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TECHNICAL SPECIFICATION

Photovoltaic power systems – Reliability practices for operation

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PHOTOVOLTAIC POWER SYSTEMS – RELIABILITY PRACTICES FOR OPERATION

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The text of this Technical Specification is based on the following documents:

Draft	Report on voting
82/1993/DTS	82/2039/RVDTS

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

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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- withdrawn,
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INTRODUCTION

Key objectives of this document are to inform users of reliability tools and assessment methods (historic, predictive, and analytical) that can satisfy the stakeholders needs for dependable PV Power System (PVPS) operation. Stakeholders will be able to use this information as a common basis for reliability assessments, effective operation and maintenance (O&M) planning and execution, reporting, communication of field data, and reliability metrics. Reliability feedback to stakeholders is an objective to be further defined by the stakeholders themselves as individual stakeholders will have differing needs for data and reporting. This document provides a fundamental process for ensuring reliability needs can be understood and met. IEC TS 63019 addresses availability which is a higher-level metric that combines reliability and maintainability, and it complements this document as a key normative standard. It should be used in combination with this document.

Many of these tools and methods can be used to consider design alternatives or to support design validation during the project phases. The ability to target critical components and discrete O&M actions will have demonstrated value in practice. The characterisation of components lifetimes is derived from real-time capability assessments, and historical records of reliability metrics. Failure estimates used in design will be replaced with recorded data over time. The overall application of reliability practices in this document is intended to be practical and reduce the costs of failures.

Using a design for reliability (DfR) approach, normative requirements are identified for the development, engineering, procurement, and construction (EPC), and (O&M) phases of PVPSs. In this document, they are defined as tasks or work products. The concept of PV plant reliability stretches into many different aspects of planning, modelling, operation, and maintenance. The use of a methodical approach using reliability and system engineering tools to apply reliability practices aid in different ways. By improving understanding of the reliability of critical and key components, informed decisions can be made regarding the trade-offs between higher reliability and system component costs, or increased maintenance with lower initial cost approaches.

Original equipment manufacturers (OEMs) are key reliability stakeholders and will receive stakeholders' specifications addressing reliability inputs as well as field failure information. Clarity on intended function, definitions of failure, and how to implement reliability practices through the phases of PV system design, component and subsystem specification, operation and analyses are included.

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PHOTOVOLTAIC POWER SYSTEMS – RELIABILITY PRACTICES FOR OPERATION

1 Scope

This document outlines methods that can be utilized to ensure reliability throughout the PVPS project phases. It is derived from a management motivation for long lasting and cost-effective energy performance, energy production, secure production and revenue, and safe function. The application of reliability practices in this document is designed to be practical and reduce the costs of unreliability.

The reliability planning documents throughout the phases include purpose, scope, limitations, schedule, reference documentation, tasks, and standards. The work products build on the documentation concurrently with the PVPS concept, design, specifications, studies, procurements, and hiring of services. They are consistent with the project implementation scheduling, including financing, insurance, underwriting, or other decisions, specification, design, operating or maintenance planning and activities.

It is a phased approach, as there are specific needs for actions by the defined phases, decision process and stakeholders involved.

This document further identifies and defines a normative minimum set of processes and tools to meet the requirements of this document. The phases are development, EPC, and O&M. These phases may not be universally applied and different parties in industry may have different nomenclature and organizing principles. It is recognized that some organizations may be vertically organized with multiple capabilities. An owner’s engineer may also have a role. The thrust here is that however organized, the reliability tools, practices, and methods are assigned with needed data collected and preserved for relevant analytics as generally outlined in this document. It includes as a minimum, the identified work products and deliverables in this document identified specifically in Clauses 5, 6, and 7. Integrated reliability products are identified in this document on a task by task progression phased throughout the project. While these tasks are part of the minimum set of actions and deliverables, it is recognized that additional specificity is required. The reliability program plans provide clarification (contractual in many cases) on approaches through the various phases. The plans are approved by the management and/or ownership at the beginning of the phases. The expert practitioners may choose to seek approval for alternate approaches as “approved equals” as the reliability program plans (RPP) are optimized, clarified, and submitted for approvals. It is also acknowledged that commercial software can be a valuable and professional aid in implementation of analyses and tracking data and the plans are where those practices can be identified.

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While this document identifies normative requirements for reliability of an operating PVPS, it has functional definitions of the various tasks described above and below as the minimum set. This document performs the role of a functional specification and serves as a structure and an aid to data collection, design, and O&M decisions. It provides parent requirements for a subordinate family of documents that will describe in detail the scope and contractual elements for the design and O&M of the PVPS. The purpose is to drive improvement in the reliability of PVPS project approaches.

Some of these work products and documents are kept up to date through the phases as major decisions may necessitate. A historian system to keep, maintain data and analyses, and reports is kept for ready access of documentation needs.

Reliability metrics cannot be derived without important failure information. Determining the answers to common questions may require the PVPS operation to properly collect the requisite data, such as what equipment or portion of the plant is failing, how long, how often, and how much these failures will cost in repair and lost energy production? Asset management questions include the source of the outage (i.e., Whose clock is it on? Was the outage due to internal or external forces? What power/energy was generated? What was expected?). Effective reliability design integration should reduce overall system costs through reduction and/or mitigation of failures and their consequences. There are initial costs associated with design analyses and reviews, component selection, and analysis of reliability testing. Failure to perform reliability practices in both design/specification and operations/maintenance results in a lower reliability PVPS and resultant costs for field repairs and replacements, and the impact to energy generation.

It is important to address the OEMs' design role in the PVPS design. The scope of this document is primarily focused on the total system from a perspective of the three defined phases. Within the EPC phase falls the design and specification of components. Mitigation of the component reliability risk falls on the builder/OEMs as well as the owner/operators. After the EPC specifications, it is the OEM who designs, builds, and tests the components, considering the physics, environments, chemistry, metallurgy, and other parameters needed for robust operation, including specifications for materials and subcomponents. All aspects are considered as a "systems engineering" process (Incose) and maintaining the supplier/customer interface needs management in the warranty period and beyond in the following operations and maintenance. It is anticipated that some major components may be selected early near the time of financing the project. Failure assessments and reliability design integration of those components are made prior to specification and procurement.

Reliability assessments performed during the development phase help to support common probabilities of performance exceedance where confidence levels are often stated as P50 and P90. These are statistical probability numbers often stated as 50 % or 90 % confidence. For example, the P50 figure is the annual average (statistical) level of generation over a specified interval, usually a year. The P90 figure is the confidence that the annual generation that is predicted to be met or exceeded 90 % of the time, usually over a year.

These estimates are often directed toward the variability of the resource but the health and condition of the PVPS is equally important. The general attention to reliability, probabilities, statistics, and the process of "designing reliability in" is intended to bolster the important metrics of energy production probabilities. The reliability approaches of this document should also help to support the sale of the project and subsequent potential resales.

IEC TR 63292 was written as a precursor to this document and is informative with additional descriptions on the role of individual reliability tools and techniques as well as the benefits of those approaches.

