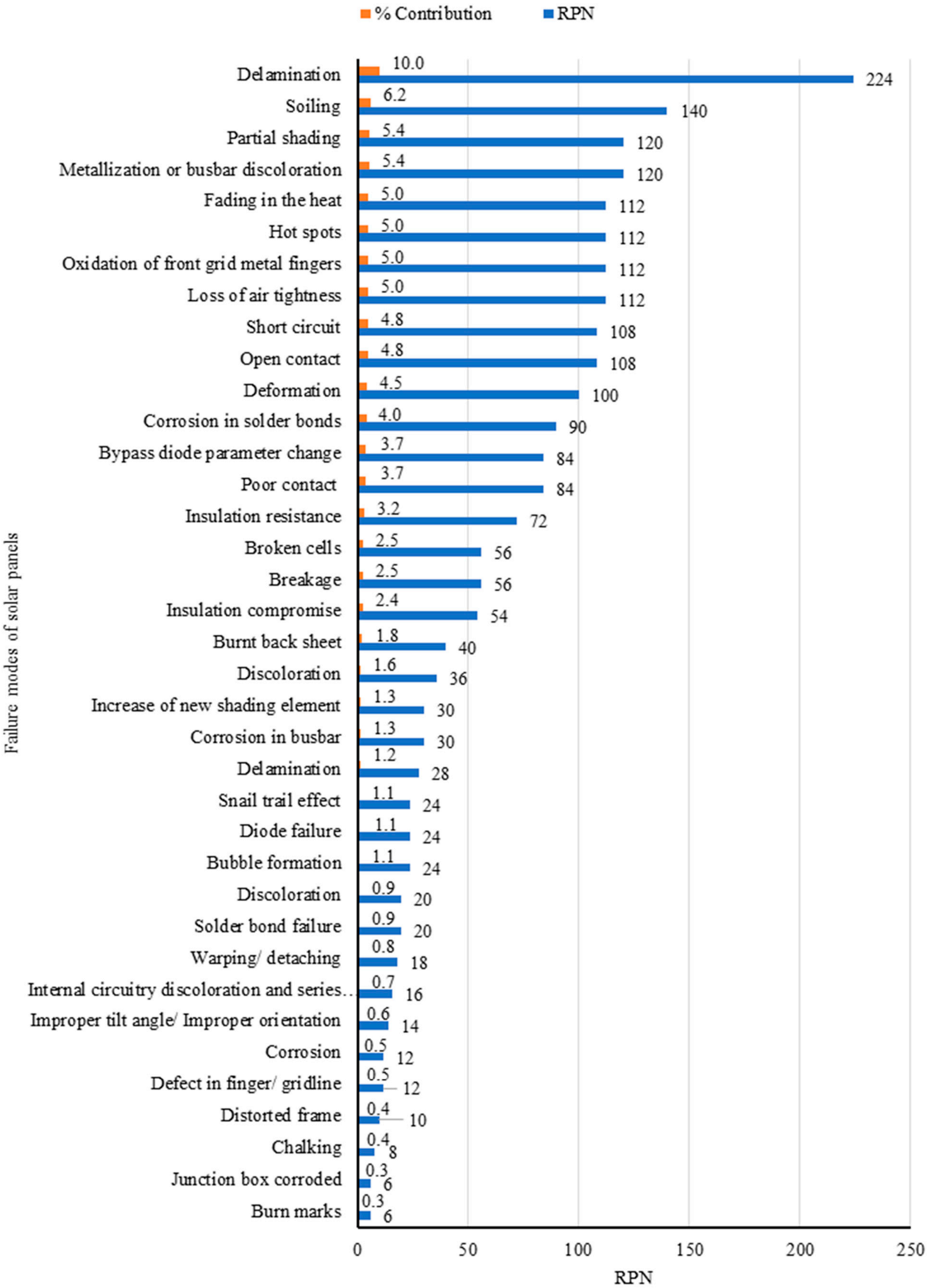


Figure 5. RPN for failure modes of solar panel.

