SolarPower Europe

Operation & Maintenance

Best Practice Guidelines

Version 6.0

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Foreword

Welcome to the sixth edition of SolarPower Europe's Operation & Maintenance (O&M) Best Practice Guidelines.

O&M is vital to ensuring the solar PV industry's long-term success, especially in the EU. As solar deployment grows and digital technologies evolve, harmonising best practices is crucial for scaling operations efficiently while maintaining quality standards, supporting sustainable growth.

O&M is a key segment of the solar industry, creating significant jobs and economic value in Europe, and driving global innovations, particularly in digitalisation. Since the first version in 2016, the guidelines have become a living document, evolving with input from an active community of experts.

The new guidelines exclude the Asset Management chapter, as it was addressed in a separate publication since 2020. They now offer expanded content, including an extended Power Plant Maintenance chapter, a new section on Common Tests and Inspections, and more detailed coverage of revamping and repowering, focusing on end-of-life aspects, contractual advice, and dismantling challenges. Additionally, the innovation and trends chapter has been updated to showcase emerging technologies and innovative solutions.

This update comes at a time when the importance of quality across the solar PV value chain is growing, as highlighted by SolarPower Europe's Lifecycle Quality Workstream. The Solar Quality Summit, launched in 2023, has become a key forum for discussing quality in the solar sector. Since the last version of the O&M guidelines, SolarPower Europe has also published best practices for Engineering, Procurement & Construction, Lifecycle Quality, and End-of-Life Management.

To support the global dissemination of best practices, the O&M Best Practice Guidelines were translated into German, adapted for the Tunisian market, and adapted for the Indian market in collaboration with the German development cooperation GIZ and India's National Solar Industry Federation (NSEFI). The www.solarbestpractices.com platform remains a valuable resource, providing access to our reports, tools, and checklists, as well as a directory of companies that adhere to best practices.

We thank our members for their ongoing engagement, which underscores the importance of O&M and Asset Management. We look forward to continuing our work in 2025 and invite stakeholders to join our Task Force to enhance solar O&M services even further.

Stelios Antellis
Head of Global Strategic Operation, Astronergy

Chair of the SolarPower Europe Lifecycle Quality workstream

Walburga Hemetsberger
Chief Executive Officer, SolarPower Europe

Chair of the SolarPower Europe Lifecycle Quality workstream:
Stelios Antellis, Astronergy

Vice-Chairs of the SolarPower Europe Lifecycle Quality workstream:
Wojtek Swietochowski, Aboenergy

Coordinator of the SolarPower Europe Lifecycle Quality workstream:
Nikoletta Fodor, SolarPower Europe

Contributions and co-authors:
Andreas Stiedl (Huawei); Calin Sas (Sunrock); Christian Braun (ISE); Cecilia Moramarco (Sunrock); César Hidalgo López (DNV); Daniel Barandalla (UL Solutions); David Melgar (ISE); Giuseppe Farinato (Kiwa); Gautier Moulin (aevy); Ioannis Tsanakas (CEA-INES); Katia Prada (DNV); Laura Azcona (DNV); Patricio Sánchez (Kiwa); Pablo Sebastian Enriquez Paez (BayWa r.e.); Rafael Gomez (RP Global); Sebastian Leon (UL Solutions); Thomas Sauer (EXXERGY); Viola Hoffmann (Above); Wojtek Swietochowski (Aboenergy); Yong Sheng Khoo (QE-Labs)

Supported by:
Intersolar Europe

Acknowledgements:
SolarPower Europe would like to extend special thanks to all the Task Force members that contributed to this report with their knowledge and experience. This work would never have been realised without their continuous support.

Please cite as:
SolarPower Europe (2025): *Operation & Maintenance Best Practice Guidelines/Version 6.0*

For media use and queries:
Bethany Meban, SolarPower Europe b.meban@solarpoweurope.org

Date of publication:
February 2025

ISBN:
9789464444247

Contact:
info@solarpowereurope.org

Design:
Onehemisphere, Sweden. contact@onehemisphere.se

Thanks to our Sponsor Members:
BayWa r.e. edp enel plenitude First Solar HUAWEI Iberdrola lightsource bp LONGi Solar sunnova Trinasolar WACKER

Project information:
The SolarPower Europe Lifecycle Quality workstream originally started as the O&M Task Force in April 2015. Its scope then expanded to include Asset Management in 2019, and EPC in 2020, covering the entire lifecycle of solar PV projects. The first version of the O&M Best Practices Guidelines was published in June 2016 and since then, the Task Force has updated the Guidelines regularly. The SolarPower Europe O&M Best Practices Guidelines reflect the experience and views of a considerable share of the European O&M industry today. There has been no external funding or sponsoring for this project.

Lifecycle Quality Workstream Members

SolarPower Europe would like to thank the members of its Lifecycle Quality workstream that contributed to this report including:

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List of Abbreviations

AC	Alternating current
AMP	Annual Maintenance Plan
AMR	Automatic meter reading
AMS	Annual Maintenance Schedule
API	Application Programming Interface
CCTV	Closed Circuit Television
CMMS	Computerised maintenance management system
COD	Commercial operation date
CSMS	Cybersecurity management system
DC	Direct current
DMS	Document management system
DOR	Division of responsibility
DSCR	Debt service coverage ratio
DSL	Digital Subscriber Line
DSO	Distribution System Operator
EH&S	Environment, health, and safety
EMS	Energy Management System
EPC	Engineering, procurement, construction
EPI	Energy Performance Index
ERP	Enterprise Resource Planning System
ESS	Energy Storage System
FAC	Final acceptance certificate
FIT	Feed-in tariff
FTP	File Transfer Protocol
GPRS	General Packet Radio Service
H&S	Health and safety
HV	High voltage
IEC	International Electrotechnical Commission
IGBT	Insulated-Gate Bipolar Transistors
IPP	Independent power producer
IR	Infrared
IRENA	International Renewable Energy Agency
KPI	Key performance indicator
kW	kilowatt
kWh	kilowatt-hour
kWp	kilowatt-peak
LAN	Local area network
LCOE	Levelised Cost of Electricity
LTE-M	Long-power wide-area network
LPWAN	Long Term Evolution, category M1
LV	Low voltage
MAE	Mean absolute error
MIT	Minimum irradiance threshold
MPPT	Maximum Power Point Tracking
MV	Medium voltage
MW	Megawatt
O&M	Operation and Maintenance
OEM	Original equipment manufacturer
OS	Operating system
PAC	Provisional acceptance certificate
POA	Plane of array
PPA	Power purchase agreement
PPE	Personal protective equipment
PR	Performance Ratio
PV	Photovoltaic
RMSE	Root mean square error
ROI	Return on investment
RPAS	Remotely Piloted Aircraft System (drone)
SCADA	Supervisory Control and Data Acquisition
SLA	Service-level agreement
SPV	Special purpose vehicle
STC	Standard Test Conditions (1000 W/m^2, 25°C)
TAM	Technical Asset Management
TF	Task force
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply

List of Figures and Tables

High-quality O&M services are key to mitigating risks, lowering LCOE, and maximising ROI in the solar industry

Operation and Maintenance (O&M) has become a standalone segment within the solar industry, and it is widely acknowledged by all stakeholders that high-quality O&M services mitigate potential risks, improve the levelised cost of electricity (LCOE) and Power Purchase Agreement (PPA) prices, and positively impact the return on investment (ROI). Responding to the discrepancies that exist in today's solar O&M market, the SolarPower Europe O&M Best Practice Guidelines make it possible for all to benefit from the experience of leading experts in the sector and increase the level of quality and consistency in O&M. These Guidelines are meant for O&M service providers as well as investors, financiers, asset owners, asset managers, monitoring tool providers, technical consultants, and all interested stakeholders in Europe and beyond.

This document begins by contextualising O&M, explaining the roles and responsibilities of various stakeholders such as operations service providers, asset managers, and maintenance providers, and by presenting an overview of technical and contractual terms to achieve a common understanding of the subject. It then outlines the different components of O&M, classifying requirements into minimum requirements, best practices and recommendations.

Environment, Health & Safety

Environmental problems are normally avoidable through proper plant design and maintenance, but where issues do occur, the O&M service provider must detect them and respond promptly. Environmental compliance may be triggered by components of the PV system itself, such as components that include hazardous materials and by-products that may be used by the O&M service provider such as herbicides and insecticides.

In many situations, solar plants offer offer biodiversity opportunities for agriculture, and are a valuable natural habitat for plants and animals alongside the primary purpose of power production. However, solar plants are electricity generating power stations and have significant hazards present which can result in injury or death. Risks should be reduced through proper hazard identification, careful planning of works, briefings of procedures to be followed, documented and regular inspection, and maintenance. Personnel training and certification and personal protective equipment are required for several tasks. Almost all jobs have some safety requirements such as fall protection for work at heights and electrical arc-flash, lock-out tag-out, and general electrical safety for electrical work, eye, and ear protection for ground maintenance.

Personnel & training

It is important that all O&M personnel have the relevant experience and qualifications to perform the work in a safe, responsible, and accountable manner. These Guidelines contain a skills' matrix template that helps to record skills and identify gaps.

Skilled O&M personnel are the driving force behind safe, seamless, and powerful operations

Power plant operation

Operation is about remote monitoring, supervision and control of the PV power plant and it is an increasingly active exercise as grid operators require more and more flexibility from solar power plants. Power plant operations also involves liaising with or coordination of the maintenance team. A proper PV plant documentation management system is crucial for operations. A list of documents that should be included in the as-built documentation set accompanying the solar PV plant (such as PV modules' datasheets), as well as a list of examples of input records that should be included in the record control (such as alarms descriptions), can be found in the Annex of these Guidelines. Based on the data and analyses gained through monitoring and supervision, the O&M service provider should always strive to improve PV power plant performance. As there are strict legal requirements for security services in most countries, PV power plant security should be ensured by specialised security service providers.

Power plant maintenance

Maintenance is usually carried out on-site by specialised technicians or subcontractors, according to the operations team's analysis. A core element of maintenance services, preventive maintenance involves regular visual and physical inspections, functional testing, and measurements, as well as the verification activities necessary to comply with the operating manuals and warranty requirements. The Annual Maintenance Plan (see an example in *Annex E*) includes a list of inspections and actions that should be performed regularly. Corrective Maintenance covers activities aimed at restoring a faulty PV plant, equipment, or component to a status where it can perform the required function. Extraordinary Maintenance actions, usually not covered by the O&M fixed fee, can be necessary after major unpredictable events in the plant site that require substantial repair works. Additional maintenance services may include tasks such as module cleaning and vegetation control, which could be done by the O&M service provider or outsourced to specialist providers.

Common test and inspections

Common tests and inspections are integral to ensuring the performance, safety, and reliability of PV systems throughout their lifecycle. These activities involve routine and specialised assessments to detect issues, maintain efficiency, and prolong the system's lifespan. This chapter outlines the primary tests performed during the lifecycle of PV systems, key inspection methods, and industry best practices based on international standards such as IEC 62446.

Revamping and repowering

Revamping and repowering are usually considered a part of extraordinary maintenance from a contractual point of view – however, due to their increasing significance in the solar O&M market, these Guidelines address them in a standalone chapter. Revamping and repowering are defined as the replacement of old, power production related components within a power plant by new components to enhance the overall performance of the installation. This chapter presents the best practices in module and inverter revamping and repowering and general, commercial considerations to keep in mind before implementation.

KPIs are the heartbeat of solar PV performance—measuring efficiency, response, and O&M excellence

Spare Parts Management

Spare Parts Management is an inherent and substantial part of O&M aimed at ensuring that spare parts are available in a timely manner for Preventive and Corrective Maintenance to minimise the downtime of a solar PV plant. As a best practice, the spare parts should be owned by the asset owner while normally maintenance, storage and replenishment should be the responsibility of the O&M service provider. It is considered a best practice not to include the cost of replenishment of spare parts in the O&M fixed fee. However, if the asset owner requires the O&M service provider to bear replenishment costs, the more cost-effective approach is to agree which are "Included Spare Parts" and which are "Excluded Spare Parts". These Guidelines also include a minimum list of spare parts that are considered essential.

Data and monitoring requirements

The purpose of the monitoring system is to allow supervision of the performance of a PV power plant. Requirements for effective monitoring include dataloggers capable of collecting data (such as energy generated, irradiance, module temperature, etc.) of all relevant components (such as inverters, energy meters, pyranometers, temperature sensors) and storing at least one month of data with a recording granularity of up to 15 minutes, as well as a reliable Monitoring Portal (interface) for the visualisation of the collected data and the calculation of KPIs. Monitoring is increasingly employing satellite data as a source of solar resource data to be used as a comparison reference for on-site pyranometers. As a best practice, the monitoring system should ensure open data accessibility to enable an easy transition between monitoring platforms and interoperability of different applications. As remotely monitored and controlled systems, PV plants are exposed to cybersecurity risks. It is therefore vital that installations undertake a cyber security analysis and implement a cybersecurity management system. To evaluate monitoring tools, it is recommended to refer to the Monitoring Checklist of the Solar Best Practices Mark, which is available at www.solarbestpractices.com.

Key Performance Indicators

Important KPIs include PV power plant KPIs, directly reflecting the performance of the PV power plant; O&M service provider KPIs, assessing the performance of the O&M service provided, and PV power plant/O&M service provider KPIs, which reflect power plant performance and O&M service quality at the same time. PV power plant KPIs include important indicators such as the Performance Ratio (PR), which is the energy generated divided by the energy obtainable under ideal conditions expressed as a percentage, and Uptime (or Technical Availability) which are parameters that represent, as a percentage, the time during which the plant operates over the total possible time it can operate. O&M service provider KPIs include Acknowledgement Time (the time between the alarm and the acknowledgement), Intervention Time (the time between acknowledgement and reaching the plant by a technician) and Resolution Time (the time to resolve the fault starting from the moment of reaching the PV plant). Acknowledgement Time plus Intervention Time are called Response Time, an indicator used for contractual guarantees. The most important KPI which reflects PV power plant performance and O&M service quality at the same time is the Contractual Availability. While Uptime (or Technical Availability) reflects all downtimes regardless of the cause, Contractual Availability involves certain exclusion factors to account for downtimes not attributable to the O&M service provider (such as force majeure), a difference important for contractual purposes.

All best practices mentioned in these Guidelines are beneficial and relevant for solar PV systems of all sizes

Contractual framework

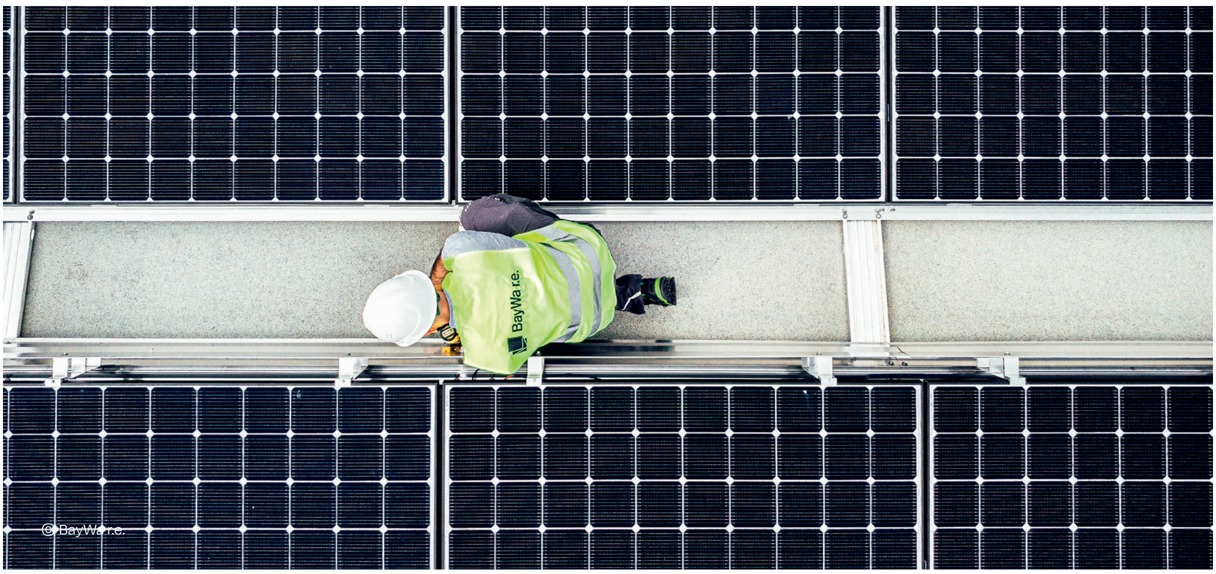
Although some O&M service providers still provide Performance Ratio guarantees in some cases, it is a best practice to only use Availability and Response Time guarantees, which has several advantages. A best practice is a minimum guaranteed availability of 98% over a year, with Contractual Availability guarantees translated into Bonus Schemes and Liquidated Damages. When setting Response Time guarantees, it is recommended to differentiate between hours and periods with high and low irradiance levels as well as fault classes, i.e., the (potential) power loss. As a best practice, we recommend using the O&M template contract developed as part of the Open Solar Contracts, a joint initiative of the Terrawatt Initiative and the International Renewable Energy Agency (IRENA). The Open Solar Contracts are available at www.opensolarcontracts.org.

Innovations and trends

O&M service providers are increasingly relying on innovations and more machine and data-driven solutions to keep up with market requirements. The most important trends and innovations shaping today's O&M market are summarised in this chapter, grouped into three "families": (1) Smart PV power plant monitoring and data-driven O&M, (2) Retrofit coatings for PV modules, and (3) O&M for PV power plants with storage.

O&M for rooftop solar

All best practices mentioned in these Guidelines could be theoretically applied to even the smallest solar system for its benefit. However, this is not practical in nature due to a different set of stakeholders and financial implications. This chapter assists in the application of the utility-scale best practices to distributed solar projects, which are shaped by three important factors: (1) a different set of stakeholders – owners of distributed systems not being solar professionals but home owners and businesses, (2) different economics – monitoring hardware and site inspections accounting for a larger share of investment and savings, and (3) a higher incidence of uncertainty – greater shade, lower data accuracy, and less visual inspection.



Chapter 1

Introduction

This chapter emphasises the importance of professional Operation & Maintenance (O&M) services in ensuring the long-term performance of solar photovoltaic (PV) systems. It explains how high-quality O&M reduces risks, improves LCOE, PPA prices, and ROI. The chapter also addresses the confusion among asset owners and investors about O&M requirements, highlighting the need for best practices and clear performance metrics. It outlines SolarPower Europe's O&M Best Practice Guidelines, which provide a framework of minimum requirements, best practices, and recommendations, to enhance O&M service quality and investor confidence.

1.1 Rationale, aim and scope

A professional Operation & Maintenance (O&M) service package ensures that the photovoltaic system will maintain high levels of technical, safety and consequently economic performance over its lifetime.

Currently, it is widely acknowledged by all stakeholders that high quality O&M services mitigate the potential risks, improve the levelised cost of electricity (LCOE) and Power Purchase Agreement (PPA) prices and positively impact the return on investment (ROI). This can be highlighted if one considers the lifecycle of a PV project which can be broken down into the 4 phases below. The O&M phase is by far the longest:

- Development (typically 1-3 years)
- Construction (a few months)
- Operation & Maintenance (typically 30+ years)
- Decommissioning and disposal (a few months)

Therefore, increasing the quality of O&M services is important and, in contrast, neglecting O&M is risky. The PV industry – a "young" industry that evolves also in the services segment – offers a wide range of practices and approaches. Although this is partly logical, reflecting the specificities of each system, topologies, installation sites and country requirements, there is a confusion or lack of clarity and knowledge of many Asset Owners and funding authorities (investors or/and banks) of what the minimum requirements or scope should be. A few years ago, when feed-in tariffs were very high and favourable, there was an obvious lack of risk perception in combination with an underestimated performance metrics definition which hindered the proof of value of a professional and high-quality service provision.

Today, existing standardisation still does not fill in all the gaps or clarify all the requirements and their implementation. Although in maintenance, there are several technical international standards that can be followed and which also cover tasks related to planning, scheduling and administration, when it comes to the practical Power Plant Operation, there are many shortcomings. Therefore, it is crucial to develop and disseminate best practices to optimise Power Plant Operation and thus energy production, power plant management and the resulting benefits. Best practices that set the quality bar high will enhance investors' understanding and confidence. For this version 6.0, a list of international standards has been added to support these best practises and to avoid misunderstandings. For more detailed information, please refer to *Annex A*.

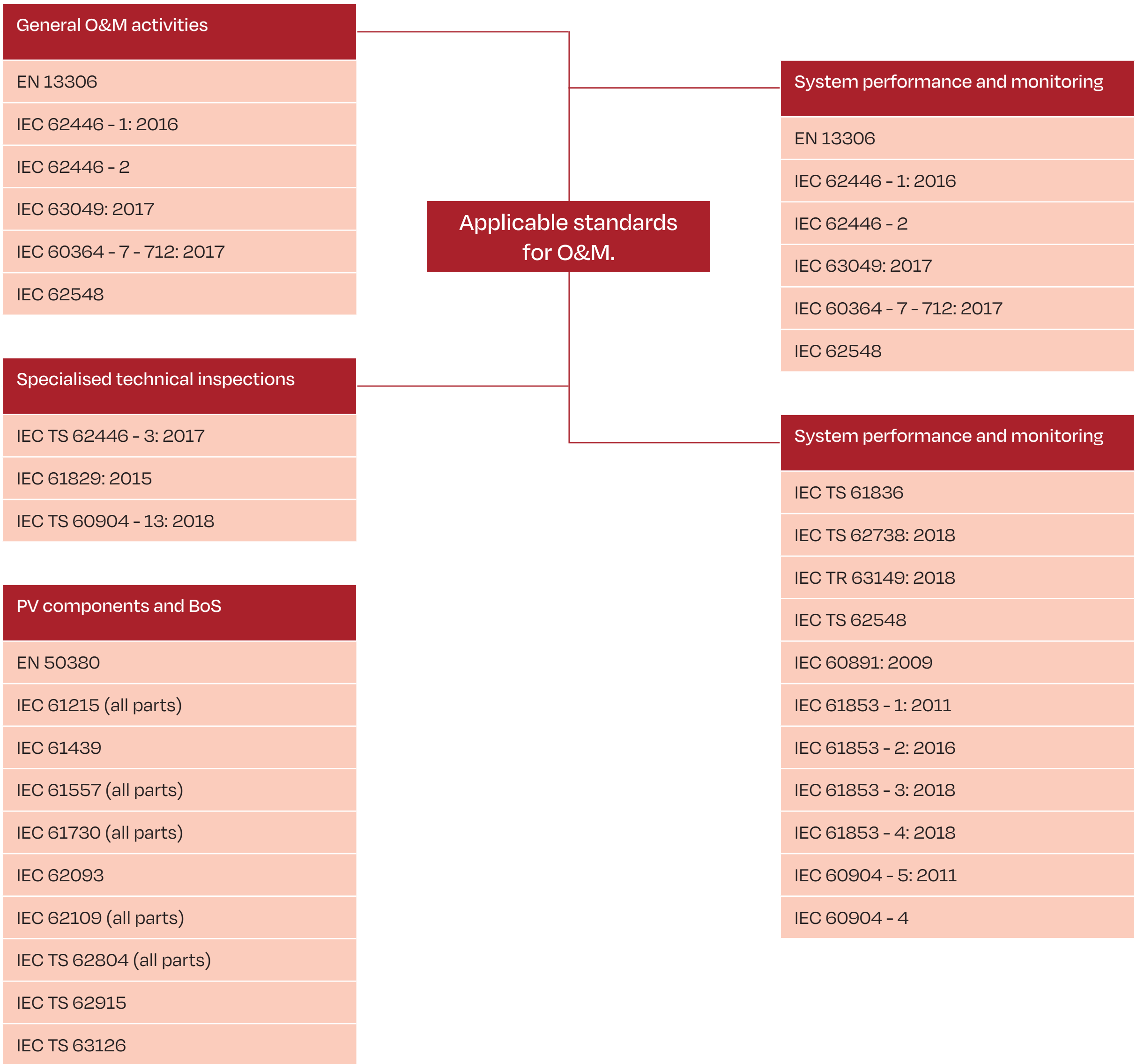
SolarPower Europe's O&M Best Practice Guidelines are a key tool to set quality standards for service providers and enhance investors' understanding and confidence.[1] The value proposition of these Guidelines is that its industry-led, containing the knowledge and the experience of well-established and leading companies in the field of O&M service provision, project development and construction (EPC), asset management, utilities, manufacturers, and monitoring tool providers.

The scope of the current work includes the utility-scale segment and more specifically, systems above 1 MW. Specificities related to O&M for distributed solar installations are explained in *Section 13.2 Distributed Residential Solar Portfolios*. These Guidelines are based on the experience of companies operating globally (with a concentration in Europe), therefore, it provides high-level requirements that can be applied worldwide. Specific national considerations such as legal requirements are not included and should therefore be considered separately if these Guidelines are to be used in specific countries.

1 In addition to the O&M Best Practice Guidelines we recommend SolarPower Europe's Asset Management Best Practice Guidelines, another useful tool to enhance investors' confidence and improve service quality in the field of solar asset management. This report can also be downloaded from www.solarpowereurope.org.

Figure 1

Overview of a selection of applicable standards for O&M.



Note: : This list is not exhaustive, and new standards are under development
Source: SolarPower Europe

The content covers technical and non-technical requirements, classifying them when possible, into:

1. **Minimum requirements**, below which the O&M service is considered as poor or insufficient, and which form a minimum quality threshold for a professional and bankable service provider

2. **Best practices**, which are methods considered state-of-the-art, producing optimal results by balancing the technical as well as the financial side

3. **Recommendations**, which can add to the quality of the service, but whose implementation depends on the considerations of the Asset Owner or Asset Manager, such as the available budget

As for the terminology used in this document to differentiate between these three categories, verbs such as *"should"* indicate minimum requirements, unless specified explicitly otherwise, like in: *"should, as a best practice"*.

1.2 How to benefit from this document

This report includes the main considerations for a successful and professional O&M service provision. Although it has not been tailored for each stakeholder, its use is similar for all: understanding the mandatory requirements and the necessity of professional O&M and incorporating the recommendations accordingly into the service package. Any of the directly relevant stakeholders (*see the following section*) can benefit from this work, tailor it to their needs without lowering quality standards, and know what to ask for, offer or expect, in relation to O&M service provision.

Although the focus is European, most of the content can be used in other regions around the world. The requirements described in the maintenance part apply without changes in regions with conditions like Europe and a moderate climate; additional requirements or modifications can easily be made for other regions with unique characteristics. With regards to the operations and technical asset management part, the requirements apply to PV assets regardless of their location.

Health, Safety, Security, and Environment

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The Asset Owner has ultimate legal and moral responsibility for ensuring the health and safety of people in and around the solar plant, the security of the site, and the protection of the surrounding environment. The practical implementation is normally subcontracted to the O&M service provider. In some cases, the Asset Manager can provide or prescribe the systems, which are then implemented by the O&M service provider. This chapter will investigate specific areas of Health, Safety, Security, and Environmental (HSSE) policy and coordination that relate to O&M service providers. For a general overview of the fundamentals of HSSE coordination, please refer to *SolarPower Europe's Lifecycle Quality Guidelines V 1.0 (available at www.solarpowereurope.org).*

2.1 Health, Safety, and Security

Managing the risks that solar plants pose to the health and safety (H&S) of people, both in and around the plant, is a primary concern of all stakeholders. Solar plants are electricity generating power stations and pose significant hazards which can result in permanent injury or death. Risks can be mitigated through proper hazard identification, careful planning of works, briefing of procedures to be followed, and regular and well documented inspection and maintenance (see also section *Power plant security*).

The dangers of electricity are well known and can be effectively managed through properly controlled access and supervision by the O&M service provider. Any person accessing a solar PV power plant should expect some form of introduction to ensure they are briefed on any hazards and risks. Staff working on electrical equipment must be appropriately trained, have sufficient experience, and be supervised. It is also key that others working around the equipment - for example panel cleaners - are equally aware of the potential risks and have safe methods of working around HV and LV electricity.

Hazardous areas and equipment should carry appropriate markings to warn personnel of possible hazards and wiring sequence. Such markings should be clear and evident to all personnel and third parties (and intruders) entering the plant premises.

As well as the inherent dangers of a typical solar plant, every site will have its own set of individual hazards which must be considered when working on the plant. An up-to-date plan of hazards is important for the O&M service provider to manage their own staff and provide third party contractors with adequate information. It is usually the case that the O&M service provider holds the authority and responsibility for reviewing and, where necessary, rejecting works taking place in the plant. Failure to carry this out properly has important consequences for general safety.

Besides workers on the solar plant, it is not unusual for other parties to require access to it. This may be the Asset Owner, or their representative, the landowner, or, in some situations, members of the public. It is important that the plant access control and security system keeps people away from areas of danger and that they are appropriately supervised and inducted as necessary.

The Asset Owner is ultimately responsible for compliance with H&S regulations within the site/plant. The Asset Owner must make sure that the installation and all equipment meet the relevant legislations of the country and, that all contractors, workers, and visitors respect the H&S Legislation by strictly following the established procedures, including the use of established personal protective equipment (PPE).

At the same time, the O&M service provider should prepare and operate their own safety management systems, previously agreed with the Asset Owner, that take into account site rules relating to H&S and the potential hazards involved in the works. The O&M service provider should ensure that they, and all subcontractors, comply with H&S legislation.

The Asset Owner will expect the O&M service provider to assume the role and duties of the principal contractor under the relevant national regulations governing H&S. This involves the O&M service provider proving that they are competent and are able to allocate enough resources to fulfil these duties.

Before starting any activity on-site, the Asset Owner will deliver a risk assessment and method statements to the O&M service provider who will provide a complete list of personnel training certifications and appoint a H&S coordinator. During the whole duration of the contract the O&M service provider will keep the H&S file of each site up to date.

The O&M service provider must have their personnel trained in full compliance with respective national legal and professional requirements. This generally includes obtaining certification necessary for working in a variety of environments, such as MV and/or HV electrical plants. Within Europe, referral to European Standards is not sufficient (examples of standards used today are ISO 14001, OHSAS 18001 etc).

To achieve a safe working environment, all work must be planned in advance. Normally written plans are required.