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

A word of caution. An obvious concern is that a defined reliability system appears imposing at first sight. It is not the intention that the effort to have a greater cost than its benefits. The resultant specifications and design fit the business/financial needs of the project. The cost of ensuring reliability is weighed against the costs of not ensuring reliability at achievable levels over the life of the system.

It is not within the scope of this document to determine the method of information acquisition. IEC 61724-1 has pertinent requirements and IEC TS 61724-3:2016,6.2.5 specifically identifies measured data. These standards differ on approach for different levels of system nature and size, and it is recognized that applicability is most apparent for utility scale systems. However, the reliability aspects have like applicability for systems of any size and are recommended for appropriate use. The failures and impacts will be similar.

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The types of data and data collection systems are assessed for what is key and what is not while addressing the initial and future data requirements. The Pareto techniques later described allow insights to be gained on the vital few as per an 80/20 rule, where 80 % of the problems typically arise from 20 % of the components. Key data are collected for sorting by Pareto principles, and this document provides references to other documents that address data requirements.

Formulas in the referenced standards provide normative guidance for standardization. Examples and guiding principles for developing methods for calculation and estimation of reliability metrics, are subject to the knowledge and coordination for use by the involved stakeholders. Reliability aspects are critical, and the ownership and management of the projects define exactly the scope of what is to be done contractually and by whom.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes recommendations 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 60300-1:2014, *Dependability management – Part 1: Guidance for management and application*

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

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

IEC 61078, *Reliability block diagrams*

IEC 61649:2008, *Weibull analysis*

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

IEC 61724-1:2021, *Photovoltaic system performance – Part 1: Monitoring*

IEC TS 61724-3:2016, *Photovoltaic system performance – Part 3: Energy evaluation method*

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions, and symbols*

IEC 62740, *Root cause analysis (RCA)*

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

IEC TR 63292, *Photovoltaic power systems (PVPSs) – Roadmap for robust reliability*

ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995) – Supplement 1: Propagation of distributions using a Monte Carlo method*

IEEE 762-2006*: IEEE Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity*

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3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 and the following apply.

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

3.1.1
availability
ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided

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
dependability
measure of the degree to which an item is operable and capable of performing its required function at any (random) time during a specified mission profile, given that the item is available at mission start

3.1.5
derating
using an item in such a way that applied stresses are below rated values or lowering of the rating of an item in one stress field to allow an increase in another stress field

3.1.6
failure
event or inoperable condition in which a PVPS, a subsystem, or a component did not, or could not, perform as intended when required

3.1.7
forced outage
damage, fault, failure or alarm that has disabled a system or component

3.1.8
failure reporting and corrective action system
FRACAS
closed loop experience process used to improve dependability of current and future designs by feedback of testing, modification, and use

3.1.9
incident
event or inoperable condition in which a PVPS, a subsystem, or a component did not, or could not, perform as intended, or was prevented from operation due to external constraints

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3.1.10
lowest level of repair
lowest level of item (component, assembly, module, card, box, or subsystem) that is repaired or replaced as the result of failure of the end item

3.1.11
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

3.1.12
mean time between failure
MTBF
statistically based parameter (usually expressed in hours) that allows comparisons to be made between the reliability of different products

3.1.13
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

3.1.14
mean time to repair
MTTR
basic measure of maintainability assuming that all parts, equipment and personnel are immediately available

3.1.15
reliability
probability that an item (component, assembly, or system) can perform its intended function for a specified period of time under stated conditions per IEC TS 63019 as modified from IEEE 762

3.1.16
repair
to restore equipment damaged, faulty or worn to a serviceable condition

3.1.17
repowering
planned event in the service life of a plant wherein the plant is repopulated with the latest generation of PV modules/panels, new inverters, other power components, or mechanical items to increase energy production to original or greater levels

3.1.18
service life
time that any manufactured item can be expected to be economically serviceable or supported by its manufacturer

3.1.19
scheduled maintenance
planned repair or replacement of items before expected failure based on strong historical evidence. Includes predictive maintenance which is performance of maintenance before a known failure mechanism or mode can occur by periodic inspection, test or measurement

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3.1.20
systems engineering
transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using total systems principles and concepts, and scientific, technological, and management methods

3.1.21
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

DfR	Design for Reliability
EPC	Engineering, Procurement, Construction
FMECA	Failure Modes Effects and Criticality Analysis [sometimes referred to as Failure Modes and Effects Analysis (FMEA) in common or partial usage]
FRACAS	Failure Reporting and Corrective Action System
IEEE	Institute of Electrical and Electronics Engineers
FTA	Fault Tree Analysis
LLC	Life Cycle Cost
McT	Mean Corrective Time
MTBF	Mean Time Between Failure (repairable item)
MTTF	Mean Time to Failure (replaceable item)
MTTR	Mean Time to Repair
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
RAM	Reliability, Availability, Maintainability
RBD	Reliability Block Diagram
RCA	Root Cause Analysis
RPP	Reliability Program Plan

4 Interrelationship of reliability, availability and maintainability

4.1 General

The discipline of reliability analysis is mature and often uses the acronym RAM derived from the combination of reliability, availability, and maintainability. The RAM attributes can be assessed using 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.

4.2 Information model

Availability, as shown in IEC TS 63019:2019, Table 1 is an important aspect of PVPS. As indicated by the definitions of availability and available state in that document, there are multiple reasons for availability loss. IEC TS 63019 has identified and information model to map these causes. 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

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requires detailed information about the inherent and operational availability and the principal metrics of maintenance.

Table 1 – Information category overview for a PVPS

<table>
<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="13">INFORMATION AVAILABLE</td><td rowspan="8">OPERATIVE</td><td rowspan="3">IN SERVICE</td><td>FULL CAPABILITY</td><td></td></tr>
<tr><td>PARTIAL CAPABILITY</td><td>Degraded
Derated
Other</td></tr>
<tr><td>SERVICE SET POINTS</td><td></td></tr>
<tr><td rowspan="5">OUT OF SERVICE</td><td rowspan="3">OUT OF ENVIRONMENTAL SPECIFICATION</td><td>Irradiance Received Below Threshold for Energy Conversion</td></tr>
<tr><td></td></tr>
<tr><td>Other</td></tr>
<tr><td>REQUESTED SHUTDOWN</td><td>Internal
External</td></tr>
<tr><td>OUT OF ELECTRICAL SPECIFICATION</td><td></td></tr>
<tr><td rowspan="4">NONOPERATIVE</td><td colspan="2">SCHEDULED MAINTENANCE</td><td>Specific Services
Scope</td></tr>
<tr><td colspan="2">PLANNED CORRECTIVE ACTION</td><td>Retrofit
Upgrade</td></tr>
<tr><td colspan="2">FORCED OUTAGE</td><td>Response
Diagnostics
Logistics
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>

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This document continues the effort started with IEC TS 63019. Availability and performance are, in large part, determined by the reliability of components and subcomponents and the ability of the O&M process to expeditiously repair or maintain the plant in operable condition. Many different states (information categories) of PVPS operation can exist (Some of these follow in all caps consistent with IEC TS 63019 nomenclature).