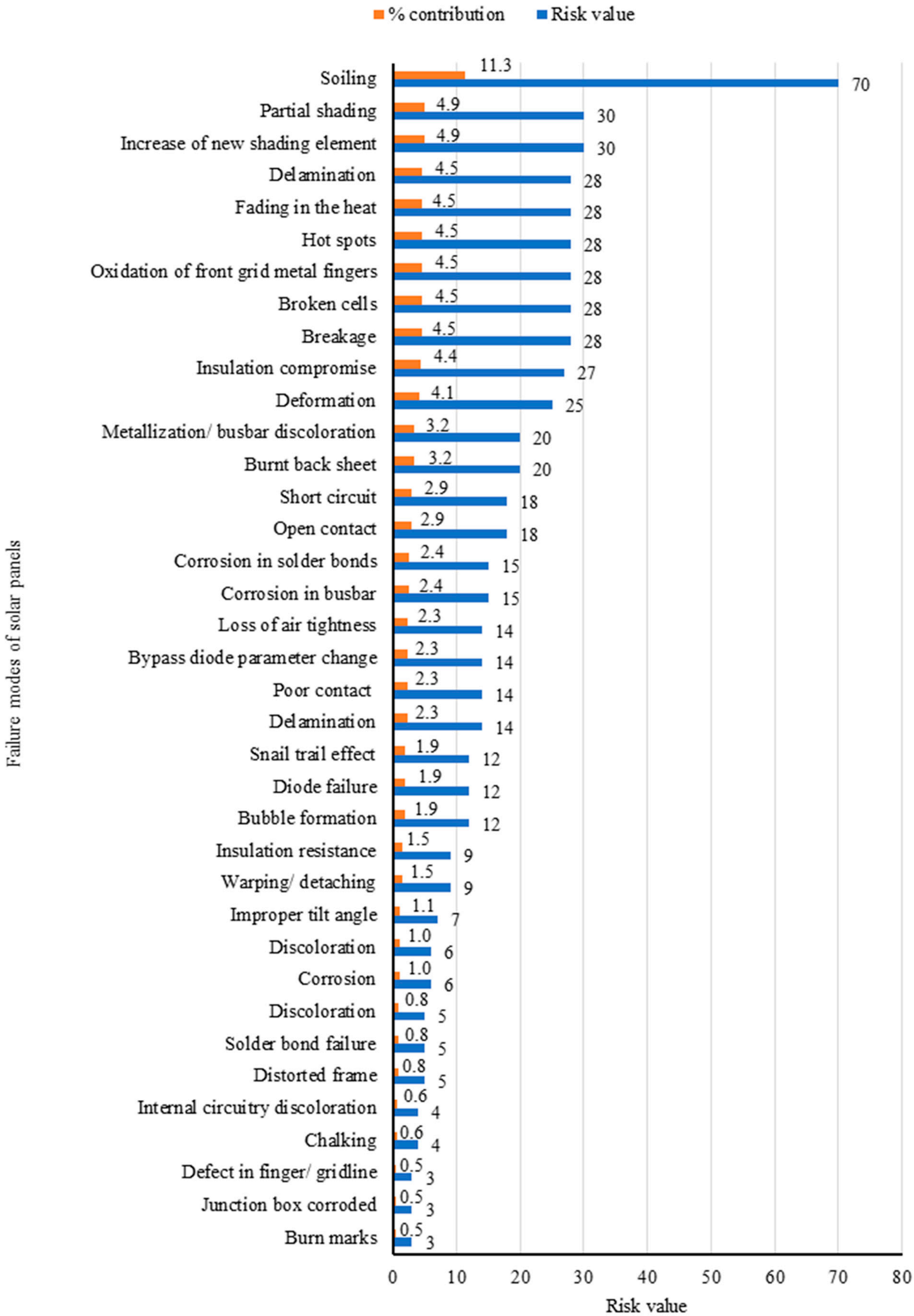