Risk assessments which detail all the hazards present and the steps to be taken to mitigate them need to be produced.

The following dangers are likely to exist on most solar plants and must be considered when listing hazards and identifying risks. The severity of any injuries caused are exacerbated by the terrain on which solar plants are built and their remoteness.

Medical problems

It is critical that all personnel engaged in work on solar plants have considered and communicated any pre-existing medical problems and any additional measures that may be required to deal with them. Due to the presence of power electronics and high currents there are electromagnetic fields present everywhere which can affect medical devices (e.g. pacemakers).

Slips, trips, and falls

The terrain, obstacles and equipment installed on a solar farm provide plenty of opportunities for slips, trips and falls both at ground level and whilst on structures or ladders; and for roof-top or carport systems, fall-protection and additional equipment is required when working at heights.

Collisions

Collisions can occur between personnel, machinery/vehicles and structures. The large areas covered by solar farms often necessitate the use of vehicles and machinery which, when combined with the generally quiet nature of an operational solar plant, can lead to a lack of attention. General risks such as difficult terrain, reversing without a banksman and walking into the structure supporting the solar panels require special attention.

Strains and sprains

Lifting heavy equipment, often in awkward spaces or from uneven ground, presents increased risk of simple strains or longer-term skeletal injuries.

Electrocution

Operational solar plants, whether energised or not, present a significant risk of electrocution to personnel. This risk is exacerbated by the nature and voltage of the electricity on site and the impossibility of total isolation. Staff engaged in electrical work obviously suffer the greatest risk but everybody on site is at risk from step potential and other forms of electrocution in the event of a fault. Specific training needs to be given to all those entering a solar farm on how to safely deal with the effects of electrocution. In addition to general electrical safety, common issues for solar PV power plants include arc-flash protection when working on energised circuits; and lock-out-tag-out to ensure circuits are not unintentionally energised.

Fire

Several sources of combustion exist on a solar farm, the most common being electrical fire. Others include combustible materials, flammable liquids, and grass fires. Safe exit routes need to be identified, and procedures fully communicated. All personnel need to be fully aware of what to do to avoid the risk of fire and how to act in the event of a fire. Additionally, fire extinguishers adapted to fires of electrical origin must be installed in key places such as AC distribution cabinets, HV transformers, etc. It is best practice to privilege carbon-dioxide based fire extinguishers as they minimise material damage to collateral components, thus increasing the ratio of recoverable equipment.

Mud and water

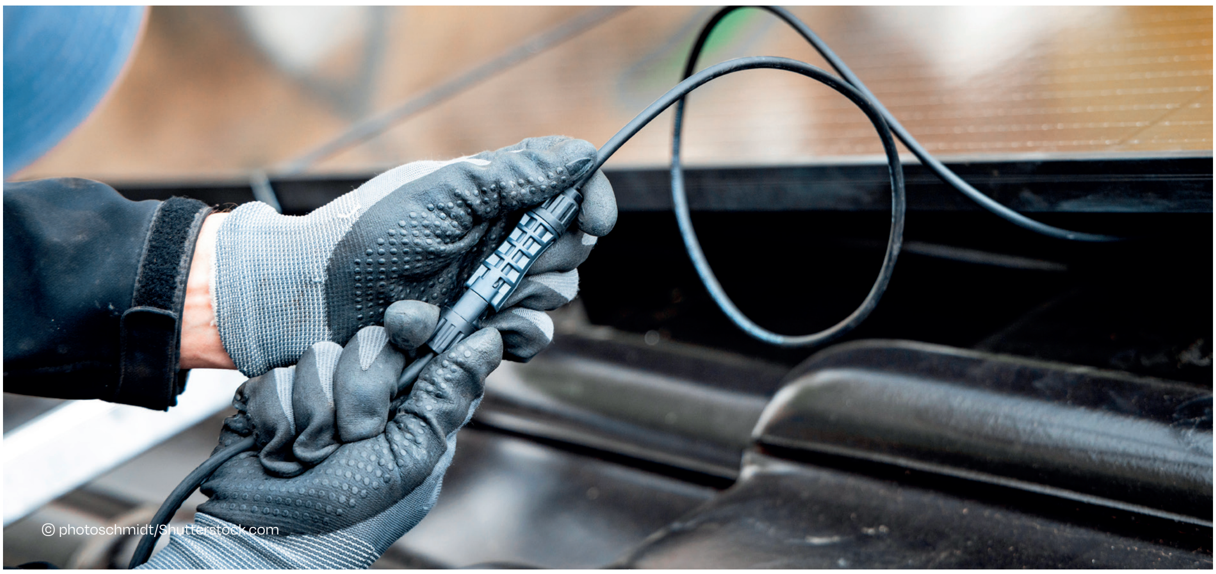
Many solar farms have water travelling through them such as streams and rivers, some have standing water, and some are floating arrays. Mud is a very common risk particularly in winter as low-grade farmland is often used for solar farms. Mud and water present problems for access as well as electrical danger.

Mechanical injury

Hand-tools, power tools, machinery, and mechanisms such as unsecured doors can present a risk of mechanical injury on site.

Weather

The weather presents a variety of hazards, the most significant of which is the risk of lightning strike during an electrical storm. Due to the metal structures installed on a solar farm an electrical storm is more likely to strike the solar array than surrounding countryside. A solar farm must be vacated for the duration of any electrical storm. Working in cold and rainy weather can cause fatigue and injury just as working in hot sunny weather presents the risk of dehydration, sunburn, and sun stroke. Working during sunny days for undertaking maintenance and/or testing on site can lead to sunstroke. To avoid this, drinking sufficient water and staying in the shade is recommended. During wintertime, removing snow is also a hazard as it can hide pre-existing hazards or trigger risk of falling from the rooftop. Best practice is to have personnel visiting solar installations equipped with lone working devices that connect to an alerting system, coupled with accessible information about the nearest first aid point.



Wildlife and livestock

The renewable energy industry is proud to provide habitats for wildlife and livestock alongside the generation of electricity. Some wildlife, however, presents dangers. There are plants in different regions which can present significant risk, some only when cut during vegetation management. Animals such as rodents and snakes, insects such as wasps, and other wildlife and livestock can present significant risks. The nature of these risks will vary from place to place, and personnel need to be aware of what to do in the event of bites or stings. Snakes, spiders, ticks, bees, and bugs are common and pose a number of hazards where snake bites could be lethal, spider bites can cause pain and inflammation, tick bites could result in tick bite fever, bees can cause allergic reactions and bugs could fly into people's eyes. It is therefore important that all precautions are taken to prevent or manage these incidents. Storage and application of pesticides, herbicides, and rodent poisons also introduce health and safety hazards. For example, Glyphosate was very common in controlling vegetation at solar PV power plants and has been found to be carcinogenic. Mowing has several hazards including flying objects. Every job at a solar PV site should have safety precautions identified and implemented

Everyone entering a solar farm, for whatever reason, should have been trained in the dangers present on solar farms and be trained for the individual task that they will be performed. They should have all the PPE and tools necessary to carry out the work in the safest way possible. The work should be planned, and everyone concerned should have a common understanding of all aspects related to the safe execution of their task. Different countries will mandate written and hard copy paperwork to meet legislation, but best practice is to exceed the minimum requirements and to embrace the spirit of all relevant legislation.

Best practice in H&S sees the ongoing delivery of training and sharing of lessons learned. By increasing the skills of persons involved in the industry, we can make the industry safer and more productive.

As a best practise, it is advised to create and implement Life-Saving Rules as part of the Health and Safety programmes. Life-Saving Rules are a set of non-negotiable guidelines designed to prevent severe injuries or fatalities in workplaces. These rules address high-risk activities such as working at heights or controlling hazardous energy, focusing on behaviours and practices that, if violated, have the potential to lead to serious harm.

It is advised conducting a Last Risk Assessment, a final, real-time evaluation of potential hazards and risks immediately before beginning a task or activity. A Last Risk Assessment ensures that workers assess the current environment, conditions, and potential changes that could impact safety.

Electrical Safety

Electrical safety in solar photovoltaic (PV) plants is crucial for both worker protection and plant efficiency. This is governed by strict standards such as IEC 60364 and EN 50110, which ensure the establishment of a clear and effective safety framework. Key roles are defined for Low Voltage (LV) and High Voltage (HV) systems, including responsibilities for LV and HV responsible persons, as well as an overarching Electrical Safety Manager (QEPIC). These roles are supported by rigorous appointment procedures, documentation, and regular reviews to maintain safety competence.

Additionally, safety practices like work permits for high-risk electrical tasks, PPE usage, and systematic switching procedures are critical for reducing electrical hazards. Comprehensive training and fostering a strong safety culture within the plant are necessary for ongoing risk mitigation. Maintenance and inspections, along with the adoption of advanced technologies, help identify and address potential electrical issues.

For those seeking more detailed information on electrical safety protocols, *Annex A* is included that provides deeper insights into best practices, safety documentation, and the specific requirements for ensuring electrical safety across all systems and operations in solar PV plants.

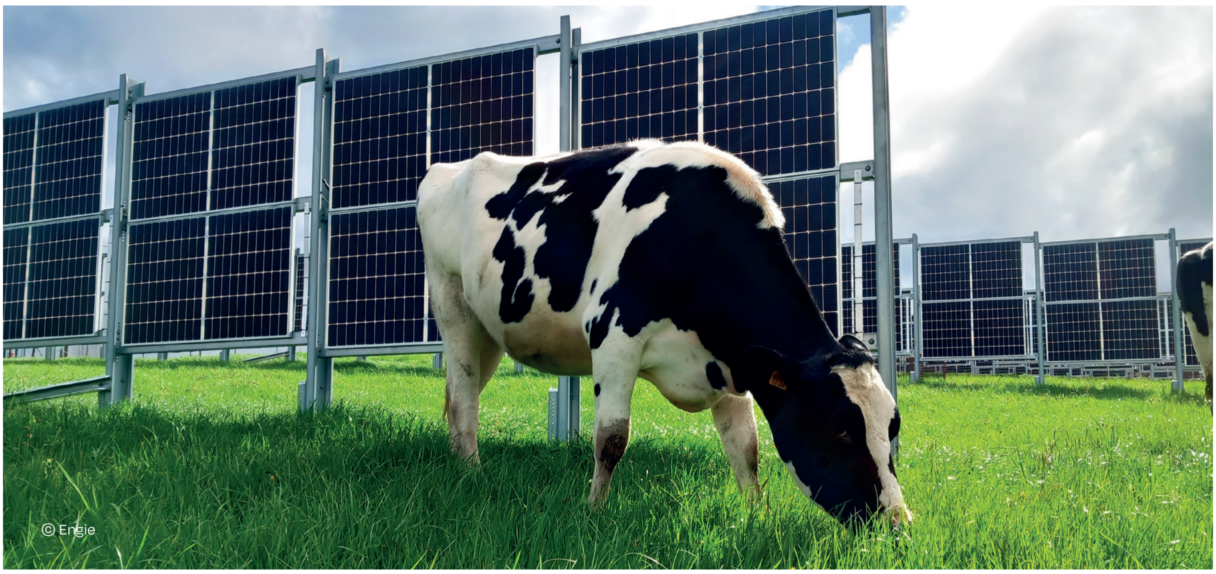
2.2 Environment

Renewable energies are popular because of their low environmental impact, and it is important that solar plants are operated and maintained to minimise any adverse effects. Environmental problems can normally be avoided through proper plant design and maintenance – for example, bunds and regular inspection of HV transformers will reduce the chances of significant oil leaks – but where issues do occur the O&M service provider must detect them and respond promptly. Beyond the environmental damage there may be financial or legal penalties for the Owner of the plant.

Legal obligations to be fulfilled by the O&M service provider (or the Technical Asset Manager) may include long-term environmental requirements to be implemented either on-site or off-site. Typical requirements can be, amongst others, water tank installation, tree clearing, drainage system installation, amphibian follow-up, edge plantation, and reptile rock shelter installation. Such requirements should be implemented and managed by the O&M service provider to comply with the relevant regulations. As a best practice, the O&M service provider's environmental preservation activities can go beyond legal obligations.

Other aspects that need to be considered as best practice, are recycling of broken panels and electric waste so that glass, aluminium and semiconductor materials can be recovered and reused, and hazardous materials disposed of in a safe manner, complying with legal requirements. In areas with water scarcity, water use for module cleaning should be minimised.

In many situations, solar plants offer an opportunity, where managed sympathetically, to provide opportunities for agriculture and a valuable natural habitat for plants and animals alongside the primary purpose of generation of electricity. A well thought out environmental management plan can help promote the development of natural habitats, as well as reduce the overall maintenance costs of managing the plant's grounds. It can also ensure the satisfaction of any legal requirements to protect or maintain the habitat of the site. In any case, environmental requirements from building permits should be complied with. Maintenance services should comply with things such as the proper application of herbicides, pesticides, and poisons used to control rodents. The use of solvents and heat-transfer fluids should also be controlled. Cleaning agents (soap) should be environmentally friendly (no chlorine bleach) and applied sparingly to avoid over-spray and run-off.



Box 1

Preserving and enhancing the Natural Capital values of large-scale solar plants

The growth in ground-mounted solar parks is occurring at a time when there is increasing recognition of the benefits the natural environment provides to society, and how these are under threat from ongoing environmental degradation. When well-managed and in suitable locations, solar parks offer an opportunity to improve the state of the natural environment alongside their primary purpose of generating electricity. This potential is becoming increasingly pertinent with the development of national policies that prioritise the environment, such as the UK Government's 25-Year Environment Plan which stipulates the need for 'net environmental gain', EU directives such as the Habitats Directive (92/43/EEC), and global frameworks such as the Sustainable Development Goals. Further, promoting good environmental stewardship will enhance the solar industry's profile, contribute to corporate Environmental, Social and Governance (ESG) objectives, help to meet planning policy goals, and improve community and landowner relations.

'Ecosystem Services' and 'Natural Capital' are two related frameworks that are being used to characterise and quantify the benefits that the environment provides for us. Natural Capital is the stocks of environmental assets (e.g. water, air, soil, and living material), from which ecosystem goods (e.g. crops and drinking water) and ecosystem services (e.g. climate regulation and pollination) that society rely on are derived.

Solar parks offer an excellent and relatively untapped opportunity to enhance natural capital and ecosystem services as they occupy a notable amount of land for 25-40 years, which is predominantly used solely to produce low carbon energy. The land remains relatively undisturbed, apart from by maintenance activities. Moreover, because the parks are commonly located in agricultural landscapes, the land they occupy and its immediate surroundings, stand to benefit significantly from enhancement. For example, introducing pollinator habitats on solar parks could improve pollination of surrounding crops leading to higher yields, and changes to the intensity of mowing and grazing can be used to enhance biodiversity.

Within the UK, collaborative research between solar park stakeholders, nature conservation bodies and researchers has produced the Solar Park Impacts on Ecosystem Services (SPIES) decision support tool. The SPIES tool provides an accessible, transparent, and evidence-based means of informing management actions on and around solar parks. It is free to use (see www.lancaster.ac.uk/spies) and enables users to explore the impacts of different management scenarios, which can be outputted as pdf documents suitable to support planning applications.

Whilst currently deployed in a UK context, alternative versions of SPIES could be readily developed for other European ecosystems. By engaging more actively in the natural capital and ecosystem services agendas, the European solar industry would boost its environmental credentials, enabling it to continue to produce urgently needed low-carbon electricity while also improving the state of the natural environment upon which society relies.

The SPIES tool is a collaboration between Lancaster University and the University of York funded by the Natural Environment Research Council (NE/N016955/1 & NE/R009449/1). The web-based version of the SPIES tool was developed by Simomics Ltd.[2]

2 For more information, see: www.lancaster.ac.uk/SPIES and www.energyenvironment.co.uk.

The SolarPower Europe Solar Sustainability Best Practice Benchmark discusses how to make sure that biodiversity is increased on a solar PV power plant:

- Local best practices should be considered
- Decision frameworks and decision support tools should be used
- Local experts should be consulted

By doing this and after discussion of various management methods, a management plan should be decided, which defines certain objectives concerning biodiversity and describes the activities by which to achieve them. Some typical measures are:

- Categorically forbidding the use of herbicides
- Reducing the frequency of vegetation cutting to the necessary minimum (not all areas need the same frequency)
- Reducing vegetation in different phases to make sure that there are always untouched parts
- Limiting the number of sheep per hectare to avoid over-grazing (if sheep are part of the management plan)
- Planting hedges with local species at the borders of the plant
- Creating piles of stones as microbiotopes for reptiles
- Arranging heaps of dead wood
- Keeping specific surfaces vegetation-free
- Removing cut grass in specific areas

These activities should be accompanied by regular surveys by local experts, to control evolution of biodiversity. They shall propose changes to the management plan if this is necessary for achieving the objectives.

2.3 Transitioning from O&M to End-of-life (EoL) management

Based on the growth of solar PV installations, we can estimate that about 1-1.2 million solar PV modules are installed every day around the world. With this in mind and with an estimated average annual failure rate of 0.2% in the field, we may anticipate today ~8 million solar PV modules to fail every year, corresponding to a weight of 144 kt of potential annual solar PV waste from solar PV failures only. Adding also other solar PV waste sources and streams, such as the decommissioning of solar PV modules due to end of service lifetime, repowering, insurance claims, etc., the cumulative solar PV waste is expected to reach up to 8 Mt by 2030.

Reported field experiences show that, most solar PV modules with diagnosed/classified failures that are decommissioned, follow a linear EoL management approach: they enter the waste stream and are either disposed as waste (the majority of the time) or recycled. Currently less than 10% of decommissioned modules are recycled. However, experts from the IEA PVPS Task 13 and the CIRCUSOL project estimate that 45%-65% of them, can be diverted from the disposal/recycling path, towards repair and second life solar PV (re-use) or, as aforementioned, revamping.

To ensure the technical-economical bankability of solar PV re-use and second life solar PV, within the O&M framework and the overall solar PV value chain, it is important to:

- Identify the addressable "target volume", i.e., the failed solar PV modules (or strings), the repair of which is technically feasible, and the occurrence or distribution of such failures.
    - Determine the post-repair efficiency and/or post-revamping reliability of these modules.
    - Integrate optimal sorting-repair-reuse and logistics procedures in the current solar PV O&M value chain, embracing circular economy business models.

Transitioning from PV O&M to EoL management requires streamlined PV triage and qualification methods, as well as efficient PV repair strategies. These are essential for preparing PV modules for reuse and ensuring a viable second-life PV market.

Current industry practices and insights into these areas are inconsistent and scarce, with a lack of standardisation. On this basis, we identify certain future R&D pathways and challenges to be addressed, to support the development, growth, and bankability of second life solar PV and circular PV O&M business:

- Industrialisation and qualification of new solar PV module designs-for-circularity: including "repair-friendly" solar PV components, modular designs, and deployment of repair technology solutions in upscaled re-manufacturing lines
- Identification and tracking solutions (e.g. RFID) at solar PV components/modules/system level, to facilitate reverse logistics, sorting/inventory of solar PV and warehouse operations
- (Automated) detection, diagnostics, and classification (incl. recommendation) of repair or re-use operations in solar PV asset management tools for solar PV plants
- Standardisation/technical specifications for on-site quality control and sorting, as well as off-site design qualification and type approval protocols, towards solar PV reuse-repurposing-recycling
- Synergies of solar PV Asset Owners and O&M service providers, with innovators in supply chain/ reverse logistics technologies, also leveraging AI/machine learning aided logistics, sorting, warehouse operations, inventory management for circular solar PV economy.

The recently published report End-of-Life Management Best Practice Guidelines by SolarPower Europe provides detailed insights and guidelines concerning the transition from operations to EoL. It refers notably to the PV reuse market landscape, second-life business models and the "preparing for reuse" technical framework for PV panels and other balance-of-system (BOS) components.

Chapter 3

Personnel and Training

It is of critical importance that all O&M personnel have the relevant qualifications to perform works in a safe, responsible, and accountable manner. It is difficult to define exactly the suitable employee profile to carry out the work but, in general, it is not advisable to be rigid in the necessary requirements. The necessary knowledge and experience can be gained through different career paths.

Generally, starting off with the philosophy that the personnel qualification can be best defined when all relevant standard operating processes are defined. This will enable the definition of the tasks that need to be fulfilled, and in the context with the company strategy, also the number of staff can be derived. From this baseline, it is best practice to write a job specification sheet for each project. The job specification usually contains the following chapters that can be as well used as a document that can be sent to potential job applicants:

1. Brief description of the company
2. The role, including
    a. The organisational structure (immediate job environment = reporting line towards the next level up and down as well as team members on the same level, not the entire structure)
    b. Main objectives and responsibilities
3. Starting date
4. Remuneration and benefits
5. The ideal profile
6. The ideal experience
7. Work environment, safety, security, environmental

Providing such a structured preparation enables any candidates as well as the company to manage expectations. For part 4, the description can be somewhat openly phrased towards a potential candidate, however, for internal purposes, it is important to establish a pay-scale that is competitive on the one side, however, also fits within the available budget as well as with the internal pay-structure.

It is not uncommon for some positions to be filled to have a candidate sign a non-disclosure agreement prior to providing a detailed job description as outlined above.

The solar industry benefits from a wide range of skills and experience. Team members with a range of electrical, mechanical, financial, business and communications skills are required to handle different tasks and all of them strengthen the positive impact of the service being provided.

As the solar industry scales up globally, it follows that skills training will also need to be scaled up to meet the demand for qualified labour. It is therefore incumbent on all employers in the industry to create a training scheme both internally and externally which creates opportunities for qualifications and development. Whilst it is inevitable that some staff will choose to leave, it is unrealistic to imagine that any company can always employ readily skilled and qualified staff.

Proper standard (general and job specific) training material is a crucial asset, plus establishing a learning success control measure.

Qualification can be sourced internally or externally. Whatever the case may be, the learning objectives, content, to be achieved skill set etc. should be clearly expressed in a specification sheet for each job. The sum of all these training specifications results in a training matrix. The creation and the maintenance of a training matrix as in *Annex B* as well as employee specific qualification certifications should be stored and retrievable in the personnel records. The training matrix enables a company to record skills, both formal and informal, to identify gaps and to provide training to fill the gaps. The personnel record also indicates for which tasks an employee can be dispatched (e. g. a "floater" being able to fulfil several tasks).

Whether an employee needs a certain training or not depends on their personal skill set. In some cases, it might be helpful to test the skillset to find out whether or not a training is necessary. That said, an important aspect of training programmes is also team building in the case of a team training program.

As the industry grows, there is a rapid rate of technological change as well as emergent best practices, which require a programme of continuous personal development to which both individuals and companies need to be committed.

The matrix goes beyond any educational background and focuses on the skills required universally by O&M service providers. Therefore, many of the skills/requirements may need to be adjustable to fit different practices and regulations across Europe.

Chapter 4

Power Plant Operation

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Operations concerns remote monitoring, supervision, control of the solar PV power plant, and technical performance optimisation. It also involves subcontracting and coordination of maintenance activities. Power plant operation used to be a more passive exercise in the past, but with increasing grid integration efforts, more active and flexible operation will be required by grid operators. Examples include ordered shutdowns, power curtailment, frequent adjustment of settings such as power factor (source reactive power), frequency tolerances, and voltage tolerances. This section gives an overview of the operation tasks and requirements.

The following figure provides an overview of the most important tasks associated with power plant operation.

Figure 2

Overview of the most important tasks in Power Plant Operation

Documentation Management System (DMS)*

The DMS is an important requirement which allows changes to be traced during the lifetime of plant's operation. The important aspects to trace the PV plant management information are:

Information
- Components and manuals
- Plant location overview
- PV plant layout
- Electrical diagrams
- EH&S rules

Management control
- Storage of documents
- Logbook of modification
- Access management

Record control
- Alarms linked with maintenance tasks
- O&M automatic logbook
- Unavailability documentation and recording

Emergency plan

Plant performance monitoring and supervision

The O&M service provider is responsible for monitoring and supervision of PV plant performance. In the Fault Management there are different roles and interaction levels:

1st level support

Control room
- Faults detecting
- Ticketing

Coordination of actions
- Site Technician
- Analysis and fault resolution on site

2nd level support
- PV engineers
- Account managers
- Project managers

3rd level support
- Vendor's experts
- Project managers
- Accounting managers

Optimisation of O&M

AI based solutions

Upcoming solutions based on Big-Data-Analysis will help to optimised O&M based on recorded data of actual and similar PV plants.

Power plant controls

AI based solutions

The Power Plant Controller is a control system that can manage several parameters, such as:

- Absolute Active Power Control
- Power Factor Control
- Ramp Control
- Frequency Control
- Reactive Power Control
- Voltage Control

Power Generation Forecasting

The O&M service provider may provide forecasting services, if required by the Asset Owner. Forecast requirements are characterised by:

- Forecast horizon (typically below 48 hours)
- Time resolution (typically 15 minutes to one hour)
- Update frequency:
  - Day-ahead forecasts
  - Intraday forecasts
  - Combined forecasts

The most common KPIs for forecast quality are:

- Root Mean Square Error (RMSE)
- Mean Absolute Error (MAE)

Note: It is worth noting that there are several mature industries that have standards (such as ISO 19650:1:2018) for information management repositories and work needs to be done to adopt these

Figure 2 - continued

Overview of the most important tasks in Power Plant Operation

Performance analysis and improvement

The O&M service provider is responsible for the performance monitoring quality. The data, collected for different time aggregation, should be analysed at the following level:

Minimum requirement	• Portfolio level under control of the O&M • Plant level • Inverter level
Recommended	• String level, PV module level

Grid Code Compliance

The O&M service provider is responsible for operating the PV plant in accordance with the respective national grid code. The requirements provided by the grid operator are usually:

- Power quality
- Voltage regulation
- Management of active power
- Management of reactive power
- Specific behaviour in exceptional grid conditions

The specificities and quality requirements depends on point of connection and the voltage level of the grid.

Reporting and Technical Asset Management

The Operation team provides periodical report. For more details see SolarPower Europe's report *Asset Management Best Practices Guidelines V.2* (www.solarpowereurope.org)

Management of Change

In the event that the design of a PV power plant needs to be adjusted, the O&M service provider should be involved from the beginning in the following phases:

- Concept
- Design works
- Execution

SCADA/monitoring system needs to be updated after every change.

- Documentation of inverter replacement date
- Inverter manufacturer and type
- Inverter serial number

In order to optimise the activities, the adjustments needs to be applied to the following:

- Site Operating Plan
- Annual Maintenance Plan
- Annual Maintenance Schedule

Power Plant Security

It is necessary that, together with the O&M service provider, the Asset Owner puts in place a Security protocol in case of trespassing on the PV plant. A specialised security service provider will be responsible for:

- Intrusion systems
- Surveillance systems
- Processing alarms
- Site patrolling

An intrusion system may be formed by:

- Simple fencing or barriers
- Intrusion detection
- Alerting system
- Remote closed-circuit television (CCTV) video monitoring
- Backup communication line (recommended)

Process for liaison with local emergency services, e.g. police should be considered.

4.1 Documentation Management System (DMS)

Solar PV power plant documentation is crucial for an in-depth understanding of the design, configuration, and technical details of an asset. It is the Asset Owner's responsibility to provide those documents and, if not available, they should, as best practice, be recreated at the Asset Owner's cost.

Before assuming any maintenance and/or operational activities, it is important to understand in-depth the technical characteristics of the asset. There are two important aspects related to the management of this information:

- Information type and depth of detail/as-built documentation
- Management and control

Moreover, for quality/risk management and effective operations management a good and clear documentation of contract information, plant information, maintenance activities and asset management are needed over its lifetime. This is what is called here:

- Record control (or records management)

Currently, there are different types of DMS available, along with a series of standards (ISO), that can be implemented. This is an important requirement that would allow any relevant party to trace any changes during the lifetime of the plant's operation and follow up accordingly (e.g. when the O&M service provider changes, or the teams change, or the plant is sold etc).

Information type and depth of detail/as-built documentation

The documentation set accompanying the solar PV power plant should, as a best practice, contain the documents described in *Annex C*. The IEC 62446 standard also covers the minimum requirements for as-built documentation.

In general, for optimum service provision and as a best practice, the O&M service provider should have access to all possible documents (from the EPC phase). The Site Operating Plan is the comprehensive document prepared and provided by the plant EPC service provider, which lays out a complete overview of its location, layout, electrical diagrams, components in use and reference to their operating manuals, HSSE rules for the site and certain further topics. All detailed drawings from the EPC service provider need to be handed over to the O&M service provider and being stored safely for immediate access in case of solar PV power plant issues or questions and clarifications with regards to permits and regulation.

When storing documents , thought must be given to accessibility. As a minimum, project documentation should be available in a searchable PDF format to facilitate the identification of key information. Moreover, project drawings, such as the as-built design, should be editable in case they need correcting, or change management processes mean they need to be updated.

Management and control

Regarding the document control, the following guidelines should be followed:

- Documents should be stored either electronically or physically (depending on permits/ regulations) in a location with controlled access. Electronic copies should be made of all documents, and these should be searchable and editable

- Only authorised people should be able to view or modify the documentation. A logbook of all the modifications should be kept. As a best practice, logbooks should at a minimum contain the following information:
  - Name of person, who modified the document
  - Date of modification
  - Reason for modification and further information, e.g. link to the work orders and service activities
- Versioning control should be implemented as a best practice. People involved should be able to review past versions and be able to follow through the whole history of the document. The easiest way to ensure this is through using an electronic document management system with built in version control, which should be considered a best practice

Record control

A key point is that necessary data and documentation are available for all parties in a shared environment and that alarms and maintenance can be documented in a seamless way. Critical to the Operations team is that the maintenance tasks are documented back to and linked with the alarms which might have triggered the respective maintenance activity (work order management system log). Photographs from the site should complement the documentation (when applicable). Tickets (ticket interventions) should be stored electronically and made available to all partners. The Asset Owner should also maintain ownership of these records for future references.

To improve future performance and predictive maintenance, it is crucial to keep a record of past and ongoing O&M data, workflows and alarms. This record should seek to link these elements in a cost-effective way, following an agreed naming convention. This will improve accessibility and allow for easier tracing, facilitating comprehensive lessons learned exercises, and resulting in concrete future recommendations for the client. These analyses should also be recorded.

