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TECHNICAL REPORT

colour inside

Photovoltaic power systems (PVPSs) – Roadmap for robust reliability

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ELECTROTECHNICAL
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PHOTOVOLTAIC POWER SYSTEMS (PVPSs) –
ROADMAP FOR ROBUST RELIABILITY

FOREWORD

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IEC TR 63292 which is a technical report, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
82/1671/DTR	82/1716/RVDTR 82/1716A/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

Mandatory information categories defined in this document are written in capital letters; optional information categories are written in bold letters.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
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INTRODUCTION

Reliability of a PVPS or its components is perceived in many ways depending on the perspective of the observer. This document addresses many of these perspectives ranging from component failures to the human factors needed in operations and maintenance (O&M) of a PVPS. Technically, reliability is the probability that a product or a system will perform its intended functions satisfactorily without failure and within specified performance limits for a specified length of time, operating under specified environmental and operational conditions. Stated as such, reliability analysis is a physics problem in that it includes what, how, and why of failure. Reliability is determined by a variety of factors (failure modes) and each failure mode is generally characterized as an average or mean time to or between failure or by failure rates (commonly failures per unit of time) or by failure distributions. Causes include failure mechanisms such as overstress and below specification strength, natural and induced environmental exposures, chemical aging, radiation, and other factors such as weak or intermittent manufacturing quality or shipping and handling induced damage that lead to a component failure. The failed items will need repair or replacement through a function of maintenance actions. Reliability analysis and best practices should be applied throughout the concept and design phases to identify, pre-empt, prevent, forestall, or mitigate such failures during planned operation. Cognizance of reliability factors is important for owners, and others performing project or program financial and technical risk asset management.

Acquiring data to find and understand failure trends, spares forecasting, manpower forecasting, obsolescence planning and repeating component failures requires a management focus to mitigate or eliminate recurring issues and document accurate failure tracking. The ability to estimate the resulting loss of Photovoltaic Power System (PVPS) capability forms the basis for how to allocate time, power, energy and even cost for reporting reliability metrics or, more directly, unreliability due to failure events and/or trends, which in turn, necessitate corrective actions.

Assuring reliability can generally be viewed as two specific and major interrelated efforts:

a) concept and design phase, and

b) the operational and maintenance (O&M) phase.

During concept and design evidence of prior product failures and system history and current testing data are used to estimate the reliability of the system(s). The evidence comes in the form of data from historical operation of existing plants that has sufficient breadth of information to provide the basic reliability information as well as attributes such as the failure distribution (e.g., normal, Weibull, exponential, etc.), failure mechanisms and failure modes, and required corrective actions. With rapidly advancing technologies the concept and design phases also require using engineering judgement, experience, design trade-off assessments, and design/reliability testing of new components for developing failure models. For instance, understanding the physics of failure applies to the design assessment.

During O&M, the owner/operators and the O&M contractor implement a failure detection and data acquisition system that likewise provides data for analysis of the current failures including root cause, failure modes, and failure rates by documenting and tracking the failures and then using the data to develop corrective action plans and when feasible changing the design to accommodate new stresses or to correct a flawed design.

Effective reliability practices will reduce overall system costs through reduction of failures and their consequences. There are initial costs associated with design analyses and reviews, component selection, and analysis of reliability testing. In this context, reliability should be viewed as an investment in the plant or company future. Failure to perform reliability practices results in a low reliability product and its ramification of extended costs for field repairs and replacements, impact to energy generation, problems during warranty, or worse, the loss of business.

This document continues the effort started with the availability technical specification (IEC TS 63019). Availability is closely related to PVPS operational capability, health and condition and to produce energy and is a real-time or historical measure. The availability of a system or component is impacted by contractual and non-contractual reliability specifications, maintenance metrics and a corresponding maintenance and repair strategy, and also external factors such as site environmental and grid conditions. Reliability has a focus more closely aligned on the capability of the components, their health and condition, systems to sustain production, and what manner of operations, maintenance, analysis and actions are effective for economic asset management of the PVPS.

The PV industry has had a recent period of rapid growth of installations. Existing PV plants are starting to age. Concurrently, new and evolving products are being introduced and a lack of reliability data is a general issue of concern as often there is insufficient testing or test data to properly assign the reliability attributes to these new technologies. This goes to the intended function of the systems, which is a topic for addressing through reliability analyses to determine the impact of known and unknown (postulated) failures and/or the effects of underestimated declining performance. There has been expressed levels of dissatisfaction for many plants not meeting power/energy expectations and, in some cases, this has led to plant shutdowns or expensive upgrades or down rating (derating) of the plant. In some instances, the loss of or the renegotiations of power purchase agreements has also occurred.

Clarity is needed to specifically address issues of the intended function not meeting appropriate specifications, and to numerically assess reliability performance and economic impacts. Throughout, there is competition in the market with cost pressures and without the expectations of continuous process improvement, those pressures will continue to exist.

The motivation for addressing reliability in the implementation and operation of a PVPS is founded in the desire for long lasting energy performance, energy production, secure production and revenue, and safe function. Management of a PVPS may come in many forms, but for reliability to be properly addressed, it is derived from a commitment to establish practices from the beginning development of concept and plans to take necessary actions and financial investment to ensure results and avoid the costs of unreliability. The commitment for reliability must begin at the highest levels of the organization and for those who have financial risks in the project, the course of action must be defined and implemented in a manner similar as that of environmental safety, health and quality. This document is supportive of that approach and defines methodology for accomplishment.

An intention of this document is to be a precursor examination of the reliability issues for further address in a task to produce an IEC Technical Specification on this topic.

While this document identifies reliability tools, topics and procedures, there are commercial products available to perform analyses and there is no assessment of those tools or to provide recommendations for one tool over another in this document.

PHOTOVOLTAIC POWER SYSTEMS (PVPSs) – ROADMAP FOR ROBUST RELIABILITY

1 Scope

PVPS component and system reliability engineering works to define the PVPS probability of making the indicated value such as energy or revenue, also at a given statistical confidence level for an estimate. This needs to be assessed properly as an accurate levelized cost of energy (LCOE) results from identifying and acting on a set of quantifiable metrics based upon real measured data of actual plants under the widest variety of real site conditions. In many instances, the use of P numbers (which stands for "percentile") may not be clearly understood and as a result, inappropriate conclusions drawn which have a financial result. P values are used to establish the confidence that one can require to provide the assurance that the item will meet specification. A P50 value, for example, provides that there is a 50 % confidence in the value used in reliability predictions. This value of confidence translates to the median of the population or in other words, it is equivalent to a coin toss on whether the value is valid. It is better to have a higher confidence that the system will work to specification. For reliability metrics, this is typically defined as being a P90 or P95 values. This level of confidence significantly characterizes financial and technical risk plant availability.

The failure rates and mode become important for predicting future failures. In a worst case, significant wear out failures may be indicative of serial failures and attention is warranted. A needed caution is the components may have multiple failure modes and root cause analyses may be useful discerning the failure modes.

The LCOE calculations may not adequately include all the relevant costs, i.e. all-in costs, and risks which create further uncertainty. That uncertainty has a high probability of coming to inaccurate conclusions and choices.

Ideally, the owners, maintainers and operators should look for reliability issues early in the concept, system, and hardware and software design engineering efforts. Otherwise, the defects in software code and poor design or weak components will manifest themselves in a multitude of unexpected failures resulting in unwanted and unexpected risks and costs.

In addition, there is another issue that is a by-product of unexpected costs. Organizational angst is the result of not addressing issues at specification prior to design that in turn results in organizational effort, time, and expense in the solving of problems (often originally simple) that become quite complicated after the plant has been built. Because this effort may not be adequately budgeted, and places additional stress on the organization, it tends to have a negative impact on the human performance of scope and adds risk to the PVPS performance.

Without analysis of accurate field data and metrics, there are a series of negative results that include unidentified or unexpected levels of plant failures and degradation. Lack of ongoing (from concept to end-of-life project phases) reliability analyses, the results of inaction raise unaddressed costs, risks, reduced plant capacity and capability, and potential for plant derating. All these issues could potentially result in substantial negative financial impacts to the owners, insurers, users and/or operators.