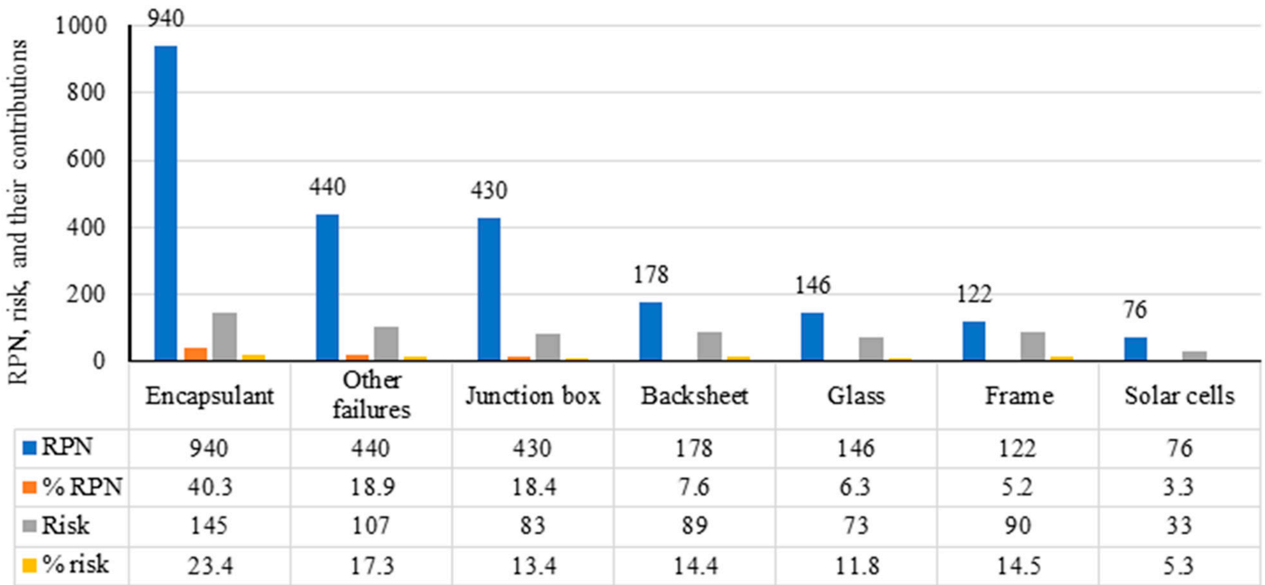