There should be proper documentation for curtailment periods as well as repair periods when the plant is fully or partly unavailable. This will all be recorded by the monitoring system to measure the energy lost during maintenance activities. For this, having the correct reference values at hand is crucial. For important examples of input records that should be included in the record control, see *Annex D.*

As in the case of the as-built documentation, all records, data and configuration of the monitoring tool, and any sort of documentation and log that might be useful for proper service provision must be backed up and available when required. This is also important when the O&M service provider changes.

Plant performance monitoring and supervision

The Operations team of the O&M service provider is responsible for continuously monitoring and supervising of the solar PV power plant conditions and its performance. This service is done remotely using monitoring software systems and/or plant operations centres. The O&M service provider should have full access to all data collected from the site to perform data analysis and provide direction to the Maintenance service provider/team. For more information on monitoring tools please refer to *SolarPower Europe's Monitoring Best Practice Checklist* (available at www.solarbestpractices.com).

Besides the data from the site, if a CCTV system is available on-site, the O&M service provider should, as a best practice, be able to access it for visual supervision and also have access to local weather information.

The O&M service provider is responsible for being the main interface between the plant Owner, the grid operator, and the regulator (if applicable) over the lifetime of the O&M contract regarding production data. The Asset Owner should be able to contact the Operations team via a hotline during daytime, when the system is expected to generate electricity. The Operations team is also responsible for coordinating accordingly with the Maintenance service provider/team.

For more information on monitoring requirements, see *Chapter 9. Data and monitoring requirements.*

4.2 Fault Management

Fault Management involves the detection, categorisation, and resolution of incidents through a structured support system. Multiple levels, from 1st Level Operations to specialised 3rd Level Support, coordinate efforts to ensure timely fault resolution and maintain system performance.

Normally, in Fault Management (Incident Management) several roles and support levels interact:

- With the help of monitoring and its alarms the Operations Center (Control Room) detects a fault. It is responsible for opening a "ticket" and coordinating troubleshooting actions. It collects as much information and diagnostics as possible to establish initial documentation, tries to categorise the issue and, where possible, to resolve it instantly. This is known as 1st Level Support. Then it tracks the incidents until their resolution

- If the fault cannot be sufficiently categorised, the Operations Center may call out a field technician who can be a local electrician or member of the maintenance team. This person will analyse and try to resolve the fault on-site (1st Level Support). Their knowledge and access rights may be not sufficient in some situations, but they can fix most faults to an adequate level. They may also contact the vendor's hotline to help them with the diagnosis

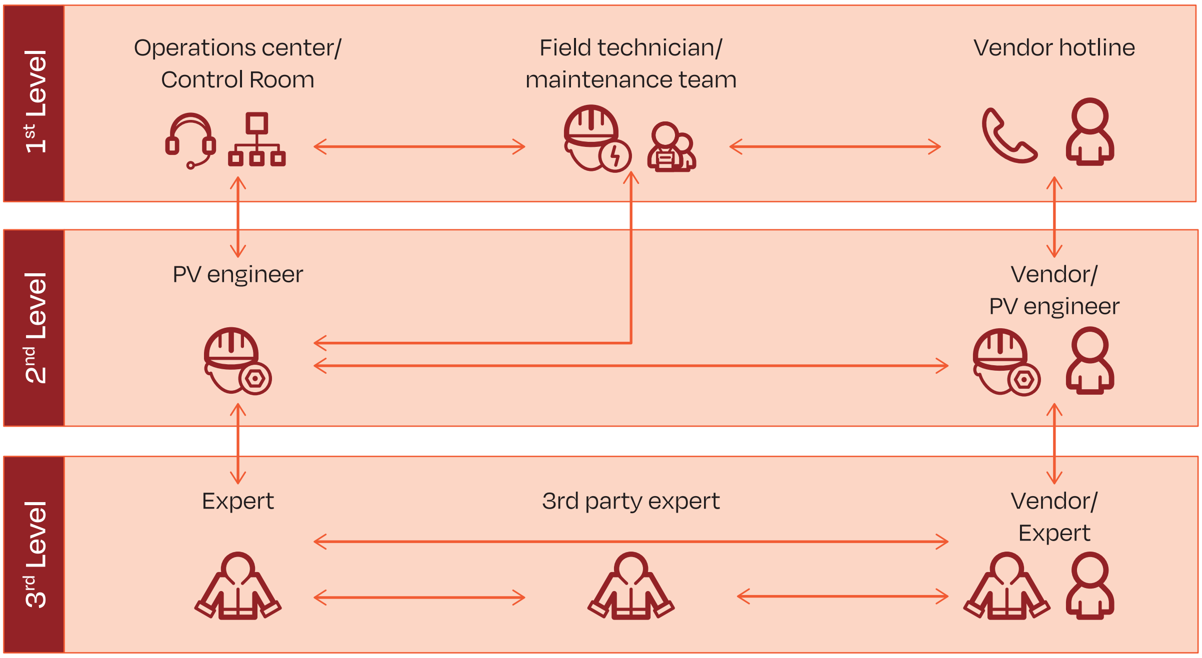
- If 1st Level Support is not able to resolve the incident right away, it will escalate it to 2nd Level Support. This consists of solar PV engineers or Project/Account Managers who have greater technical skills, higher access permissions, and enough time to analyse the fault in depth. They may be internal or of the vendor's staff

- If an incident requires special expertise or access, 2nd Level engineers might need to contact experts (in-house or from the vendor or a third party). This is known as 3rd level support. In some organisations the Project/Account Managers can cover both 2nd and 3rd Level Support, based on their seniority and experience

- When the fault is solved, the Operations Center closes the ticket

Figure 3

Support levels in Fault Management



Performance analysis and improvement

The O&M service provider ensures that the performance monitoring is done correctly.

In general, the data should be analysed at the following levels:

1. Portfolio level (group of plants) under control of the O&M service provider (minimum requirement)

2. Plant level (minimum requirement)

3. Inverter level (minimum requirement)

4. String level (as a recommendation)

5. PV Module Level (as a further recommendation)

The analysis should show the required data on the levels listed above and for different time aggregation periods from the actual recording interval up to monthly and quarterly levels.

The analysis should also include the option for having custom alarms based on client specific thresholds such as business plan data or real-time deviations between inverters on-site.

In particular, the agreed KPIs should be calculated and reported (see *Chapter 10. Key Performance Indicators*). Special attention should be paid to the fact that KPI calculations should take into consideration the contractual parameters between O&M service provider and Asset Owner, to provide an accurate and useful calculation for evaluation and eventually liquidated damages or bonuses.

Optimisation of O&M

An essential part of Operations is the analysis of all the information generated throughout O&M, such as Response Time, and how this correlates to the various classifications of events and root causes. Another vital part of Operations is the analysis of costs incurred for various interventions, categorised into materials and labour. Having such information helps to further optimise the asset by reducing production losses and the cost of O&M itself. For more information on optimisation of O&M please refer to *Chapter 5. Power Plant Maintenance* and *Chapter 8. Spare Parts Management*.

Further optimisation of O&M will be based on upcoming solutions in using AI and Big-Data-Analysis, which will be able to suggest optimisations based on recorded data of the actual and similar PV plants.

Power plant controls

If applicable, the Operations team can be the point of contact for the grid operator for plant controls. The Operations team will control the plant remotely (if possible) or instruct the qualified maintenance personnel to operate breakers/controls on site. The O&M service provider is responsible for the remote plant controls or emergency shutdown of the plant (if possible) and in accordance with the respective grid operator requirements (see also below section on Grid code compliance), regulations, and the aggregator's requirements. The plant control function varies from country to country and in some cases from region to region. The respective solar PV power plant control document for the area details regulations issued by the grid operator and (energy market) regulator.

The Power Plant Controller itself is a control system that can manage several parameters such as active and reactive power and ramp control of solar PV power plants. The set points can normally be commanded either remotely or locally from the Supervisory Control And Data Acquisition System (SCADA). Moreover, the system should be password protected and log all the executed commands. Any executed commands should release real-time notifications to the Operations team.

The following list shows typically controlled parameters in a solar PV power plant:

- Absolute Active Power Control
- Power Factor Control
- Ramp Control (Active and Reactive Power if needed)
- Frequency Control
- Reactive Power Control
- Voltage Control
- Control of Grid Code related parameters

Power Plant Control Layers

Effective solar PV plant operation hinges on a well-defined power plant control strategy. This strategy dictates how the plant responds to grid requirements while optimising energy production. Control policies should clearly differentiate between technical and commercial considerations, grid stability & equipment safety being core priorities before commercial behaviour.

Overall, there are three key layers to consider: dynamic local power control, centralised power control linked to curtailment and remote decentralised power control for grid commands. At the basis, local control the safe and efficient operation of the plant itself. It manages parameters like inverter output and internal voltage regulation. Centralised Power Control meanwhile is divided between curtailment decisions at the level of the aggregator, and those related to grid control which happen in a more immediate time horizon. For the aggregator, the focus is on grid stability and market participation. The aggregator, may remotely adjust power output based on pre-determined curtailment policies. Curtailment refers to the intentional reduction of power generation, typically triggered by grid constraints or economic factors. On the other hand, the grid operator may issue controls, prioritising grid security and stability which supersede aggregator or local control settings.

By understanding these control layers, policy distinctions, and technical considerations, plant operators can ensure a balance between grid needs, commercial interests, and optimal solar PV power plant operation.

Power Generation Forecasting

Forecasting services for solar PV power generation are generally offered by operators of solar PV monitoring services. However, external services can also provide this function. When the Asset Owner requires Power Generation Forecasting from the O&M service provider, they could opt for a service level agreement with the forecast provider. Forecasting may have an influence on the contract agreement for electricity dispatching between the Asset Owner and a trading service provider.

The requirements for forecasts may differ from country to country and also depend on the contract agreement for electricity dispatching between the Asset Owner and a trading service provider. Forecast requirements are characterised by the forecast horizon, the time resolution, and the update frequency, all depending on the purpose. For power system or power market related purposes, forecast horizons are typically below 48 hours, and the time resolution is 15 minutes to one hour, in line with the programme time unit of the power system or the market. Common products are day-ahead forecasts, intra-day forecasts and combined forecasts. Day-ahead forecasts are typically delivered in the morning for the next day from 0 to 24 and updated once or twice during that day. Intraday forecasts are delivered and updated several times per day for the rest of the day and should be delivered automatically by the forecast provider.

For long-term planning of unit commitment and maintenance decisions, forecasts with longer time horizons are used, typically one week or more.

Solar PV Power Generation Forecasts rely on numerical weather predictions, satellite data and/or statistical forecasting and filtering methods. Most products combine several of these techniques. Good practice requires numerical weather predictions for day-ahead forecasting and a combination with satellite data for intra-day forecasts. In all cases, good practice requires statistical filtering which in turn requires a near-real-time data feed from the monitoring system to the forecast provider. For best practice, the forecast provider should also be informed about scheduled outages and the expected duration of forced outages.

The most common KPIs for forecast quality are the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE). They are normalised to peak power and not to energy yield.

Grid code compliance

The O&M service provider, and in particular the Operations team is responsible for operating the solar PV power plant in accordance with the respective national grid code. The operator of the grid to which it is connected (either low voltage grid or medium voltage grid or high voltage grid) provides the requirements for power quality, voltage regulation and management of active and reactive power. In some countries (and/or regions) specific grid codes for renewable energy generators have been issued. Specific behaviour in exceptional grid conditions, e.g. reaction on short circuits and similar under-/overload conditions require stable operation and active grid support by GFM (grid forming) are upcoming requirements in grid code standards on national, regional and international levels.

Depending on the voltage level of the grid the plant is connected to, the specificities and quality requirements for the solar PV power plant change. Grids with a higher voltage level usually have more specific and demanding requirements.

Most of the grid-connected utility-scale solar PV power plants in Europe must undergo an external test to meet the grid operator requirements. These plant tests allow the grid operator to adjust the power output from the solar PV power plant according to the grid capacity and power frequency requirements.

The O&M service provider is expected to be familiar with all the details of the grid code and grid operator requirements. Depending on the regulations, either the grid operator themselves is steering the solar PV power plant controller (with remote signals) or the Operations team is managing the plant controller under the direction of the grid operator.

Management of change

If the design of a solar PV power plant needs to be adjusted after the Commercial Operation Date, the O&M service provider should, as a best practice, be involved by the Asset Owner and the EPC service provider. They can even be a main contributor, if not the leader, of this change process. Reasons for such changes can be motivated by non-compliance of the solar PV power plant with the capacity predicted by the EPC service provider, by regulation change (introduction of new solar PV power plant controls regulations), by the unavailability of spare parts or components, or for an upgrade to the solar PV power plant. These events can trigger new design works, procurement and installation of new equipment and adjustment of O&M procedures and/or documentation. It may also impact certain performance commitments or warranties provided by the O&M service provider, which will need to be adjusted.

The O&M service provider should be involved in changes to the solar PV power plant from the beginning. Concepts, design works, and execution need to be coordinated with ongoing O&M activities. Any changes should also be reflected in the plant SCADA and monitoring systems. For data continuity and long-term analysis, the monitoring system should be able to trace all changes of electrical devices. This should include documentation of inverter replacement date, manufacturer and type, and serial number in a structured way for further analysis (e.g. spare part management, Predictive Maintenance analysis). The monitoring of replaced devices will also help the O&M service provider verify that the new component is correctly configured and is sending high quality data. Adjustments to the Site Operating Plan, the Annual Maintenance Plan and the Annual Maintenance Schedule need to be applied, and the O&M service provider needs to familiarise the O&M staff with the operating manuals of the new equipment. These types of changes will have an impact on Spare Parts Management and inventory (replacement). Depending on the significance of the change, the O&M annual fee might need to be adjusted.

It is advisable that the O&M service provider lead these sorts of change processes. The O&M service provider is the trusted partner of the Asset Owner and should advise the Owner when they are making decisions on changes to the plant. In the case of major changes, the Owner should also consider informing lenders about the decision process and provide concepts, proposals, calculations and updates.

The fixed O&M fee does not usually cover change services. The Asset Owner and the O&M service provider should manage changes in a formalised way. This procedure should include the following steps: description of proposed change (including time plan, costs, consequences, and alternatives), authorisation of the change by the Asset Owner, realisation of the change, documentation by the O&M service provider and acceptance.

Power plant security

It is important that the solar PV power plant, or key areas of it, are protected from unauthorised access. This serves the dual purpose of protecting the plant's equipment and keeping members of the public safe. Unauthorised access may be accidental with people wandering into the plant without realising the dangers, or it may be deliberate for the purposes of theft or vandalism.

Together with the O&M service provider and the security service provider, the Asset Owner must put in place a Security Protocol in case an intrusion is detected.

In most countries there are strict legal requirements for security service providers. Therefore, solar PV power plant security should be ensured by specialised security service providers subcontracted by the O&M service provider. The security service provider will be responsible for the proper functioning of all the security equipment including intrusion and surveillance systems. They are also responsible for processing alarms from the security system by following the Security Protocol and the use of the surveillance systems installed on site. The security system provider will be also responsible for any site patrolling or other relevant services. The security service provider should also assume liability for the security services provided. The O&M service provider will coordinate with the security service provider and may choose to act as an intermediary with the Asset Owner.

A security system may be formed of simple fencing or barriers but may also include alarm detection and alerting systems and remote closed-circuit television (CCTV) video monitoring. If solar PV power plants have CCTV systems in place, an access protocol would be required when reactive and planned works are carried out. This will ensure that authorised access is always maintained. This can be done by way of phone with passwords or security pass codes, both of which should be changed periodically.

For additional security and in high-risk areas it is advisable to have a backup communication line installed (often, the first thing that gets damaged in case of vandalism is communication with the surveillance station) as well as an infrastructure for monitoring connectivity and communication with the security system. As well as any remote monitoring, it is likely that provision for onsite attendance is required when significant events occur. Processes for liaising with local emergency services should be considered.

Within the solar plant, there may also be additional areas with restricted access, for example locations containing Hazardous Voltage equipment. When authorising access to the parks it is important that all workers and visitors are appropriately informed of the specific access and security arrangements and where they should keep off. Warning signs and notices can form an important part of this and may be compulsory depending on local regulations.

As well as the general security of the site over the lifetime of the park, particular attention should be made to periods of construction or maintenance when usual access arrangements may be different. It is important that security is always maintained particularly when there are activities that may be of more interest to members of the public or thieves.

The Asset Owner will likely have insurance policies in place directly or indirectly and these will be dependent on certain levels of security and response being maintained. Failure to meet these may have important consequences in the case of an accident or crime.

4.3 Reporting and Technical Asset Management

The Operations team is responsible for providing periodic reporting to the AM or directly to the Asset Owner. In many cases, the Operations team also assumes further TAM responsibilities. For more details on reporting and other TAM tasks, see SolarPower Europe's report *Asset Management Best Practices Guidelines V.2* (*www.solarpowereurope.org*).

4.4 Cooperation with Distribution System Operator (DSO)

The O&M contractor (or its dedicated department, like Control Center) should be appointed as the first to contact and the most important stakeholder (representative) for DSO in order to perform Operations at power plant that affects the grid connections or production.

Contacts between O&M provider and DSO should be regulated by the agreement between plant owner and grid operator while investments preparation. Contact list with all employees from O&M service provider and operators from DSO should be actualised every time when personnel changes.

DSO should inform O&M provider about any anomalies on grid that requires any operations on the grid like connection/disconnecting form a grid, stopping generation or limiting generation. Also, every time if O&M provider needed to disconnect plant form a grid for example to prepare workplace need to inform DSO in advance.

Works performed by O&M provider, but on "grid side" need to have a permission from DSO, because they are responsible for a grid quality, while O&M service provider should ensure safety workplace.

All O&M provider employees needed to have qualifications for electric operations and also necessary experience.

Chapter 5

Power Plant Maintenance

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This chapter summarises the critical aspects of maintenance in solar PV power plants, emphasising the collaboration between on-site technicians, subcontractors, and operations teams to ensure optimal performance. It covers various maintenance types—preventive, corrective, predictive, and extraordinary—highlighting their distinct roles and importance.

Maintenance is usually carried out on-site by specialised technicians or subcontractors, in close coordination with the Operations team's analyses. In modern solar PV power plants, automation of maintenance tasks is becoming more prevalent. However, this practice is still developing and is not widespread currently. The following figure provides an overview of the four main types of power plant maintenance.

Figure 4

Overview of the different types of Power Plant Maintenance

Included in all O&M contracts

Preventive Maintenance

Preventive Maintenance comprises the core elements of PV plant maintenance services. It includes regular visual and physical inspections, and verification that all the key components of the solar plant are in good working order. The maintenance is carried out at predetermined regular intervals according to prescribed OEM& O&M manuals and are included in the "Annual Maintenance Plan".

Corrective Maintenance

Maintenance text to be changed: Corrective Maintenance corresponds to any activity performed to restore PV plant systems, equipment or components to a functioning state. It occurs after a failure detection by remote monitoring or during an on-site inspection. Corrective Maintenance includes Fault Diagnosis, Temporary Repair & Permanent Repair and can be divided into 3 levels of intervention: Intervention without the need of substitution, with the need of substitution and with the need to intervene on the software of a device.

Predictive Maintenance

Predictive Maintenance is a condition-based intervention carried out following a forecast derived from the analysis and evaluation of the significant parameters of the degradation of an item. The site must have "intelligent" equipment and an appropriate monitoring software system, allowing the Operations team to perform regular monitoring, supervision, forecast and performance data analysis of the main equipment of the PV plant (transformer, inverter, combiner box and/or DC array)

Extraordinary Maintenance

Extraordinary Maintenance actions are necessary when major unpredictable events require substantial activities to restore the previous plant conditions. These interventions are required for damages due to Force Majeure, damages due to a theft or fire, endemic failures of the equipment, modifications required by regulatory changes and equipment wear or deterioration due to design faults.

Additional Services

The O&M agreement can foresee services other than electrical and mechanical plant maintenance. Some of these additional services are generally included in the scope of work and the O&M annual fixed fee and some are not. Additional services include PV site maintenance activities such as panel cleaning and vegetation control, general site maintenance tasks like waste disposal and maintenance of buildings and on-site measurements such as I-V curve measurement on modules or thermal inspections.

5.1 Preventive Maintenance

Preventive Maintenance (also called "scheduled maintenance") activities are the core element of the maintenance services to a solar PV power plant. It comprises regular visual and physical inspections, as well as verification activities.

The current standard is that maintenance of all key components is carried out at predetermined intervals or at least according to prescribed OEM and O&M manuals. These are included in a detailed Annual Maintenance Plan which provides an established time schedule with a specific number of iterations for carrying out the maintenance.

It must also maintain the equipment and component warranties in place and reduce the probability of failure or degradation. The activities must also be consistent with respective legal issues such as national standards for periodic inspection of certain electrical components, as well as asset insurance plans. This means that a number of varying factors (warranties, legal standards, insurance plans) influence the activities of the Annual Maintenance plan next to general maintenance considerations. The O&M contract should include this scope of services and each task frequency and ideally identify a priori which components to look at during the implementation of operation & maintenance activities.

It should be noted that the various maintenance activities require personnel qualified to carry them out. The O&M service provider must ensure that they have the appropriate range of skills available to fulfil their contractual obligations (for more information on maintenance activities and the skills they require, see *Annex B* of these Guidelines and *Annex A of the Lifecycle Quality Guidelines*).

The "**Annual Maintenance Plan**" (see *Annex E* or download it from www.solarpowereurope.org) developed as an attachment of this report includes a list of regular inspections per equipment (e.g. module, inverter etc) and per unit of equipment (e.g. sensors, fuses etc). In a component-cohort based approach, additionally to time and frequency activities are repeatedly performed on a pre-selected set of components in order to track the evolution of components over time.

Preventive Maintenance also includes ad-hoc replacement of parts of inverters or recalibration of sensors. In general, it is important to follow detailed Preventive Maintenance procedures, which are agreed upon in the Annual Maintenance Plan.

Box 2

Example Preventive Maintenance

An example of Preventive Maintenance is thermographic inspection which aims to identify defective panels on a solar PV power plant. Indeed, several categories of anomalies (hot spots, hot strips, moisture ingress, soling, etc.) can occur, significantly reducing the whole plant productivity. Relevant inspection procedures are performed either by operators with handheld cameras or using remotely piloted drones or piloted aircraft equipped with dedicated thermal and optical payloads.

5.2 Corrective Maintenance

Corrective Maintenance covers the activities performed by the Maintenance team to restore a solar PV power plant system, equipment or component to a status where it can perform the required function. Corrective Maintenance takes place after a failure detection either by remote monitoring and supervision or during regular inspections and specific measurement activities (see *Annex E*).

Corrective Maintenance includes three activities:

Table 1

Three Levels of corrective maintenance

Level of Intervention	Characteristics	Required labour skill	Example Activity
1st level	No need for substitution	Maintenance team	Restart of an inverter
2nd level	Substitution of a component	Maintenance team/ solar PV Engineer	Substitute a fan to restore inverter functionality
3rd level*	Intervention on the software	Solar PV Engineer/ 3rd party expert	Reconfiguration or Parametrisation of an inverter

1. Fault Diagnosis also called troubleshooting to identify and locate the cause of the fault
2. Temporary Repair, to restore the required function of a faulty item for a limited time, until a full repair is carried out
3. Full repair, to restore the required function permanently

A key aspect of corrective maintenance is to be able to track failures to their root cause. This is most often a problematic manufacturer/model/serial number but may also be linked to installation errors or environmental conditions such as temperature inside enclosures. Corrective Maintenance processes should also track the efficacy of responses to problems (what fixes the problem reliably?).

3rd level activities could be included in the O&M agreement or billed separately to it, depending on the specific scope of work agreed between the parties. Generally, however, this intervention is excluded by the contractual scope of work, especially when the device manufacturers' maintenance team or third-party licensed company needs to intervene.

Interventions for reconditioning, renewal, and technical updating, save for the cases where those actions are directly included in the scope of the contract, should be excluded from Corrective Maintenance, and included in the Extraordinary Maintenance (see *5.4. Extraordinary Maintenance*).

The scope of Corrective Maintenance activities and its "border" or definition with respect to Preventive Maintenance requires specific attention and it should be properly defined in the Maintenance contract. For an easier comprehension, an example is presented below:

- A cable termination tightening activity using a torque device for correct fixation should be under the Preventive Maintenance scope of works, but depending on the quantity and/or frequency, it could be considered a Corrective Maintenance activity. The Annual Maintenance plan therefore states the extent of each planned activity.

Usually, Corrective Maintenance work must be accomplished within the contractually agreed minimum Response Times (see *Chapter 10 section Response Time and Chapter 11 section Response Time price adjustment*).

Contractual agreements can foresee that the included Corrective Maintenance will be capped on a per year basis.

5.3 Predictive Maintenance

Predictive Maintenance is defined as a condition-based maintenance carried out following a forecast derived from the analysis and evaluation of the significant parameters of the degradation of the item (according to EN 13306). These parameters can be either based on a (1) monitoring software system or (2) on the analysis of tests and inspections carried out as part of the preventative maintenance and stored in a smart digital representation of the solar farm.

A prerequisite for a good Predictive Maintenance is that the devices on-site can provide information about their state, in such a way that the O&M service providers can evaluate trends or events that signal deterioration in a device. As a best practice, the device manufacturer should provide a complete list of status and error codes produced by the device, together with the detailed description of their meaning and their impact on the functioning of the device. Additionally, a standardisation of status and error codes through inverters and dataloggers from the same brand should be followed and, in the future, this standardisation should be common to all manufacturers.

The Operations Team should select "intelligent" equipment set with sufficient sensors and opt for a monitoring software system that provides basic trending and comparison (timewise or between components and even between solar PV sites) functionalities (minimum requirement).

The Operations team of the O&M service provider enables Predictive Maintenance thorough continuous or regular monitoring, supervision, forecast and performance data analysis (e.g. historical performance and anomalies) of the solar PV power plant (at the DC array, transformer, inverter, combiner box or/and string level). This can identify subtle trends that would otherwise go unnoticed until the next round of circuit testing or thermal imaging inspection and that indicate upcoming component or system failures or underperformance (e.g. at solar PV modules, inverters, combiner boxes, trackers., etc. level).

Predictive maintenance based on Component Condition Monitoring requires to first establish a digital representation of a solar site (digital twin), including a geospatial as well as an electrical and component-based understanding of the site. Within this digital representation it is crucial to rely on a standardised naming convention of all components, component properties (make, model, etc), as well as ideally component serial numbers.

Ideally, since these approaches don't exclude each other, signals for predictive maintenance activities can be provided through both methods. Before deciding which Predictive Maintenance actions to recommend, the Operations team should implement and develop procedures to effectively analyse historical data and faster identify behaviour changes that might jeopardise systems performance. These changes of behaviour are usually related to the pre-determined or unpredicted equipment degradation process. For this reason, it is important to define and to monitor all significant parameters of wear-out status.

Following such analysis, the Maintenance team can implement Predictive Maintenance activities to prevent any possible failures which can cause safety issues and energy generation loss.

For efficient Predictive Maintenance, technical expertise is required, which is at best a combination of knowledge of the respective system's performance, related equipment design, operation behaviour. Ideally, it is a process that starts at commissioning and the recreation of a baseline. This baseline will then represent the entire solar PV system operation, how different pieces of equipment interact with each other, and how the system reacts to "environmental" changes. Looking into the future, more and more automatic predictions will be provided by the respective systems, making this trend available also to less technically sophisticated O&M providers.

Predictive Maintenance has several advantages, including:

- Optimising the safety management of equipment and systems during their entire lifetime
- Helping to anticipate maintenance activities (both corrective and preventive)
- Delaying, eliminating and optimising some maintenance activities
- Reducing time for repairs and optimising maintenance and Spare Parts Management costs
- Reducing spare parts replacement costs
- Increasing availability, energy production and performance of equipment and systems
- Reducing emergency and non-planned work
- Improving predictability

The following four specific examples show how Predictive Maintenance might be implemented.

Box 3

Example Predictive Maintenance

An O&M service provider signs a new contract for a solar PV power plant equipped with central inverters. Analysing its backlog of maintenance, the O&M service provider knows that these inverters showed signs of power loss due to overheating at several points in the past. This might be related to problems in the air flow, filter obstructions, fans, or environmental changes (high temperature during summer). A decision was taken to monitor the temperature of IGBTs (Insulated-Gate Bipolar Transistors). An "air flow inspection" was performed, prior to any emergency action being required, to determine whether power loss was related to air flow. This type of activity is a condition-based inspection performed after the detection of a change in a significant parameter. It is also considered as a type of Predictive Maintenance. The final purpose is to identify if, for example, the ventilation systems will need some upgrade, replacement, or if there is any type of air flow obstruction or even if a filter replacement or cleaning is required.

5.4 Extraordinary Maintenance

Extraordinary Maintenance actions are necessary when major unpredictable events (Force Majeure) take place in the plant that require substantial activities and works to restore the previous plant conditions. Additionally, it also describes any maintenance activity generally not covered or excluded from the O&M Contract).

Extraordinary Maintenance interventions are required for:

- Damages that are a consequence of a Force Majeure event
- Damages resulting from theft or fire
- Serial defects or endemic failures on equipment, occurring suddenly and after months or years from plant start-up
- Modifications required by regulatory changes

Additionally, in cases where the O&M service provider and the EPC service provider are different entities, the following occurrence should also be considered as Extraordinary Maintenance:

- Major issues that the O&M service provider becomes aware of during its ordinary activity. These could be defects or other problems that are not a consequence of equipment wear or deterioration and can be reasonably considered to have been caused by design mistakes (e.g. "hidden" defects that require re-engineering)

"Force Majeure" events affecting solar PV power plants include high winds, flooding, hurricanes, tornadoes, hail, lightning, and any number of other severe weather events. Extraordinary Maintenance associated with severe weather include safety shutdown, inspection to document damage, electrical testing (integrity of circuits and grounding), remove/repair/replace decisions, and recommissioning confirming proper operation and documenting changes made during repairs.

Generally, these activities are billed separately in the O&M contract and are managed under a separate order. It is advisable that the O&M contract includes the rules agreed among the parties to prepare the quotation and to execute the works. Both a "lump sum turn-key" or a "cost-plus" method can be used for such purposes.

Although not necessarily maintenance interventions, revamping and repowering can also be included in the Extraordinary Maintenance list in the O&M agreement, or at least managed with the same rules. For more information on this, see *Chapter 7. Revamping and Repowering*.