Reliability of a PVPS requires a comprehensive approach to identify, maintain, correct, and understand costs. Some critically necessary specific gaps for the PV industry need advancement:

a) A standard way to define failure statistics for PV, for PV components and specifically PV modules where failure can be either catastrophic- or degradation-driven. This can be accomplished by a bottoms-up fault tree nodal model with further guidance on how each of the nodal distributions can be derived qualitatively.

b) Defining a common nomenclature of describing failures in the field so that failure statistics can be gathered and analysed (i.e., failure coded or word search capability). Further there needs to be coordination between the various stakeholders to standardize data capture in a format that allows for meta-analysis. Different levels of data can be used for different or enhanced understanding of reliability issues depending on available technology and installed capability. Improvement in monitoring is assumed but there is a need to create standardization criteria, and details on data capture.

c) Defining a standard for how operational failure data is classified, root cause identified, and reported to aid objective b) with guidance or criteria established or cited.

Reliable systems, processes, and procedures produce energy more safely at a consistently lower cost while reducing waste, unnecessary labour, unplanned O&M, and unnecessary organizational angst while providing additional actionable information to continually build and operate better, higher producing and safer plants.

An obvious concern is that the system appears imposing at first sight. It is not the intention that the effort be a greater cost than its benefits. The resultant specifications and design shall fit the business /financial needs of the project. The cost of ensuring reliability needs to be weighed against the costs of not ensuring reliability at achievable levels. The types of data and commitment to data collection, however, should be tempered while addressing the initial and future data requirements. The Pareto techniques allow insights to be gained on the vital few as per the 80/20 % rule (see 7.11). However, much data needs to be collected and this provides references to other documents that address data.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-192, *International Electrotechnical Vocabulary (IEV) – Part 192: Dependability*

IEC 60300-1:2014, *Dependability management – Part 1: Guidance for management and application*

IEC 60300-3-3:2017, *Dependability management – Part 3-3: Application guide – Life cycle costing*

IEC 60812:2018, *Failure modes and effects analysis (FMEA and FMECA)*

IEC 61078:2016, *Reliability block diagrams*

IEC 61215 (all parts), *Terrestrial photovoltaic (PV) modules - Design qualification and type approval*

IEC 61649:2008, *Weibull analysis*

IEC 61703:2016, *Mathematical expressions for reliability, availability, maintainability and maintenance support terms*

IEC 62740:2015, *Root cause analysis (RCA)*

IEC TS 63019:2019, *Photovoltaic power systems (PVPS) – Information model for* availability

ISO 9001: 2015, *Quality management systems – Requirements*

ISO 55000:2014, *Asset management – Overview, principles and terminology*

IEEE 493, *DoD Failure Modes and Distributions, Gold Book*

3 Terms, definitions and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

The International Organization for Standardization (ISO) and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO online browsing platform: available at http://www.iso.org/obp

3.1 Terms and definitions

3.1.1
availability
ability of an item—under combined aspects of its reliability,maintainability, and maintenance support—to perform its required function at a stated instant of time or over a stated period of time

3.1.2
available state
where the PVPS, a subsystem, or a component is capable of providing service, regardless of whether it is actually in service and regardless of the capacity level that can be provided

3.1.3
confidence level
probability that the value of a parameter falls within a specified range of values

3.1.4
derating
a) using an item in such a way that applied stresses are below rated values

b) lowering of the rating of an item in one stress field to allow an increase in another stress field

3.1.5
failure
event or inoperable condition in which a PVPS, a subsystem, or a component did not, or could not, perform as intended when required

3.1.6
forced outage
damage, fault, failure or alarm that has disabled a system or component

3.1.7
inherent availability
steady state availability considering only corrective downtime and no other causes

3.1.8
lowest level of repair
lowest level of item (component, assembly, module, card, box, or subsystem) that is replaced as the result of failure of the end item

3.1.9
maintenance action
element of a maintenance event. One or more tasks (i.e., fault localization, fault isolation, servicing and inspection) necessary to retain an item in or restore it to an operable condition

3.1.10
maintenance event
one or more maintenance actions required to effect corrective and preventive maintenance due to any type of failure or malfunction, false alarm or scheduled maintenance plan

3.1.11
maintenance task
maintenance effort necessary for retaining an item in or changing/restoring it to a specified condition

3.1.12
maintenance time
element of downtime which excludes modification and delay time

3.1.13
maintenance:
actions necessary for retaining an item in or restoring it to a specified condition

3.1.14
Mean corrective maintenance time
MCT
basic measure of time needed for corrective maintenance

3.1.15
Mean Time Between Failure
MTBF
basic measure of reliability for repairable items. The mean number of life units during which all parts of the item perform within their specified limits, during a particular measurement interval under stated conditions.

3.1.16
Mean Time to Failure
MTTF
basic measure of reliability for non-repairable items. The total number of life units of an item population divided by the number of failures within that population, during a particular measurement interval under stated conditions.

3.1.17
Mean Time to repair
MTTR
mean time to replace or repair a failed component

3.1.18
reliability
probability that an item (component, assembly, or system) can perform its intended function for a specified period of time under stated conditions

3.1.19
repair
to restore equipment damaged, faulty or worn to a serviceable condition

3.1.20
repowering
planned event wherein the plant is repopulated with the latest generation of PV modules/panels, new inverters, power components, or mechanical items due to wear and fatigue

3.1.21
scheduled maintenance
planned repair or replacement of items before expected failure based on strong historical evidence. Includes preventive maintenance which is performance of maintenance before a known failure mechanism or mode can occur

3.1.22
unavailability
operational state when the equipment is not capable of operation because of operational or equipment failures, external restrictions, testing, work being performed, or some adverse condition

3.2 Abbreviated terms

EPC	Engineering, Procurement, Construction
FMEA	Failure Modes and Effects
FRACAS	Failure Reporting and Corrective Action
FTA	Fault Tree Analysis
KPI	Key Performance Indicators
LCOE	Levelized Cost of Energy
MCT	Mean Corrective Time
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
O&M	Operations and Maintenance
PFMEA	Process Failure Modes and Effects Analysis
PV	Photovoltaics
PVPS	Photovoltaic Power System
RAM	Reliability, Availability, Maintainability
RBD	Reliability Block Diagram
RCA	Root Cause Analysis
TR	Technical Report
TS	Technical Specification
YOY	Year on Year

4 Background

Asset managers and owners dealing with the PVPS failure to meet expectations or specifications and the resulting field problems share these concerns and can benefit from the reliability discipline and its toolkit of analyses and approaches. A key objective of this document is to advise users of recommended reliability topics and tools, related information, and approaches for use in predictive and assessment analytical models, all in order to satisfy the stakeholders' needs for dependable PVPS operation. Stakeholders will be able to use this information as a common basis for reliability assessments, effective O&M planning and execution, reporting and communicating of field data and reliability metrics. Reliability feedback to stakeholders is an objective to be defined by the stakeholders themselves. Individual stakeholders will have differing needs for data and reporting and shall be sensitive to that variability of specific needs.

Many of these items can be used to support business case validation during the project phases and the ability to target critical components and discrete O&M actions that can have demonstrated value in practice. The resulting findings can aid as valuable lessons for future or next generation power plants. The lifetime goals for the components include real-time capability assessment and longer for reporting of reliability metrics. The overall application of reliability practices here is intended to be practical and reduce the costs of failure.

The concept of PV plant reliability stretches into many different aspects of planning, modelling, operation, and maintenance. The use of a systematic system engineering approach and using reliability and system engineering tools to define reliability can aid in several different ways.

- Financial modelling of PV plants will take into account a level of plant availability, usually measured at an inverter level of resolution (but sometimes even down to the combiner, string level or module level), which can be inferred by proper monitoring, data collection, and analysis. The reliability of key components has a direct impact upon the plant availability and therefore the financial model. By improving understanding of the reliability of critical and key components, informed decisions regarding the trade-off between higher cost, higher reliability and therefore higher availability can be made versus lower cost approaches that result in lower availability.
- The impact of component failures on plant availability can also be minimized by having an ample stock of spare parts. Through knowledge of failure rates as available, and restocking logistics and time, the parts inventory can be optimized for use and costs.
- Many of the key PV plant components are covered by warranty or guarantees for several years, but, following the expiration of the guarantees, understanding of the magnitude of component replacements should be derived from the previously developed failure rates. Given the long lifetime expectations for PVPS, particularly for electronic components, a good understanding of random and wear out failure modes and its impact on the maintenance policy is critical and this may require a component or subsystem level FMEA and failure estimation exercise. This is useful for maintenance reserve accounts and the financial model. This reinforces the need to capture reliability data from even before the onset of energization of the PVPS, not just at a contractual point of change later. This will be addressed as a requirement in a future technical specification to ensure sound and complete reliability data.
- There are forms of recoverable and unrecoverable degradation. PV modules may require replacement beyond a certain point of lost capability. Such degradation may or may not be considered failures per se and may not affect availability by its strict definition, but it does affect the overall plant performance and as a boundary case and even drive replacement of components or redesign of power plant as remediation. By understanding the probabilities of exceedance of degradation percentages, one can better estimate the risk and account for it adequately in a design and performance model. Clarity on intended function, definitions of failure, and how to address specification and determination is needed. It is considered that degradation greater than defined expectations is a reliability issue and is a topic for consideration.