Plant failures, both hardware and software, fall under the category of FORCED OUTAGE. Failure in this context is any malfunction regardless of source that results in a loss of power production capability other than uncontrollable external influences outside of specified limits. After FORCED OUTAGES occur, reliability and maintainability metrics can, to a certain extent, be derived from the activities to measure them. These affect the Mean Time To/Between Failure (MTTF/MTBF), Mean Time to Repair (MTTR), and Mean Corrective Maintenance Time (McT). Examining the subcategories leads to handling of response, diagnostics, logistics, and repair and restoration among other considerations. Degradation falls under the category of PARTIAL CAPABILITY and derating.

All outages and instances of unavailability are to be tracked by time series data systems with identification of cause and duration from entry to exit and extent of components affected, (individual component vs. total system impact) in accordance with IEC TS 63019. External impacts (i.e., curtailment) shall also be tracked with manual inputs as necessary.

4.3 Link to IEC TS 63019

Table 1 FORCED OUTAGES (capitalization consistent with IEC TS 63019 for information model categories) 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.

PARTIAL CAPABILITY includes degradation and possible plant or equipment deratings. These are not necessarily complete failures but rather a matter of degree where they may not be capable of performing their intended function at a level required, needed or expected. Some degradation in pink highlight, is anticipated for components over time (aging).

OUT OF ENVIRONMENTAL SPECIFICATION situations occur and do damage to the system or components. These occur if the environmental conditions exceed the design envelope, capability, robustness, or derating of parts against stress of the components to operate and/or survive. While the damage is not an inherent failure of the PVPS, considerations may include whether it should be assessed for future design or specification upgrade. Insurance and warrantees may be a factor for these environmentally caused damages. This is an example of where intrinsic and extrinsic factors both come into the O&M examinations, but the consequence is that outages and equipment repair or replacements will be the ultimate consequence. While the damage is not an inherent failure of the PVPS, outages and equipment repair or replacements will be the consequence.

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 ability 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, specification, 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.

The optional level 5 is an area where users can add clarity for unique 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. 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 for return to service.

These conditions might not be readily observed in good part because of an overbuild of the DC element of the system, and thus they fail to indicate ongoing deterioration and degradation of the system; an important consideration if energy storage is to capture this clipped energy.

IEC TS 63019 includes the topic of masking and provides the foundational definition: “PV system masking occurs when single and/or multiple system specification, defects, anomalies, total or partial faults, or failures evolve and negatively impact the condition of the system and its energy production capability but may not be typically or readily observed.” This is an example of PARTIAL CAPABILITY. These conditions might not be readily observed in good part because of an overbuild of the DC capacity of the system, and thus they fail to indicate ongoing deterioration and degradation of the system; an important consideration if energy storage is to capture this clipped energy. This masking is examined in the Renewable and Sustainable

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Energy Reviews (RSER) article. Figure 1 shows symbolically that the energy lost to clipping may in fact mask energy lost to other causes. Clipping time data accumulated historically can serve as a relative indicator of such masking and be more readily observable as referenced in this RSER article. Degradation greater than expected is a reliability issue.

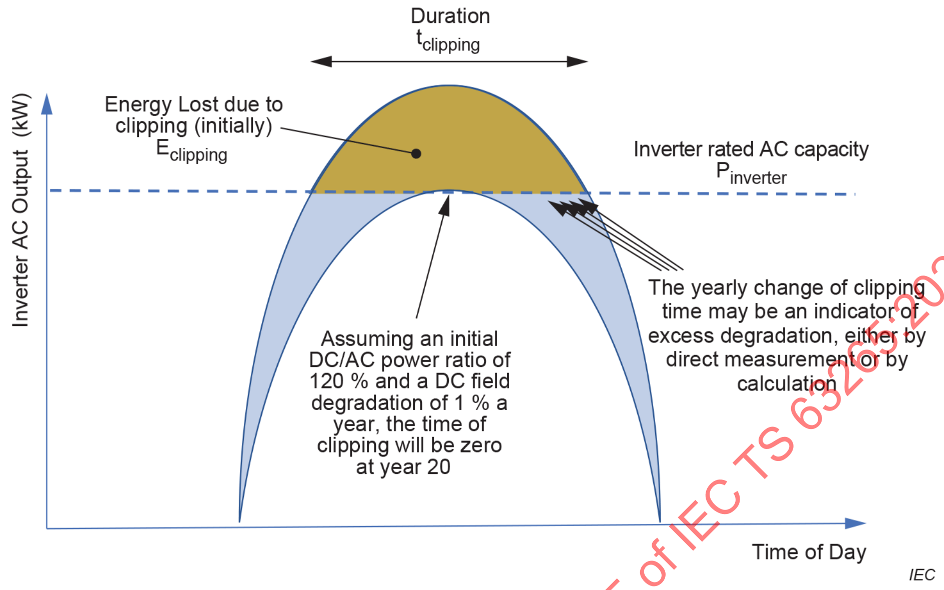

Figure 1 – Clipping time decline

4.4 Benefits and justification for a robust reliability program

IEC TR 63292 has been published not only to address the "what" of reliability, but to also determine the "why" of reliability. As such, it has more depth to some of the tools and topics of reliability practices and some other related topics, such as:

- Reliability basics (with formulas)
- Availability basics (with formulas)
- Maintainability basics (with formulas)
- Dependability
- Stakeholders' interests
- Risks.

5 Development phase of a PVPS project

5.1 General

Reliability plans define what is to be done and how it can be integrated with the design and specification of components, the larger PVPS and how O&M is to be accomplished with select deliverables, data collection, analyses, and reporting. Clauses 6 and 7 define additional reliability aspects and further clarification of criteria and plans should be made by the PVPS project ownership and management stakeholders.

5.2 Initial reliability program plan, design for reliability

The concept stage is the initial visioning stage for a PVPS. It will entail activities to identify market or other stakeholder needs, define/identify the general operational usage profiles, operating environment and timeline, performance and RAM requirements, system specification goals and objectives, human/organizational aspects, or regulatory requirements (such as traceability, safety, environment, sustainability, retirement, site restoration and waste disposal) and other constraints. From this, the functional and the preliminary reliability requirements shall

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be defined and analysed for tangible and feasible design or purchasing solutions identified from broadly detailed system technical specifications.

Effective and thorough project specifications, albeit preliminary, are to be defined to establish reliability requirements, prior to detailed engineering, procurement, construction (EPC) bidding on the project. There is recognition of the terms such as basis of design, asset management plans and it is the responsibility that by whatever nomenclature is given, that the performance and reliability aspects are properly identified and specified. The RPP shall include the specification of reliability tools and approaches as determined by qualified reliability practitioners throughout the phases as appropriate. All parties responsible for reliability actions are to be identified within the scope, inputs, outputs, and schedules of performance up to and including targets for reliability performance, as may be deliberately chosen. This document identifies the reliability tasks and attempts to initially define the depth by phases of the project.