After the approval by the Asset Owner of the O&M service provider's proposal, activities may commence, subject to availability of the required equipment and special machinery (if required).

The potential loss of energy between the event occurrence and full repair is very difficult to determine in the SPV financial model. However, many of the above events can be reimbursed to the Asset Owner by the insurance company under any "All Risk Insurance" coverage that is in place. Relevant conditions and requirements according to the insurance policies of the Asset Owner need to be shared with the O&M service provider.

Best Practices of O&M agreements regarding Extraordinary Maintenance activities include:

- General rules to quantify price and to elaborate a schedule to perform repair activities, and the right of the Asset Owner to ask for third party quotations to compare to the quotation of the O&M service provider. In this case a "right-to-match" option should be granted to the O&M service provider
- The obligation for the Asset Owner to have in place a consistent "All Risk Property" Insurance including loss of profit

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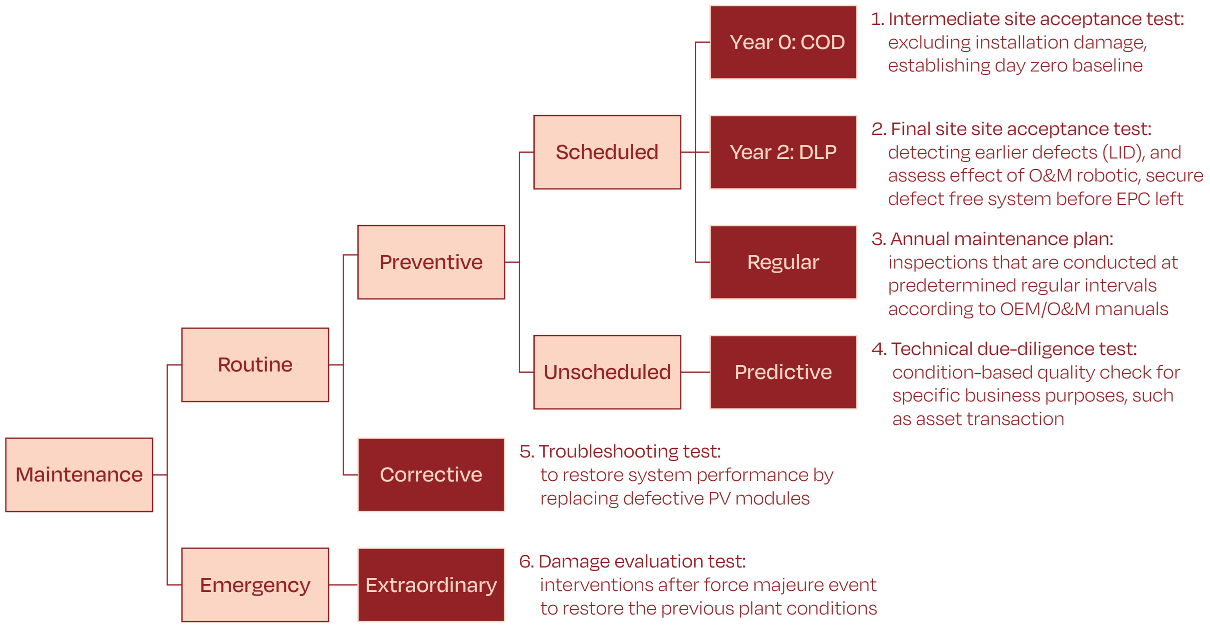
Common Tests and Inspections

The previous chapter explored the range of maintenance activities conducted throughout the lifetime of a PV system. This chapter delves into the various tests performed at different maintenance intervals to ensure the optimal performance and longevity of photovoltaic (PV) systems.

At different maintenance schedules, various tests are performed to ensure optimal performance and longevity of photovoltaic (PV) systems. The maintenance schedules and typical tests are summarised in Figure 5.

Figure 5

Maintenance schedules and typical tests



Source: Courtesy of Quantified Energy Labs, 2024

There are six main tests performed throughout the PV lifecycle, each serving a specific purpose. These tests include:

1. **Intermediate site acceptance test:** This test is performed after the installation is complete to exclude installation damage and establish a day-zero baseline for the PV system which provides a reference point for future performance evaluations and helps in identifying any deviations or issues that may arise over time. More information on this point can be found in the EPC Best Practices Guidelines.[3]

2. **Final site acceptance test:** This test ensures that the PV system is free from defects and is operating as expected before it is handed over to the owner or operator. More information on this point can be found SolarPower Europe's EPC Best Practices Guidelines.

3. **Annual maintenance test:** These inspections are conducted at predetermined regular intervals according to original equipment manufacturer (OEM) and O&M manuals. The annual maintenance test includes a comprehensive evaluation of the PV system's performance and condition, identifying any wear and tear or potential issues that may affect its efficiency. Regular maintenance helps in prolonging the lifespan of the system, reducing the risk of unexpected failures, and ensuring consistent energy production.

4. **Technical due-diligence test:** This condition-based quality check is performed for specific business purposes, such as asset transactions or refinancing. The technical due-diligence test provides an in-depth assessment of the PV system's current state, evaluating its performance, reliability, and potential risks. This test is crucial for potential buyers, investors or lenders to make informed decisions regarding the value and viability of the PV asset.

5. **Troubleshooting test:** When performance issues are detected, a troubleshooting test is conducted to identify and replace defective PV modules or components. This test involves pinpointing the root cause of the problem and implementing corrective actions to restore the system's performance. Troubleshooting tests are essential for maintaining the efficiency of the PV system and minimising downtime, ensuring that the system continues to operate at optimal levels.

3 https://solarbestpractices.com/guidelines/detail/foreword

6. **Damage evaluation test:** After force majeure events, such as natural disasters or extreme weather conditions, a damage evaluation test is performed to assess the damage to the PV system. This test involves inspection of the affected components, determining the extent of the damage, and implementing necessary repairs or replacements to restore the system to its previous condition. Besides providing documentation of the damage for insurance claims and legal or financial processes, these tests document the post-recovery state of the system to ensure it is functioning properly after the damage event.

For the six tests above, there are series of inspection methods outlined IEC 62446 series, which set standards for the testing, documentation, and maintenance of PV systems to ensure safety and performance. Some of these inspection models are summarised in Table 2 below.

Table 2

Inspection methods

Inspection Method	Purpose	Procedure
Visual Inspection	Checks for physical damage, proper installation, correct labelling, and overall visual condition.	Inspect for damaged modules, loose connections, and adherence to installation guidelines.
Continuity and Grounding Verification	Ensures proper grounding connections and electrical continuity throughout the system.	Verify all metal parts are properly grounded and ensure no open circuits in the grounding system.
Open-Circuit Voltage Measurement	Verifies the functionality and correct stringing of the PV array.	Measure the open-circuit voltage of the PV strings and compare with manufacturer specifications.
Short-Circuit Current Measurement	Confirms the short-circuit current output and estimates the maximum power output potential.	Measure the short-circuit current and compare to expected values.
Insulation Resistance Test	Ensures no leakage currents and minimises the risk of electrical faults.	Measure insulation resistance between live conductors and grounded parts. Includes wet insulation tests.
Polarity Test	Verifies the correct polarity of connections to prevent malfunctioning and damage.	Check that the polarity of all DC connections is correct.
Functional Test	Simulates various operating scenarios to verify system functionality under different conditions.	Test inverter startup and shutdown processes and other functional aspects of the PV system.
String I-V Curve Scanning	Evaluates the I-V characteristics to assess performance and identify issues like shading or soiling.	Use I-V curve tracers to measure and analyse the I-V characteristics of the PV strings.
Electroluminescence (EL) Imaging	Detects microcracks, cell degradation, and other hidden defects in PV modules.	Apply a forward bias to the module to induce electroluminescence and capture images with EL cameras.
Infrared (IR) Thermography	Detects thermal anomalies in PV modules and BOS components to identify hotspots and other issues.	Use thermographic cameras to capture thermal images and analyse for excessive heat generation.

Three key inspection methods are discussed in detail below:

String I-V Curve Scanning

String I-V Curve Scanning is an essential inspection method for evaluating the electrical performance of PV modules and strings. It helps in identifying and diagnosing performance issues, ensuring the optimal operation of the PV system. String I-V scanning is covered by the standard IEC 62446-1 on the maintenance of PV systems. Through I-V scanning, we can assess performance, identify degradation, and detects issues such as shading, soiling, and module mismatches in a string of modules. To carry out this procedure, the steps are as follow:

1. **Connection:** Connect the I-V curve tracer to the PV string
2. **Measurement of environmental conditions:**
   - Measure the irradiance using and irradiance meter
   - Measure PV module temperature using a temperature sensor
3. **Measurement:** Measure the voltage and current output of the string across a range of operating conditions
4. **Plotting:** Plot the I-V curve to visualise the electrical performance
5. **Analysis:** Analyse the curve for deviations from expected performance, such as lower peak power, reduced fill factor, or abnormal knee points
6. **Correction:** Correct the I-V curve measurements for standard test conditions (STC) based on the measured irradiance and temperature
7. **Comparison:** Compare the measured I-V curve with manufacturer specifications and previous baseline measurements to identify potential issues

Electroluminescence (EL) imaging

Electroluminescence (EL) Imaging is a critical inspection method for detecting microcracks and other hidden defects in PV modules that are not visible through standard inspections. It enhances the accuracy of maintenance diagnostics, leading to more effective repairs and replacements. This technique provides a detailed view of the module's internal health, helping to ensure the overall reliability and performance of PV systems. EL imaging is a relatively new process, whose standardisation is only happening as of 2025 with the publication of IEC TS 62446-4: Photovoltaic modules and plants - Outdoor electroluminescence imaging.

The electroluminescence procedure requires dedicated equipment including EL cameras, imaging systems and a DC power supply. The steps to implement the EL inspection include:

1. Image Capture:
    a. Ensure the PV modules are disconnected from the inverter and other DC circuits to prevent any unintended current flow
    b. Connect a suitable DC power supply to the PV modules or strings under test and apply a forward bias
    c. Position the EL camera to ensure the PV modules to be tested is within the field of view
2. Analysis: Examine the captured images for defects such as microcracks, inactive cell areas, and potential degradation
3. Comparison: Compare the EL images with baseline images or manufacturer specifications to identify and quantify defects

Inspection methods vary for EL, with different levels of complexity and various benefits and costs, which make them relevant for different typologies of PV systems from rooftops to large utilities. Mounting a camera on a tripod or framing system is among the simplest set ups, while still enabling the capture of high-quality images with sufficient exposure time. It does come with drawbacks, being labour-intensive and impractical for locations such as rooftops, tall trackers, and floating PV systems. Even with a well-designed framing system, the throughput is limited to around 1,500 to 3,000 modules per night, making it less suitable for large-scale inspections. Daylight EL imaging is another solution which relies on electrical modulation for imaging. It is more flexible, as it can be conducted during both day and nighttime. However, it is relatively slow, with a throughput of fewer than 500 modules per eight-hour shift, which limits its scalability for larger installations. Drones are rapidly emerging as a key solution for speed and flexibility, notably for hard to reach locations. Drones may be equipped with CMOS or InGaAs cameras.

- CMOS cameras are not highly sensitive to EL wavelengths, necessitating long exposure times. Stabilising a drone for several seconds in an outdoor environment poses significant challenges, resulting in a throughput of only 1,200 to 2,400 modules per eight-hour night shift
- InGaAs cameras are a highly efficient solution for EL imaging by drones, reaching a throughput of 10,000 to 15,000 modules per eight-hour night shift and delivering high-quality images, making it ideal for inspecting large-scale solar farms. However, the higher initial capital expenditure and system complexity create a higher entry barrier

EL imaging is a versatile and highly effective method for detailed inspections of PV modules. The various technologies and methodologies associated with EL imaging allow for flexibility and scalability in its application.[4]

4 Further details can be found in the works 'Outdoor Luminescence Imaging of Field-Deployed PV Modules' by Kunz et. al.

Infrared (IR) thermography

Infrared thermography is a critical inspection method used to detect thermal anomalies in PV modules and other Balance of System (BOS) components, such as inverters, transformers, and electrical connections. Common issues identified through IR include hotspots, which may lead to various defects including total failure of a module. These inspections are essential for maintaining the efficiency and reliability of solar PV systems by identifying and resolving potential issues early. IT thermography inspections should comply with IEC TS 62446-3 - Photovoltaic modules and plants - Outdoor infrared thermography.

To proceed with IR measurement of PV modules, drones or aircraft equipped with thermographic cameras are typically used, enabling high throughput. During data acquisition, the drone or aircraft's flight path is pre-programmed to cover the entirety of the solar PV asset. Thermographic images and visual photos or videos are recorded during the flyover. Alongside IR capture, additional geolocation services and 3D modelling of the entire plant may be offered.

Following data acquisition, various processing steps are necessary to establish a diagnosis of anomalies and assess the root causes of PV failures. They for instance include:

- Geolocation of PV Modules: Manual or automated location of the inspected solar PV modules, recreating the layout with precise geolocation down to individual module ID or serial number

- Thermal Anomalies Detection and Classification: Manual or automated detection of thermal anomalies, identifying affected solar PV modules on the plant's layout

- Solar PV Module Failure Analysis: Diagnosis and root-cause analysis of solar PV module failures, linking thermal anomalies to specific failures

- Data Analytics: Basic or advanced data treatment to describe the impact of failures, including degradation trends, failure distribution, and power loss assessments

- Maintenance Implementation Plan: Recommendations for actions needed to minimise yield losses, translating findings into preventive or corrective operations

- Reporting: Standard is a presentation of results on interactive digital software solutions summarising findings, including power loss estimates and financial implications. Reports are usually housed in cloud-based platforms for easy access and comparison with previous inspections

Beyond modules, IR imaging can also be carried out on other components of the BOS, typically with the use of handheld thermographic cameras. There, the data acquisition proceeds through a detailed inspection of BOS components, such as inverters, transformers, and electrical connections, capturing thermal images of each component with the thermographic camera (which must first be set for the right temperature range). During post processing, thermal anomalies in BOS components are analysed, identifying areas of excessive heat generation.

Infrared thermography is effective for detecting thermal anomalies in PV modules and BOS components. Drones with thermographic cameras are used for rapid, large-area inspections, while handheld IR cameras are essential for detailed diagnostics, particularly for module connectors and components not visible from above. This two-step approach ensures comprehensive and accurate detection of issues, enhancing the reliability and performance of solar PV systems.

Additional Services

Table 3 presents a non-exhaustive list of additional services. For more information on whether these additional services are generally included in the O&M agreement or not, see *11.3. Scope of the O&M contract*.

Table 3

Examples for additional maintenance services

	Additional services
Solar PV site maintenance	Module cleaning
	Vegetation management
	Snow or sand removal
General site maintenance	Pest control
	Waste disposal
	Road management
	Perimeter fencing repair
	Maintenance of buildings
	Maintenance of Security Equipment
On-site measurement	Weekly/monthly meter readings
	Data entry on fiscal registers or in authority web portals for FIT tariff or other support scheme assessment (where applicable)
	String measurements – to the extent exceeding the agreed level of Preventive Maintenance
	Thermal inspections, I-V curve tracing, electroluminescence imaging (for more information, see *Chapter 6 Common Tests and Inspections*) – to the extent exceeding the agreed level of Preventive or Predictive Maintenance activities

Some of these items can be considered as a part of Preventive Maintenance. This depends on the agreement between the asset owner and the O&M service provider.

The O&M agreement can foresee services other than those pertaining to electrical and mechanical plant maintenance as per the above sections. Some of these additional services are generally included in the scope of work and the O&M annual fixed fee, and some are not.

Additional services not included in the O&M contract scope of work can be requested on demand and can either be priced per service action, or based on hourly rates applicable to the level of qualification of staff required to perform the works. These hourly rates usually escalate at the same rate as the O&M Service fee. In some cases, a binding price list for the delivery of some of these additional services can be included in the O&M contract as well.

Module Cleaning

Regular module cleaning is an important part of solar maintenance, and the problems associated with soiled modules are often underestimated. Prolonged periods of time between cleans can result in bird droppings etching modules and lichen growth, both of which can be extremely difficult to remove. The intensity and type of soiling depend heavily on the location of the solar PV system (e.g. its proximity to industrial areas, agricultural land, or railway lines).

Module cleaning methods therefore vary from manual, to robotic and mechanical and each have their own advantages and disadvantages. The frequency of cleaning should be decided on a site-by-site basis, and it may be that certain parts of a site will need cleaning more often than other parts of the same site.

Maintenance topics related to snow mitigation for PV systems include manual and automated snow removal techniques, the use of heating elements, and the application of hydrophobic or ice-phobic coatings to prevent snow adhesion. Additionally, warranty considerations are crucial; it should be ensured that any snow mitigation methods used do not void the manufacturer's warranty

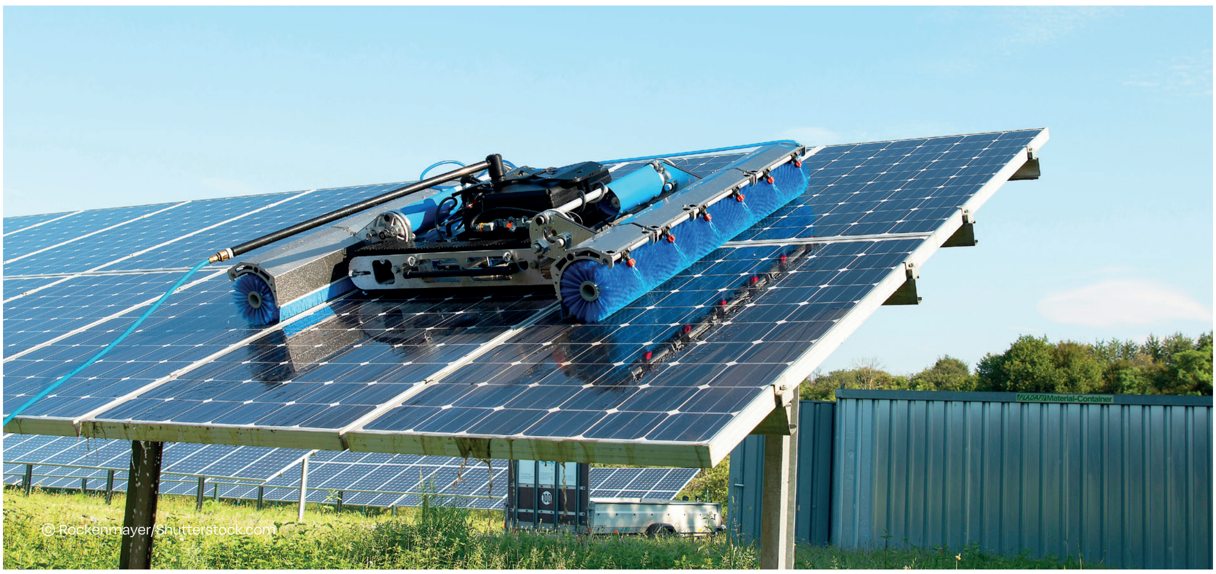
When choosing a module cleaning company, asset owners and O&M service providers should check the following:

- The suggested method of cleaning is fully in-line with the module manufacturer's warranty and according to specifications from IEC 61215 (e.g. maximum pressure load)

- Quality of water and detergents: The modules should be cleaned with high quality, ultra-pure water, not tap, mains or borehole water. Detergents must be biodegradable and comply with local environmental regulations. Water runoffs must be planned for and ensure they don't lead to negative environmental impacts

- H&S considerations should be made with regard to keeping staff safe on site. This should include some form of H&S accreditation and specific training for solar module cleaning, including working at height, if cleaning roof mounted modules

Some of these items can be considered as a part of Preventive Maintenance. This depends on the agreement between the Asset Owner and the O&M service provider.



Vegetation Management

Vegetation management can represent a significant portion of the operations costs of a solar PV system. Some key items to consider in vegetation management:

- Damage Reduction: Vegetation management can reduce direct mechanical damage caused by vegetation - especially woody vegetation - growing into modules and structures. Damage can also be caused by direct shading causing hot-spot formation on modules, potentially leading to long-term module damage

- Performance Enhancement: Vegetation can cause module shading, which leads to degraded module performance. This effect is disproportionate to the amount of shading, so a small amount of shading can cause a significant amount of power loss

- Erosion Control: Vegetation is critical for soil stabilisation and avoidance of erosion damage on sites. Uncontrolled erosion can cause significant structural damage on a project over time

- Carbon Sequestration: Continuous vegetation management can assist in increasing soil carbon sequestration, especially with the use of grazing animals, who are able to fertilise the soil while enhancing soil carbon capture

- Biodiversity Enhancement: The use of natural pollinators and native vegetation can enhance local biodiversity. This can improve community engagement, lead to reduced vegetation management costs, and in some cases add revenue streams to a project

- Community engagement and social license to operate: Vegetation management can be one of the most visible maintenance activities for local communities and can affect aesthetics, noise pollution, erosion, runoff, and chemical contamination concerns. Vegetation management done well can enhance relations with the community and local councils and improve the social license to operate. Done poorly, vegetation management can cause conflict with local communities and planning councils and can lead to potential legal concerns

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Some options for vegetation management are outlined in Table 4 below.

Table 4

Vegetation management options

	Advantages	Disadvantages
Manual mechanical removal Human operated mowers and trimmers used periodically throughout the year	• Adaptive to different vegetation sizes (e.g. manual removal of woody growth) • Flexible access to different parts of the site	• Costs • Potential for module damage • Quality is dependent on contractors • On site safety variance due to differences in contractor quality
Automated/robotic mechanical removal Use of autonomous robots which can mow defined patterns in an array while actively avoiding obstacles	• Costs • Ability for increased mowing • Ability to integrate into predictive models of vegetation growth	• Difficulty adapting to different site conditions. E.g. water pooling, obstructions • Difficulty removing some types of vegetation (e.g. woody vegetation)
Grazing Use of grazers (typically sheep) managed by an on-site shepherd for vegetation control. Grazers are typically transported to site periodically for vegetation management	• Costs (dependent on grazer availability) • Good local community engagement can enhance social license to operate • Erosion control through ground fertilisation • Soil carbon sequestration	• They will not eat everything e.g. thistle and woody plants • Quality dependent on farming partners • Costs can be high if supply of grazers is low
Chemical Herbicide use for large area vegetation control	• Costs • Speed • Coverage – it is easy to get large and consistent coverage on site	• Can cause significant erosion • Runoff concerns can cause environmental damage • Permitting required and not legally allowed in some locations • Can hurt community relations and reduce social license to operate
Passive vegetation control through system design Designing systems with high ground clearance and seeding with low growth natural vegetation or natural pollinators	• Low operating costs • Potential for enhanced community engagement • Potential for additional project revenue streams	• Higher project capital costs • Increased system design costs for specifying appropriate local vegetation

Chapter 7

Revamping and Repowering

This chapter focuses on revamping and repowering in the context of solar PV O&M, which is often classified as extraordinary maintenance from a contractual standpoint. It covers the benefits of revamping and repowering, different types of these processes, key performance indicators (KPIs) associated with them, and the structure of repowering/revamping contracts. Additionally, the chapter addresses the end-of-life process for solar PV systems, providing a comprehensive overview of these critical aspects.

Revamping and repowering are usually considered as part of Extraordinary Maintenance from a contractual point of view – however due to their increasing significance in the solar O&M market, these Guidelines are addressing them in a standalone chapter.

7.1 Definition and rationale of revamping and repowering

Revamping and repowering are defined as the replacement of old, power production related components of a power plant with new components to enhance its overall performance. Revamping involves component replacement, but without substantially changing the plant's nominal power, whereas repowering involves increasing it. The difference between revamping and repowering, and ordinary replacement is that the former aims to increase performance by exchanging all components within a functional area or a significant ratio of them. The following sections focus principally on repowering but also broadly apply to revamping and even repairs and Extraordinary Maintenance.

There are several reasons why repowering of solar PV power plants can be a necessary and/or beneficial investment. For an overview, see the following figure.

Figure 6

Differences Between Revamping and Repowering and their Main Drivers

Revamping

Involves replacement of components (mainly inverters and modules), but without substantially changing the plant's nominal power.

Repowering

Involves replacement of components (mainly inverters and modules), which causes a substantial change to the plant's nominal power.

Main drivers for Revamping or Repowering

- Aging solar assets: By the end of 2021, we expect more than 900 GWp of PV capacity installed worldwide. The fleet of modules and inverters is getting older which leads to an increased failure rate, higher degradation and expiring warranties
- Unavailability of spare parts and support: Many manufacturers of modules and inverters have left the market. This complicates the supply of spare parts or repair solutions and may leave an exchange of components as the only alternative
- Technological Improvements: The technological advancement of modules and inverters has been significant. Thus, exchanging components can lead to an improved performance and availability. As further benefits, new components offer higher design flexibility and advanced features at reduced maintenance costs. Another example is installing a battery storage system on an existing plant
- Decreasing prices: The prices for PV components have decreased substantially. This trend helps to create an economically feasible re-investment case
- Additional benefits: A repowering project usually includes additional benefits, such as new warranty terms and compliance with the latest regulations. Furthermore, it brings the opportunity to correct potential planning mistakes from the initial construction

7.2 Types of Revamping Projects

Revamping a PV project is a process that upgrades or replaces the components of a PV system. Depending on technical, regulatory and economic factors, operators may opt for total or partial revamping.

Total Revamping

Full revamping involves a comprehensive upgrade or replacement of most or all components in the PV plant. This may include:

- Solar Panels: Replacing all old solar panels with new, more efficient models
- Inverters: Updating all inverters to modern, higher-efficiency units
- Mounting Structures: Redesigning and replacing mounting structures to better support the new panels and optimise their orientation
- Electrical Infrastructure: Upgrading or replacing wiring, junction boxes, connectors, and other electrical components
- Monitoring and Control Systems: Implementing advanced monitoring and control systems to enhance performance tracking and system management
- Balance of System (BoS) Components: Updating all ancillary equipment, including transformers, switches, and protection devices

Partial Revamping

Partial revamping or repowering in photovoltaic (PV) plants refers to the process of upgrading or replacing certain components of an existing solar power system to improve its efficiency, performance, or extend its operational life. Unlike a full revamping, which involves a complete overhaul of the entire system, partial revamping targets specific parts of the PV plant. This approach can be more cost-effective and less disruptive while still achieving significant improvements.

Key components that might be involved in partial revamping include:

- Solar Panels: Replacing outdated or underperforming solar panels with newer, more efficient models
- Inverters: Updating inverters to modern, more efficient versions that can handle higher capacities and improve energy conversion rates
- Mounting Structures: Enhancing or replacing the mounting structures to better align panels for optimal sunlight capture or to support new, heavier panels
- Electrical Components: Upgrading cabling, connectors, and other electrical components to reduce losses and improve safety
- Monitoring Systems: Implementing advanced monitoring and control systems to better track performance and identify issues promptly

Partial revamping is typically undertaken to address specific issues such as declining performance due to aging components, advancements in technology that offer better efficiency, or changes in regulatory requirements. It allows plant operators to incrementally improve their systems without the need for the significant investment required for a full system replacement.

7.3 Types of Repowering Projects

PV projects are increasingly undergoing repowering as major breakthrough in PV technologies allow to deliver much higher power for the same area, or improve technical or economic efficiency of the system, typically with a view to increase rated capacity or availability of the PV plant.

Progressive Repowering

Progressive repowering is a process of gradually adding, upgrading and improving existing photovoltaic (PV) systems. This approach involves the partial and progressive addition or replacement of the system's components (such as solar modules, inverters, and other electronic components) with more modern and efficient technologies, rather than a complete overhaul in a single intervention. The main scope of this type of repowering is to increase progressively the installed capacity of the PV Plant, it is worth saying that this model works only for non-incentivised PV parks.

Total Repowering

Total repowering involves a comprehensive replacement of all major components of a photovoltaic (PV) system, including solar modules, inverters, mounting structures, cabling, and often monitoring and control systems. This approach is typically undertaken when the existing system has reached the end of its operational life or when significant advancements in PV technology make it economically viable to completely upgrade the system. Total repowering aims to maximise energy yield, improve system reliability, and potentially increase the rated capacity of the PV plant. This type of repowering is particularly suitable for large-scale, non-incentivised PV parks or plants located in high-value electricity markets, where maximising output and efficiency is paramount.

Benefits of Photovoltaic Repowering

Progressive photovoltaic (PV) repowering allows to improve the performance of existing systems while minimising costs, and delivering environmental benefits. The core benefit of progressing repowering is improved efficiency. By replacing outdated solar modules with new-generation models, the system's overall energy production can be significantly increased thanks to higher conversion efficiency in newer PV technologies. Similarly, upgrading inverters improves energy management while minimising conversion losses. As repowering happens, operational costs can come down significantly since modern PV components are not only more reliable but also require less maintenance, leading to lower long-term management expenses. Specifically, when undertaking progressive repowering, operators optimise the system's lifespan. Gradually upgrading components to maximise the operation of the system while maximising the utilisation of initial investments.

Moreover, the introduction of new PV technologies allow a better integration with smart energy management systems, notably for energy storage, and other innovations that enhance the system's efficiency and flexibility in the grid.

Repowering also delivers environmental benefit, increasing PV generation capacity with minimal environmental impacts linked to land use, delivering ever lower GHG/kWh produced. Progressive repowering, by maximising components use also allows to maximise the life-cycle benefits of PV components. Repowering aligns with evolving energy policies and regulations. Incremental upgrades can ensure compliance with updated standards while supporting broader sustainability goals and the transition to a cleaner energy mix.

Progressive photovoltaic repowering represents a sustainable and economic strategy to enhance the performance of existing PV systems, contributing to the transition towards more efficient and reliable renewable energy sources. There are numerous ways of repowering a solar PV power plant. In the following we will concentrate on the two most important opportunities of module and inverter repowering.

Module Repowering

Modules with irreparable defects that cannot be directly replaced in a like-for-like swap may force the investor to consider a module repowering. This can be carried out for the entire solar PV power plant or for specific parts. When repowering is focused on partial module replacement, exchanging more modules than is technically required is advised as this keeps old modules intact as spare parts for the future.