5 Interrelationship of Reliability, Maintainability and Availability (RAM)

5.1 General

The discipline of reliability analysis often uses the acronym RAM derived from the combination of reliability, availability, and maintainability. The reliability, availability, and maintainability (RAM) attributes can be assessed using several commercial tools and standard methodologies that provide for the assessment and understanding of the current and future state of the PVPS. In addition, this data provides a means to make improvements in the current plant and provide the basis for improved specification for future plants.

Availability is a higher-level metric and a mathematical function of both reliability and maintainability and is addressed below.

5.2 Availability basics

Availability, as shown in IEC TS 63019, is an important aspect of PVPS. However, energy availability alone, as viewed as performance, does not allow one to determine or assess the status of the system with respect to underlying equipment failures, maintenance and trends. To determine the state of the plant as a design metric and or during operation requires detailed information about the inherent and operational availability and the principal metrics of maintenance.

Reliability is both a reported (through historical tracking) and predictive metric that stakeholders use to numerically characterize their requirements and use to verify that that the PVPS is meeting specification or contract. Various stakeholders' reliability metrics may require somewhat different PVPS attributes to satisfy their needs for detection of failure trends that lead to detriments in ability to produce power, increase operating cost, increase LCOE, or produce contractual defaults. and possible liquidated damages. The available state is where the PVPS, a subsystem, or a component is capable of providing power/energy, regardless of whether it is actually in service and regardless of the capacity level that can be provided.

High availability is facilitated through high reliability parts, and/or efficient and timely maintenance and is a critical component of a PVPS by which to maintain the ability to generate power/energy when requested or required. The information model includes categories for maintenance and the constraints of the external operating conditions.

Availability is a measure of the degree to which an item is in an operable and committable state (i.e. its health and condition). As such there are several different metrics related to availability based on the equipment reliability and maintainability attributes. Because the function of power/energy production depends on availability, resource, grid capability, and demand, this document addresses these states as part of the information model as categorized in IEC TS 63019.

Addressing the equipment, the operational availability, A_O, can be found as:

$$A_O(t_{op}) = \frac{Total\ up\ time\ (Operating\ Hours)}{Total\ up\ time + total\ Corrective\ Maintenance\ time}$$

Establishing availability requires reliability and maintainability data. For the purposes of this document, the time is tracked in the categories to determine the availability metrics for n items over the total time T or the operating interval t_{op}. In addition, there is an attribute called inherent Availability related to the MTBF and MTTR as:

$$A(Inherent) = \frac{MTBF}{MTBF + MTTR}$$

Time in reliability terms relates to the plant components (by category, such as transformers, inverters, fuses, combiners, etc.) working over some defined period of time. In addition, there is a consideration for the duty cycle that the equipment has during normal operation. The best-case scenario is that the sun shines every day over a year. If this is true, then the best-case result is that the plant sees 4 380 sunshine hours a year – minus the time that is lost until the insolation/irradiation rises sufficiently for the plant to provide power to the grid or its load.

The first is the cumulative reliability which is total operating hours (or cycles) nT, divided by the total failures to that point in time, x, from the day the equipment was turned on.

$$MTBF = \frac{nT}{x}$$

For example: 100 inverters (n) operating over 5 years or 15 000 h per unit (T) and having 100 total failures (x) implies that the MTBF is 15 000 h. The other is reliability trend data, which is usually based on performance over each month, quarter or year and the number of failures that occur in those periods.

$$MTBF(t) = \frac{nt_{op}}{x(t_{op})}$$

Where

n is the number of like items,

t_{op} is the operating interval, and

$x(t_{op})$ is the number of failures x as a function of the operating interval.

For this example, the inverters may have had 5 failures the first year, 9 the next, 15 for year 3, 20 for year 4 and 51 for year 5. The apparent reliability of 15 000 MTBF is now only 5 882 h.

The data along with deeper examination and expanded calculations allow for trend analysis, cost estimating, maintenance projections, spare projections, and more, as may be needed by various stakeholders.

Inherent Availability is the attribute of the equipment that accounts for the time to repair or restore to functional specification assuming that all equipment, support equipment, spares, and requisite manpower are immediately available.

5.3 Maintainability basics

Maintenance activities considers the relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair. Maintenance activities also consider the probability that an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.

For, example, the complexity of the inverter system and safety implications drives the skill level of maintenance personnel necessary and the local availability of the skilled person becomes critical. This implies understanding of service staffing levels, spare part availability and logistics play a critical role for central inverters and needs attention in the planning of the system.

That is, the less time, manpower and tools needed to affect a repair action improves the maintainability of the item. Thus, to specify maintenance attributes it is necessary to identify and quantify a measurable requirement. Maintainability has a generalized measurement metric of Mean Time to Repair (MTTR). There are other attributes such as Mean Corrective maintenance Time (MCT), and logistic maintenance that affect plant availability.

The mean time to repair includes such elements as time to verify the fault, troubleshoot (if needed), access, remove higher level items, remove, replace, verify the repair, reinstall higher level items and closeup the equipment. The logistics maintenance time shall include the elements from detecting the fault, dispatching, waiting for special test/support equipment (if needed), perform the repair (MTTR) and then return the special test/support equipment, return to base and the completion of the failure report.

5.4 Reliability basics

The mission or more accurately, the usage profile of a PVPS is to provide energy over its lifetime as efficiently and reliably as possible given the quality of the components and understanding of the site, grid, and environment. The term reliable however has little meaning or value since stating that something is reliable or more reliable implies a measurement that often does not exist, as we see in its use as a marketing term. Stakeholders in PVPS should understand that if the requirement exists for reliable equipment then it is required that the term should be defined, and a measurement value addressed in the specification along with how the requirement is to be verified.

Starting with the lowest level of repairability, the failure distribution should be established, and the definition of reliability specifically addressed. The generally used definition for reliability is: the probability that an item (component, assembly, or system) can perform its intended function for a specified interval under stated conditions. There are a large number of variables that can affect the life of a part or component or assembly and depending on the specific technology, i.e., semiconductor, power semiconductor, mechanical, electrical, and other part technologies, the reliability is heavily dependent on how the part is manufactured, how and where it is used, the operating environments, and the operating stresses.

The generalized form for the probability can be found in the Weibull distribution where the 3-parameter probability is found through:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

where

$f(t)$ is survival probability at time t,

β is the shape factor,

η is the characteristic life, and

γ is the failure free operating period.

Although it is possible to specify a failure free period for an item or even a small number of items, when component variability, manufacturing variability and operational variables are accounted for in moderate to large populations there is a finite probability of failure for parts beginning on day one. The 3 parameter Weibull is more often shown as a two-parameter probability with γ set to 0.

The characteristic life is derived from a plot of the failure data with the Mean Time to or Between Failure (MTTF or MTBF) given as:

$$\bar{T} = \gamma + \eta \cdot \Gamma\left(\frac{1}{\beta} + 1\right)$$

Where $\Gamma()$ is the gamma function and the failure free period is assumed to be 0. To find the probability of success one can use:

$$r(t) = 1 - f(t)$$

Users are referred to IEC 61703:2016. See 7.6 for additional discussion.

5.5 Link to IEC TS 63019

Building on the information model (Table 1) data will have already been collected for the outages of components and systems. Reliability information is needed from the lowest level of repair item to end items such as inverters, transformers, switches, etc. Forced outages have entry and exit points and the activities include response, diagnostics, logistics, repairs/replacements, and other associated activities. From this, availability can be calculated in accordance with IEC TS 63019 recognizing that other causes also result in outage time.

The coloured sections highlight areas where reliability considerations exist. The red section is for FORCED OUTAGES and that is where damage, fault, failure, or alarm has disabled components or systems. The repetitive nature and frequency of these events are a measure of the reliability.

The pink area of PARTIAL CAPABILITY identifies degraded as an optional category. Degradation is not necessarily a complete failure but rather a matter of degree where components may not be capable of performing their intended function at a level required, needed or expected. Some degradation is anticipated for components over time (aging), and degradation greater than expected is considered to be a reliability issue.

The yellow section is where OUT OF ENVIRONMENTAL SPECIFICATION situations occur and do damage to the system or components. These occur if the environmental conditions exceed the design capability and robustness of the components to operate and/or survive. While the damage is not an inherent failure of the PVPS, outages and equipment repair or replacements will be the consequence.