Figure 6. Risk assessment of the solar panel.

4.4. Criticality Analysis of Components and Their Dominating Failure Modes

Figure 7 depicts the criticality ranking of the components of the solar panels according to their RPN and risk values. The encapsulant is the most critical component, with RPN and risk values of 940 and 145, respectively. Special attention should be given to the encapsulant during inspection and maintenance activities. It contributes 40.3% and 23.4% of the total RPN and risk value, respectively. The junction box and other failures are moderate and contribute nearly 37.3% of the RPN and 30.7% of the risk. Critical observation of the junction box is required, and external factors that cause the panel to fail or degrade should be monitored carefully to prolong the panel's life.



	Encapsulant	Other failures	Junction box	Backsheet	Glass	Frame	Solar cells
RPN	940	440	430	178	146	122	76
% RPN	40.3	18.9	18.4	7.6	6.3	5.2	3.3
Risk	145	107	83	89	73	90	33
% risk	23.4	17.3	13.4	14.4	11.8	14.5	5.3

Figure 7. RPN of components of solar panels.

Figure 8a,b show the critical faults of the frame and glass. Deformation and soiling are the dominating failure modes.

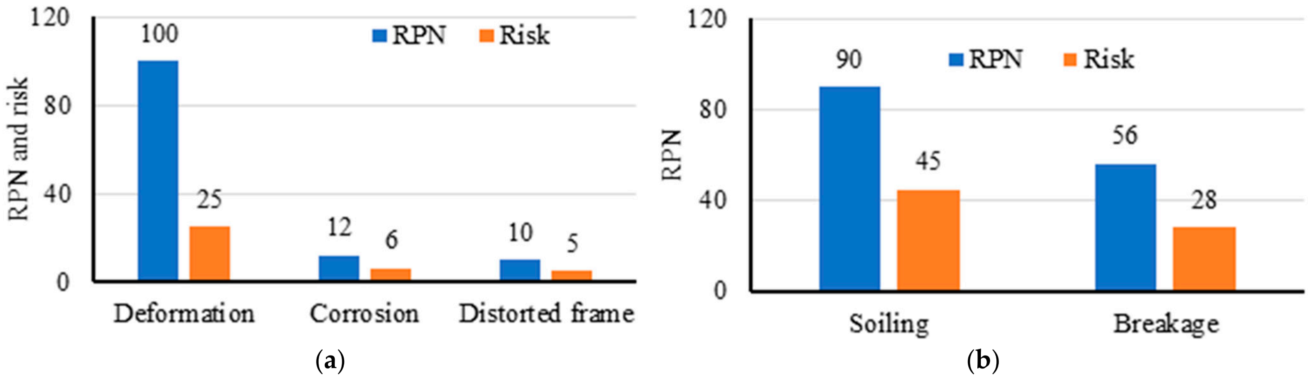
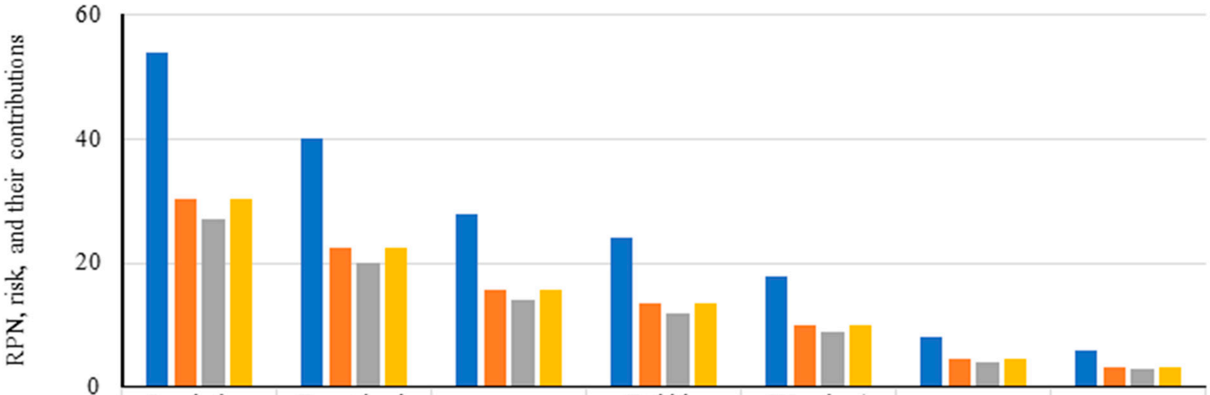