Due to the rapid development of solar PV technology it is not very likely that the same components are still available on the market in the required quantity or at a competitive price. Certainly, exchanging identical modules would make repowering very simple. However, this would mean spending money to maintain performance, instead of taking advantage of opportunities to raise efficiency at a lower proportional cost. Where different modules are used for the repowering project, the following aspects need to be considered during planning and execution:

Mechanical installation

If the modules have different dimensions in height, length and width, compatibility with the mounting system needs to be considered. Such issues may be solved by the introduction of new module clamps but in extreme cases (e.g. changing from thin film to crystalline modules) a new mounting structure needs to be installed. To avoid a total overhaul of the plant's infrastructure, agile repowering strategies such as changing from central to string inverters, replacing transformers etc. should be considered.

Various factors, such as module weight also need to be taken into account: if the new module is heavier and has a larger surface area the structural impacts on the mounting system or the building need to be checked and managed. Compliance with relevant electrical safety is also key; for instance the new modules need to be integrated into the grounding system as before

Electrical installation

Depending on the rated power and the electrical characteristics of the new module type a new string design may be required. In that case, the maximum DC power, voltage and current need to be in-line with the inverter requirements?

In general, mixing components with different electrical characteristics at one inverter or at least one MPP tracker should be avoided. Alternatively, bypass diodes can be integrated as protection in case of failures such as reverse current. Moreover, the dimensioning of existing cables and fuses needs to be checked and verified to ensure it is suitable for the new DC-layout

Due to the evolution of standards and technologies, it is likely that the new module type will have different connectors. Therefore, the string cable connector needs to be replaced accordingly.

Further considerations

A module repowering may be subject to and impacted by various regulatory aspects, which will vary from country to country, and may even depend on the regulatory or support framework of the initial installation (e.g. if benefiting from a feed in tariff?). The regulatory body should be contacted well in advance to clarify aspects such as:

- Maximum power to be installed
- Requirements for proving the faults of modules
- Registration of new modules
- Disposal of old modules

Module repowering should be considered as a relevant interference into the electrical system. All affected strings should be tested and documented according to IEC 60364-7-712:2017, IEC 60364-6:2016 and IEC 62446-1:2016 after the repowering project. The new string layout should notably be optimised while considering shading or DC/AC ratio. Furthermore, an in-depth check of the mounting structures, cables and connectors should be performed. If only a small share of the modules are exchanged and power measurements of the old type of modules are being performed, it is recommended to install the old modules according to their remaining power. This means all modules in one string or connected to one MPP tracker should have similar power to reduce mismatching losses. Depending on the state of the old modules (and the regulatory requirements), they may either be sold to the secondary market or should be disposed or recycled by a professional provider.

Inverter Repowering

Inverters have a limited lifetime, typically shorter than some other components of the PV system such as modules or mounting structures. With increasing age and wear, the likelihood of failures and breakdowns increases. If the warranty of a device has expired, a technically and economically suitable solution needs to be identified. Some manufacturers or service providers offer repair and spare parts services. With new components it might even be possible to increase the efficiency of an older inverter (e.g. by replacing an old control board with a new device that has improved performance characteristics, such as Maximum Power Point (MPP) tracking). If an identical replacement inverter, repair services or spare parts are not available, using a new component becomes inevitable. There are different strategies for inverter repowering which should be evaluated on a case-by-case basis:

- Partial or complete exchange: If only some of the inverters are affected, a partial exchange of the inverter fleet of the solar PV system can be an option. This potentially reduces the overall costs, but it can also increase the complexity regarding the electrical design or the implementation of two different inverter types into one communication concept on-site. If the repowering does not affect all inverters on-site, it is advisable to store the old devices as potential spare parts. Additionally, it can be practical to exchange more inverters than technically required to store those as potential exchange devices for future defects of the old inverter type

- Exchange of same or different power class: Exchanging inverters with the same power class is easier for the DC and AC integration. However, replacing multiple devices through one with a larger power class can increase the system efficiency and reduce the component costs as well as future maintenance costs

When an inverter repowering is planned, several factors need to be considered:

Mechanical installation

If the new inverters have different dimensions or weight, a suitable solution for the installation or mounting of the inverter needs to be prepared. The same applies for proper cabling if DC or AC connections are changed. The manufacturer of the new device might have different requirements mounting the inverter with regards to fixings, distance to other components or to the roof, ventilation, etc. All such requirements need to be checked and implemented. The new inverters also need to be integrated into the grounding system according to the standards and the manufacturers specifications.

Electrical installation

The integration of the DC side to the new inverters needs to follow the DC input requirements of the new inverter. The string length and the number of connected strings may need to be adjusted to suit the technical parameters of maximum current and voltage as well as ideal operational conditions. In case larger inverters are installed, additional DC combiner boxes might be required, and different, or additional fuses may need to be integrated. If different inverter sizes are installed, the integration to the AC side needs to be re-engineered. This includes the cable diameters, protection devices (fuses) and connectors. In all cases the applicable electrotechnical rules and regulations need to be followed.

Communication system

Before choosing an adequate inverter, compatibility with the physical communication cables should be checked. The installed data logger needs to support the new inverter's data protocol, otherwise, an update or exchange of the data logger will also be necessary. Moreover, if different inverter types are installed, it can be an option to integrate the different component types on different phases of one communication cable or integrate them into one network. The compatibility of the datalogger and the monitoring platform to work with different inverter types at one solar PV system needs to be validated.

Further considerations

An inverter repowering might be subject to various regulatory aspects, which will vary from country to country. The responsible regulatory institution should be consulted well in advance to clarify aspects such as:

- Maximum power to be installed
- Compatibility to grid code and plant certificate

Inverter repowering should be considered as a relevant interference into the electrical system. All affected cables and connectors should be tested and documented according to IEC 60364-7-712:2017, IEC 60364-6:2016 and IEC 62446-1:2016 during the repowering project. The new inverters should be optimised towards shading or DC/AC ratio. When the new inverter has more advanced features than the old one (e.g. multiple MPP tracker), this could be an additional advantage for the repowering project. Other technical considerations, such as the noise levels of the inverters may vary, and it should be adequately checked against the permitting restrictions and the neighbouring activities. Depending on the state of the old inverters, they can be either kept as potential spare parts, sold to the secondary market. If these options are not practical, the devices should be disposed of or recycled by a professional service provider.

Moreover, following the installation of a new inverter or parts, updated or different maintenance scope and intervals need to be included into the Preventive Maintenance schedule and all involved people should be informed about the changes and accordingly trained regarding Preventive and Corrective Maintenance. It is also useful to point that in some cases, inverter repowering may be profitable even when the old inverter still operates with full availability, especially when a new inverter produces more energy due to higher efficiency or better operating conditions.

7.4 Key O&M KPIs and their role in identifying Revamping Opportunities

O&M KPIs (Key Performance Indicators) are crucial metrics that help monitor the performance and health of photovoltaic (PV) systems (see more in *Chapter 10. Key Performance Indicators*). By regularly analysing these KPIs, operators can identify underperforming components or inefficiencies, thus highlighting opportunities for PV revamping. Here's how PV O&M KPIs help in this process:

Table 5

Crucial metrics for monitoring the performance and health of PV systems

KPI	What it measures	How it helps
Energy yield (kWh)	The total energy produced by the PV system.	A lower-than-expected energy yield can indicate inefficiencies or issues with specific components, such as degraded modules or inverters. By identifying these underperforming parts, operators can target them for revamping.
Performance Ratio (PR)	The ratio of the actual energy output to the theoretical energy output of the system, considering the irradiance received.	A declining PR suggests that the system is not performing optimally. This could be due to various factors such as soiling, shading, module degradation, or inverter inefficiencies. Targeted revamping can address these issues.
Availability (Av)	The percentage of time the PV system is operational and capable of producing energy.	Low availability can be a result of frequent breakdowns or maintenance issues, often linked to aging or failing components. Replacing these components can improve system availability.
Inverter efficiency	The efficiency of inverters in converting DC electricity from solar panels to AC electricity.	Inverters typically have shorter lifespans compared to modules. Lower inverter efficiency can significantly impact overall system performance. Upgrading inverters can lead to better performance and higher energy yield.
Soiling losses	The energy losses due to dirt, dust, and other particulates on the solar panels.	Persistent high soiling losses can indicate the need for more frequent cleaning or the implementation of anti-soiling technologies or coatings.
Operational costs	The costs associated with maintaining and operating the PV system.	Rising operational costs can signal inefficiencies. Revamping can reduce these costs by replacing high-maintenance components with more reliable ones.
MTBF (Mean Time Between Failures)	The average time between system or component failures.	A low MTBF indicates frequent failures, suggesting that components are aging or of poor quality. Upgrading these components can enhance system reliability.

By systematically tracking and analysing these KPIs, operators can pinpoint specific areas where the PV system is underperforming. This data-driven approach allows for targeted revamping efforts, ensuring that upgrades are made where they will have the most significant impact on improving system efficiency, reliability, and overall energy production.

7.5 Structure of a Revamping/Repowering Contract

A PV revamping/repowering contract is a detailed agreement between the system owner and the contractor outlining the scope, terms, and conditions for upgrading an existing photovoltaic (PV) system. The structure can change depending on the contractor, the country, the legislation, etc. Below are the key components typically included in such a contract:

Table 6

Revamping/Repowering Contract components systems

No.	Chapter	Usual Content
1	Introduction and Background	• Overview of the existing PV system • Purpose and objectives of the revamping/repowering project
2	Scope of Work	• Detailed description of the tasks to be performed, including specific components to be replaced or upgraded (e.g. solar modules, inverters, wiring) • Timeline and milestones for project completion • Specifications for new equipment and technologies to be installed
3	Responsibilities of the Parties	• Obligations and duties of the contractor, including procurement, installation, testing, and commissioning of new components • Responsibilities of the system owner, such as providing access to the site and necessary documentation
4	Performance Guarantees	• Performance benchmarks for the upgraded system, such as expected energy yield, performance ratio, and efficiency improvements • Penalties or incentives based on the achievement of these benchmarks
5	Payment Terms	• Detailed payment schedule, including milestones for partial payments and final payment upon project completion • Terms for additional costs or changes in project scope
6	Warranties and Guarantees	• Warranty period for new components and workmanship • Guarantees related to system performance post-revamping
7	Compliance and Standards	• Adherence to local, national, and international standards and regulations • Necessary permits and approvals required for the project
8	Health, Safety, and Environmental Policies	• Safety procedures and protocols to be followed during the project • Environmental considerations and mitigation measures
9	Risk Management	• Identification of potential risks and mitigation strategies • Insurance requirements for both parties
10	Termination Clauses	• Conditions under which the contract can be terminated by either party • Consequences and liabilities in case of early termination
11	Dispute Resolution	• Methods for resolving disputes, such as mediation, arbitration, or litigation • Jurisdiction and governing law

7.6 Potential risks faced by the Revamping/Repowering Contractor

The following table outlines the potential risks faced by the Revamping/Repowering Contractor during the project lifecycle. It categorises risks across various domains, detailing their nature and potential impacts to provide a comprehensive understanding of challenges that may arise.

Table 7

Potential risks faced by the revamping/repowering contractor systems

Type of Risk	Risk Name	Potential Impact
Technical risks	Compatibility issues	New components might not be fully compatible with existing system infrastructure, leading to integration challenges
	Performance Risks	Upgraded system might not achieve the expected performance improvements, leading to penalties or disputes
Operational risks	Downtown	The system may need to be taken offline during the revamping process, which could lead to financial losses for the system owner
	Supply Chain Delays	Delays in procuring new components could extend the project timeline and increase costs
Financial risks	Cost Overruns	Unexpected expenses due to unforeseen technical issues or changes in project scope
	Payment Delays	Delays in receiving payments from the system owner, impacting the contractor's cash flow
Legal and regulatory risks	Compliance	Failure to meet regulatory requirements or obtain necessary permits can lead to fines or project delays
	Contractual Disputes	Disagreements over contract terms, performance benchmarks, or project scope can result in legal disputes
	Incentives Loss	On incentivised PV Plants, not knowing the local incentives policy and limitations can lead to loss the government incentives on the plant, that can result in high liquidated damages and/or legal disputes
Safety risks	Accidents	Risk of accidents during the installation and integration of new components, potentially leading to injuries or fatalities
	Liabilities	Legal liabilities arising from accidents or damage to the existing system during the revamping process
Environmental risks	Waste Management	Proper disposal of old components and managing environmental impacts associated with the revamping process
Reputational risks	Project Delays	Delays or failures in project delivery can damage the contractor's reputation and lead to loss of future business opportunities
		Delays or failures in project delivery can damage the contractor's reputation and lead to loss of future business opportunities

7.7 End-of-life process for dismantled materials after a Revamping/ Repowering Project

After a PV revamping/repowering project, dealing with the end-of-life (EoL) disposal of old and replaced materials is a crucial step to ensure environmental sustainability and regulatory compliance. This process involves several key considerations and steps to manage the disposal of materials such as solar panels, inverters, wiring, and other components that are no longer in use.

Solar panels and other PV system components contain materials that can be harmful to the environment if not disposed of properly. These include metals, polymers, and hazardous substances such as cadmium or lead in certain types of panels. Responsible disposal practices help mitigate the environmental footprint of the revamping project and support the broader goals of sustainable energy practices.

Different countries and regions have specific regulations governing the disposal of electronic waste (e-waste). Ensuring compliance with these regulations is essential to avoid legal repercussions and potential fines. Compliance often involves working with certified e-waste recycling facilities that can handle the materials according to local and international standards.

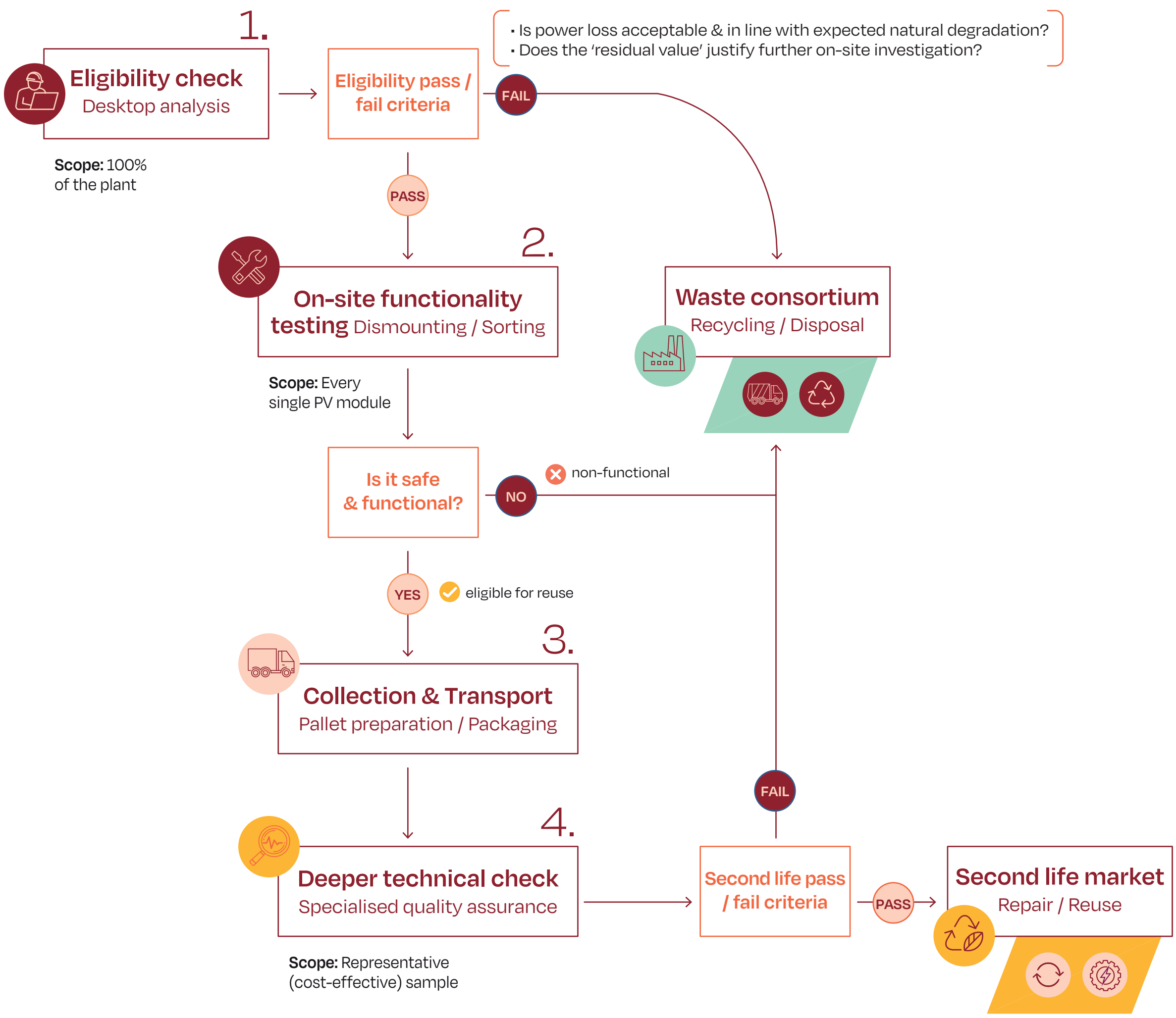
Many materials in old PV components can be recovered and recycled, reducing the demand for raw materials and supporting the circular economy. Effective recycling programmes can extract valuable metals like silver, copper, and aluminium, as well as glass and silicon, which can be reused in manufacturing new products . More on this to be found in SolarPower Europe's *Sustainable Solar Report at www.solarpowereurope.org.*

Steps in the Disposal Process

The following section outlines the key steps involved in the disposal process, providing a clear, numbered overview for better understanding and implementation.

Figure 7

Procedures for preparation for reuse



Source: Adapted from SolarPower Europe's Sustainable Solar Report

Benefits of Proper Disposal

Environmental Protection: Proper disposal prevents harmful substances from entering the environment, protecting ecosystems and human health.

Resource Efficiency: Recycling old PV components conserves natural resources and reduces the environmental impact of mining and manufacturing new materials.

Regulatory Compliance: Adhering to e-waste regulations avoids legal issues and promotes corporate responsibility.

Sustainable Development: Responsible disposal practices support the sustainable growth of the renewable energy sector and contribute to a circular economy.

By prioritising the end-of-life management of materials in a PV revamping/repowering project, stakeholders can ensure that the environmental benefits of solar energy are maximised, even as the systems themselves are upgraded and improved. It is worth saying that for Revamping projects carried out at incentivised PV plants, the regulatory companies asks for the disposal and dismantling certificate, as well as all the serial numbers of the old main disposed components. This is mandatory for not losing the incentives.

General Repowering Considerations

Although, a repowering project is mainly technically driven, for the owner of the solar PV system it is a commercial re-investment case. Therefore, it is of great importance to calculate a detailed and solid business case before starting the project, and review it during the project stages. All technical and commercial data, such as historical performance, future performance, revenues, costs, extended life span and changed maintenance requirements need to be considered to come up with a prognosis of the future income streams. With this, a classical return on investment or break-even calculation can be performed and presented to the investor as the basis for a decision.

As an additional analysis, calculating the sensitivities of the most important factors is recommended. This will provide a better understanding of the influence of changing conditions (e.g. if the costs for the project will change or the projected performance will be different to the assumptions).

Each repowering activity should be approached as an individual project, which can be structured as follows:

Performance analysis

- Historical yield assessment & identification of performance issues
- Verification of issues on site with additional inspections or testing
- Determination of root causes and areas for improvement

Potential assessment

- Technical feasibility study of different options
- Commercial analysis, taking investment costs and additional revenues or reduced losses into account
- Analysis of the regulatory requirements and their implications
- Risk assessment for the case where the solution does not meet expectations

Solution Design

- Detailed technical engineering
- Determination of all costs for time and material
- Setting up project plan
- Update commercial analysis with more precise information

Implementation

- Execution of repowering measures
- Project management
- Constant quality control
- Commissioning and documentation
- Update of maintenance guidelines

Review

- Technical evaluation regarding reliability and performance
- Commercial evaluation regarding costs and return on investment

A rigorous project management and quality control across all project stages will ensure a realisation of the project in time, budget and quality. Similarly, reporting to the Asset Manager and Asset Owner should be provided throughout all stages of a repowering project.

Spare Parts Management

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This chapter focuses on the crucial distinction between consumables and spare parts in maintenance operations. It also highlights the importance of effective spare parts management, covering key aspects such as stocking, storage, replenishment, ownership, and responsibility. Finally, this chapter addresses best practices for maintaining proper stock levels, and ensuring the right storage conditions to support smooth and efficient operations.

It is important to differentiate between Consumables and Spare Parts.

Consumables are items which are intended to be depleted or worn out relatively quickly and then replaced. They are necessary for the regular operation of the solar PV power plant and O&M service providers should always have consumables on stock and maintenance crews should carry consumables with them, together with the relevant tools.

Spare Parts are all the items (materials, component and equipment such as modules or inverters) listed on the Spare Parts List, not in use or incorporated in the solar PV power plant, intended to replace similar items in the solar PV power plant.

Spare Parts Management is an inherent and substantial part of O&M services that should ensure that spare parts are available in a timely manner for Corrective Maintenance to minimise the downtime of (part of) a solar PV power plant. The following considerations have to be made in Spare Parts Management:

- Ownership and responsibility of insurance
- Stocking level and management
- Location of storage
    a. Proximity to the plant
    b. Security
    c. Environmental conditions

Although it is best practice for the O&M service provider to be responsible for replenishing the spare parts stock, it is not necessarily responsible for the full cost of doing so. Some Asset Owners require O&M service providers to be fully responsible for the cost of all spare parts within the O&M fee, however, the more cost-effective approach is to agree a set of **Included Spare Parts** and **Excluded Spare Parts**. Similarly, a financial limit for Included Spare Parts can be negotiated.

Included Spare Parts are those which the O&M service provider is to be responsible for within the O&M fee. Excluded Spare Parts are those which the Asset Owner is responsible for the cost of replenishing and do not fall within the O&M service provider's O&M fee. This is a flexible approach allowing the Asset Owner and O&M service provider to agree which spare parts fall into which category. It enables both parties to have a level of cost certainty whilst balancing this with the Asset Owner's appetite for risk. The contract should contain provisions on who is liable in the event that a spare part is unavailable. The various parties are responsible for their replenishment and bear the associated production loss.

Ownership of spares is often with the Asset Owner from delivery to site or placement in the spares stock. In the case of excluded spare parts, ownership transfers to the Asset Owner from the date that the O&M service provider receives payment for the same.

Maintenance, storage, and replenishment are the responsibility of the O&M service provider. Besides ownership matters, it is very important to make sure, upon mutual agreement, that one of the parties undertakes the responsibility of insuring the spares: as a recommendation spare parts stored on-site should be insured by the Asset Owner and spare parts stored off-site should be insured by the O&M service provider.

For a new solar PV power plant, the initial spare parts for two years from COD are procured by the Asset Owner, or the EPC service provider on behalf of the Asset Owner. However, it is best practice for the EPC and O&M service providers to have agreed upon the list. The O&M service provider should, as a best practice, recommend additional spares that they deem them necessary to meet the contractual obligations (e.g. availability guarantees).

Generally, it is not economically feasible to stock spare parts for every possible failure in the plant. Therefore, the O&M service provider, especially those with high experience in the second level of the corrective maintenance, together with the Asset Owner should define the stocking level of specific spare parts that make economic and operational sense (Cost-Benefit Analysis).

An important decision process is the definition of the spare parts list. It's common to consider a limit quantity of the main component, often as result of an EPC inheritance; not considering that exist a wide range of possible unavailability generated by specific details that fail within a main component. The presence of this simple material within the spare parts could reduce considerably the off period of part or the full plant. Sometimes, these materials are listed within the component O&M manual, in other case the operation of the PV plant create lesson learned to use to update accordingly the spare part list.

Large suppliers are now offering the so called "Service Level Agreements, SLA" for specific PV plant components or services. These agreements specify in detail how the services will be provided, how fast (KPI) and the means of measuring these levels. Projects can benefit from the security of a supplier whose main job will be making sure that components are available according the contractual requirements.

For example, if a specific part in a solar PV power plant has a frequency of failure at least of once every year or more and the loss of revenues due to such failure is greater than the spare part cost, it is important to have such a spare part kept available. This can also apply for parts with a long replenishment period. Similarly, one must consider the management risk that a fault can cause. For example, if a component of a SCADA system stops working, there is no resultant power loss. However, there is a risk of not being able to detect future power loss if this part is not replaced. Some very large O&M service providers now propose using the spare parts in their different warehouses in place of, or in addition to the Asset Owner's spares stock. Since they operate many sites, they limit the shortage of unusual spare parts by maintaining a small stock.

Regarding the stocking level, due to the very different configurations and sizes of solar PV power plants, it is very difficult to define a hard number for stocking specific spare parts, however 0.2% of total module quantity is often found in commercial contracts. Furthermore, the regional portfolio of the O&M service provider might also influence this and, as mentioned above, the determination of spare items and quantity is also driven by the O&M service provider's contractual commitments and guarantees. To define the stocking levels of Spare Parts and Consumables, the following parameters should be taken into consideration:

- Frequency of failure
- Impact of failure
- Cost of Spare Part
- Degradation over time
- Possibility of consignment stock with the manufacturer
- Equipment reliability
- Replenishment time (Service Level Agreement)
- Management risk

However, for any given utility-scale solar PV system there are certain spare parts that could be considered as essential to have – no matter the cost.

Table 8 below summarises a minimum list. This list is not exhaustive and system requirements and technology developments can lead to this list being updated following discussion with manufacturers, amongst others.

Table 8

Minimum list of spare parts (non-exhaustive) for a PV power plant at utility-scale (e.g. 5MWp)

No.	Spare part	Market suggestion
1	Fuses for all equipment (e.g. inverters, combiner boxes etc) and fuse kits	
2	Modules	0,5-1%
3	PV Connectors	0,5%
4	String cabling	2km (6mm^2)
5	LV AC cabling	200-400m
6	Inverter spares (e.g. power stacks, circuit breakers, contactor, switches, controller board etc)	According to supplier O&M maintenance guidelines, MTBF, and MTTR
7	For String inverters	According to contractual availability, at least 1 unit
8	Uninterruptible Power Supply (UPS)	
9	For MVS stations, UPS	1 per 10 UPS units
10	Voltage terminations (MV)	3-5
11	MV joints	3
12	Power plant controller spares	
13	PV surge arrester class II	20
14	PPC	1
15	SCADA and data communication spares	
16	Fiber optic	200m, 2 Patch panels, 2 patch cords
17	Transformer and switchgear spares	
18	Fuses for LV switchgear	20
19	Weather station sensors	
20	Datalogger	1
21	Windspeed sensor	1
22	Cell temperature sensors	1
23	Insulated cable Pyranometer	1

Table 8 - continued

Minimum list of spare parts (non-exhaustive) for a PV power plant at utility-scale (e.g. 5MWp)

No.	Spare part	Market suggestion
24	Motors and gearboxes for trackers and tracker control board	As per supplier recommendations, contractual availability and O&M guidelines
25	Harnesses and cables	O&M Company
26	Screws and other supplies and tools	O&M Company
27	Specified PV module connectors (male and female should be from the same manufacturer)	0,5%
28	Structures components	
29	Joints, e.g. end and middle clamps	50
30	Screws and nuts	1 set
31	Security equipment (e.g. cameras)	According to insurance requirements. At least one full kit per access gate in PVPP so in case of failure CCTV can be immediately reactivated
32	Tracker or Structure components (e.g. piles, screws, clampings)	
33	Array boxes (If applicable)	
34	Fire detection and suppression system	1 set

Regarding the storage and warehousing, this should be done in locations where the spare parts cannot be damaged (e.g. by humidity or high temperature variations) and are easily identifiable as being owned by the Asset Owner. Additionally, the storage sites should have appropriate security measures.

The decision to have either an on-site or an off-site warehouse facility or just an agreement with the suppliers to provide the spare parts, depends on many factors, including the kind of part, the commercial agreement, and the facilitation of the service provision. If the spare parts owned by the Asset Owner are stored off-site, such spares should be stored separately and be clearly identified as the property of the Asset Owner. If the O&M service provider exchanges spare parts, an agreement should be drawn up with the supplier that ensures the warranty is not voided.

While proximity to the plant is a parameter that needs to be evaluated on a case-by-case basis, security and environmental conditions are very important as they could lead to a loss of property either through thefts or damage.

Chapter 9

Data and Monitoring Requirements

This chapter explores the pivotal role of SCADA (Supervisory Control and Data Acquisition) systems and effective data management in optimising solar photovoltaic (PV) plant performance. It highlights how these systems enable real-time monitoring, fault detection, and automation, contributing to improved efficiency and reliability. By leveraging robust data governance, advanced analytics, and integration frameworks, SCADA systems ensure seamless operations, secure communication, and data-driven decision-making. Together, these tools form the foundation for maximising energy production and ensuring the long-term sustainability of solar PV installations.

Effective SCADA (Supervisory Control and Data Acquisition) and data management systems play a pivotal role in optimising the performance of solar photovoltaic (PV) plants. These systems enable enhanced monitoring and fault detection by providing real-time and historical data, facilitating early identification of issues to minimise downtime and maximise energy production. Additionally, the collection and analysis of data support the calculation of Key Performance Indicators (KPIs), which are vital for benchmarking efficiency, identifying improvement opportunities, and tracking progress. SCADA systems also automate critical plant operations such as inverter control and grid synchronisation, reducing manual intervention and improving overall efficiency. By integrating operational data with weather or historical records, operators gain deeper insights into plant performance and contributing factors. Moreover, digitalising procedures and maintenance activities enhances accessibility, consistency, and knowledge sharing, streamlining operations and improving service quality.

In essence, a well-designed data and monitoring system acts as the central nervous system of a solar PV plant. By effectively collecting, analysing, and utilising data, we can achieve optimal performance, maximise energy production, and ensure long-term plant health and profitability.