The orange highlight sections are where maintenance actions will require outages of components or systems. This is for necessary actions beyond the repairs or replacements under forced outages. Planned corrective actions are unique improvements or enhancements that may be determined to be beneficial for dependable and effective PVPS operation.

Suspended maintenance situations are outside of management control and can include force majeure impacts on the availability to perform maintenance activity. While restoration is important, efforts to mitigate and reduce failures in the first place is needed as can be facilitated during the systems concept and design phases and through improved O&M approaches as well. Data is an important contributor and is required to satisfactorily perform an analysis for PVPS components and systems. With reliability considerations in mind, a reliability pathway will also assess the issues inherent in the design and operation to forestall future failures and unreliability for service lifetimes of systems and components.

Table 1 – Information category overview for a PVPS (modified from IEC TS 63019:2019)

<table>
<tr><th colspan="5">Information categories</th></tr>
<tr><th>Mandatory Level 1</th><th>Mandatory Level 2</th><th>Mandatory Level 3</th><th>Mandatory Level 4</th><th>Optional Level 5</th></tr>
<tr><td rowspan="20">INFORMATION AVAILABLE</td><td rowspan="10">OPERATIVE</td><td rowspan="5">IN SERVICE</td><td>FULL CAPABILITY</td><td></td></tr>
<tr><td rowspan="3">PARTIAL CAPABILITY</td><td>Degraded</td></tr>
<tr><td>Derated</td></tr>
<tr><td>Other</td></tr>
<tr><td>SERVICE SET POINTS</td><td></td></tr>
<tr><td rowspan="5">OUT OF SERVICE</td><td rowspan="2">OUT OF ENVIRONMENTAL SPECIFICATION</td><td>Irradiance Received Below Threshold for Energy Conversion</td></tr>
<tr><td>Other</td></tr>
<tr><td rowspan="2">REQUESTED SHUTDOWN</td><td>Internal</td></tr>
<tr><td>External</td></tr>
<tr><td>OUT OF ELECTRICAL SPECIFICATION</td><td></td></tr>
<tr><td rowspan="9">NONOPERATIVE</td><td colspan="2" rowspan="2">SCHEDULED MAINTENANCE</td><td>Specific Services</td></tr>
<tr><td>Scope</td></tr>
<tr><td colspan="2" rowspan="2">PLANNED CORRECTIVE ACTION</td><td>Retrofit</td></tr>
<tr><td>Upgrade</td></tr>
<tr><td colspan="2" rowspan="4">FORCED OUTAGE</td><td>Response</td></tr>
<tr><td>Diagnostics</td></tr>
<tr><td>Logistics</td></tr>
<tr><td>Repair</td></tr>
<tr><td colspan="2">SUSPENDED</td><td></td></tr>
<tr><td colspan="3">FORCE MAJEURE</td><td></td></tr>
<tr><td colspan="4">INFORMATION UNAVAILABLE</td><td></td></tr>
</table>

The optional level 5 is an area where users can add clarity for situations and incidents and how there are treated and reported. For instance, degradation of modules is to a certain extent covered by warrantees and can be expected to be monitored in various ways including field. The maintenance activities are where O&M practices will play a strong role in reducing downtime and require extensive human activities on a continuous basis. Forced outages will occur randomly and the operator's planning and preparation will be needed for expeditious management.

6 Dependability

6.1 Dependability uses reliability tools and topics

The IEC has produced standards on the topic of dependability (IEC 60300-1 and IEC 60300-3-3). These documents have a strong relationship to reliability, and while they list generic practices for any technology, they contain appropriate guidance and select considerations for use that are summarized in this clause. The phases of a project have unique opportunities for addressing dependability and reliability issues and the resultant plans, designs and specifications will provide for means to make the PVPS more robust. Towards that end, these standards on dependability are organized according to the stages of the life of projects (ranging across concept, development, realization, utilization, enhancement, and retirement) recognizing that the dependability discussion applies functionally and care should be used to consider risks throughout the stages of the PVPS project.

Reliability and dependability differ significantly with respect to measurement. Reliability provides specific requirements that meet functional criteria while dependability is usually measured as being available or not. Dependability is a perspective of the user and may be thought of as fulfilling the stakeholders' requirements needs and expectations. Financial reliability can be considered in the perspective of Dependability. Its noticeably clear and fundamental metrics are fulfilled by the execution of the commitment as previously stated, to establish practices from the beginning to take necessary action to ensure results and avoid the costs of unreliability. Reliability is rigorous in that it is an exercise and process of aligning Dependability needs, numerically through analysis, specifications, testing and other procedures. In this, it is important to acknowledge that reliability must be designed-in, specified-in, and planned-in.

A summary of these phases and recommendations with added PV specific elements follow.

The concept stage is the initial visioning stage for a PVPS. It can entail activities to identify market or other stakeholder needs, define/identify the general operational usage profiles, operating environment and timeline, performance and RAM requirements, human/organizational aspects or regulatory requirements (such as traceability, safety, environment, sustainability, retirement and waste disposal) and other constraints. From this, functional and non-functional requirements and the preliminary reliability requirements can be defined and analyzed for tangible feasible design or purchasing solutions identified from broadly detailed system technical specifications. It is recommended that effective and thorough project specifications are defined to establish requirements, needs and expectations prior to engineering, procurement, construction (EPC) bidding on the project.

Risk assessment during the concept stage should focus on the feasibility of concept design and technology selection for project implementation. Selection of design options is based on the best practical engineering approach is to achieve requirements and manage risks within the constraints imposed. [modified from IEC 60300-1:2014]

During the transition to the development phase, most of the reliability tasks can be applied to the product to track progress toward contractually specified reliability metrics, assess the impact on the proposed system, and identify any weaknesses in the system and parts over the life of the project. This necessitates the application of prior history failure data validated with field-based measurements as well as failure modes and mechanisms where available application of root cause analysis data from prior failures is present.

The evaluation of the concept leads to the selection of the design, development, cost and schedule including operating and maintenance philosophy, strategy and field tactics, system architecture, engineering modeling and testing and an O&M strategy. A systematic evaluation of the integrated proposed supplier item functions and their interactions with external environments is conducted to validate the final configuration. Risks associated with the selected design are assessed in more detail and proposals to mitigate or eliminate the risks specified. Relevant modeling and probabilistic approaches can be used at this stage to achieve detailed dependability predictions in order to consolidate the design and specifications. [modified from IEC 60300-1:2014].

The realization stage implements construction and installation of final components. It will include detailed designs, specifications and in some cases, testing. The realized items can be a combination of hardware and software functions. Realization includes assembly of components, integration of the items' functionality, verification of subsystems, and installation. Acceptance procedures should be established with the customer with possible trials in the actual operating environment prior to commissioning. Validation should be a part of the trial to provide objective evidence of conformance to specifications. References to standards without further specification in contract terms or a Reliability Plan should be made explicitly clear. For instance, the extent of met station monitoring in a large PV field should be reflected in the drawings submitted for approval. An O&M strategy will be finalized for approvals. Commissioning of a PVPS will likely be a transitional effort into the first year of operation. [IEC 60300-1:2014]

The utilization stage is when the item is deployed for delivery of functionality or service with support for its operational capability by means of the established maintenance philosophy and O&M plans. An effective maintenance (or operation) strategy that provides reliability feedback will have appropriately been defined prior to utilization. The process activities include operating and maintaining the item in accordance with performance requirements, training for operators and maintainers to maintain skills competency, establishment of a service relationship, and record keeping on item performance status and reporting failure incidents to initiate timely corrective and preventive actions. Failure reporting should be done periodically with monthly, quarterly and annual summary reports being used to assess failure trends. Critical item performance should be monitored and checked on a regular basis to ensure that dependability, regulatory and quality of service objectives are met. Data collection and sampling can be used to estimate service dependability. Risk assessment during operation and maintenance can deal with issues that arise due to changing conditions [modified from IEC 60300-1:2014]

The enhancement (upgrade or repowering) stage is needed to improve plant performance and can apply to components or systems. The process activities can include hardware or software upgrades for additional maintenance and improvements simplifying procedures to improve operational efficiency. Relevant modeling and probabilistic approaches can be used to assess the impact of the possible enhancements and select the best solutions for risk assessment during the life of the plant.

Repowering considers and defines an approach to extending the life of the PV plant. It does so while providing emphasis on plant production and revenue, improving the system's performance, health and condition throughout its lifecycle (Balfour). Repowering is a planned event wherein the plant is repopulated with the latest generation of PV modules/panels, new inverters, power components, or mechanical items due to wear and fatigue. The Arrhenius formula can be used to calculate the effect of temperature on the aging of polymers and semiconductors.