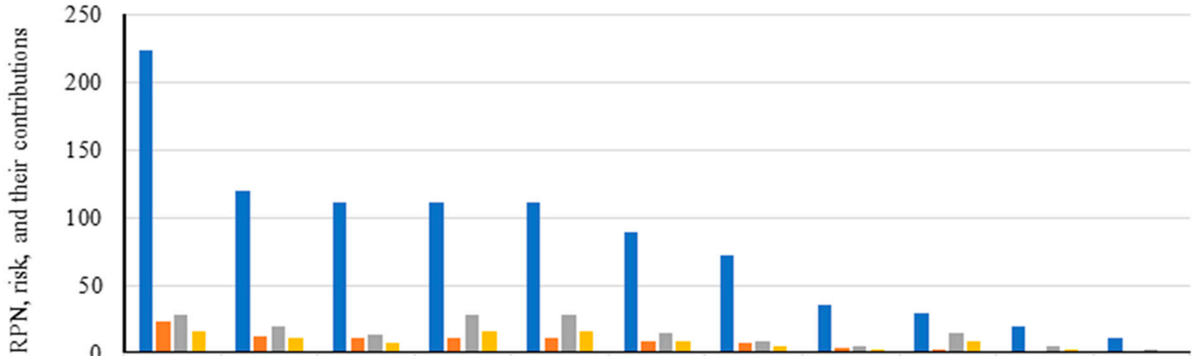
Figure 8. Criticality analysis of (**a**) frame and (**b**) glass.

Insulation compromise and a burnt back sheet are the dominating failure modes of the back sheet and contribute nearly 52.8% to the RPN and risk, as shown in Figure 9. Delamination, bubble formation, and wrapping/detaching were found to be moderately critical failure modes. Figure 10 shows that 11 failure modes cause the encapsulant to fail or degrade. Delamination is the most critical failure mode, contributing nearly 23.8% of the RPN and 16.4% of the risk. The next four failure modes contribute nearly 58.1% to the RPN and 52.7% to risk.



	Insulation compromise	Burnt back sheet	Delamination	Bubble formation	Warping/ detaching	Chalking	Burn marks
RPN	54	40	28	24	18	8	6
% RPN	30.3	22.5	15.7	13.5	10.1	4.5	3.4
Risk	27	20	14	12	9	4	3
% risk	30.3	22.5	15.7	13.5	10.1	4.5	3.4

Figure 9. Criticality analysis of back sheet.



	Delamination	Metallization or busbar discoloration	Loss of air tightness	Oxidation of front grid metal fingers	Hot spots	Corrosion in solder bonds	Insulation resistance	Discoloration	Corrosion in Busbar	Solder bond failure	Defect in finger/ gridline
RPN	224	120	112	112	112	90	72	36	30	20	12
% RPN	23.8	12.8	11.9	11.9	11.9	9.6	7.7	3.8	3.2	2.1	1.3
Risk	28	20	14	28	28	15	9	6	15	5	3
% Risk	16.4	11.7	8.2	16.4	16.4	8.8	5.3	3.5	8.8	2.9	1.8

Figure 10. Criticality analysis of encapsulant.

Figure 11 shows the failure modes of the junction box along with their RPNs, risk values, and percentage contributions. Open contact and short circuits are the most critical failure modes; their contributions are 50.2% in the RPN and 43.4% in risk. Poor contact and bypass diode parameter changes are moderately crucial failure modes. Regular inspection and U-I measurement can minimize the junction box's failure probability.