It is recognized that appetite for risk or risk tolerance will vary by differing stakeholders. This fact should be acknowledged, documented, and considered as a constraint on project implementation.

Failures and failure rates are critical for the planning and estimates and a future database of them feeds the FRACAS process and other reliablity aspects. Throughout this process the analytic results shall provide feedback to design or operations. When issues are found that are identified that need remedy, or otherwise allow for improved performance or reduced costs, actions shall be determined and planned for modification or actions. Pareto prioritization, which is part of this document, is useful for asset managment, especially with regard to costs of alternatives under consideration for process improvements. Pareto guidance is generally to focus on the vital issues first.

The RPP may include items that are not causally related to the design of the PVPS but can pose risks to financial reliability such as accuracy of performance modelling, climate change, robustness of the grid, terms, and security of power purchase agreements, and other environmental, institutional, and/or force majeure impacts. IEC TS 63019 has a broad range of information model categories that can map availability (or unavailability) to these categories thus informing energy and revenue loss. Timekeeping for these items is required. In fact, in North America, availabilities and major loss events are under consideration as requirements from North American Electric Reliability Corporation (NERC).

Reliability assessments performed during the development phase help to support common probabilities of performance exceedance where confidence levels are often stated as P50 and P90. These are statistical probability numbers often stated as 50 % or 90 % confidence. For example, the P50 figure is the annual average (statistical) level of generation over a specified interval, usually a year. The P90 figure is the confidence that the annual generation that is predicted to be met or exceeded 90 % of the time, usually over a year.

These estimates are often directed toward the variability of the resource but the health and condition of the PVPS is equally important. The general attention to reliability, probabilities, statistics, and the process of “designing reliability in” is intended to bolster the important of metrics of energy production probabilities. The reliability approaches of this document should also help to support the sale of the project and subsequent potential resales.

Early project activities based on estimates of reliability performance will need to be replaced over time with actual PVPS data. Each phase will have specific needs and approaches. Analytical documents, design and specifications, and similar other records shall be kept from the initiation of a project throughout its lifetime of the PVPS. Creation of a Weibull or similar form of database of field component population failures shall be maintained for ownership (curated) during the warrantee period and for use after, and for new owners during a change of ownership. Obtaining, collecting and preservation of data is needed throughout the phases for reliability and other purposes. Data acquisitions feeds the data analysis and this is a function to be designed into the PVPS.

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As identified in Science Direct, *Design for Reliability* (DfR) "aims to understand, identify, and prevent underlying failures before the devices are built. In designing a product, engineers usually miss the following characteristics:

a) key failure modes and failure rate of the product,
b) key failure modes that may be present in the service environment,
c) usable life of the product,
d) cost of maintenance required to sustain the inherent reliability,
e) availability, and
f) rigorous testing.

DfR is a relatively new concept, and it is an important step in building the reliability of a product or component (in other words, to achieve built-in reliability)". IEC 61703 is useful for definitions of metrics regarding O&M practices.

It is expected that selection of modules and inverters may be well underway by the time financing is secured. The development work products should also be well underway concurrent with that selection with sufficient reliability assessments to support the selection process and to "design for reliability" of those and other interfacing components.

This initial RPP will need to plan the entire PVPS project through its phases, subject to future plans with more definitive guidance. It shall include outline specifications for scope of work activities implementing reliability throughout the PVPS project as well as stating the specific reliability approaches for the design and specifications produced for hardware acquisitions.

Development phase RPP work product:

- Initial RPP which includes early definition for the three phases and corresponding work products as outlined in this document. It may describe reliability targets and additional work products as determined to be necessary.

5.3 Critical items list

During the conceptual development of the PVPS, the siting, scoping, sizing, and other considerations formed during the initial effort are to be fully considered. Primary among these elements may be the early consideration of PV modules, inverters, trackers, and other critical components that form the PVPS. These components will be purchased, and the reliability input needs shall be met before procurement. They will require special attention to design, specification, testing, or condition monitoring throughout the lifetime phases. These components shall be identified by placement on a critical items list to ensure they are identified for increased attention due to the vital need to ensure that reliability is "designed in" for their operational life.

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The critical items list may be developed in concert with a Pareto assessment process to identify the key reliability issues that can arise or are impacting at any point in time. Many of these items shall be determined by required assessment of risks, in particular operating environments. The purpose is to focus on the equipment that is vital and may have significant costs and/or consequences of failures. Consideration of these events are needed to adequately address the issues for corrective or mitigative approaches throughout the operational period. The purpose of the critical items list is to focus management's attention on items that need to be resolved during development or the design phase as a corrective action loop for influencing the lifetime costs.

Many of these items will have standards, IEC and otherwise, that shall be applicable to function, design, operation, and limitations. Integration of selected components will form a constraint on how the remainder of the PVPS is integrated with them for design and operation. Environmental issues are of great importance and the FMECA assessment will have an interface with them, and the conceptual development and selection shall be integrated through concept and the EPC phases for fully integrated design (and specification) for reliability. Characterization of environmental conditions, for everything ranging from irradiance and performance to operating envelopes, limitations, constraints, limits, loads, etc., is required. From this may also come a definition and criteria of failure if performance is not met.

The critical item list helps to identify component specifications. Critical or not, these specifications shall also include design integration interfaces and specification that include reliability aspects. These aspects should include reference to design and manufacturing standards, environmental and operational parameters, quality, product testing, systems and acceptance testing, other features as determined by the EPC or whomever specifies the procurements.

The OEMs are key stakeholders especially as regards future business, reputation, product certification including required reporting, and in-field product reliability monitoring. The OEM (of many different components) is typically the most important stakeholder due to the fact that it is the party that can most easily prevent and later reduce the impact of unreliability of the PVPS. For example, any information that the EPC and/or plant owner has to properly address the known failure modes for the PVPS needs to be provided. The OEM shall be aware of the environmental, operational, and other constraining design conditions at the proposed PVPS. Management of this OEM and customer interface at this phase and later during operations is important, and communications and management of supplier/customer reliability interface should be addressed in the planning.

Development phase work product for identification of the critical items:

- Critical items list
- Site-specific environmental assessment (which is vital but not specifically a reliability product)
- High level but site-specific performance, operational, and functional requirements
- PVPS operational availability target as specified by the ownership management.

Stakeholder agreement on who gets what data produced throughout all phases of project, is needed for future incorporation of process improvements. Data and documents should be kept up to date through the phases as major decisions may necessitate. A historian system to keep, maintain data and analyses, and reports is to be kept for ready access of documentation needs.

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5.4 Preliminary failure modes and effects and criticality analysis and other fault analyses

An FMECA 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 systems, environment, and personnel. The purpose of performing an FMECA 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. An FMECA provides a systematic method for identifying modes of failure together with their effects on the item or process. It will establish how items or processes might fail to perform their function - the causes of failure modes, so that any required treatments can be identified. Such improved outcomes include, but are not limited to, improved reliability, reduced environmental impacts, reduced procurement and operating costs, and enhanced business confidence.