This is often a cost versus benefit assessment to determine the return on investment on extending the life of the plant beyond planned retirement or to ensure meeting the contracted life of the plant. It is driven in part because of degradation or limited life of solar modules, connectors, and/or mechanical items such as fan motors and power components. It is understood that various PVPS installations will be operating under different business models and this should be factored into upgrades and/or repowering.

Some of the activities done in this stage include [modified from IEC 60300-3-3:2017]:

- hardware and software updates/upgrades and or replacements,
- collection and analysis of data specifically related to verifying capability of existing systems and their support plans and processes (O&M),
- process and system performance assessment from commissioning to upgrade or repowering date,
- addressing shortcomings of current processes and make changes as needed,
- evolution of maintenance and operational plans, including refinement of a spare parts strategy with observed failure rates and operator determination of inventory needs, and
- modifications of systems to achieve changing requirements and more certain data including the refinement of a spare parts strategy once actual failure rates are better understood.

The enhancement stage dovetails with the PLANNED CORRECTIVE ACTIONS in IEC TS 63019. It categorizes actions needed to correct or mitigate problems or inadequacies of design relative to the operating environment of functional/performance needs.

For complex items, a strategy of decommissioning could be established to formalize planning and implementation of the decommissioning process to meet regulatory and/or contractual requirements. In addition, benefits (i.e. negative costs, or income) may result from reclamation, recycling, sale, or re-deployment [IEC 60300-3-3:2017]. However, site restoration may be addressed in permitting documents where the site shall be returned to its initial use, or as per other agreements by property ownership or regulation. This is critical to include careful consideration of the impacts of the system, its design, construction in all the activities that will take place during its lifecycle.

6.2 Stakeholders interests throughout the PVPS

The stakeholders have many overlapping interests regarding reliability. As identified in the previous clause, many of these elements are used in the early phases of a project and then the focus evolves with utilization/operation with failures, corrective actions, and the understanding the resulting performance consequences to the PVPS. The stakeholders will have inherently different risks and thereby different information needs. Table 2 provides a simplified illustration of primary interests, topics and metrics that are used and useful albeit still interdependent with the other stakeholder roles.

Table 2 – Primary reliability interest of stakeholders

Stakeholder	Interest/objective	Tools/topics	KPIs/metrics
Owner	Dependable Profitable	Reliability Plan Risk assessment Management	Revenue stream PVPS health and condition Availability Data analytics/Pareto Life Cycle costs
Financier	Profitable/ Sustaining	Reliability Plan Risk assessment PVPS Management	Revenue stream PVPS health and condition Availability Data analytics/Pareto Life cycle costs
Insurer	Dependable Risks managed	Risk assessment FMEA	FMEA Failure rates Actuals Claims data Root cause Fault tree
Prime contractor/ EPC	Defined Requirements	Production modelling Predictive reliability Acceptance testing	RBDs Performance models Critical items
Manufacturer/ Vendors	Product design Dependability	Environment Usage Product testing Field feedback	Failure rates Warranty exposure Root cause
Operator	PVPS management Production Performance	Management Production modelling Predictive reliability Dependability	Revenue stream PVPS health and condition Availability Data analytics
Maintainer	PVPS health and condition Repairs/replacements	Training Qualification Reporting system Troubleshooting/ Repair	Failure characterization Time of effort Documentation
Off-taker	Dependable Available	Production modelling Data analytics	Availability Revenue stream
Regulators/ Grid operator	Dependable Available	Production modelling Data analytics	Availability Data analytics

7 Reliability tools and topics

7.1 General

Recognizing that industry approaches and terminology are varied; this work will begin with established best practices suitable for stakeholders. The term "without failure" in the reliability definition shall be further clarified by establishing population size, failure distributions and confidence levels through data analysis and/or assumptions. Failure distributions and restoration times are useful measures of the frequency or repairs/replacements, maintainability, and serviceability of components and systems. Repairs are dependent on spares inventories, logistics, labour, and tool resources. These can be addressed by logistic and maintainability models.

The operation of a PVPS will depend on the budget, siting, scope, environment, specification, design, and planned O&M of the project. Embedded in these costs, concept and system design decisions are the impacts on the reliability. Considering reliability early in development will aid both availability and reliability of the system. Some of these factors and items for consideration are considered in this document.

Reliability is closely related to dependability in that reliability considers all aspects of the environments, usage and user profiles. The application of reliability practices here is designed to be practical and reduce the costs of unreliability. The objectives are:

- To maximize production while optimizing life cycle costs (LCC)
- To maintain lifetime goals of plant components
- To provide a standardized approach to characterize reliability and unreliability for a PVPS
- To provide standard methodologies for determining the appropriate forms of RAM predictions and assessments of the PVPS over varying time periods including real time capability assessment or longer for reporting of reliability metrics to stakeholders
- To provide basis for reporting comprehensive reliability metrics to stakeholders, including
  - Product design and performance improvements
  - Financial asset management and technical risk assessment O&M strategies and optimization improvements
  - Regulatory reporting requirements
- To collect appropriate O&M data into a database to determine historical PVPS condition and metrics for future analyses including remaining useful life expectations under specified operating parameters
- To provide a comprehensive digital record keeping and data system
- To optimize the life cycle cost over the life of the plant to include repairs, upgrades and enhancements.
- To address specification as a function life cycle cost control and energy production by effectively providing a component cost analysis over time

This document puts forward recommended practices for a basic set of reliability tools to be put into place by a designated and assigned party of the project team, who has access of the field data produced. The data comes from field and site operations, the manufacturer or independent 3rd party testing. Other roles for reliability assessments should be determined by the management of the ownership and key stakeholders for lifecycle PVPS management. These best practices and recommendations identified in this document have been developed as a precursor for an IEC Technical Specification and will be further refined and addressed for the operational period of a PVPS in that future TS.

The following illustration Figure 1 shows that with the employment of select tools certain information flows occur with an expectation of understanding PVPS unreliability and its consequences. The boxes indicate tools and the arrows show an interactive information flow. These are addressed below.

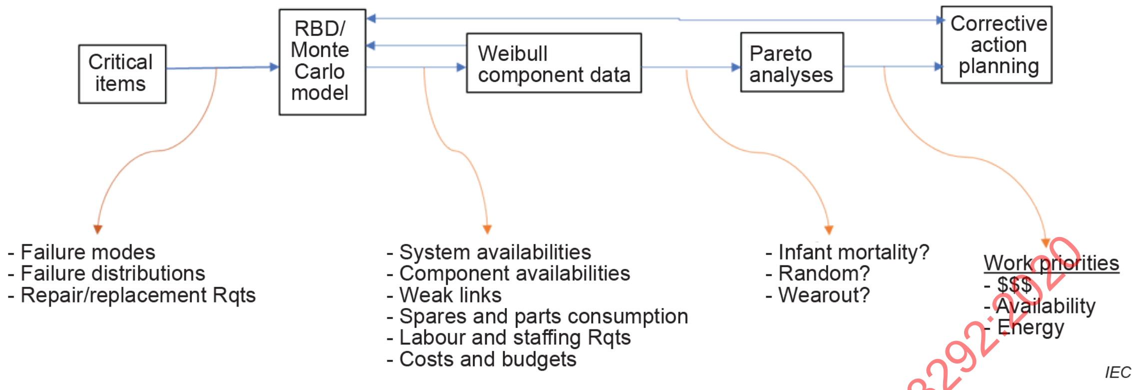

Figure 1 – Reliability tools information flow

It is recognized that reliability practices cannot be adequately performed without adequate management budgeting, specification, commitment, and planning. The IEC has numerous standards that can be used to generically address the needs of and approaches for reliability and this document builds on those with specific adaption for PVPS use. The items shown above in boxes represent some of the reliability topics and tools which are needed for the implementation of a reliability plan to accomplish the goals stated throughout this document. These are further identified and described in the following subclauses.

7.2 Reliability Block Diagram (RBD) / Monte Carlo simulations

What:	A graphical representation to illustrate the PVPS and model functions for calculations of reliability performance.
Why:	The system availability can be calculated based on assumed failure data that eventually is replaced with actual PVPS data.

A reliability block diagram (RBD) is a pictorial representation of a system's successful functioning. It shows the logical connection of (functioning) components (represented by blocks) needed for successful operation of the system (hereinafter referred to as "system success"). Therefore, an RBD is equivalent to a logical equation of Boolean variables and the probabilistic calculations are primarily related to constant values of the block success/failure probabilities.

The purpose of the RBD is in evaluating the availability, reliability, failure frequency, costs and other dependability measures as may be applicable to a given system or component should be examined by the analyst prior to deciding to use the RBD (IEC 61078).