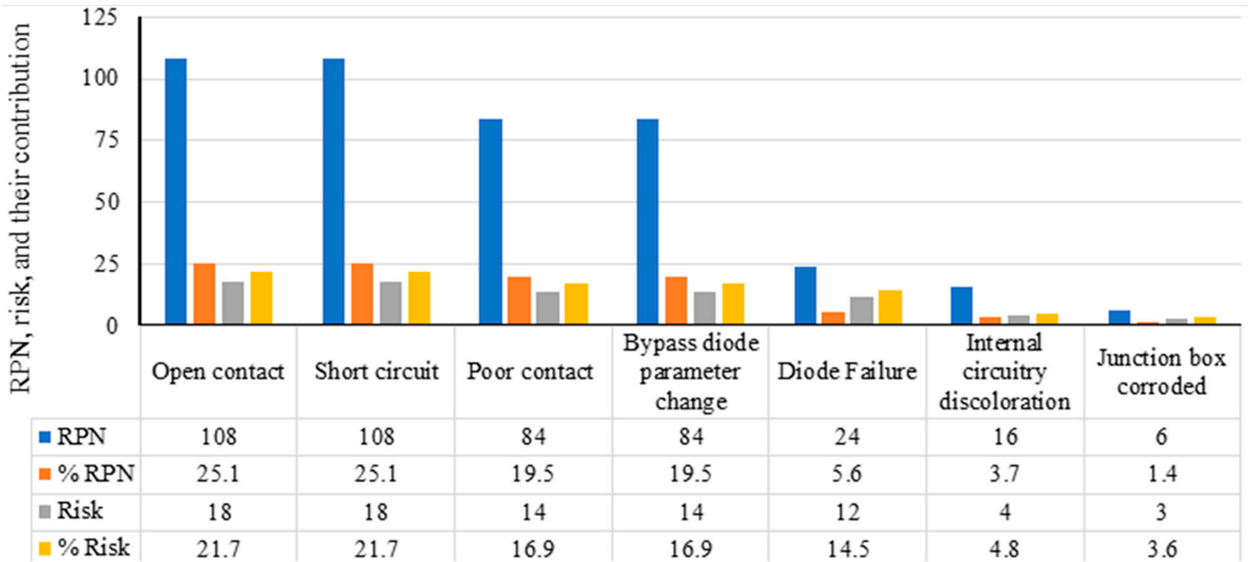


Figure 11. Criticality analysis of junction box.

Partial shading and fading in heat are the most critical failure modes due to external events, as shown in Figure 12. Their total RPNs and risk value contributions are 77.3% and 54.2%, respectively. The partial shading effect is primarily due to new construction near the panels and growing grass above the height of the solar panels. Proper care can significantly minimize the probability of partial shading and new shading elements. The snail trail effect is due to soiling and the incorporation of shading elements, and its likelihood of occurrence increases due to the cascading effect. Improper orientation or an incorrect tilt angle occurs due to design and construction errors. Addressing and rectifying these issues during the initial design phase is necessary as the expenses involved in making modifications later on are prohibitively high.

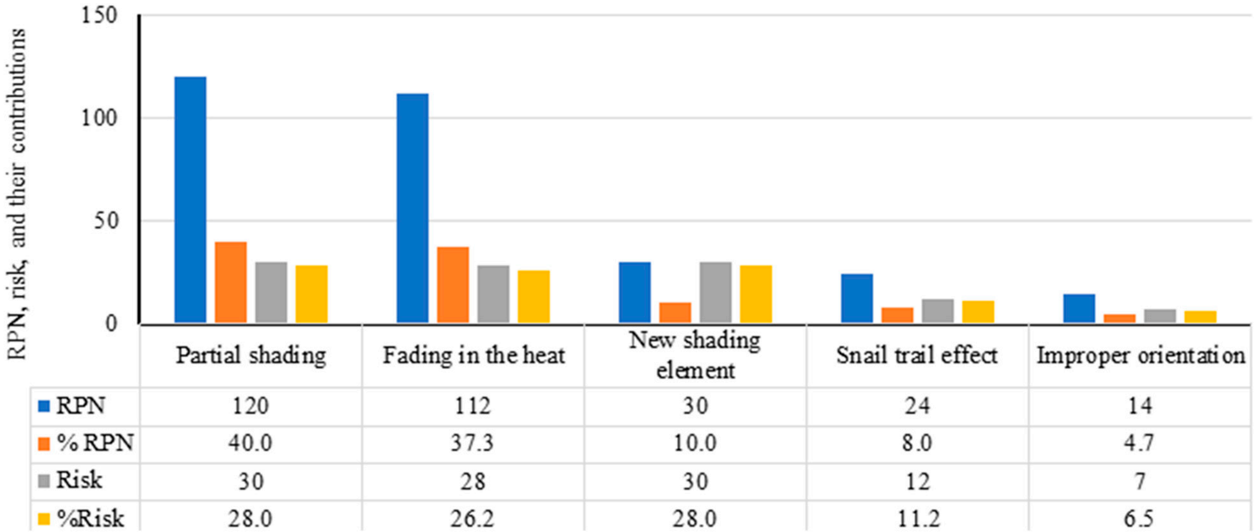


Figure 12. Other failures of the solar panel.