For the purposes of this document, we will use the FMECA term but in practice acknowledge the use of an FMEA as well. An FMECA addresses a single failure mode (such as leakage, voltage overstress, mechanical overstress, etc.) and determines what the effect is at the local, next, and system levels.

The IEC has developed IEC 60812 which explains how failure modes and effects analysis (FMEA), including the failure modes, effects and criticality analysis (FMECA) variant, is planned, performed, documented and maintained. This standard shall guide the FMEA and FMECA efforts. It is recognized that FMECAs will largely be repetitive with prior FMECA assessments except for site specific risks and new equipment and components that have limited field experience.

A Fault Tree Analysis (FTA) is required to assess the likelihood that the plant can have single mode or cascading failures and or safety failures that can lead to serious injury or death. The FTA utilizes the FMECA to establish the common failure effects and aggregates into an overall probability.

Recognizing that the development phase is conceptual at first, the FMECA, FEMA, and the FTA (further described in 6.3 will also be conceptual, identifying common issues and site-specific concerns, on a preliminary basis, and as background for the specification and further evolution of these failure elements for the next phase and prior to procurement.

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. At the development phase the site-specific environment is the primary prerequisite and work product that enables a preliminary assessment for critical component environmental envelopes.

Development phase work product for the Failure Modes and Effects and Criticality Analysis:

- Site-specific environmental assessment (in concert with critical items list application)
- Failure Modes and Effects and Criticality Analysis FMECA
- Preliminary determination of FMECA acceptability for items on the critical items list coordination and subsequent reassessment and use in the EPC phase (e.g., fault tree model).

5.5 High level reliability model

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 (hereafter 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 with guidance from (IEC 61078). Commercial software exists that provide the capabilities for these functions.

An RBD for a PVPS illustrates the highly modular design of a PVPS and the repeated nature of subsystems. It is like an electrical one-line diagram and can be used for comparative purposes especially for understanding lost energy due to faults in specific equipment. It can easily show where the outages may be at any instant during operation. These highly repeated design blocks also provide a way to understand common mode failures across the PVPS. Examples can be found in defective software or common components that are not properly tested or rated for operation in the equipment and system operating environment.

An RBD shall be created to model the PVPS. By populating the model with assumed or known failure rates and repair times, it can simulate the operation of the PVPS and provide various availability results. It can also identify weak links that lead to quantified losses of availability. RBDs can be used for parametric studies to overcome poor performance through design alternatives 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 determining enhancements.

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

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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.

Depending on the scope of the development phase, the simulations may be limited to the components identified by the critical items list and to support procurements prior to the EPC phase. See 6.4 for additional information.

As illustrated in Annex B of IEC TS 63019:2019, the following RBD, Figure 2, is a simplified representation at a high level (major components). Large PVPSs will have much greater numbers of PV strings, combiners, inverters, and energy with many more pathways in the DC and larger AC collection systems, Annex B of IEC TS 63019:2019 further addresses the issue of energy availability whereby the alternate methods of determining by resource and modelling-based performance (using IEC TS 61724-3), include energy-weighted availability approach, fractional specific power estimation techniques, and addressing lost production in the information model. These outages and other events are also elaborated upon in verification Clause D.7 of IEC TS 63019:2019.

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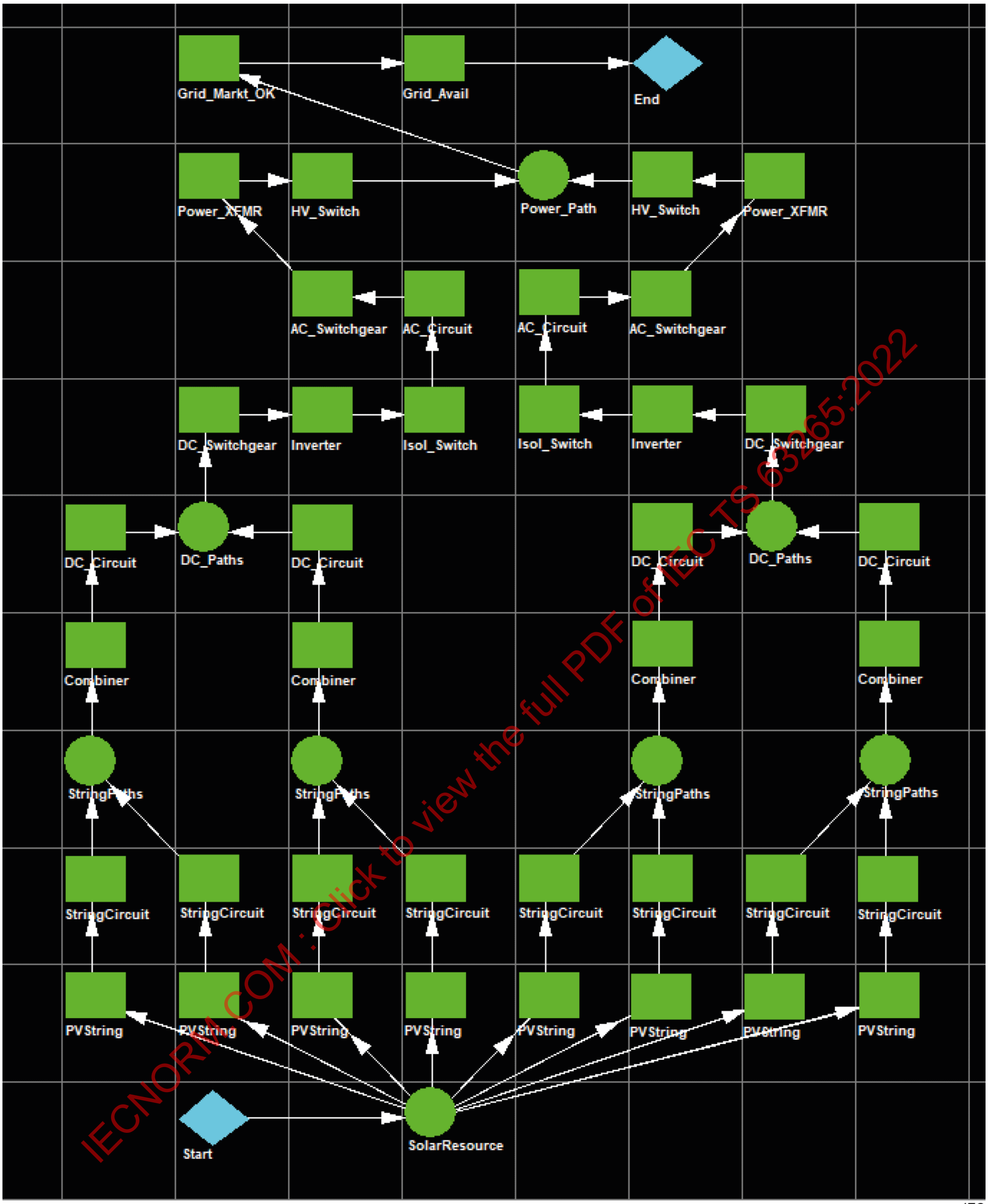

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Figure 2 – Example high level reliability block diagram

Development phase work products for the high-level reliability model:

- Failure rate estimates or mathematical distributions (at least for critical components)
- Repair/replacement estimates or distributions (at least for critical components)
- Spare part inventory estimates
- Availability assessment consistent and concurrent with conceptual design
- Reliability block diagram and simulation
- Report.