An RBD for a PVPS will illustrate the highly modular design of a PVPS and the repeated nature of subsystems. It is similar to a one-line diagram and can be used for comparative purposes especially for understanding lost energy due to faults in specific equipment. Further, these highly repeated design blocks also provide a way to address common mode failures across that PVPS such as those found in defective software or common component that is not properly rated for operation in the equipment. An RBD can be used for probabilistic calculations knowing or assuming failure rates. It can identify weak links that lead to quantified losses of availability. RBDs can be used for parametric studies to overcome poor performance through design alternates and the knowledge of about maintenance for failures, spare parts consumption logistical impacts on availability. It can be used prior to design completion or afterwards for determine tradeoffs or enhancements. It can help to anticipate, understand, and/or prepare for failures and this is useful for minimization of technical risks. However, once the operational phase (utilization) begins, the reliability focus will be on unreliability; that is failures that will need to be identified and reported, repairs implemented and as possible, problems corrected.

The RBDs are often used in combination with Monte Carlo simulations. The simulations can be used to assess system and component reliability and availability using the failure and repair distributions (assumed or actual based on PVPS data of failure and repair, manpower, parts consumption, logistics and times). By using the RBD as a model and assessing the results of the simulation, opportunities can be discovered for improving system and component availability, costs, and uptime. The modelling will allow for revision after operation to address identified weaknesses and improve performance. The Monte Carlo models provide understanding and insight using data and have predictive value. It is useful for determination of using equipment with lower failure rates, manpower on site verses strategic response time, and stocking levels of part, and other trade-offs.

The process addresses both reliability and availability and is used through simulating random processes of failures over life, repair and replacements. It is expected that initially these items will be made using best estimates but over time it can be repopulated to either confirm the estimates or understand the impact of plant reliability performance to determine impacts and need to PVPS enhancements or O&M modifications.

Some key parameters to determine the availability impact are:

a) The 'failure rate' of a component as provided by a manufacturer, and how that failure rate changes over time (i.e. year 1 failure rate is different to year 15 failure rate);
b) The manpower time to repair that component, and the availability of manpower on site;
c) The availability of spare parts, and lead time to receive spare parts if none are available on site;
d) The impact of the failure on availability – whether it stops generation of a section of plant completely (for example an inverter part breaks), or whether it causes a power loss (for example a tracker is stuck in the wrong position);
e) Ways of assessing the power loss, and the impact on performance; and
f) The maintenance policy on occurrence of events and costs for such maintenance.

The Monte Carlo assessment is useful for these aspects, providing a calculational basis for their derivation and this can be the basis for economic decisions.

7.3 Failure Modes and Effects Analysis (FMEA)

What:	Potential failures are identified and the effects of each is considered to determine the need for design or specifications changes required to eliminate to mitigate the failure effect.
Why:	To eliminate or mitigate consequences of failures. The advantage is that this is done during the concept and the design and development stage when the cost to fix a problem is at its lowest.

An FMEA is a systematic method of evaluating an item or process to identify the ways in which it might potentially fail, and the effects of the mode of failure upon the performance of the item or process and on the surrounding environment and personnel. This document describes how FMEAs are performed. The purpose of performing an FMEA is to support decisions that reduce the likelihood of failures and their effects, and thus contribute to improved outcomes either directly or through other analyses. Such improved outcomes include, but are not limited to, improved reliability, reduced environmental impact, reduced procurement and operating costs, and enhanced business reputation.

FMEA is the application of physics to the failure modes and mechanisms (the stresses that can induce failure). The FMEA addresses a single failure mode (such as leakage, voltage overstress, mechanical overstress, etc.) and determines what the effect is at the local and system levels. The tool is useful in finding potentially weak areas of the design as well as identification of critical failures or ones that result in the major loss of power in the plant and identifying appropriate measures for mitigation.

For a PVPS, the FMEA, will include identification of the technical risks to reliable operations throughout the process of design, manufacturing, testing, transport, installation, operations, maintenance. All risks will need to consider the environment in which these aspects take place, known and anticipated risks to specialized components of the PV modules and inverter, and conventional risks to PVPS infrastructure. The components will be subject to accumulating faults and failures of PV modules, arrays, inverters, wiring, connectors, and structures. Special environmental concerns of the PVPS exposed to the elements over the life of the plant include cumulative damages to heat, wind, dust and soiling, biohazards, and neglect.

It is recognized that appetite for risk or risk tolerance will vary by differing stakeholders. This fact should be acknowledged and considered in the plans implementing PVPS reliability as a constraint on project implementation

An FMEA provides a systematic method for identifying modes of failure together with their effects on the item or process, both locally and globally. It may also include identifying the causes of failure modes. Failure modes can be prioritized to support decisions about treatment. (IEC 60812: 2018)

7.4 Fault Tree Analysis

What:	A top down or bottoms up process of defining problems and through combinations of failures, find the root issues for correction or mitigation.
Why:	The tool can aid design decisions and help to inform inspection and maintenance strategies. The understanding of fault consequences can aid in consideration of capacity, redundancy, and features to isolate faults.

Fault Tree Analyses are a tool to combine data from reliability predictions or data, failure modes and effects analyses and safety assessments to generate a cumulative failure rate or probability of occurrence of a specific plant or end item failure. This is a tool to also identify high cost or consequence failures such as the main substation transformer. Some failures also can lead to safety issues such as the increasing rate (year to year) of fires caused by solar systems. Useful in design, weak links can become apparent and identify areas where special provisions are needed.

7.5 Failure Reporting and Corrective Action System (FRACAS)

What:	A system for identifying, assessing and implementing O&M actions to systematically removing recurring reliability problems.
Why:	Fixing reliability problems requires data. The data is needed to record and analyse the root cause in order to take actions to correct or mitigate the failures.

FRACAS is a process for gathering data needed to determine the MTBF or MTTF metrics for items that fail. The data provides the basis for further assessment of the failures to determine the failure distributions and the potential for common cause failures which supports Root Cause Analysis (RCA) which is the determination of the source of the failure. It also provides the source of capturing the various times needed to determine the mean time to repair, maximum corrective maintenance time and the various additional metrics that support the assessment of the total cost of a maintenance action.

This process is needed as the problem statement defined the need to define a common nomenclature of describing failures in the field so failure statistics can be gathered and analysed. Coordination between the various stakeholders to standardize data capture in a format that allows for both individual plant assessments as well as industry wide standardization.

A failure incident report was identified in IEC TS 63019. Such reporting of failures forms the input to subsequent database for stakeholders to be shared consistent with accepted processes of confidentiality. Another need is that a large accumulation anonymized data, similar to that of IEEE 493 Gold Book, be created for industry wide benefit. Another aspect of failure reporting and corrective action exists in the management of the supplier customer interface. Certainly, warranty coverage is one process but for improvement of reliability more is needed. Feedback to suppliers of field failures and other performance metrics is a form of data sharing. The management and practices of this will be up to the parties involved, but with mixed failures and causes (and returns) this is important to all parties. The customer, armed with armed with failure modes/conditions and other data, will inform vendors considerations of improving the function of products. The supplier can add population data from other customers and the Nevada format of data collection may be useful when examining many product returns. It is expected that systems engineering for improvement will come from pertinent data, some degree of analysis and assessment, providing feedback, and setting of reliability goals. The goal setting should be motivated by business needs and as a function of the organizations' preference for risk management. A best practices process or criteria for such asset management from a logical and business standpoint is derived from an effort to ensure that new products should be at a minimum equal or better than prior experience and supports the spirit of continuous improvement.

7.6 Maintainability and other RAM terms

What:	The measure of a component or systems to be retained or restored to the level of its intended function and specification, often in units of time.
Why:	Optimal performance of repeating maintenance tasks require considerable human, logistical, tooling, spares and consumables. The time and effort expended for service outages, repair and replacements, and condition verification is a recurring cost.

Maintainability is a metric of returning (or replacing) an item to service after a failure. It includes all actions for servicing and repair. Equipment deteriorates over time with wear and tear, and the stresses of the operating environment. Maintainability is generally stated as a time metric and the restoration time distributions are useful in the Monte Carlo modeling. Costs will be associated with this activity.

Users are referred to IEC 61703:2016. The introduction of that document refers to IEC 60050-192 which provides definitions for dependability and its influencing factors, reliability, availability, maintainability and maintenance support, together with definitions of other related terms commonly used in this field.

Some of these terms are measures of specific dependability characteristics, which can be expressed mathematically. It is important for the users to understand the mathematical meaning of those expressions and how they are established. This is the purpose of IEC 61703:2016 which, used in conjunction with IEC 60050-192, provides practical guidance essential for the quantification of those measures.