9.1 Implications of Data, Infrastructure, and Governance

Optimising solar PV installations requires effective data management practices. The key elements:

- Standardised Data Management:
    - Ensures data accuracy, consistency, and accessibility
    - Involves defined collection protocols, data ownership structures, and quality control mechanisms
    - Standardised formats and metadata improve discoverability and analysis
- Robust Data Infrastructure:
    - Traditional storage may struggle with ever-growing data volumes
    - Consider cloud storage, distributed processing frameworks (Hadoop/Spark), and robust security
    - Utilise data lakes for raw data and data warehouses for structured analysis
- Data Governance Frameworks:
    - Build on standardised procedures with a comprehensive management framework
    - Define roles, access controls, and ensure adherence to regulations
    - Mitigate risks like data breaches, privacy violations, and non-compliance
- Modern Data Governance Paradigms:
    - Data lineage tracks data origin and transformations, fostering trust and transparency
    - Data provenance focuses on data origin and ownership, aiding compliance and attribution

By integrating these elements, organisations can cultivate a data-driven culture that empowers informed decision-making, enabling teams to act strategically based on accurate insights. This approach unlocks the full potential of data assets, driving innovation and operational optimisation across processes. Ultimately, such integration positions organisations for sustainable success, allowing them to thrive in an increasingly data-centric landscape.

9.2 Concepts

Interoperability-overcoming Data Silos

A significant challenge in solar PV installations is the presence of disparate systems that hinder data exchange, resulting in limited visibility and suboptimal performance. The solution lies in achieving interoperability, which enables seamless communication between SCADA (Supervisory Control and Data Acquisition) systems and Service Management Systems (SMS). This integration ensures cohesive data flow, enhancing operational transparency and facilitating better optimisation of plant performance.

Key Strategies:

- **Standardised Protocols:** Use common protocols like Modbus or IEC 60870-5-104 for device-to-SCADA communication. Consider IEC 61850/61870 for broader system integration

- **Open Interfaces:** Leverage RESTful APIs for effortless data exchange between SCADA, monitoring, and external applications

- **Unified Data Model:** Implement a standardised data model for consistent data interpretation by the central platform, enabling a holistic view

Integrating SCADA, SMS, and financial systems provides enhanced visibility, enabling comprehensive analysis and informed decision-making. Streamlined operations are achieved through the automation of tasks and workflows, optimising maintenance processes and service dispatch. By incorporating extensible data models and broad protocol support, the system is future-proofed to integrate new digital services seamlessly. This robust communication infrastructure empowers data-driven decisions, improves operational efficiency, and ensures the solar PV system's adaptability to evolving technological demands.

SCADA

A SCADA system serves as the mission control centre for a solar PV plant, comprising a comprehensive suite of hardware and software designed to perform the following critical functions. Its primary functions include:

- **Real-time monitoring:** Continuously gathers data on power generation, inverter status, weather conditions, and more

- **Control and automation:** Based on pre-programmed settings or manual commands, the SCADA system can adjust tracker positions, trigger safety shutdowns, and perform other actions

- **Data acquisition and storage:** Collects and stores historical data to enable performance analysis, fault detection, and trend identification

- **Alarm management:** Monitors for critical conditions and generates alerts for potential issues

The specific hardware and software components of a SCADA system can vary depending on the size and complexity of the solar PV plant. Smaller installations might utilise a cloud-based SCADA system, while large-scale solar farms may have a more distributed architecture. However, we typically find field devices, data acquisition and processing devices and a communication network on the hardware side, while software allows to store, process, analyse and visualise this data, while ensuring sound communication between devices. Table 9 summarises the various hardware and software components of a SCADA system.

Table 9

Hardware and Software Components of a SCADA system

Component	Description
Hardware Components	
Field devices	Sensors, meters, inverters, trackers, and weather stations that generate raw data.
DAUs/RTUs	Intelligent devices that collect data from field devices, pre-process it, and transmit it to the master station.
Communication network	Wired or wireless network that transmits data between devices.
Software Components	
Master station software	Central software application that receives, processes, analyses, and visualises data. Provides a human-machine interface (HMI) for monitoring, control, and data access.
Communication protocols	Standardised protocols for data exchange between devices and the SCADA system (e.g. Modbus, DNP3).
Database management system (DBMS)	Software for storing and organising historical data.

OSI Model

The OSI (Open System Interconnection) model provides a structured framework for understanding data communication within solar PV SCADA systems. By defining the specific roles of each layer, it clarifies how data flows seamlessly from solar panels to control centres and external services, ensuring efficient and reliable communication.

The Layers:

- **Physical Layer:** The foundation - hardware connections (cables, fibers) that transmit raw data. (Think: Ethernet cables linking devices to the network)

- **Data Link Layer:** Ensures error-free data transfer. (Think: Protocols like IEEE 802.3 that manage communication between devices on the local network)

- **Network Layer:** Routes data packets across networks. (Think: IP protocols that direct data from the plant to the control center or cloud)

- **Transport Layer:** Guarantees reliable data delivery. (Think: TCP for secure transmission and UDP for streaming data from panels)

- **Session Layer:** Manages communication sessions between applications. (Think: Protocols like NetBIOS that establish connections for data transfer)

- **Presentation Layer:** Translates data for applications. (Think: Encryption and format conversion to ensure data is readable by the HMI)

- **Application Layer:** Provides network services to applications. (Think: SCADA software interfaces, APIs for connecting with other systems, and cloud analytics platforms)

A robust SCADA system offers numerous benefits, including secure and efficient data flow, with each OSI layer contributing to optimised plant performance and secure data transmission. Reliable data exchange enhances management capabilities by enabling informed decision-making. Ultimately, a well-designed SCADA system adhering to the OSI model supports improved plant operations and strengthens overall management efficiency, making it a cornerstone of effective solar PV plant management.

Vertical Integration

Vertical integration in solar PV SCADA systems offers a holistic approach to plant management by unifying control across all levels, from field devices to enterprise systems. This integration optimises performance, enhances reliability, and extends asset life by enabling seamless data flow and robust connectivity between operational and management layers.

Seamless Data Flow

At the core of vertical integration is the efficient flow of real-time data:

- Field devices, such as Programmable Logic Controllers (PLCs) and Remote Terminal Units (RTUs), transmit data to the central SCADA system.

- The SCADA system processes this data, executes control commands, and integrates with higher-level systems, including:

    - **CMMS (Computerised Maintenance Management Systems):** For effective maintenance planning

    - **ERP (Enterprise Resource Planning):** To support data-driven decision-making at the organisational level

Vertical integration in SCADA systems offers significant benefits for modern solar PV plants. Real-time monitoring and control enable informed decisions that maximise energy output while minimising downtime, optimising overall performance. Predictive maintenance, powered by data analysis, enhances reliability by preventing failures and ensuring continuous operation. Additionally, integration with CMMS and ERP systems streamlines maintenance planning, operating conditions, and spare parts management, extending the lifecycle of assets. As a best practice, vertical integration empowers solar PV plants to exceed performance, reliability, and asset management goals, leveraging the advantages of digital transformation in the renewable energy sector.

9.3 Hardware and Infrastructure

Hardware and Setup

To ensure a reliable and efficient solar PV system, specific hardware components and setup configurations are essential. These components work together to maintain optimal performance, secure communication, and uninterrupted operations.

Table 10

Hardware components

Component	Minimum Requirement	Best Practices	Recommended
Router	Basic device ensuring connectivity and remote access via a cellular network.	Sophisticated device with advanced security features for secure remote access.	Premium device with enhanced security and remote access capabilities.
Switch	Facilitates communication between essential devices within the network.	PoE switch powers devices and facilitates efficient data flow within the cabinet and across the plant.	Managed Switch (PoE+): Supports higher power output and advanced management capabilities.
Inverter logger	Runs the manufacturer's software for data acquisition and monitoring.	Advanced application with extensive functionalities for data handling, monitoring, and control.	Top-tier application with comprehensive data management features.
PLC input/ output	Allows connection and communication with peripherals using industrial protocols.	Connects and manages peripherals, ensuring system harmony.	High-end interface supporting various industrial communication standards.
Field devices	Set of inverters and sensors ensuring smooth communication.	Comprehensive set including advanced inverters, combiner boxes, and diverse sensors.	State-of-the-art inverters, smart combiner boxes, and a full range of sensors.
UPS	Provides consistent power to critical components for reliable operation.	High-capacity unit for extended power backup.	Enterprise-grade unit for comprehensive power backup solutions.
Power supply	Delivers power to devices not supported by the network switch's power over ethernet.	Dedicated power source for all required devices.	High-efficiency units for powering all necessary devices.
Power plant controller	-	Enables sophisticated remote management of power output.	Advanced algorithms for grid support and optimisation; fully integrated control system.
Power analyser	-	Monitors and analyses power quality and consumption at the grid connection.	Detailed insights into grid performance and energy usage.
Monitoring cabinet	Offers protection for all equipment from environmental factors.	Provides superior protection against environmental elements.	Premium enclosure with additional features for long-term equipment protection.
Active temperature & humidity control	-	Maintains optimal conditions for equipment operation.	Advanced system for precise environmental control of equipment.
Configuration	Securely configured network to manage inverters and power plant controllers.	Secure network segment with network security features to enhance data integrity.	Robust security protocols and dedicated network segments for maximum system integrity.

Table 10 details the essential hardware and configurations for a reliable solar PV system, outlining minimum, best practice, and recommended setups for components like routers, switches, inverters, UPS systems, and environmental controls. These elements ensure optimal performance, secure communication, and system reliability. Proper hardware configuration enables the creation of a digital twin, a virtual model of the physical system that enhances solar energy management through advanced analytics, predictive maintenance, and real-time optimisation, improving efficiency and minimising downtime.

9.4 Sensor Selection and Control Capabilities for Solar PV Plants

Besides computing and network, a SCADA system comprises two crucial aspects: sensing and acting. Sensors gather data on various environmental and operational parameters, while control capabilities ensure appropriate actions based on the collected information. The below section details sensor selection following the IEC 61970 standard, along with essential control functionalities within switching and protective equipment. We'll also explore recommendations that go beyond best practices for enhanced monitoring and control.

When designing and configuring a solar PV plant, it is essential to adhere to the minimum requirements outlined by IEC 61970, along with additional considerations for optimal performance and monitoring. These requirements ensure accurate data collection, system efficiency, and reliable operation.

Irradiance Sensors

Pyranometers

A pyranometer should be installed for each Plane-of-Array (POA) orientation to ensure accurate irradiance measurements, which are essential for calculating the Performance Ratio (PR) and Energy Performance Index (EPI). To maintain consistent and reliable data, the pyranometers must be traceable to a national reference. For precise POA irradiance measurements, it is recommended to use first-class pyranometers with an accuracy of +/- 0.5%.

Irradiance Cells (Low-Cost Alternative)

One irradiance cell should be installed per Plane-of-Array (POA) orientation for every 5 MWp of installed capacity. With an accuracy of +/-2.0%, these cells are suitable for general performance monitoring but are not ideal for calculating the Performance Ratio (PR) and Energy Performance Index (EPI). In best practice scenarios, irradiance cells can serve as a backup to pyranometers.

Module Temperature Sensors

Two temperature sensors should be installed per Plane-of-Array (POA) orientation for every 5 MWp of installed capacity to ensure accurate temperature monitoring. These sensors must maintain high thermal conductivity contact with the module backsheet and have an accuracy of +/- 1°C. Module temperature data is crucial, as Performance Ratio (PR) and Energy Performance Index (EPI) calculations are often temperature-corrected in most contracts (see *Section Performance Ratio and Section Energy Performance Index*).

DC Current and Voltage Sensors

String inverters typically include integrated current and voltage sensors at the string or Maximum Power Point Tracking (MPPT) input level, while central inverters provide similar sensors at the DC input level. However, monitoring at the string level is necessary for string combiner boxes, as it is not usually provided by default.

Grid Watcher

A Grid Watcher is essential for ensuring automated and safe grid re-energisation after grid-related shutdowns or imbalances, ensuring the system complies with grid regulations and operational safety.

Breaker and Switch Control

Main breakers and switches in the AC distribution cabinet and combiner box must be capable of shutdown via a shutdown signal. This is typically achieved using contact relays with on/off state signals through a 1/0 digital input.

Energy Meter

The energy meter should allow for both analog or digital connection to the logger, preferably through Modbus. Pulse reading can also serve as an acceptable alternative.

Security Monitoring

CCTV cameras and presence motion sensors enhance security and monitoring at solar plants. While not required by IEC 61970, weatherproof cameras with night vision are useful for perimeter security and remote inspections, especially when integrated with the SCADA system for centralised video feeds and motion detection alerts. Motion sensors, strategically placed around the plant perimeter, detect unauthorised activity and trigger alarms. Outdoor-rated sensors with adjustable sensitivity help minimise false alarms and, when linked to the SCADA system, provide real-time alerts, potentially paired with CCTV cameras for visual verification.

Soiling Sensor

Soiling sensors are essential for measuring the soiling ratio and index, which directly impact module performance and OPEX. These sensors can trigger automatic cleaning actions to maintain optimal performance. It is recommended to use mature, SCADA-ready sensors with Modbus communication for seamless integration into the system, ensuring consistent and accurate data for decision-making.

Horizontal Pyranometer

A horizontal pyranometer provides Global Horizontal Irradiance (GHI) data for calculating Performance Ratio (PR) and Energy Performance Index (EPI), as well as serving as a redundancy measure for Plane-of-Array (POA) pyranometers. An accuracy of +/- 1.0% is generally sufficient to meet most monitoring and performance needs.

Wind Sensors

Wind sensors measure critical parameters such as wind speed, direction, and gusts, which are important for various aspects of plant operation. With an accuracy of +/- 2 m/s for speed, +/- 5° for direction, and +/- 1 m/s for gusts, these sensors are valuable for:

- Forecasting module performance
- Predicting soiling conditions
- Supporting design assumptions related to mechanical stress resistance, particularly in high-wind areas (sensor installation at 10 meters above ground is typical)

Weather Station

A comprehensive weather station is essential for measuring humidity, precipitation, and other relevant weather parameters. Selecting a SCADA-compatible weather station ensures seamless integration and reliable data acquisition, contributing to more accurate performance predictions and optimisation strategies.

Bi-directional Breaker and Switch Control

Switching devices, such as breakers and switches in AC distribution cabinets and combiner boxes, should be electronically controllable for full remote operation. Consider using Intelligent Electronic Devices (IEDs) with communication protocols like IEC 61850. These devices enable advanced control capabilities within the SCADA system, allowing for more efficient and automated operations.

Energy Meter Integration

Full integration of energy meters with the SCADA system using Modbus TCP communication protocol enhances the robustness and reliability of data acquisition. Energy meters with built-in communication functionalities allow for seamless integration, providing accurate and real-time data on energy generation and consumption.

Modular Compute Device at the Edge

Implementing a modular compute device at the edge of the network offers several advantages. These devices typically feature low-power processors like ARM, providing enough processing power for real-time data analysis and secure data storage. Supporting various communication protocols (e.g. Modbus, IEC 61850), they ensure smooth integration with sensors and SCADA systems. Additionally, these devices facilitate remote operation through data pipelines to the cloud for centralised monitoring and analysis. By incorporating intelligent control with edge intelligence, these devices can make autonomous decisions based on pre-defined algorithms and real-time sensor data, even during internet outages, ensuring continued optimal operation.

- **Spectral Irradiance Sensors:** These sensors analyse sunlight wavelengths, offering detailed insights into spectral mismatch losses. Particularly useful for multi-junction or emerging PV technologies, integrating spectral irradiance sensors with SCADA enables advanced performance analysis and optimisation.

- **Soil Moisture Sensors:** By monitoring soil moisture, these sensors optimise irrigation systems and help reduce dust accumulation on modules. SCADA-compatible soil moisture sensors allow for seamless integration, supporting broader control strategies.

Exceeding the IEC 61970 sensor and control requirements offers significant advantages for solar PV plant operations. By leveraging best practices such as integrating soiling sensors, SCADA-compatible weather stations, and bi-directional control, plants can optimise cleaning schedules, enhance performance, and enable efficient remote operation. Additionally, incorporating advanced security measures like motion sensors and CCTV cameras allows for real-time intrusion alerts and centralised monitoring, ensuring the safety and integrity of the plant. These practices not only improve operational efficiency but also contribute to reduced OPEX and maximised energy production.

Communication Protocols

Wired protocols

Wired communication protocols are crucial for data exchange and efficient monitoring in solar PV plants. Choosing the right protocol depends on factors such as plant size, complexity, and budget.

Here are the key options:

Modbus: A simple and widely adopted protocol with a master-slave architecture. While easy to implement, it lacks scalability and security for larger plants.

- **Sunspec Compliance:** Ensures a common data language between Modbus devices from different vendors, enhancing compatibility

- **IEC 60870-5-104:** Known for its reliability, error correction, and time-stamped data, IEC 60870-5-104 is more complex and expensive than Modbus but suitable for larger plants

- **IEC 61850:** A future-proof protocol designed for smart grid integration, offering intelligent communication and interoperability. However, it requires a significant upfront investment, making it ideal for large-scale plants

For smaller plants, Modbus is often the best choice due to its simplicity and widespread adoption. In contrast, IEC 60870-5-104 and IEC 61850 are better suited for larger plants due to their reliability and advanced features.

In addition to communication protocols, the network infrastructure plays a key role in ensuring optimal performance. Industrial Ethernet is popular for its high bandwidth and reliability, while fieldbus networks (RS-485) provide a cost-effective solution for smaller or dispersed plants. Fiber optics offer high-speed data transmission over long distances and are immune to electromagnetic interference, making them ideal for large sites.

In conclusion, selecting the appropriate communication protocol and network infrastructure—such as fiber optics for high-speed data transfer—is essential for maximising the performance and seamless integration of a solar PV plant within the smart grid.

Wireless protocols

Wireless communication protocols are essential for transmitting data from devices like inverters and solar panels in solar farms. The best protocol for your farm depends on several factors, including data volume, speed requirements, power sources, and the farm's size.

For **smaller farms** with lower data needs, **Bluetooth Low Energy (BLE)** is a good choice. BLE is ideal for direct device-to-mobile communication but has a limited range of about 100 metres. To cover larger areas, additional gateway nodes may be required.

For larger **farms, Zigbee** is a better option. It offers a range of up to 1,000 metres and supports mesh networks, allowing for more reliable communication across vast areas. However, managing its mesh network can be more complex than BLE, although it is optimised for low power consumption.

For **long-range communication, Wi-Fi** provides high bandwidth, making it ideal for real-time applications like security cameras. However, its high power consumption and potential security vulnerabilities should be carefully considered. **LPWAN (Low-Power Wide-Area Network)** is another option, suitable for long-distance, low-power communication from dispersed sensors. While LPWAN offers slower data transfer rates and higher latency compared to BLE and Zigbee, it works well for basic data transmission across large areas. **Cellular 4G** offers a reliable long-range solution for large, geographically spread-out farms or farms with a capacity exceeding 500 kWh. It provides high bandwidth and low latency, making it suitable for real-time data transfer, but comes with higher energy consumption and recurring costs.

Ultimately, the best wireless protocol for your solar farm depends on its specific needs and constraints. Consider the technical performance, power requirements, and operational factors, especially in the context of energy trading dynamics.

9.5 Data Types, Indicators & Formats

Data Types

For effective operation and maintenance (O&M) of solar PV installations, SCADA systems require a minimum set of data to ensure grid integration, safety, and performance monitoring. This data aligns with IEC 61850 and 61970 standards and serves as the foundation for generating operational reports and tickets.

Table 11

SCADA Data Types for Solar PV O&M: Requirements and Best Practices

Data type	Essential requirements	Best practices
Sensor data	Irradiance (IEC 61724-1): Real-time measurements for grid integration and PPAs	Temperature (IEC 61724): Include temperature data for performance issues. String Monitoring: DC voltage/current for underperforming strings
Inverter data	Power Output (IEC 61850): Monitor real-time power output	Power Characteristics (IEC 61850): Include AC/DC voltage, current, and power factor for grid stability
	Status alarms	
System status	Breaker Status (IEC 61850): Track circuit breaker status for safety during maintenance.	Transformer Health: Monitor transformer health data (e.g. oil temperature) to prevent overheating and optimise power delivery
		Grid Connection (IEC 61850): Track parameters (voltage, frequency) to ensure grid stability and compliance to interconnection agreements
Alarms	Devices with embedded computing generate alarms further enhanced by the monitoring platforms	
	Digital twin data analysis	
Data enrichment	Enhance SCADA data with basic metadata including device type, location, installation date, manufacturer specifications...	Comprehensive metadata including details relevant to performance analysis
Operational Data Objects (using SCADA data)	Service Tickets: Generate service tickets based on SCADA data anomalies	
	Reports: Create reports using SCADA or field measurements for KPIs like energy generation and system availability. Also reports as outcome of the service tickets	
	Videos: CCTV videos generated by the security system	
Data analysis	-	Utilise SCADA data for real-time monitoring, historical analysis, and generation of automated reports based on user-defined parameters. Configure alerts for deviations from expected performance to enable proactive maintenance

By collecting these minimum data types, we ensure several important outcomes. First, grid compliance is achieved, fulfilling grid integration requirements and PPA terms, as outlined in IEC 61850 and 61724-1. Safety assurance is also maintained through continuous monitoring of breaker status, in accordance with IEC 61850. Performance monitoring is enabled by tracking real-time power output and irradiance data, as recommended in IEC 61724-1, allowing for effective assessment of plant performance. Additionally, improved operations and maintenance (O&M) are facilitated by the generation of service tickets and reports, enabling proactive maintenance and ensuring full compliance with industry-standard contracting frameworks for O&M and asset management.

Building upon the minimum requirements, best practices expand the data collection and utilisation for enhanced O&M. By following these best practices, solar PV professionals can achieve several key benefits. Improved performance is one of the primary advantages, as early detection of underperforming strings and potential inverter issues allows for timely corrective actions, ensuring the plant operates at optimal efficiency. Additionally, monitoring grid connection parameters helps maintain grid stability, ensuring compliance with interconnection agreements and contributing to the overall stability of the grid. Enhanced operations and maintenance (O&M) is another significant benefit, as real-time monitoring, historical analysis, and automated alerts enable proactive maintenance, reducing downtime and extending the lifespan of plant assets.

Recommendations Beyond Best Practices: Data for a Fully Data-Driven O&M System

For a truly data-driven approach to solar PV operations and maintenance (O&M), consider collecting these additional data types beyond best practices:

1. Advanced Data Analysis:

    - **Weather Forecasts (e.g. irradiance, ambient temperature):** Enables proactive performance predictions and optimisation strategies

    - **Historical Performance Data (e.g. power output, string monitoring):** Facilitates trend analysis for predictive maintenance, allowing for corrective actions before issues arise

2. Financial Modeling Integration:

    - **Energy Production Costs:** Integrates with SCADA data to assess financial performance against benchmarks and PPAs (e.g. cost per kWh generated)

3. Data Lake:

    - **Weather Data:** Provides environmental context for SCADA data analysis, improving performance insights

    - **Financial Information (e.g. operation & maintenance costs):** Enables cost-benefit analysis and data-driven resource allocation for O&M activities

4. Machine Learning/AI models & agents (see *Chapter 12. Innovations and Trends*): Analyses vast amounts of data including:

    - **SCADA Advanced analytics AI models (sensor data, inverter data, system status):** Identifies patterns and anomalies in real-time operation for proactive maintenance

    - **O&M Activity Data assistants (service ticket data, inspection reports):** Provides historical context for machine learning algorithms to improve fault detection and root cause analysis

Indicators

Effective O&M of solar PV plants relies on a comprehensive set of device-measured indicators. In Table 12, we categorise these indicators based on IEC 61970 minimum requirements, best practices, and recommendations. Additionally, the subchapter lists some recommendations beyond best practices.

Table 12

Device-measured indicators based on IEC 61970 minimum requirements, best practices

Indicator type	Essential requirements	Best practices
Irradiance	**Plane-of-Array (POA) Irradiance (W/m²):** Measured by pyranometers with +/- 0.5% accuracy (recommended) for precise data used in PR and EPI calculations (mandatory per IEC 61970 Chapter 11). Deviations from expected irradiance levels can indicate shading or tracker malfunction.	**Horizontal Irradiance (GHI) (W/m²):** Measured by a horizontal pyranometer, GHI data provides redundancy for POA pyranometers and is used for PR and EPI calculations. Accuracy of +/- 1.0% is generally sufficient.
Module temperature	**Module Temperature (°C):** Measured by embedded or attached sensors with +/- 1°C accuracy (preferred) to assess potential performance issues. Temperatures exceeding manufacturer specifications can lead to power output reduction, necessitating cleaning or cooling strategies.	
DC power	**String Combiner Box DC Input Current (A) per String:** Monitored by current sensors within combiner boxes, providing insights into individual string performance. Significant deviations from expected current can signify problems within a particular string.	
	Inverter Input DC Voltage (V): Measured at inverter input terminals, DC voltage data helps analyse string performance and potential issues like cable losses or module mismatch. Deviations from expected voltage levels can signify problems within a particular string.	
	Inverter Input DC Current (A): Measured at inverter input terminals, DC current data helps identify string-level anomalies. A string with lower than expected current compared to others could indicate potential module degradation or faulty connectors.	
AC power	**Inverter Output AC Power (kW):** Inverters provide real-time AC power output data, the primary indicator of overall plant performance. Sudden drops or abnormal fluctuations can signal inverter problems or potential grid disturbances.	
Grid connection	**Grid Connection Parameters (voltage, frequency):** Measured by protection relays at the point of interconnection to ensure grid stability and adherence to interconnection agreements (IEC 61850). Deviations outside the allowed range can necessitate adjustments or communication with the grid operator.	**Power Quality Monitoring:** Analyses grid parameters like voltage harmonics, power factor, and flicker. Deviations from acceptable ranges can signify power quality issues requiring corrective actions to ensure grid stability and potential cost avoidance.
Security	**Perimeter Intrusion Detection (On/Off):** Triggered by security cameras, motion sensors, or fence breach sensors to alert of potential security breaches.	
	Communication Network Status (On/Off): Indicates functionality of the communication network used for data transmission between devices and the SCADA system. Network outages can disrupt data collection and monitoring capabilities.	

Table 12 - continued

Device-measured indicators based on IEC 61970 minimum requirements, best practices

Indicator type	Essential requirements	Best practices
Energy Measurement	**Energy Meter Reading (kWh):** Measured by the energy meter at the point of interconnection, this data provides insights into total energy production over a specific period. It serves as a baseline for assessing overall plant performance and financial returns.	
Soiling	**Soiling ratio:** Measured by dedicated sensors, this indicator compares actual irradiance to POA irradiance, highlighting potential soiling buildup and prompting cleaning activities for optimal generation.	
Wind	**Wind Speed (m/s):** Measured by wind sensors, wind speed data helps with: ▪ Forecasting module performance: High winds can impact power output. ▪ Predicting soiling: Increased wind can remove dust buildup. ▪ Supporting design assumptions: Wind data verifies the plant's mechanical stress resistance in high-wind areas (e.g. sensor mounted at 10 meters above ground).	
	Wind Gusts (m/s): Monitors sudden increases in wind speed, which can potentially cause mechanical stress on the PV system components.	
	Wind Direction (°): Provides context for wind speed data, aiding in understanding how wind interacts with the solar panels (e.g. headwind vs. tailwind).	
Weather station	**Weather Station Data:** Measures various parameters including: ▪ Humidity (%): High humidity can promote dust accumulation and impact inverter efficiency. ▪ Precipitation (mm): Rainfall can clean dust buildup but may also lead to temporary power output reduction. ▪ Ambient Air Temperature (°C): Ambient temperature data helps assess potential performance impacts and supports efficient inverter cooling strategies	
Compute module	**Compute Module Status (On/Off):** Indicates functionality of the compute device at the network edge, responsible for real-time data processing, analysis, and communication with the SCADA system. Module outages can disrupt data processing and control capabilities.	
	RAM Usage (%): Monitors memory utilisation by the compute module, ensuring sufficient resources for data processing tasks. High RAM usage can lead to performance degradation.	
	CPU Usage (%): Tracks central processing unit utilisation, identifying potential resource constraints that could impact real-time data analysis.	
	Local Storage Available (GB): Provides insights into remaining storage capacity for historical data and processed information.	
	Connectivity Speed (Mbps): Monitors the data transfer rate between the compute module and the SCADA system, ensuring efficient communication for real-time operations	
	Status (Operational/Degraded/Faulty): Indicates the overall health of the compute module, enabling timely identification and resolution of potential issues.	
	Device Health Indicators: Provides detailed information on various aspects of compute module health, such as fan speed, temperature, and power supply voltage. This data allows for proactive maintenance and prevents unexpected outages.	

Beyond best practices, advanced indicators such as **Spectral Analysis** and **Soil Moisture** provide deeper insights for performance optimisation. Spectral irradiance, measured in W/m²/nm using dedicated sensors, offers a detailed breakdown of sunlight wavelengths, enabling the analysis of spectral mismatch losses—particularly valuable for multi-junction or emerging PV technologies. Integrating these sensors with SCADA enhances data collection and system understanding. Similarly, soil moisture data, expressed as a percentage, supports the optimisation of irrigation systems to reduce water usage and minimise dust accumulation on solar modules. SCADA-compatible sensors ensure seamless integration, promoting both efficiency and improved power output.

Data Quality and Curation

Effective solar PV operations rely on high-quality data for accurate performance monitoring, proactive maintenance, and optimised decision-making. However, data collected from diverse sensors (energy meters, inverters, weather stations) across geographically dispersed plants, often in harsh environments, is susceptible to various quality issues.

Data quality challenges can significantly impact the accuracy and reliability of performance metrics and trend analysis. Common issues include missing data, which can occur due to sensor malfunctions, communication errors, or network outages. These gaps hinder KPI calculations and trend analysis. Additionally, outliers and spikes, such as unrealistic data points (e.g. negative irradiance values), can skew performance metrics if not properly identified and addressed. Extended periods of missing data, resulting from sensor failures or network interruptions, also disrupt time-series analysis and forecasting models. Inconsistent or corrupted data, often referred to as "junk values," can compromise data pipelines and affect downstream analytics. Moreover, sensor drift, the gradual degradation of sensors over time, introduces persistent biases, leading to inaccurate performance assessments.

To address these data quality challenges, several best practices for data curation and validation can be implemented. One key approach is the use of automated data validation processes, which leverage domain-specific knowledge and statistical methods to detect and correct issues in real time. Techniques such as Z-score anomaly detection, Inter-Quartile Range (IQR) outlier detection, and limit checking can help identify unrealistic data points and sensor malfunctions. For missing data, imputation methods like linear or spline interpolation can be applied for short gaps, while more advanced techniques such as k-Nearest Neighbours (KNN) imputation can handle longer intervals.