The high level RBD/simulation shall be populated at the components level in the development phase and a greater level of detail is expected during the later phases, especially for expected failure modes. Effective reliability design integration should reduce overall system costs through reduction and/or mitigation of failures and their consequences. There are initial costs associated with design analyses and reviews, component selection, and analysis of reliability testing. Failure to perform reliability practices in both design/specification and operations/maintenance results in a lower reliability PVPS and resultant costs for field repairs and replacements, and the impact to energy generation.

6 EPC phase of a PVPS project

6.1 General

Clarification and interfaces should be established in the respective planning documents. Organizational descriptions such as EPC may be referred to as Engineer in some locations. While many of these tasks will be performed by the EPC, it is recognized that some may be performed by the owner's engineer or other party, with needed reliability attributes included and prior to EPC bidding. Some PVPS projects may be organized differently from the phases identified it this document for instance, vertically integrated through all three phases. The requirements identified in this document should apply nonetheless with assignments to ensure appropriate application of reliability implementation.

6.2 EPC reliability program plan

The EPC shall review and refine the development RPP for items within the EPC analysis, design, and specification work scope. It shall include the specification of reliability tools for PVPS and its components, and approaches as determined by the qualified reliability practitioners throughout the EPC phases.

An approach to DfR shall be included in the RPP. It should identify considerations to be performed as a complementary activity with the engineering of the full PVPS through the actions of design, specification, and analysis.

The physical nature of the reliability issues in the operating environment provides opportunities to better understand failure mechanisms. root cause analysis (RCA) and updating the FMECA are necessary. There are many reliability tools and topics that can be used to analyse data and reliability specific aspects of engineering. Risk assessment during the design and specification phase 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. See IEC 60300-1:2014.

It is important to address the OEM's design role in the PVPS design. The scope of this document is primarily focused on the total system from a perspective of the three phases defined in this document. Within the EPC phase generally falls the design and specification of components. Mitigation of the component reliability risk falls on the builder/OEMs as well as the owner/operators. After the EPC specifications, it is the OEM who designs, builds, and tests the components, considering the physics, environments, chemistry, metallurgy, and other parameters needed for robust operation, including specifications for materials and subcomponents. All aspects are considered as a "systems engineering" process (Incose) and maintaining the supplier/customer interface needs management in the warranty period and beyond in the following operations and maintenance. It is anticipated that some major components may be selected early near the time of financing the project. Failure assessments and reliability design integration of those components are made prior to specification and procurement.

Designing for maintainability is also required. This will include consideration of the full suite of opportunities including redundancy, modularization, isolation of failed elements, bus interconnect switching, instrumentation and identification of faults, DAS and SCADA with data historian capabilities, access to components for repair and replacements, and other items for

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the maximation of energy performance and/or minimization of O&M costs shall be made with consideration of trade-offs between initial and operating costs. The EPC RPP may list items for trade-offs and mitigations of issues that have been identified in the development work products and which are also updated during this phase in the conduct of design and specification. EPC considered recommendations for reliability targets may be included or produced in the RPP or as a product of the resultant designs.

Practitioners are reminded that IEC TR 63292 includes additional and informative discussions on reliability tools and topics beyond what is specified in this document.

EPC phase work product for the RPP:

- EPC RPP.

6.3 Update FMECA, FMEA, FTA, and risk minimization approaches

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Building on the bases provided during development regarding failures and risks to components and systems, the EPC shall update the fault and failure analysis with system design information, including:

- Consideration of failure risks at an additional lower level beyond primary equipment to subcomponents likely to see meaningful failures.
- Anticipation and/or design mitigation of risks to specialized components like the PV modules and inverter, and conventional risks to PVPS infrastructure such as cabling and connectors.
- 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, irradiance (radiation), wind, weather extremes dust and soiling, biohazards, and neglect.
- Identification of other technical risks to reliable operations throughout the process of design, compatibility between equipment, manufacturing, testing, transport, installation, operations, and maintenance.
- Defined criteria of failure by component.

These risks necessitate activities to understand approaches to mitigate or eliminate impacts. Building on the development RPP the stated risk tolerance should be acknowledged as previously documented and considered in the plans implementing PVPS reliability planning as a constraint on project implementation.

Some of the items that an FMECA provides support for include O&M scope and methods, essential and critical items, limitations and constraints, human factors engineering, safety, fault tree analysis (FTA) in conjunction with the reliability model below and troubleshooting guides.

EPC phase work product for updating the FMECA, FMEA, FTA, and risk minimization approaches:

- Updated FMECA, FMEA.
- Fault tree analysis.
- Risk minimizations and trade-offs inputs to reliability model.

6.4 Detailed reliability model and Monte Carlo modelling

The high-level reliability block diagram and resultant model, including simulation function, should be expanded to include major subcomponents and analyses made based on all updated environmental, FMECA, FMEA, FTA and other failure data available. It is expected that qualified EPCs will have the competitive advantage of first-hand knowledge related to failures and that such information can be factored into the estimations. The process should build on the model previously performed, consistent with the developing design of the PVPS.

Monte Carlo simulations are often used for modelling and software is available that combine the RBDs as part of the models. They 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). Given the awareness that failures and responses are variable in nature, random sampling is used to model the system. The model uses the distributions for random occurrences and assign probabilities through the use of many runs of the model to approximate system response. Monte Carlo calculations are a common tool used in commercial reliability software.

By using the RBD as a model and assessing the results of the simulation, opportunities are discovered for improving system and component availability, costs, and uptime. The modelling support will allow for system revisions for design and future operational modifications to address identified weaknesses and improve performance. The Monte Carlo models shall be assessed for its predictive value and 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. Some key parameters to be determined are:

a) The ‘failure rate’ of components as estimated or determined by empirical means.
b) The manpower time to repair components, and the manpower needed overall.
c) Spare part inventories assumed or projected.
d) Logistical delays include staging of resources.
e) The impact of the failure on availability.
f) Ways of assessing the power loss, and the impact on performance.
g) The maintenance policy on occurrence of events and costs for such maintenance for budgeting.

The Monte Carlo simulation assessment is useful for these aspects, providing a calculational basis for their derivation and this can be the basis for economic decisions. Much of this is for risk minimizations and trade-offs for the reliable design process. ISO/IEC Guide 98-3 provides a basis for the evaluation of uncertainty of measurement, and its implementation by a Monte Carlo method.