The use and practice of these terms is expected to be further elaborated upon in a future Technical Specification.

7.7 Critical items list

What:	The critical items are identified for increased attention due to the vital need to ensure appropriate resolution. Often related to critical components, they may require special attention to design, specification, testing, or condition monitoring throughout the lifetime phases.
Why:	This list focuses stakeholders' attention on the vital nature of these items on PVPS lifetime costs

The critical items list is developed in concert with a Pareto assessment process to identify the key reliability issues that can arise or are impacting at given point in time. The purpose is to focus on the equipment that is vital and has significant costs and/or consequences during problems. Consideration of these events are needed to adequately address the issues for corrective or mitigative approaches throughout the operational period.

With usual engineering practices, acceptance testing are tests to be performed on the components and systems to determine if the contractual requirements for function and performance have been met. Inspections will be included. Acceptance criteria should be pre-defined for determination of meeting the specifications. In PVPS systems, a record of performance over the first year of operation may be conducted before commissioning.

7.8 Data analysis

Reliability Analyses – Data from FRACAS is plotted and assessed for its characteristics. The data are then compared to attribute models to assess the failure trends, having excessive number of failures (MTBF/MTTF is lower than expected) and performing Pareto analysis to determine the driving items of maintenance. There are several useful distributions that can characterize the reliability attributes of an item. These are:

a) Weibull

$f(t:\beta,\mu,\gamma) = \frac{\beta}{\mu}(\frac{t-\gamma}{\mu})^{\beta-1}e^{-(\frac{t-\gamma}{\mu})^{\beta}}$ Weibull distribution is applicable to a broad range of failure modes and mechanisms.

b) Gaussian or normal

$F(t|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}}\int_{t_1}^{t_2} e^{-\frac{(t-\mu)^2}{2\sigma^2}}dt$ normal distribution applicable to items that have a wearout mechanism such as bearing, motors, brushes, etc.

The CDF is given by: $\frac{1}{2}[1+\text{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)]$

c) Log normal

$F(logt|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}}\int_{t_1}^{t_2} e^{-\frac{(logt-\mu)^2}{2\sigma^2}}dt$ normal distribution applicable to items that have a wearout mechanism such as bearing, motors, brushes, etc.

The CDF is given by: $\frac{1}{2}[1+\text{erf}\left(\frac{Logx-\mu}{\sigma\sqrt{2}}\right)]$

d) Exponential (a special case of the Weibull)

eTaking the Weibull 3 parameter formula above and setting gamma to 0 and beta to 1 then

$f(t:\mu) = \frac{1}{\mu}e^{-(\frac{t}{\mu})}$ or $\mathrm{F(t)} = e^{-(\frac{t}{\mu})}$

One advantage of the Weibull distribution is that it can be plotted in semilog format for "seeing" failure trends over time.

IEC 61649:2008 provides methods for analyzing data from a Weibull distribution using continuous parameters such as time to failure, cycles to failure, mechanical stress, etc. This standard is applicable whenever data on strength parameters, e.g. times to failure, cycles, stress, etc., are available for a random sample of items operating under test conditions or in-service, for the purpose of estimating measures of reliability performance of the population from which these items were drawn. The main changes with respect to the previous edition are as follows: the title has been shortened and simplified to read "Weibull analysis"; and provision of methods for both analytical and graphical solutions have been added.

The shape factor derived from the Weibull analysis identifies a means to understand the failure and failure trend (decreasing, constant or increasing failure rates).

When shape factor beta is $\beta < 1$, failure rates are declining (MTBF is increasing) with time as the components are have infant mortality failure modes, e.g., manufacturing errors (cold solder, incomplete attachment of parts), weak or defective parts, incorrect parts installed and or incorrect substitution of parts.

When shape factor beta is $\beta \approx 1$, failure rates are relatively constant with time and appear to occur randomly over time. When shape factor beta is $\beta > 1$, failure rates are increasing (MTBF is decreasing) with time as occurs with wear out, corrosion, erosion, fatigue and chemical (such as batteries) aging failures.

7.9 Root Cause Analysis (RCA)

What:	An informed approach to determine the cause of a failure. It considers the operational environment, appropriate historical data and seeks evidence to explain the failure.
Why:	The RCA is a precursor activity to the solution.

IEC 62740:2015 describes the basic principles of root cause analysis (RCA) and specifies the steps that a process for RCA should include. This standard identifies several attributes for RCA techniques which assist with the selection of an appropriate technique. It describes each RCA technique and its relative strengths and weaknesses. RCA is used to analyse the root causes of focus events with both positive and negative outcomes, but it is most commonly used for the analysis of failures and incidents. Causes for such events can be varied in nature, including design processes and techniques, organizational characteristics, human aspects and external events. RCA can be used for investigating the causes of non-conformances in quality (and other) management systems as well as for failure analysis, for example in maintenance or equipment testing. RCA is used to analyse focus events that have occurred; therefore, this standard only covers a posteriori analysis. It is recognized that some of the RCA techniques with adaptation can be used proactively in the design and development of items and for causal analysis during risk assessment; however, this standard focuses on the analysis of events which have occurred. The intent of IEC 62740:2015 is to describe a process for performing RCA and to explain the techniques for identifying root causes.

RCA generally serves as input to a remediation process whereby determined actions are taken to prevent recurrence of the fault/problem por for mitigation of consequences.

The RCA will most likely build on the troubleshooting experience in the field as the technician's role is the timely restoration of function. However, the circumstances of failure and determination of the root cause will likely be a role beyond that of the technician. The observation and documenting the field conditions of failure (data), will assist in the RCA and guidance can be expected derived from organization of FRACAS practices.

7.10 Long term trend analysis

What:	Data normalization, data filtering, aggregation and performs degradation rate calculations.
Why:	Excessive (unanticipated) loss of component availability and/or degradation is considered to be a reliability problem.

Tools for analysis of photovoltaic data help evaluate PV production data over several years to obtain rates of performance degradation over time. High frequency (hourly or better) or low frequency (daily, weekly, etc.) datasets can be expected but best results are obtained with higher frequency data. The preferred method for degradation rate estimation is the year-on-year (YOY) approach, available in degradation year-on-year. The YOY calculation yields in a distribution of degradation rates, the central tendency of which is the most representative of the true degradation. The width of the distribution provides information about the uncertainty in the estimate via a bootstrap calculation.

PVPS degradation becomes a reliability issue when it occurs at a greater rate than expected through the performance models and proforma estimates of revenues. Recent installation of high DC to AC rated PVPS is a conservative approach that can mitigate degradation with broadening the shoulders of the energy day.

With the advent of industry improvement activities such as the Orange Button standardized PV taxonomies and ontologies linked with additional reliability language, consistency in communications and reporting can be improved.

As previously stated, data and numerical analysis provides better understanding of the physical nature of the systems. The example below, see Figure 2 (Balfour and Morris, see Bibliography) addresses some KPIs over time that track various aspects of performance and is indicative of increasing failures and/or degradation. In this case, power capability degrades over time and likewise, availability declines and is recovered through maintenance actions. Both affect costs and revenues.