5. Conclusions

The reliability of solar panels is crucial for ensuring consistent energy production, maximizing the return on investment, promoting renewable energy adoption, and maintaining grid stability and energy security. The FMEA is the practical approach to identifying critical failure modes and their effects and causes as solar panels are continuously exposed to diverse atmospheric conditions. A methodology for the FMEA of solar panels is developed, which uses hybrid data: data from field failures, the literature, testing, and expert evaluations. Severity, occurrence, and detection rating tables are designed using international standards specifically for solar panels. The developed approach is then used to perform an FMEA, and the critical components and their dominating failure modes are identified based on the RPN and risk value, contributing to sustainable energy practices.

The encapsulant is the most critical component, with RPN and risk values of 940 (40.30%) and 145 (23.40%), respectively. Special attention should be given to the encapsulant during inspection and maintenance activities. The junction box and other failures are moderate and contribute nearly 37.3% of the RPN and 30.7% of the risk. Critical observation of the junction box is required, and external factors that cause the panel to fail or degrade should be monitored carefully to prolong the panel's life. Delamination and soiling are the solar panels' most critical failure modes, having RPN values of 224 and 140, respectively, and contributing 16.2% to the total RPN. Partial shading, busbar discoloration, fading in the heat, hot spots, oxidation of the front grid metal fingers, the loss of airtightness, short circuits, open contact, deformation, corrosion in solder bonds, bypass diode parameter changes, and poor contact are moderately critical failure modes of the solar panel, and their contribution in RPN is 56.3%. The risk assessment reveals that the risk associated with soiling is very high, with a value of 70, and its contribution is 11.3%. Soiling also accelerates the corrosion rate, snail trailing rate, and the probability of the occurrence of several other failure modes; therefore, it should be addressed appropriately.

Critical faults in the frame and glass are deformation and soiling, respectively. Insulation compromise and a burnt back sheet are the dominating failure modes of the back sheet and contribute nearly 52.8% of the RPN and risk. Poor contact and bypass diode parameter changes are moderately critical failure modes. Regular inspection and U-I measurements can minimize the junction box's failure probability. Partial shading and fading in the heat are the most critical failure modes due to external events. The partial shading effect is primarily due to new construction near the panels and grass growing above the height of the solar panels. Proper care can significantly minimize the probability of partial shading and new shading elements. The snail trail effect is due to the soiling and incorporation of shading elements, and its probability of occurrence increases due to the cascading effect. Improper orientation or an incorrect tilt angle can be attributed to design and construction flaws and should be addressed during the initial design phase. Making modifications at a later stage can be costly and should therefore be avoided.

Scope, Limitations, and Future Directions

The data used for the FMEA of solar PV systems were collected from various sites in India. It is difficult to use the results obtained from this study as it is to predict the behavior of solar PV systems installed in countries with different climatic conditions. However, the methodology developed in this paper can be used to collect and analyze data. Furthermore, a detailed analysis can be carried out to gain more insights by gathering failure data from more solar PV system sites. An attempt can also be made to integrate data collected from various solar PV plants operating in diverse and varying environmental conditions. Action plans for a reliability improvement can be prepared based on the RPN values and criticality analysis results. The effect of implementing reliability improvement plans can also be linked with maintenance and operations costs. An attempt can also be made to establish a correlation (link) between the failures of different components, the types of correlation present, and the impact of this correlation on the overall performance, reliability, and safety of the system.

The present study focuses on identifying failure modes, causes, and effects of polycrystalline solar panels using field failure data and expert evaluations. A comparative study of polycrystalline PV panels with other types (especially monocrystalline panels) can be carried out to gain more insights as the demand for and installation of monocrystalline panels are increasing significantly.

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