EPC phase work product for the FMECA, FMEA, FTA, and risk minimization approaches:

- Updated RBD
- Updated failure and repair distributions
- Updated simulation model showing availabilities, weak links and pareto trade-offs
- Cross-correlation with the energy performance model and accuracy assessments.

6.5 Designed and specified FRACAS

Failure Reporting and Corrective Action System (FRACAS) is a system for identifying, acquiring, assessing, and implementing O&M actions for systematic resolution of individual or recurring reliability problems. From the Electropedia, it is a closed loop process used to improve dependability of current and future designs by feedback of testing, modification and use experience. This will be the system that comes from meeting this document for a PVPS. With a PVPS and a FRACAS viewpoint, here are two specific points of reality:

a) everything fails, and
b) failures are a physics problem.

Fixing reliability problems requires data. The data is needed to record and analyse the root cause to take actions to correct or mitigate the failures. As such, data acquisition and monitoring

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systems will need to be put into place within the PVPS. While most will be electronic, some may require inspections, testing, and human actions including data analysis.

As part of a preliminary O&M plan designed for reliability, the EPC will identify the data points needed by any means, incorporate them into the PVPS design and/or the proposed O&M plan for the purposes of providing data needed during operations. The data provided will form a 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 will also provide 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.

In the following O&M clause, and as described in the basis of design documents, the provisions that enable the PVPS to perform identification of faults and failures shall be identified. Combined with the preliminary O&M plan, it will form the basis for reliability during operations.

Failure identification needs may be part of the instrumentation and SCADA provisions for corrective actions. Repair and replacement may also identify capability for access, removal, safety, tooling, and other facility needs including storage.

EPC phase work product for the FRACAS design aspects:

- Data inputs, SCADA systems, and historian capability
- O&M data needed by non-SCADA capabilities and practices.

6.6 Preliminary O&M plan

With DfR features designed in for reliability, estimates of failures and repairs qualified in the simulation, estimates of spare parts, capabilities for isolation of faults, redundancy and modularity in the design, interconnect ability in the collection system buses, electronic and human data sources, etc., the EPC shall report on the features to be considered for effective O&M of the operating PVPS. Certain EPC design decisions will have impacts on O&M and will need identification as constraints on O&M. If scheduling occurs such that an O&M consultant can provide reverse guidance for design features that would be worth considering if the sufficient experience is not already held.

EPC phase work products for O&M plan:

- Preliminary O&M plan
- Design features supporting the preliminary O&M plan.

6.7 PVPS design and specification

The design and specifications are a fundamental work product of an EPC and not specifically a reliability product. EPC phase work products of design, specification, procurement, construction, installation plan and acceptance testing shall be as defined in the owner work statement and basis of design documentation. EPC phase work products to be defined by ownership. Nomenclature may vary and the basis of design is commonly understood and represents this phase.

The critical component list shall be updated to address reliability related features if not already specified:

- Determination of appropriate standards applicable to the individual components
- Maintainability assessment for repair and replacement access, in place inspection, condition monitoring needs/capabilities, and O&M tools and spare parts
- Acceptance test requirements defined

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- Reliability testing requirements i.e., accelerated life testing
- P50/P90 calculations, if applicable
- Identification of testing, inspection and spare parts and other items for the O&M phase
- Warranty provisions/requirements identified
- Integration of the work products in Clause 7
- EPC phase reliability-specific work products for design and specification
- Critical component list updated.

6.8 Documentation and stakeholder guidance

In addition to the EPC phase work products and items defined in 6.7, the ownership should ensure that communication of necessary information is pre-considered and made among other PVPS stakeholders. EPC phase work products are to be defined by ownership. Design, specifications, and reliability work products are to be maintained and updated as needed by ownership as a resource. The documents are to be made available to select stakeholders. Failure and performance information should be made available or for inspection upon sale to new ownership.

A non-exhaustive listing of documentation includes the identified work products listed in Clauses 5 and 6 and 7. Other documentation may be included as may be identified in 7.2.

Additional items may be recommended and/or specified by other direction of contract scope.

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7 O&M phase of a PVPS project

7.1 General

A failure reporting and corrective action system (FRACAS) is a process for gathering data needed to determine the MTBF or MTTF metrics among others, for items that fail. 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. Again, from a FRACAS standpoint there are two repeating specific points of reality:

a) everything fails, and
b) failures are a physics problem.

The physics problem now becomes an O&M problem.

Embedded in a FRACAS is the organizing principles for identifying and solving reliability problems. It will include organized historical data. It will also work to solve issues through understanding of root causes. The identification, analysis, corrective actions and documentation and record of actions facilitate this process. It will assess situations to deal with the most important issues. As such, it is a tool for controlling costs. Much of the tasks identified in this Clause 7 work together to form this system.

7.2 O&M plan for reliability

There are many aspects and approaches for the identification, marshalling of resources for decisions and actions, repair or replacement, return to service, and post failure incident analyses. These aspects require tracking and consideration in the design of FRACAS and other systems identified in this document.

A failure is commonly defined when an item (component, assembly, or system) cannot perform its intended function for a specified period of time under stated conditions per IEC TS 63019 as modified from IEEE 762. Care should be taken that not all loss of availability is always a failure. Forced outages are the most common form of failure but the information model also has provisions for other causes as explained in IEC TS 63019.

Within the IEA PVPS Task 13 Performance, Operation and Reliability of Photovoltaic Systems, failure descriptions are currently under development, and some are referenced in the bibliography. In North America, NERC has issued cause codes for outages for generating plants and a future document for PV is pending.

For purposes of this document, the PVPS operations will self-identify the causes of component or system outages through logging of unavailability incidents, determination of repair and replacements at the lowest levels, and further root cause analyses. Availability reporting is common among contracts and through utility sector management authorities.

There may also be cases where components are damaged when subjected to environmental conditions beyond their specified limits. These occurrences are not failures of design or installation per se but are broken and in need of repair or replacement, nonetheless. Still problematic, they fall under unavailability tracking and reporting.

Planned corrective actions may be undertaken to fix any design errors, technology improvements may facilitate improved efficiency or operation, and repowering plans may involve component replacements. Repowering planning includes potential improved manufacturing, increased capability (e.g., efficiency) and addressing the known degradation effects due to wear and fatigue.

The EPC design and the O&M provider may require certain additional resources for the functions above including:

- Bill of material, taxonomy
- Critical item list issues such as fire safety
- Technical component data
- Control points
- Maintenance plans
- Inspections, tests
- Modules, where nameplate and documentation exist
- Sampling
- Machine or component history, equipment logs
- Equipment diagnosis criteria
- OEM or aftermarket resource system
- Work and materials usage schedules
- Work plans
- Spare parts and projected materials usage.

From the above items the O&M provider shall assemble and produce an O&M plan for reliability suitable for determination of work scope and compatible with the following normative requirements in this Clause 7. The focus should be on the vital issues as determined by the critical components list as well as Pareto prioritization.

Users are reminded that the information model and tracking of outages by individual category availabilities are defined in IEC TS 63019 and as a normative standard in this document.