Additional best practices include implementing data lineage tracking to document data origin, transformations, and quality checks. This facilitates root-cause analysis of discrepancies and ensures transparency in the data pipeline. Regular sensor calibration and maintenance schedules are also crucial to minimise sensor drift and maintain data accuracy. Furthermore, data cleansing and standardisation processes help remove identified anomalies, format data consistently, and manage missing values using appropriate imputation techniques. Finally, maintaining data version control enables tracking changes, facilitates rollbacks in case of errors, and supports historical analysis with different versions of the data.

Data Formats

Data format is critical for solar PV data usability. A breakdown of key considerations is shown in Table 13 on the following page.

Table 13

Data formats: Minimum requirements and best practices

Data format	Essential requirements (aligned with IEC standards)	Best practices
Standardisation	Use IEC 61724 for data exchange compatibility	
Clear documentation	Document data format details for each recorded data file. This includes: file extension (e.g. csv, .xml); data field definitions (variable name, data type, units), timestamp format (e.g. UTC); data encoding e.g. ASCII, UTF-8)	
Self-describing formats		Use CSV with a header row for clarity and reduced reliance on external documentation
Lossless compression		Employ techniques like gzip to minimise storage while preserving data integrity for long-term archival
Schema definition		For complex data, consider XML Schema Definition (XSD) or JSON Schema for data validation and consistency
Standardised naming conventions		Adopt consistent naming for data files and variables for clarity and easier management
Version control		Implement version control using Git to track changes and enable rollbacks or analysis with different data versions

To enhance data management and operational efficiency, several advanced recommendations can be implemented. **Cloud integration** is essential for scalability and performance, with data formats such as Apache Parquet offering optimised storage and retrieval on cloud platforms. **Real-time streaming** protocols like MQTT or WebSockets (WS) enable low-latency data transmission, ensuring timely access to critical information for decision-making. Additionally, adopting **semantic interoperability** standards such as RDF (Resource Description Framework) or OWL (Web Ontology Language) allows for sophisticated data integration and the creation of knowledge graphs.

Data in the Cloud

Cloud computing significantly transforms monitoring systems for solar PV installations, improving data management and enhancing profitability. Key benefits of cloud-based monitoring include real-time monitoring and visualisation, allowing for remote access to data and proactive issue identification to optimise power generation. Additionally, cloud-integrated digital twins—virtual replicas of the PV system—use real-time data to predict performance, enabling more effective predictive maintenance. Furthermore, cloud-based platforms streamline operations by seamlessly integrating with Computerised Maintenance Management Systems (CMMS) and Enterprise Resource Planning (ERP) systems, fostering an interconnected ecosystem that enhances maintenance workflows, optimises resource allocation, and supports data-driven decision-making for improved overall PV system health.

Data Engineering

This section explores data engineering best practices for monitoring systems in solar PV installations, focusing on storage, processing, and getting data ready for analysis. Data-driven SCADA systems with cloud-based data engineering unlock exciting possibilities for solar PV installations, paving the way for advanced optimisation, self-maintenance, and potentially even autonomous control. Addressing security, latency, and regulatory considerations is crucial for successful implementation.

Minimum Requirements

Ensure basic data capture, storage, and visualisation for system health monitoring and performance analysis. Options include local databases, file storage, FTP data transfer, basic APIs, and batch processing with threshold-based alerts.

Best Practices

Enhance capabilities with cloud storage (object storage for raw data, time-series databases for processed data), industry standard data models (e.g. CIM), flexible schema design, secure streaming protocols (MQTT, AMQP) for real-time data, hybrid data processing (batch for historical, real-time stream processing for latest data), and integration of data science libraries for advanced analytics and machine learning. Utilise cloud platforms for initial stage batch processing. Develop interactive dashboards for real-time and historical data visualisation.

Beyond Best Practices

Leverage cloud data engineering alongside SCADA functionalities for advanced optimisation and potential autonomous control.

- **SCADA Layer Integration.** Establish a bi-directional communication channel for real-time data feedback. This allows processed data from the cloud to be fed back to SCADA for:
    - Dynamic Power Optimisation: Adjust inverter settings or tilt angles based on weather forecasts and historical data
    - Predictive Maintenance Integration: Trigger preventative maintenance tasks within SCADA based on machine learning analysis of potential equipment degradation
- Advanced Data Engineering Techniques
    - Edge Computing Integration: Pre-process and filter real-time data at the SCADA system before transmission, reducing bandwidth and improving response times. Potentially lays the groundwork for autonomous control
    - Real-time Machine Learning Models: Deploy lightweight models at the edge or within the cloud processing pipeline for real-time anomaly detection and control adjustments within pre-defined constraints
- **Autonomous Control Considerations.** While fully autonomous control is complex, a hybrid approach with human oversight for critical decisions and real-time data/ML for automated adjustments can optimise performance

The benefits of advanced system optimisation in solar PV installations are significant. Real-time, data-driven adjustments ensure maximum power generation and efficiency. Predictive maintenance and automated adjustments help minimise downtime and reduce maintenance costs. Additionally, this approach lays the foundation for future autonomous control systems, enabling operations with minimal human intervention and further streamlining plant management.

Important Considerations

Important considerations for implementing autonomous control systems in solar PV installations include security, latency, and regulations. Robust security measures are essential to prevent unauthorised access and manipulation, especially when using bi-directional communication channels. Latency is also a critical factor, as real-time control requires minimal delays in data transmission and processing. It's important to assess network infrastructure and processing power limitations, particularly when deploying edge computing or real-time machine learning models. Additionally, compliance with industry regulations and safety standards is crucial to ensure the safe and lawful implementation of autonomous control functionalities.

Digital Twin

A well-designed digital twin for solar operations and maintenance (O&M) goes beyond simple visualisation to become a powerful tool for optimising plant performance. It utilises physics-based simulation models such as PVsyst or PVSol to replicate a solar plant's physical setup, including panel types, string configurations, inverter specifications, and grid connections (voltage levels, power factor). By integrating real-time sensor data—such as DC/AC current, voltage, temperature—and weather inputs like irradiance, temperature, and wind speed, a robust operational data structure is created. This structure, coupled with comprehensive metadata, ensures accurate interpretation and analysis of plant performance.

Minimum Requirements: Optimising Performance

A digital twin foundation enables several key functionalities that are critical for optimising solar plant performance:

- Performance Monitoring: By comparing real-time data with simulated outputs, a digital twin helps identify underperformance, such as string-level anomalies, allowing for prompt corrective actions

- Scenario Analysis: "What-if" simulations allow O&M professionals to assess the effects of environmental changes (e.g. irradiance variations), component degradation, or different maintenance strategies on energy generation, enabling better decision-making

Best Practices: Granular Analysis and AI Integration

Advanced digital twins incorporate more granular analysis and leverage AI to further optimise operations. Best practices include:

- **Solar Shading Analysis:** Using 3D modeling tools, digital twins can account for shading dynamics from nearby structures and objects, which can help optimise cleaning schedules and energy production

- **Individual String Modeling:** This granular approach allows for performance analysis at the string level, facilitating targeted troubleshooting and maintenance to prevent system-wide failures

- **Inverter Loss Modeling:** Detailed inverter loss models—such as partial load efficiency and reactive power management—enable more precise operational optimisations, enhancing the overall efficiency of the system

Additionally, the integration of AI and machine learning algorithms trained on historical and real-time data brings several benefits:

- **Anomaly Detection:** By analysing sensor data, AI can proactively identify potential equipment failures, allowing for early intervention and reducing the likelihood of downtime

- **Performance Forecasting:** Machine learning models can predict future energy generation based on historical data and weather forecasts, which helps improve grid integration and optimises maintenance scheduling

Beyond Best Practices: A Glimpse into the Future

Looking ahead, the potential of digital twins in solar O&M extends into more advanced, autonomous functionalities:

- **Closed-Loop Control:** Digital twins, when combined with AI, could influence the physical plant's operations. By feeding real-time insights into the SCADA system, the digital twin could adjust inverter settings dynamically based on weather conditions, maximising power output

- **Predictive Maintenance:** Advanced AI algorithms, analysing sensor data, could predict equipment degradation and trigger preventative maintenance before failures occur, thereby reducing downtime and maintenance costs

- **Collaborative Digital Twins:** A network of interconnected digital twins across multiple solar plants could facilitate knowledge sharing, process optimisation, and best practice dissemination, leading to overall performance improvements across the industry

In summary, digital twins represent a transformative tool in solar O&M, providing granular insights, enhancing predictive capabilities, and paving the way for more autonomous, optimised solar plant management in the future.

9.6 Monitoring Platforms

This section explores web platforms for solar PV plant operations and maintenance (O&M), outlining functionalities from basic to advanced. Web-based monitoring platforms are evolving from data visualisation tools to powerful platforms that leverage AI and real-time control to optimise solar PV plant performance and streamline O&M activities. This paves the way for a future of intelligent solar energy production.

Minimum Requirements: These features are foundational for effective O&M.

- Universal Data Ingestion: Read data from any solar PV platform
- Long-Term Data Archiving: Securely store all raw data in the cloud
- Detailed Asset Modeling: Create a digital twin of the plant with layout and component information
- High-Resolution Data Visualisation: Allow users to view and analyse data in various granularities
- Diverse Data Presentation: Offer multiple visualisation formats (charts, heatmaps) and ensure responsiveness across devices
- Customisable KPI Dashboards: Enable users to create personalised dashboards with chosen KPIs and drag-and-drop functionality
- Data Quality Validation: Implement mechanisms to ensure data integrity and identify anomalies
- Malfunction Detection: Use customisable alarms and machine learning to detect malfunctions and potential issues
- Field Device Alert Handling: Seamlessly receive and manage alerts from field devices and integrate them with a ticketing system
- KPI Calculation & Customisation: Calculate core KPIs and offer customisation options
- Aggregated KPI Reporting: Generate reports for individual plants or entire portfolios with user-defined formats and scheduling options
- Standardised Data Interface: Provide a secure API for data export and integration with other software systems

Best Practices for Enhanced O&M: These practices go beyond the minimum requirements and leverage data analytics for improved O&M.

- Tailored User Interface: Offer role-based interfaces with intuitive navigation and clear data visualisations for different user types (O&M provider, investor, etc.)
- User-Defined Alerts & Reports: Empower users to configure custom alerts and reports using drag-and-drop report builders with pre-defined data sets
- Integrated Ticketing System: Facilitate efficient issue resolution with a built-in ticketing system that integrates with workflow management tools
- Plant-Specific KPIs: Track and analyse KPIs specific to each plant for targeted performance optimisation

- Third-Party Data Integration: Integrate external data sources (weather, irradiance) for enhanced insights and combine sensor data with external sources

- Granular Data Downloads: Allow users to download data in various granularities for further analysis in external tools with secure download protocols

Advanced Functionalities for Real-Time Control & Optimisation: These functionalities leverage AI and real-time control for future advancements.

- Real-Time Optimisation with AI: Utilise AI and machine learning for real-time recommendations on inverter settings, cleaning schedules, or maintenance based on weather, historical data, and predictive analytics

- Predictive Maintenance: Analyse sensor data, historical trends, and weather forecasts to predict equipment failures and enable preventative maintenance actions

- Real-Time Anomaly Detection & Root Cause Analysis: Employ machine learning to analyse sensor data and identify anomalies in real-time, allowing for quicker troubleshooting

Closed-Loop Control with Safeguards (imagining future capabilities):

- Dynamic Inverter Control: Automatically adjust inverter settings based on real-time data to maximise power output

- Autonomous Cleaning Scheduling: Trigger automated cleaning schedules based on satellite imagery, weather forecasts, and historical soiling data

- Collaborative Platform Ecosystems: Imagine future developments where platforms work together

- Interconnected Digital Twins: A network of interconnected digital twins across multiple plants could facilitate knowledge sharing and best practice dissemination

- Blockchain-enabled Data Security and Transparency: Leverage blockchain technology to ensure data security, tamper-proof records, and transparent data provenance

CMMS & ERP

In this section we look at the importance of a well-orchestrated digital ecosystem for optimal solar PV plant performance and return on investment (ROI). It focuses on two crucial software systems: CMMS and ERP, outlining their functionalities and how they work together.

CMMS (Centralised Maintenance Management System): Manages the lifecycle of physical assets in a solar PV plant.

CMMS (Computerised Maintenance Management System) is a software platform used to manage the lifecycle of physical assets in a solar PV plant, helping streamline maintenance processes and improve asset performance. It tracks equipment details, schedules maintenance tasks, and integrates real-time data to enhance efficiency and minimise downtime.

Minimum requirement functionalities

- **Granular Asset Registry:** Detailed records of all plant equipment (panels, inverters, transformers, BoP components) including:
  - Manufacturer, model, serial number, installation date, specifications, warranty information
- **Preventative Maintenance (PM) Optimisation:** Creates and schedules PM tasks based on:
  - Manufacturer recommendations
  - Historical maintenance data (failure patterns, degradation trends)
  - Industry best practices (e.g. IEEE or IEC standards)
  - Real-time sensor data (for condition-based maintenance)

Best Practices for Enhanced CMMS Functionality

- **SCADA Integration:** Integrate with SCADA systems for real-time equipment data and anomaly detection, enabling proactive maintenance
- **Mobile Workforce Management:** Utilise mobile apps for technician work order access, updates, and field data capture for improved efficiency and data accuracy
- **Predictive Maintenance with Machine Learning:** Analyse historical data, sensor readings, and weather forecasts to predict equipment failures, minimising downtime and costs

Recommendations Beyond Best Practices

- **Digital Twin Integration:** Explore integrating digital twins with CMMS for further optimisation of maintenance strategies by leveraging virtual representations of physical assets
- **Augmented Reality (AR) Support:** Investigate AR technology to provide technicians with real-time overlay information on equipment during maintenance tasks, improving efficiency and knowledge transfer

ERP (Enterprise Resource Planning): An information management platform that integrates various business functions for solar energy companies.

ERP (Enterprise Resource Planning) is an integrated software platform that streamlines and automates various business functions across a solar energy company, including financial management, supply chain operations, and resource planning. It helps optimise processes such as cost control, procurement, inventory management, and logistics, offering valuable insights for decision-making.

Minimum requirements for ERP in O&M

- Financial Management with Cost Control: Tracks financial aspects including:
  - Maintenance labour costs
  - Spare parts and material costs
  - Contractor service fees
- Supply Chain Management: Facilitates procurement of maintenance materials and spare parts by managing:
  - Purchase orders with vendor management
  - Inventory levels across locations
  - Logistics and transportation optimisation

Best Practices for Enhanced ERP Functionality

- **Real-Time Data Integration with CMMS:** Establish real-time data exchange for automatic cost updates based on completed work orders and parts usage
- **Customisable Dashboards with KPI Tracking:** Develop user-specific dashboards that combine data from CMMS (work order status, maintenance costs) and ERP (inventory levels, financial performance) for informed decision-making
- **Sustainability Reporting Integration:** Integrate the ERP with sustainability reporting tools to track and report on key environmental performance indicators (KPIs) related to O&M activities

Recommendations Beyond Best Practices

- **Blockchain Integration for Secure Supply Chain Management:** Explore blockchain technology to enhance supply chain transparency and traceability for spare parts, ensuring authenticity and origin verification
- **Internet of Things (IoT) Sensor Integration:** Integrate IoT sensors with the ERP system to track the real-time location and condition of maintenance vehicles and personnel, optimising field service logistics and improving technician response times

By leveraging these digital tools and best practices, solar PV plants can achieve optimal performance, maximise ROI, and ensure efficient O&M processes.

Control Room and Monitoring Practice

A **Control Room** for operating Solar PV Plants using SCADA (Supervisory Control and Data Acquisition) is a centralised hub where operators monitor, control, and manage the operations of a solar photovoltaic plant. This facility is equipped with advanced communication systems, computer hardware, and software that allow for real-time data acquisition from the solar plant's various components such as inverters, panels, and meteorological stations.

The primary function of a Control Room in this context is to ensure the optimal performance of the solar PV plant by continuously monitoring parameters like power output, efficiency levels, and system health. Operators use SCADA systems to detect any deviations from standard operating conditions. These systems provide visualisations through graphical user interfaces (GUIs), which include detailed schematics of the plant's layout and real-time data charts.

Further we present the function and best practices for a Solar PV plant's Control Room, equipped with SCADA systems for centralised monitoring, control, and management.

The control room serves as the centralised hub for monitoring, controlling, and managing solar PV plant operations. It facilitates real-time data acquisition from various plant components, including inverters, panels, and weather stations. By continuously monitoring key parameters such as power output, efficiency, and system health, the control room ensures optimal plant performance. Through SCADA visualisations, it detects deviations from standard operating conditions, enabling timely interventions to maintain efficiency and prevent potential issues.

Effective monitoring of solar PV plant operations involves several best practices to ensure timely and efficient issue resolution. All issues, alarms, and malfunctions should be logged with timestamps in a ticketing system that tracks Service Level Agreements (SLAs), enabling organised issue tracking. Remote root cause analysis should be conducted to identify the source of detected problems without requiring on-site presence, saving time and resources. For issues requiring physical intervention, detailed work orders must be generated to guide on-site teams. Whenever possible, remote mitigation actions should be implemented promptly to address identified issues and alarms, minimising downtime and maintaining plant performance.

Monitoring Schedules

- Plant Level Monitoring (3-4 times/day):
  - Detect outages and major performance deviations (excluding curtailment)
  - Manage alarms within the platform (close acknowledged alarms, create exceptions for outages outside O&M control, link outage alarms to exceptions as needed, and clear unnecessary alarms)
- Inverter Level Monitoring (2-3 times/day):
  - Detect outages of inverters or string combiner boxes
  - Identify major deviations (outside inverter alarm configuration boundaries)
  - Close/acknowledge alarms and create exceptions for outages outside O&M control, clear unnecessary alarms
- String Level Monitoring (3-4 times/week):
  - Detect faulty strings with zero current and/or voltage
  - Identify major deviations, close/acknowledge alarms, and create exceptions for outages outside O&M control, clear unnecessary alarms
- Sensor & Data Quality Monitoring (2-3 times/week):
  - Check sensor data availability, ensure data quality (readings match physical reality), close/acknowledge alarms, and create exceptions for outages outside O&M control. Clear unnecessary alarms, especially for meters and sensors impacting Performance Ratio (PR) and Energy Performance Index (EPI) calculations. Consolidate data with alternative satellite data when sensor data is unavailable
- Data & Networking Monitoring (1-2 times/day):
  - Check mobile connection to routers, ensure data availability from loggers and devices, coordinate with the monitoring SaaS provider for displayed data, close/acknowledge alarms, and create exceptions for outages outside O&M control. Clear unnecessary alarms, considering exceptions like faulty loggers pending RMA or data discontinuity while devices remain operational

Adhering to monitoring guidelines provides numerous benefits, including comprehensive oversight of plant performance, which allows for the early detection and proactive resolution of issues. This approach helps maintain system integrity, ensuring enhanced operational efficiency and reliability. As a result, it contributes to the longevity and profitability of the solar investment, safeguarding its continued success and performance over time.

Control Room Operators

Control room operators play a critical role in the efficient and safe operation of solar plants. These highly skilled professionals typically have backgrounds in electrical engineering, renewable energy, or related fields. Their expertise is essential in ensuring the smooth operation of the plant, as they are responsible for interpreting complex data from SCADA systems in real-time and making quick, informed decisions.

A successful control room operator must possess a deep understanding of SCADA systems and be adept at analysing large datasets to identify operational anomalies or irregularities. They are highly analytical and detail-oriented, capable of recognising potential issues before they escalate, and ensuring optimal plant performance. In addition to their technical skills, they are proficient in using plant monitoring and performance management software tools, which allow them to oversee the plant's operations efficiently.

Effective communication is another key aspect of the control room operator's role. Operators must coordinate seamlessly with on-site personnel to resolve issues and ensure that any operational concerns are addressed promptly. Their ability to communicate effectively is essential for teamwork and maintaining plant safety.

Safety is a top priority for control room operators. They are rigorously trained in adhering to strict safety protocols and are well-prepared to execute emergency procedures when necessary. This training ensures that operators can manage unexpected situations without compromising the safety of the plant or personnel.

Furthermore, control room operators are committed to continuous professional development. To stay ahead of industry trends, new technologies, and best practices, they regularly update their knowledge and skills. This ongoing learning is crucial for maintaining high levels of performance and ensuring the long-term success of the plant.

For a more comprehensive understanding of the training and qualifications required for control room operators, refer to *Chapter 3. Personnel and Training*.

Data Governance

The European Union places significant emphasis on data ownership and privacy, underscoring key principles that must be adhered to. Ownership of data collected through monitoring systems and data loggers, even when stored in the cloud, must remain with the asset owner or Special Purpose Vehicle (SPV), ensuring that both current and historical data are readily accessible to them. Access to this data should be managed carefully, with specific permissions granted to stakeholders based on their roles. For instance, O&M service providers need access to support plant operation and maintenance tasks, asset managers require data for financial and commercial management, and auditors may need access during due diligence processes. To maintain security and efficiency, a minimum of two access levels should be implemented: read-only access for viewing and reporting purposes, and full access for modification and management of data settings.

Monitoring System Hardware

The monitoring system hardware can be supplied either by the O&M service provider or a third-party monitoring service provider, with distinct responsibilities in each scenario. When the O&M service provider supplies the hardware, they assume full responsibility for ensuring data protection and maintenance, safeguarding data security and integrity, as well as guaranteeing the proper functionality of the monitoring system. Alternatively, if a third-party monitoring service provider supplies the hardware, the responsibility for data protection and maintenance shifts to the third party. However, the O&M provider must still verify these aspects to ensure compliance. Additionally, the O&M provider is responsible for verifying the accuracy of performance monitoring, ensuring the data accurately reflects the plant's actual performance and adheres to industry best practices.

Data Management and Data Flows

The role of a data manager is critical in ensuring effective data governance and utilisation within the system. Data managers are responsible for defining the structure and format of collected data through data modeling. This involves organising data from sources such as monitoring systems, service tickets, and inspection reports to ensure consistency and streamline analysis. They also design data flow paths, determining how data moves from its origins, like sensors or technicians, to various applications and storage locations. This process optimises data usage and prevents bottlenecks. Ultimately, the data manager's work supports the generation of insightful reports for higher-level stakeholders, such as asset managers and energy off-takers. These reports offer valuable insights into plant performance, maintenance requirements, and energy production, enabling informed decision-making at strategic levels.

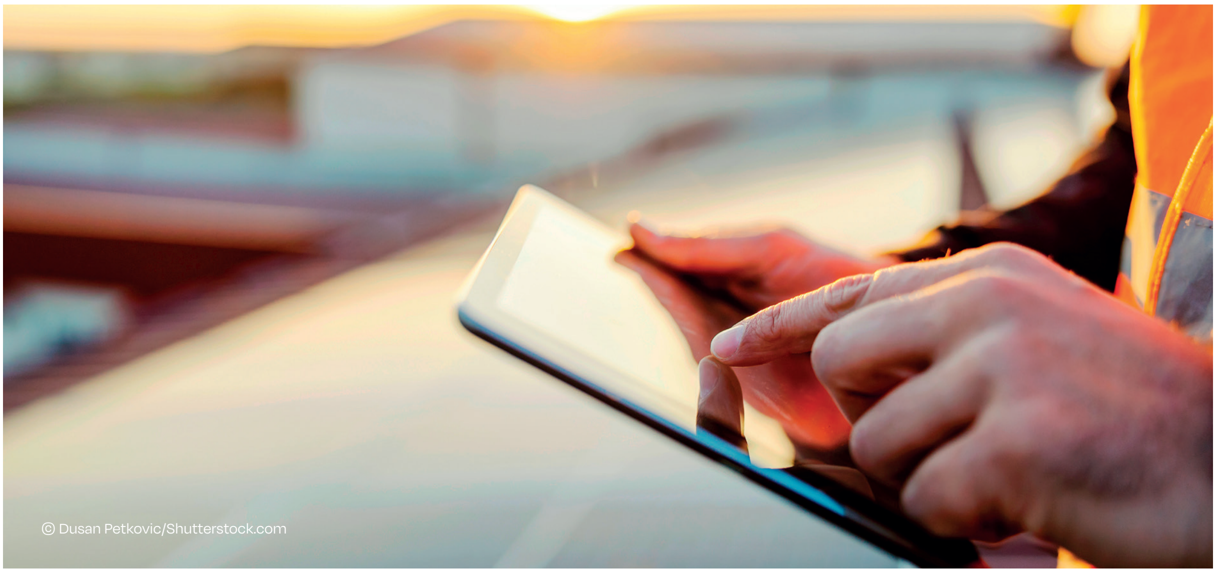
Ownership of Additional Data

Beyond monitoring data, ownership of other data types plays a critical role in ensuring comprehensive asset management. Service tickets, which include details such as repairs and parts used, are typically owned by the asset owner, though the O&M provider may have temporary access to facilitate maintenance activities. Similarly, inspection reports, containing information like visual observations and potential issues, are generally the property of the asset owner. Ownership of data within monitoring platforms, however, can vary depending on the platform and the terms of the agreement. In some instances, the platform provider may retain ownership of raw data, while processed and analysed data remains the property of the asset owner, emphasising the importance of clear contractual arrangements.

O&M Service Provider Responsibilities

Evaluating the O&M provider's ability to effectively manage and utilise the monitoring system is essential for ensuring optimal performance and data governance. If gaps in expertise are identified, the O&M provider should receive appropriate training to enhance their proficiency with the system. For third-party monitoring providers, data access must be carefully restricted to essential tasks, such as bug fixing and system development, to maintain security and protect sensitive information.

By following these best practices, asset owners can ensure their data is secure, accessible to authorised personnel, and used responsibly for optimal solar PV plant operation. This ensures a clear understanding of data ownership throughout the lifecycle of a solar PV plant and facilitates effective reporting to key stakeholders for informed decision-making.



9.7 Cybersecurity

Cybersecurity involves the implementation of tools, processes, and controls to protect systems, networks, and data from cyberattacks, thereby minimising risks and preventing unauthorised access to critical infrastructure. A key strategy in enhancing cybersecurity is **minimising network complexity** by reducing the number of devices on the network, as each device represents a potential vulnerability. Additionally, **network monitoring and traffic analysis** are crucial. Continuously monitoring network traffic can help identify unusual patterns, such as excessive bandwidth usage, which may signal a cyberattack. These measures collectively strengthen an organisation's defence against evolving cyber threats.

Securing Physical and Digital Access

Securing Physical and Digital Access focuses on protecting critical infrastructure by implementing measures to control access and safeguard against unauthorised entry, both physically and digitally. This includes enforcing stringent access policies, utilising professional-grade hardware, and maintaining up-to-date documentation and procedures to ensure comprehensive security management.

Securing physical and digital access requires a multifaceted approach to safeguard network devices and critical infrastructure. Physical access control measures should restrict entry to network devices and include deterrents against unauthorised access. A robust password policy is essential, avoiding default credentials and requiring regular updates. For secure remote access, firewalls with strict rules should control internet traffic, port forwarding must be minimised, and Virtual Private Networks (VPNs) should be used to ensure secure connections. Unique passwords must be assigned to each plant, and up-to-date documentation of network devices should be maintained to ensure thorough security coverage. Role-Based Access Control (RBAC) should be implemented to grant permissions based on user needs, while USB ports for storage devices should be disabled to prevent malware transfer. Regular verification of system administrator privileges ensures only authorised personnel have elevated access. Additionally, security incident reporting procedures must be in place for rapid threat response. Finally, investing in professional, industrial-grade hardware with advanced security and manageability features further enhances the security framework.

Vulnerability Management

Vulnerability Management focuses on proactively identifying, addressing, and mitigating security weaknesses to protect systems from potential threats and cyberattacks.

Effective vulnerability management involves several key practices to mitigate security risks. Regularly updating software and firmware on all devices is essential to address known vulnerabilities and ensure systems remain secure. Additionally, utilising up-to-date anti-virus software helps protect against malicious threats. Wireless access should be minimised, as wireless connections are typically less secure than wired ones, reducing the potential for unauthorised access. Conducting regular penetration testing and network audits with external security experts is also crucial to identify vulnerabilities and test defences through simulated cyberattacks, ensuring potential weaknesses are addressed before they can be exploited.

Employee Awareness and Training

Employee Awareness and Training focuses on equipping employees with the knowledge and tools to recognise and mitigate cybersecurity risks, ensuring a secure work environment. This involves ongoing training, access management, and proactive measures like internal audits and anti-phishing campaigns to maintain high security standards.

IT security training is crucial for educating employees on cybersecurity best practices and helping them identify potential threats. Implementing the principle of least privilege ensures that access to plant information and systems is granted only to employees who need it for their specific job functions. Employee access changes, such as when an employee leaves or changes positions, should be promptly addressed by updating plant passwords. To prevent data loss, it's important to regularly synchronise important documents and files with managed file storage solutions like OneDrive. Raising awareness through internal company posters can also help inform employees about potential cyber threats, offering tips on recognising suspicious emails, safe internet usage, and secure data handling. Regular internal audits assess the security status of IT systems and data management processes, identifying weaknesses and allowing for timely corrective actions. Additionally, controlled anti-phishing campaigns, including simulated phishing attacks, test and enhance employees' ability to recognise phishing threats and respond appropriately.