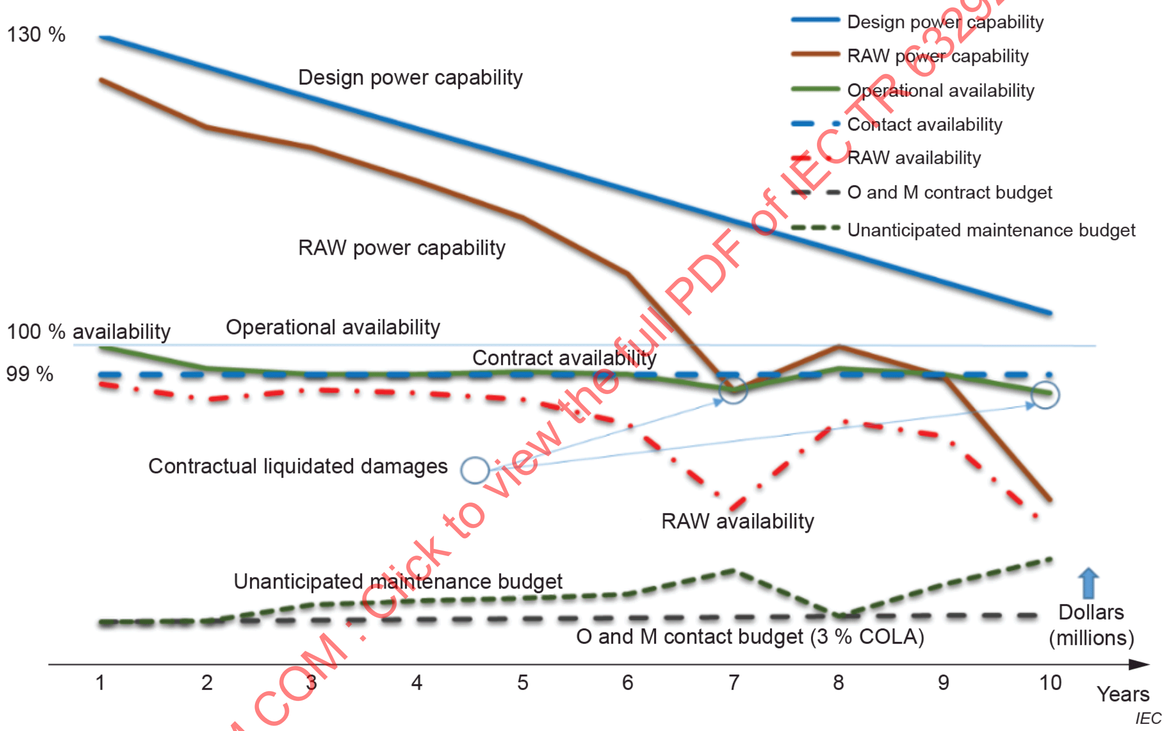

Figure 2 – Example of recommended metrics

The data plots indicate that the plant should potentially consider repowering after ten years as the raw power capability falling well below contract values in year 10. Failures need processing in any regard for keeping track of repairs, time, parts, consumables and expenses. A basic record of reliability incidents is provided in 7.5. The operations of the PVPS require much in the way of data to be produced including reporting to asset managers, financiers, off takers, grid regulators, etc. It is expected that reliability metrics or KPIs will be an important part of that full set.

7.11 Pareto analysis

What:	With consideration of the 80/20 rule, where 80 % of the problems comes from 20 % of the components, the Pareto principle focuses on the vital few problems first. A Pareto analysis will order sort events/actions according to cost, availability or other principle on a priority basis.
Why:	The Pareto distributions will determine prioritized actions for improvements of performance and/or economics.

Pareto analysis is a formal technique useful where many possible courses of action are competing for attention. In essence, the problem-solver estimates the benefit delivered by each action, then selects a number of the most effective actions that deliver a total benefit reasonably close to the maximal possible one. It is related to the identification of the "weak links" that may come from the Monte Carlo analysis.

Pareto analysis is a creative way of looking at causes of problems because it helps stimulate thinking and organize thoughts. However, it can be limited by the lack of standard categories and its exclusion of possibly important problems which may be small initially, but which grow with time.

Pareto analysis especially useful to management when the analysis and prioritization are characterized by cost.

The example in Figure 3 shows a Pareto prioritization following sorting of data that evaluates the frequency of extreme weather in work tickets in Figure 3.

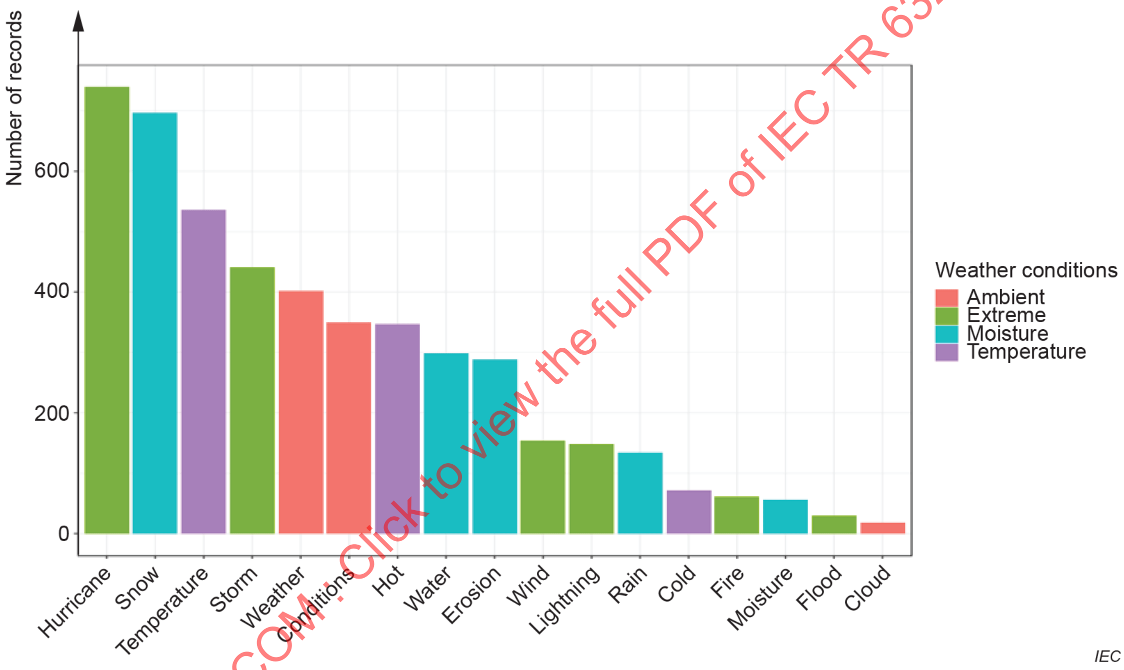

Figure 3 – Frequency analysis of key weather terms in the PVROM database

7.12 Risk analysis

The purpose of these tools is be useful for the effective incorporation of design, specification or operational approaches in the O&M practices.

A common purpose for reliability analysis is the evaluation of equipment performance and lifetimes. Reliability analyses for stakeholders are generally focused on evaluating potential failure, failure probability, and expected lifetime of the equipment and systems necessary for safe generation, collection, and delivery of electric energy from renewable energy resources, such that the overall project goals are met.

Stakeholders use reliability analysis and the estimate of equipment performance and lifetimes to better understand their risks, and likelihood of achieving project goals.

Several standard methods of reliability analysis are published to support qualitative and quantitative risk assessments in all industries. Some of the methods are referenced in Annex B. Organizations are best served by implementing reliability analysis methods judiciously and not prescriptively.

Reliability analysis methods are used within the framework of an organization's management system (e.g. ISO 55000, ISO 9001) to support risk assessments and better-informed risk-based decisions. Stakeholders apply different reliability analysis methods to meet different business objectives and goals. For example, a power plant owner uses reliability analysis methods to support asset lifecycle management objectives. An inverter manufacturer uses other reliability analysis methods to develop verification test plans for certification, time-to-market, and warranty objectives.

Not all reliability analysis methods are suitable for all stakeholders, and the resources required to implement the reliability analysis methods are not readily available to all stakeholders. The goal is to achieve the stakeholders project goals and objectives, within the resource constraints of the project.

Reliability planning helps stakeholders efficiently select suitable analysis methods for the organization's objectives and resource constraints. Reliability planning helps identify scenarios when and when not to use specific reliability analysis methods. For example, a manufacturer may plan to use Process Failure Modes and Effects Analysis (PFMEA) to mitigate risks on certain, but not all assembly lines, and only implement Root Cause Analysis (RCA) methods when equipment failure risks have changed to exceed a threshold set by the organization's risk tolerance.

Reliability analysis and risk assessment methods should be considered and supported by the organization's data collection and data management strategies to help achieve the project goals. The reliability analysis methods can be limited by the data collection and management strategy, hence the importance of reliability planning within the framework of an organization's management system.

Reliability planning ensures resources and conditions are identified to implement suitable reliability analysis methods. Suitable methods are capable of providing the correct form of a response with an acceptable degree of assurance.

7.13 Life cycle costs of reliability

As stated in IEC TS 63019, IEC 60300-3-3 is referenced herein to inform those who may recognize that costs form a constraint and are a necessary component of information management practices. Reliability theory and practice helps address costs because O&M actions related to failures can be managed and optimized for cost.

Users should be aware of IEC 60300-3-3, which offers various methods for cost estimating depending on the stage in the lifetime cycle.

Related and within the European Solar Bankability project, http://www.solarbankability.org/home.html, a risk priority approach was further developed by underlying cost caused by non-availability, malperformance, and unscheduled maintenance and repair, to "Cost Priority Numbers". See Solar Bankability http://www.solarbankability.org/results.html

7.14 Other reliability tools and topics

There are many other types and variations of reliability tools and topics and approaches. With a management commitment to reliability, it will be a function of the expertise brought to the PVPS project to identify and perform required analysis as derived from the asset management plan and or the reliability plan.