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O&M phase work product for O&M reliability plan:

- O&M reliability plan.

7.3 Failure identification

Reliability metrics cannot be derived without important failure information. Determining the answers to common questions may require the PVPS operation to properly collect the requisite data, such as what equipment or portion of the plant is failing, how long, how often, and how much these failures will cost in repair and lost energy production? Asset management questions include the source of the outage (i.e., Whose clock is it on? Was the outage due to internal or external forces? What power/energy was generated? What was expected?).

A failure incident report was identified in IEC TS 63019 and is now revised as Table 3. Such reporting of failures forms a foundation for FRACAS and the input to subsequent database for stakeholders to be shared consistent with accepted processes of confidentiality.

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Table 2 – Failure incident data tracking

Failure incident	Documentation	Advisory notes
What failed?	Component/system identified by taxonomy or ID system	Classification by information category Failure code may be applied
Where?	Physical or system locations if not included in the ID system	Unique identifiers are appropriate as part of the system taxonomy
How detected/ Identified?	What data, alarm, inspection, or analytics alerted this incident?	The failure management and O&M system may require documentation of pertinent documentation
Occurrence date/time	Trouble ticket started, logged	O&M task system documentation i.e., trouble ticket or work order
Troubleshooting?	Who, when? Diagnostics	Documentation of finding
Capacity and Availability-loss	Extent of system loss	Availability can be determined later with post analysis and Pareto selectivity
Non-availability-loss	Non-capacity, but a capability loss that needs correction	O&M task system documentation i.e., trouble ticket or work order
Notable/ abnormal conditions	Data historian required	Documentation logged
Warranty coverage?	Repair/replacement	Assignment of action for warrantee claim
Service Response	prep/logistics/parts for lowest level of repair	Records of response Note delays or logistical holds
Acceptance	Test service return protocol, verify	Record
Restoration Day/time	Return to service time	Record and outage duration
Reporting	Information model for time and contracts management (see Availability information model	Provided to or maintained by reliability/production engineering Reported as required
Insurance reporting	Repair/replacement	Assignment of action for insurance claim

Failure incident	Documentation	Advisory notes
Production impact	Repeating failures, critical item impacts, Weibull and statistics, historian, lost energy, cost tracking	Provided to or maintained by reliability/production engineering Lowest levels of repair documented since that is where the correction occurred Root cause analysis, operation beyond specified limits Reported as required or by plan
Post-incident analysis	Planned corrective actions	If determined to be warranted

This process is needed as the problem statement in IEC TR 63292 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.

For the calculation of the reliability metrics several different information sources might be taken into consideration. Some of which are processed automatically, whereas some need to be processed manually.

The following represents a non-exhaustive list of possible information sources:

- SCADA / DAS /historian files
- Inverter status codes/error codes
- Substation status codes/error codes
- PVPS status codes/error codes
- Meteorological data
- Works Management System (work orders)
- Diagnostic Information
- Manuals
- Statistics across PVPS types.

During the EPC phase the design shall have included include provisions that enable the ability perform identification of faults and failures. It will be the responsibility of the O&M provider to integrate these facilities into the O&M systems. In IEC 61724-1:2021,5.5 “A log should be kept recording unusual events, component changes, sensor recalibration, changes to the data acquisition system, changes to the overall system operation, failures, faults, or accidents.” This document makes that recommendation mandatory.

Data and data bases shall be retained throughout the life of a PVPS and provided for audits and/or sale of the PVPS. 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. The methods regarding obtaining and maintaining input data for reliability metrics should be explained in the RPP as required, specified and as submitted for approval. Monitoring and data retention will be needed, and users are referred to IEC 61724 technical specifications (which include differing level of monitoring for different sizes and types of systems).

The aggregation of the individual outages, failures, and related maintenance actions shall be summed up and reported as metrics of monthly reporting. Originally published in SAND 2015, it has been modified through continuing attempts to define a periodic report and is shown in Table 3. It is an example of a periodic report that includes faults, failures, repairs, replacements,

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and outages. This content may be considered for future best practices or contractual statements.

In some cases, a fault tree analysis can be useful. As stated in Science Direct: *Fault tree analysis,* section 4.1.2, “Any sufficiently complex system subject to failure as a result of one or more subsystems or components failing. The aim of the FTA is to use deductive logic to understand all the underlying causes of a particular failure in a sufficiently complex system so that the likelihood of failure can be reduced through improved system design (i.e. different component selection, more stringent development assurance levels and/or via system architectural improvements)”.

Table 3 – Model report content

1) Sunnyside solar plant
2) Operating companies
3) Environmental safety and health
a) Safety: Incident, cause, consequence, corrective actions
b) Environmental: Incident, cause, consequence, corrective actions
4) Plant performance (table)
a) Solar resource: Actual, expected, year to date (YTD), ratio of expected
b) Production: Actual, expected, YTD, ratio of expected
c) Availability: Specify availability of what, i.e., by inverter, by BOS, by utility system availability/external/curtailment, etc. for outages – link to item 15)
d) Percent of contracted delivery, period, YTD
5) Faults, failures, repairs, replacements, outages
– Table of events/incidents/actions—number, time, lost energy (Weibull database summary?)
6) Scheduled maintenance
– Upcoming planned actions
7) PV modules status
– Summary condition
8) Inverters’ status
– Summary condition
9) Structures and trackers status
– Summary condition
10) SCADA and communications status
– Summary condition
11) Electrical collection/transformers status
– Summary condition
12) Energy metering
– Summary condition Energy delivered Max MW generated or limit
13) Contracts
– Status
14) Other
– Summary condition
15) Performance charts, multiple and key aspects, such as:
– Degradation
– PR – Performance ratio/performance index
– CPR – Weather/Temperature-corrected PR
– Failure trends/regression model
– Top outages monthly

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This content can be merged with stakeholder standard reporting into a single report.

Solar Power Europe also has reporting recommendations that users should be aware of. See Table 1 of that report, *Proposed Indicators/values Required for the Reporting*.

O&M phase work product for failure identification:

- Failure identification report as populated by time series data and other discrete incidents from inspections or testing.

7.4 Failure database

The failures identified shall be recorded in a database. IEC 61649:2008 provides methods for analysing 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) which is sometimes illustrated as a “bathtub curve”.

- 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. This drives to corrective actions.
- Components indicated to have end of life data characteristics shall be reported as such.

The ongoing tracking of Weibull and other reliability parameters, including other failure trends, are required for historical tracking. MTBF, MTTR, and other similar metrics are a useful shorthand approach as reporting but are likely insufficient for reliability modelling where distributions are more useful.

O&M phase work product for failure database:

- Design, development, or adaption of a Weibull or equal database maintained with current and up to date failure data.

7.5 Root cause analysis

RCA is an informed approach to determine the cause of a failure and a precursor activity to an ongoing solution for repeating failures. It considers the operational environment, appropriate historical data and seeks evidence to explain the failure.

IEC 62740 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 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)

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