Comprehensive Cybersecurity Management System (CSMS)

Best practice dictates that solar PV plants implement a formal Cybersecurity Management System (CSMS) based on a thorough risk assessment. This system should follow a continuous improvement cycle, typically the plan-do-check-act (PDCA) model, and include the following key components:

- Cybersecurity Policy: A documented policy that outlines cybersecurity protocols and expectations for all personnel, establishing a clear framework for security practices across the organisation

- Roles and Responsibilities: Clearly defined roles and responsibilities for cybersecurity within the organisation, ensuring accountability and effective management of security measures

- System Architecture Analysis: A comprehensive evaluation of the plant's system architecture to identify potential vulnerabilities and implement necessary countermeasures to protect the infrastructure

- Technical Countermeasures: Implementation of various technical controls, such as firewalls, encrypted communication channels, access controls, and security monitoring tools to safeguard the system

- Physical and Procedural Controls: Enforcing physical access restrictions and maintaining updated procedures to ensure ongoing awareness and preparedness against evolving cyber threats

Data Security Requirements

In addition to general cybersecurity measures, specific security requirements must be applied to the data generated by the solar PV plant to ensure its integrity and confidentiality:

- Tickets: Implement a ticketing system with access and modification rights determined by user roles. For critical tickets, consider utilising data encryption and digital signatures to enhance security

- Reports: Control access to reports based on user roles and the sensitivity of the data. Reports should be generated in secure formats, and data classification policies must be in place to ensure proper handling of sensitive information

- Other Data: The same security principles should be applied to all types of plant data, including sensor data, historical records, and performance metrics. For non-critical data, data anonymisation can be considered as an additional layer of security

- Email Encryption: Enable email encryption for internal and external communications to ensure confidentiality and protect sensitive information from unauthorised access

- **Document Classification:** Introduce a document classification system to properly manage and secure various types of information based on their sensitivity and importance

- **Hard Drive Disposal:** Securely dispose of hard drives using methods that prevent unauthorised access to data after the drive is no longer in use, ensuring that no sensitive information is recoverable

Minimum Requirements for Cybersecurity in Data Loggers and Monitoring Systems

To ensure the cybersecurity of data loggers and monitoring systems in solar PV plants, the following minimum requirements should be implemented:

- **Data Logger Security:** Data loggers should not be directly accessible from the internet and must be protected by firewalls to prevent unauthorised access

- **Secure Data Server Connections:** Ensure that connections between data loggers and data servers are secure and restricted to authorised systems only, minimising exposure to potential cyber threats

- **Manufacturer Security Information:** Request detailed security information from data logger and monitoring platform manufacturers. This should include details about penetration testing, activation channels for command protocols, and security audits for their products

- **Secure Communication Protocols:** Utilise secure Virtual Private Network (VPN) connections for sending command functions to control devices. Implementing double authentication adds an extra layer of security for communication

Separate Partition for Service Engineers: Create a separate partition on service engineers' computers to isolate critical data and tools from other applications, ensuring that sensitive information remains secure during maintenance or servicing tasks.

Security Scenarios Tested for Continuity of Operations

It is also relevant to implement tested security scenarios that allow for a continuity of operations when faced with a disruption, and that encompass a set of procedures and actions aimed at preparing an organisation to handle various emergency situations. Regularly testing these scenarios helps assess operational readiness and the identification of potential security gaps, which enables effective risk management and minimises downtime.

It is notably relevant to test scenarios for disruptions such as:

- **Loss of access to SCADA infrastructure at the photovoltaic farm:** Simulate situations where SCADA (Supervisory Control and Data Acquisition) infrastructure is inaccessible to test the operational readiness of the team

- **Unavailability of the IT service provider:** Test responses to situations where the IT company responsible for technical support is unavailable

- **Suspected ransomware attack:** Conduct simulations of ransomware attacks to assess the team's readiness to quickly respond and recover data

- **Unavailability of a key employee:** Test procedures for replacing key employees in the event of their sudden absence

9.8 Analytics and Data Science

In this section we look at how data science and mature Artificial Intelligence (AI) can be leveraged with digital twin models of solar plants to optimise performance. Here, we focus on established practices using machine learning and Statistical techniques.

Performance Optimisation with Statistical Process Control (SPC)

Statistical Process Control (SPC) is a powerful tool for analysing historical power generation data to identify deviations from expected performance baselines. This analysis can uncover potential issues such as soiling, panel degradation, or inverter malfunctions. Control charts, such as Shewhart charts, are used to monitor key performance indicators (KPIs) like DC power output or inverter efficiency. When deviations exceed control limits, alerts are triggered, prompting further investigation to address potential problems and maintain optimal plant performance.

Time Series Analysis with Seasonality and Weather

Advanced time series analysis techniques, such as ARIMA models, are invaluable for capturing seasonal variations and weather-induced fluctuations in power generation. These models can be further enhanced by integrating exogenous variables, such as solar irradiance and ambient temperature, to account for external factors influencing performance. This integration improves the accuracy of both forecasting and anomaly detection, enabling more reliable predictions and timely identification of potential issues.

Explainable Statistical Modelling with Feature Importance

Statistical models can be employed to predict future energy production by leveraging historical data and weather forecasts. To enhance the interpretability and reliability of these models, feature importance analysis techniques, such as LIME, can be used to assess the contribution of various input features, such as historical power output and forecasted irradiance, to the model's predictions. This approach not only builds trust in the model's reasoning but also identifies opportunities for targeted data collection, further refining model accuracy and performance.

Predictive Maintenance with Supervised Learning and Root Cause Analysis

Supervised machine learning algorithms trained on historical sensor data and labelled equipment failure events can significantly improve anomaly detection by identifying subtle deviations in voltage, current, or temperature patterns that indicate potential failures. Classification algorithms, such as Support Vector Machines (SVMs) or Random Forests, are particularly adept at detecting anomalies by learning from past failure patterns. These same algorithms can also be employed for root cause analysis after anomalies are detected. By analysing sensor data associated with anomalies and comparing it with historical data from past interventions, the models can suggest the most likely causes, guiding technicians toward efficient repairs and helping to prevent similar issues in the future.

Time-Series Data Correlation with Aerial Inspection Reports

Digital twin models can be enhanced by integrating time-series data with additional information sources, such as aerial inspection reports, to provide a more comprehensive view of potential issues. By correlating sensor data with inspection findings, physical damage such as micro-cracks in panels can be identified more effectively. This integration is achieved by synchronising timestamps from data acquisition events, like sensor readings, with those of aerial inspections, enabling a unified and detailed analysis of the solar plant's performance and condition.

By leveraging these techniques, solar PV plants can achieve substantial performance optimisation. Early detection of potential issues allows for prompt intervention, while a deeper understanding of root causes ensures more effective solutions. Targeted maintenance interventions further enhance operational efficiency, leading to increased overall performance and significant cost savings.

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Key Performance Indicators

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This chapter will focus on KPIs used to assess the performance of solar PV power plants. It will cover three main categories of KPIs: Solar PV power plant KPIs, which are quantitative measures of the plant's performance; O&M service provider KPIs, which include both quantitative and qualitative indicators to evaluate the service quality provided by the O&M provider; and Solar PV power plant/O&M service provider KPIs, which assess both the plant's performance and the quality of O&M services together. These KPIs offer asset owners a comprehensive overview of the operational effectiveness of both the plant, and its maintenance services.

This section deals with Key Performance Indicators (KPIs), which provide the Asset Owner with a quick reference on the performance of the solar PV power plant. The KPIs in this chapter are divided into the following categories:

- Solar PV power plant KPIs, which directly reflect the performance of a solar PV power plant. They are quantitative indicators
- O&M service provider KPIs, which reflect the performance of the service provided by the O&M service provider. O&M service provider KPIs are both quantitative and qualitative indicators
- Solar PV power plant/O&M service provider KPIs, which reflect solar PV power plant performance and O&M service quality at the same time

The O&M service provider (or the Technical Asset Manager) is generally responsible for the calculation of the KPIs and reporting to the Asset Owner.

It is important to underline that the O&M service provider is not responsible for providing contractual guarantees for all the KPIs listed in this chapter. When there are warranties in place it is strongly advised that the party liable for the warranties is not the only one calculating the KPIs.

Figure 8

Overview of different types of KPIs

PV plant KPIs

Directly reflect the performance of the PV power plant. PV plant KPIsare quantitative indicators:

- Reference Yield
- Expected Yield
- Specific Yield
- Performance Ratio
- Temperature-corrected Performance Ratio
- Energy Performance Index
- Technical Availability (Uptime)
- Tracker Availability

O&M Service Provider KPIs

Reflect the performance of the service provided by the O&M service provider. O&M service provider KPIs are both quantitative and qualitative indicators:

- Acknowledgement Time
- Intervention Time
- Response Time
- Resolution Time
- Reporting
- O&M Service Provider experience
- Schedule attainment
- Preventive vs. Corrective Maintenance ratio

Being both PV plant KPIs and O&M Contractor KPIs

Reflect both plant and O&M service provider KPIs measuring at the same time plant performances and ability of the O&M service provider to keep the PV power plant ready to produce:

- Contractual Availability
- Energy-Based Availability

10.1 Solar PV power plant data

Solar PV power plant data can be split into three groups:

1. Raw data measurements: data obtained directly from the solar PV power plant and used for performance calculation

   The following is a list of raw data measurements that can be used to calculate KPIs:

   - AC Apparent Power produced (kVA)
   - AC Active Power (kW)
   - AC Energy produced (kWh)
   - AC Energy metered (kWh)
   - Reactive power (kVAR)
   - Irradiance[5] (reference for the plant or the sub-plants) (W/m^2)
   - Air and module temperature (Celsius degrees)
   - Alarm, status code and duration
   - Outages, unavailability events

   This is a basic list, and it is non-exhaustive.

   1. Solar PV power plant KPIs: using the raw data from the solar PV power plant to give a more balanced overview of its operation
   2. Solar PV power plant healthiness KPI: generating data and information from physical inspections of a PV power plant that can serve as potential precursors for performance and/or safety related deteriorations

Raw data measurements and Solar PV power plant KPI are ex post data, whereas Solar Power plant healthiness KPI are ex ante providing useful information and clues for future occurrences.

Reference Yield

The Reference Yield Yr represents the energy obtainable under standard conditions, with no losses, over a certain period *i*. It is useful to compare the Reference Yield with the final system yield (*See Section Performance Ratio*).

The Reference Yield
is defined as:

$$Y_r(i) = \frac{H_{POA}}{G_{STC}}$$

Where:

- $Y_r(i)$ = Reference Yield for the period *i* expressed in peak sun hours (h) or (kWh/kW_p)
- $H_{POA}(i)$ = Is the measured irradiation on plane of the PV array (POA) for the period *i* (kWh/m^2)
- G_{STC} = The reference irradiance at standard test conditions (STC) (1,000 W/m^2)

5 Although irradiance and irradiation are often used as synonyms, they do not express the same physical quantities and should not be used interchangeably (see IEC 61724-1:2017):
- Irradiance is the power of the sunlight at a specific moment per unit of area, usually expressed in Watt per square meter (W/m^2).
- Irradiation is the power of the sunlight integrated over a period of time (e.g. an hour, a day or a year). In other words, irradiation is the energy per unit of area, calculated as the sum of irradiances over a period of time. It is commonly expressed in kilowatt-hour per square meter (kWh/m^2).

Specific Yield

Specific Yield, also called final yield, Y_f is the measure of the total energy generated, normalised per kW_p installed, over a certain period *i*.

Specific Yield
is calculated as follows:

$$Y_f(i) = \frac{H_{(i)}}{P_o}$$

Where:

- Y_f(i) = Plant Specific Yield for the period *i*, expressed in (kWh/kW_p) or peak sun hours (h)
- E (i) = Plant energy production or Plant energy metered for the period *i* (kWh)
- P_o = Plant Peak DC power (nominal power) (kW_p)

This measurement integrates plant output over a chosen time frame, and since it normalises to nominal power, comparison of the production of plants with different nominal power or even different technologies (e.g. solar PV, wind, biomass etc) is possible. For example, the Specific Yield of a solar PV power plant can be compared against the Specific Yield of a wind plant for the purposes of making an investment decision. Moreover, the Specific Yield of a 5 MWp ground mounted solar PV power plant can be compared directly to that of a 1 MWp double tracker power plant, for example.

Calculating Specific Yield on the inverter level also allows a direct comparison between inverters that may have different AC/DC conversion rates or different nominal powers. Moreover, by checking inverter level Specific Yield within a plant, it is possible to detect whether an inverter is performing worse than others.

Performance Ratio (PR)

PR is a quality indicator of the solar PV power plant. As the ratio between the actual Specific Yield and the theoretically possible Reference Yield, PR captures the overall effect of solar PV system losses when converting from a nameplate DC rating to AC output. Typically, losses result from factors such as module degradation, temperature, soiling, inverter losses, transformer losses, and system and network downtime. The higher the PR is, the more energy efficient the plant is.

PR, as defined in this section, is usually used to report on longer periods of time according to the O&M contract, such as month or year. Based on PR, the O&M service provider can provide recommendations to the plant Owners on possible investments or interventions.

Performance Ratio
is defined as:

$$PR = \frac{Y_f}{Y_r} \times 100$$

Where:

- PR = Performance Ratio over a year (%)
- Y_f = Specific Yield over a year expressed in (kWh/kW_p) or peak sun hours (h)
- Y_r = Reference Yield over a year expressed in (kWh/kW_p) or peak sun hours (h)

These definitions are based on (Woyte et al. 2014) in line with IEC 61724-1:2017 and are common practice.

PR is measured for available times at the inverter or plant level.

Note that special attention is needed when assessing the PR of overrated plants, where the output of the plant is limited by the inverter's maximum AC output. In such situations, and for the period that overrating takes place, PR will calculate lower than normal although there is no technical problem with the plant. Stakeholders should be careful assessing PR values for overrated plants, although the amount of overrating is normally statistically constant or with negligible differences on a yearly basis.

Temperature-corrected Performance Ratio

In some situations, such as a commissioning test or solar PV power plant handover from one O&M service provider to another, PR needs to be measured over a shorter period, such as two weeks or a month. In such situations, using a PR formula corrected with temperature factor is recommended. This can help neutralise short-term PR fluctuation due to temperature variations from STC (25°C). As a best practice, temperature should be registered with a granularity of up to 15 minutes (referred to as period j below) and the average temperature for the time period i should be calculated by weighting the mean temperatures of the time periods j according to Specific Yield of this time period.[6]

Temperature-corrected PR can be defined as follows:

Equation 1. Temperature-corrected Performance Ratio for the period *i* (%)

$$PR_{TO}(i) = \frac{Y_i}{Y_r(i) \times [1 - \frac{\beta}{100} \times (T_{MOD}(i) - 25°C)]} \times 100$$

Where:

- $PR_{TO}(i)$ = Temperature-corrected Performance Ratio for the period *i* (%)
- $Y_f(i)$ = Plant Specific Yield for the period *i*, expressed in (kWh/kW_p) or peak sun hours (h)
- $Y_r(i)$ = Reference Yield for the period *i*, expressed in (kWh/kW_p) or peak sun hours (h)
- β = Temperature coefficient of the installed modules (%/°C)
- P_0 = Plant Peak DC power (nominal power) (kW_p)
- $T_{MOD}(i)$ = Average module temperature for the period *i*, weighted according to Specific Yield $Y_f(j)$ (°C) - *see below the formula*

Equation 2. Average module temperature for the period *i*

$$T_{MOD}(i) = \frac{\sum_{j=1}^{i} Y_f(i) \times T_{MOD_{MEAS(j)}}}{\sum_{j=1}^{i} (Y_f(i))}$$

Where:

- $T_{MOD}(i)$ = see above
- $Y_f(j)$ = Plant Specific Yield for the period *j*, expressed in (kWh/kW_p) or peak sun hours (h)
- $T_{MOD}(j)$ =Module temperature for the period *j* (°C)

6 The temperature-corrected PR calculation is not consistently applied. Therefore, this note clarifies in brief the best practice for calculating PR using the formulas provided above. There are 2 methods to apply the formula:
- In the time-weighted method, PR is weighted over a period by the time interval. An example would be if the SCADA system provides data in 1 min/5 min/10 min average values. PR is then calculated for that 1 min/5min/10 min period and the resulting PR values are then averaged. This method will generally yield higher PR values in the morning, while production is low and lower PR values mid-day, but with high energy production. Therefore, low PR value are given the same with as the high PR values and the use of an average value of the PR does not take into account the different weight that PR may have over the day. This can artificially increase the PR by up to a couple of percentage points.
- In the irradiance-weighted method, irradiance as a sum counts higher irradiance values as more impactful on the total PR for any given period. This eliminates the weighting effect and provides a more accurate PR. Therefore, all relevant measured parameters should be summed above and below the line over the calculation period before any division and calculation of PR is performed.

Equivalent annual temperature corrected performance ratio

The equivalent annual performance ratio is another relevant metric for assessing the performance of a PV system. It provides a normalised system performance that accounts for seasonal variations and long-term environmental conditions. It provides a reliable indication of system efficiency and identifies deviations from expected performance, enabling targeted O&M actions. For bifacial PV modules, it helps factoring in the impact of varying albedo and irradiance conditions on both sides of the panel when considering the bifaciality coefficient, aiding in detecting underperformance or system faults. Overall, this metric is relevant for data-driven decision-making in O&M by providing a standardised, comprehensive evaluation metric tailored to the specific characteristics of modern PV technologies.

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Temperature-corrected PR can be defined as follows - *continued*:

Equation 3. Equivalent average performance ratio for monofacial modules, and annual capture loss correction factor for temperature effects, according to IEC 61724-1:2021

$$C_{k,\ annual} = 1 + \gamma \times (T_{mod(k)} - T_{mod,\ annual\text{-}avg})$$

$$PR'_{annual\text{-}eq} = \left(\sum_k P_{out,\ k} \times \tau_k\right) / \sum_k \frac{(C_{k,annual} \times P_0) \times G_{i,\ k} \times \tau_k}{G_{i,\ ref}}$$

Where:

- $C_{k,\ annual}$ = annual performance ratio correction factor. $C_{k,\ annual}$: it is only recommended for PR calculations of weeks or months not complete years
- Y = relative maximum-power temperature coefficient in units 1/°C, typically negative
- $T_{mod}(k)$ = PV module temperature in time Interval *k*
- $T_{mod,\ annual\text{-}avg}$ = annual-average module temperature-this is typically chosen from simulation with historical data for the month of the time Interval *k*
- $PR'_{annual\text{-}eq}$ = annual equivalent performance ratio of the PV system
- $P_{out,\ k}$ = output power of a PV system at time=*k*
- T_k = transmittance of the atmosphere at a specific time, *k*
- P_0 = DC rating. It can be multiplied by (1-dg xN) where dg is the % of the yearly degradation and N is the number of years since the commencement of operation
- $G_{i,k}$ = global irradiance on the surface of the PV system at time=*k*
- $G_{i,\ ref}$ = reference solar irradiance value
- $C_{k,\ annual}$: it is only recommended for PR calculations of weeks or months not complete years

Equation 4. Equivalent average performance ratio for bifacial modules according to IEC 61724-1:2021

$$PR'_{annual\text{-}eq,\ bi} = \left(\sum_k P_{out,\ k} \times \tau_k\right) / \sum_k \frac{(C_{k,\ annual} \times P_0) \times G_{i,\ k} \times BIF_k \times \tau_k}{G_{i,\ ref}}$$

Where:

- BIF_k=bifaciality coefficient of the PV system

Box 4

Interpreting Performance Ratio

Careful attention needs to be paid when interpreting PR, because there are several cases where it can provide misleading information about the status of the solar PV power plant:

- Seasonal variation of PR *(lower PR in the hot months, higher in colder months)*

The calculation of PR presented in this section neglects the effect of solar PV module temperature on its power. Therefore, the performance ratio usually decreases with increasing irradiation during a reporting period, even though energy production increases. This is due to an increasing solar PV module temperature that results in lower efficiency. This gives a seasonal variation, with higher PR values in the cold months and lower values in the hot months. It may also give geographic variations between systems installed in different climates.

This seasonal variation of PR can be significantly reduced by calculating a temperature-corrected PR to STC, which adjusts the power rating of the plant at each recording interval to compensate for differences between the actual solar PV module temperature and the STC reference temperature of 25 °C (taking into account the temperature coefficient of the modules, given as % of power loss per °C).

- Interpretation of PR for overrated plants *(lower PR as designed)*

Special attention is needed when assessing the PR of clipping losses. In these plants installed DC power is higher than inverter AC power (DC/AC ratio higher than 1), as a consequence, during sunny periods the output of the plant may be limited by inverter maximum AC output. In such situations, when derating takes place, PR will be lower than normal although there is no technical problem with the plant – lower PR in high-production periods is in fact the consequence of a design decision. Stakeholders should be careful assessing PR values for overrated plants, although the amount of derating is normally statistically constant or with negligible differences on a yearly basis.

- Calculation of PR using GHI instead of POA *(misleading higher PR)*

Calculation of the PR using the Global Horizontal Irradiance (GHI) instead of in-plane (POA) irradiance is an alternative in situations where only GHI measurements are available. The PR calculated with GHI would typically show higher values which may even exceed unity. These values cannot necessarily be used to compare one system to another but can be useful for tracking the performance of a system over time and could also be applied to compare a system’s measured, expected, and predicted performance using a performance model that is based only on GHI.

- Soiled irradiance sensors *(misleading higher PR)*

Special attention is needed when assessing the PR using data from soiled irradiance sensors. In this case, PR will present higher values and will give the false impression that the solar PV power plant is performing better than expected and even some underperformance issues could remain hidden.

Expected Yield

Expected Yield $Y_{exp}(i)$ is the Reference Yield $Y_r(i)$ multiplied by the expected PR and thus expresses the Specific Yield that has been expected for a certain period *i*.

Expected Yield
can be defined as:

$$Y_{exp}(i) = PR_{exp}(i) \times Y_r(i)$$

Where:

- $Y_{exp}(i)$ = Expected (Specific) Yield for the period *i*, expressed in (kWh/kW_p) or peak sun hours (h)
- $PR_{exp}(i)$ = Average Expected Performance Ratio of the plant over the period *i*, based on simulation with given actual temperature and irradiation and plant characteristics. (PR_{exp} simulation is beyond the scope of the present document but for more information on this, see Brabandere *et al.* (2014), Klise and Stein (2009), NREL (2017), PVsyst (2017) and SANDIA (2017).)
- $Y_r(i)$ = Reference Yield for the period *i* (based on past irradiation data) expressed in (kWh/kW_p) or peak sun hours (h)

Note that Expected Yield is based on past values of irradiation data. Predicted Yield is based on forecasted data, from day ahead and hour ahead weather reports.

Energy Performance Index

The Energy Performance Index (EPI) is defined as the ratio between the observed Specific Yield $Y_f(i)$ and the Expected Yield $Y_{exp}(i)$ as determined by a solar PV model. The EPI is regularly recalculated for the respective assessment period (typically day/month/year) using the actual weather data as input to the model each time it is calculated. This concept was proposed in Honda et al. 2012.

Energy Performance Index
is defined as:

$$EPI_i = \frac{Y_i}{Y_{exp(i)}}$$

Where:

- $EPI(i)$ = Energy Performance Index for the period *i* (%)
- $Y_f(i)$ = Specific Yield for the period *i* (kWh/kW_p) or (h)
- $Y_{exp}(i)$ = Expected Yield for the period *i* (kWh/kW_p) or (h)

The advantage of using the EPI is that its expected value is 100% at project start-up and is independent of climate or weather. This indicator relies on the accuracy of the model. Unfortunately, there is more than one established model for calculating the Expected Yield of solar PV systems in operation and not all of them are transparent. Therefore, the use of EPI is recommended mainly for the identification of performance flaws and comparison of plants.

Technical Availability or Uptime

Technical Availability (or Uptime), Contractual Availability and Energy-based Availability are three closely related indicators to measure whether the solar PV power plant is generating electricity.

Technical Availability is the parameter that represents the time during which the plant is operating over the total possible time it can operate, *without taking any exclusion factors into account*. The total possible time is considered as the period when the plant is exposed to irradiation levels above the generator's Minimum Irradiance Threshold (MIT). Technical Availability is covered extensively in IEC TS 63019:2019.

Technical Availability
is then defined and calculated as:

$$A_t = \frac{T_{useful} - T_{down}}{T_{useful}} \times 100$$

Where:

- A_t = Technical Availability (Uptime) (%)
- T_{useful} = period of time with in-plane irradiation above MIT (h)
- T_{down} = period of T_{useful} when the system is down (no production) (h)

In the context of calculating Technical Availability for a solar PV plant, Uptime and Downtime refer to the periods when the plant is operating normally versus when it is not.

- Uptime: This refers to the time when the plant is generating power and functioning correctly. It is the period during which irradiance is above the Minimum Irradiance Threshold (MIT), which is typically around 50 or 70 W/m², depending on the plant's characteristics. This period is referred to as T_{useful}, and it excludes times when irradiance is below MIT, as this is not sufficient for power generation.
- Downtime: This refers to the period when the plant is not generating power due to various factors such as equipment failure, maintenance, or when irradiance falls below the MIT threshold. During this time, the plant is not producing power, which negatively impacts its availability.

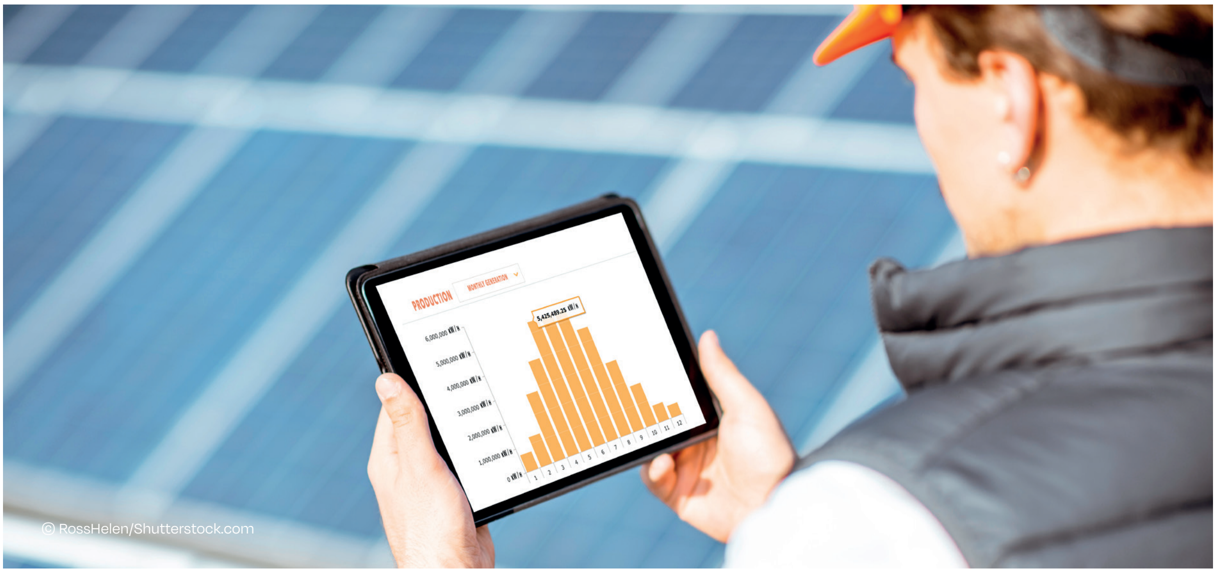
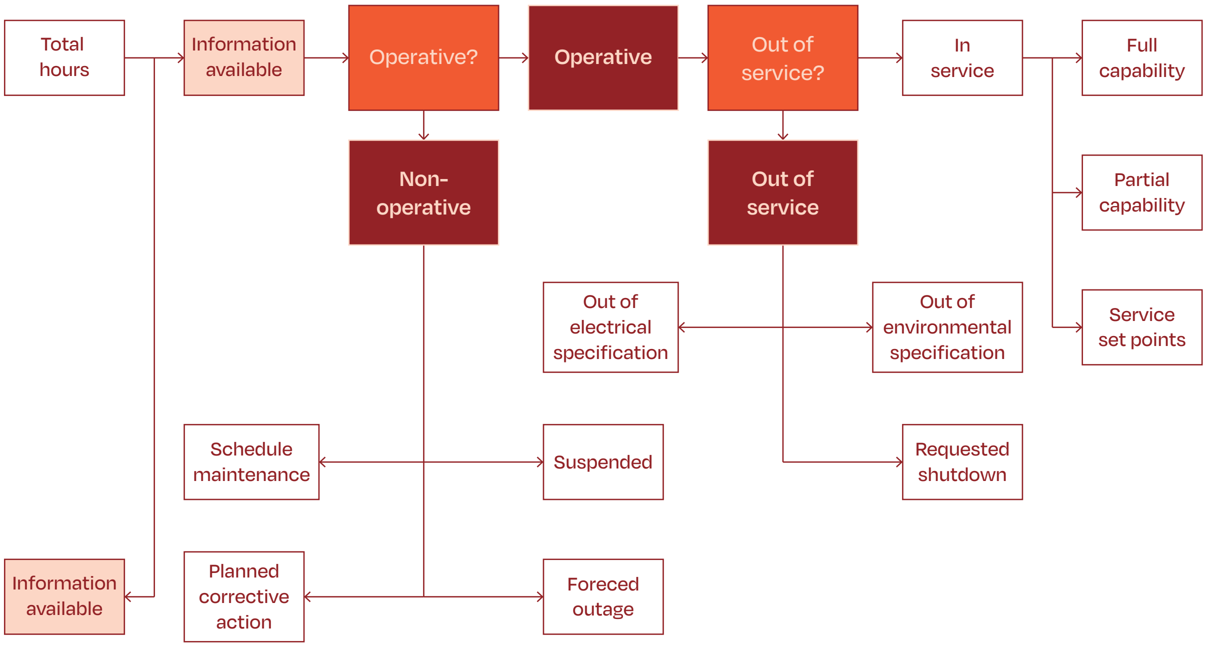


Figure 9

Technical Availability



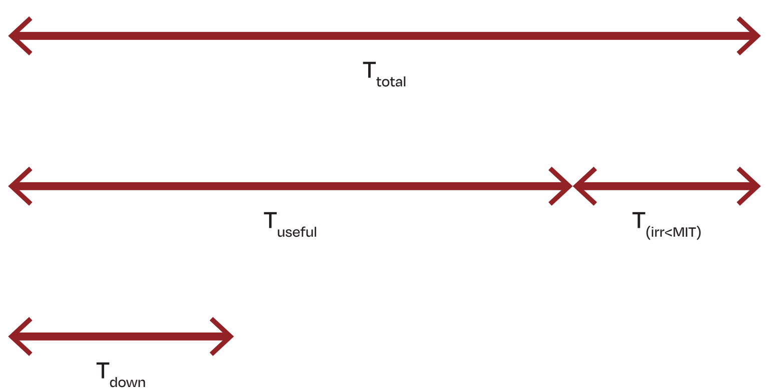
Source:

The figure below illustrates the various periods in time mentioned above.

Normally, only the time where irradiance is above the MIT is considered and this is noted above as T_{useful}, where $T_{useful} = T_{total} - T_{(irr<MIT)}$. Typical MIT values are 50 or 70 W/m^2. MIT should be defined according to site and plant characteristics (e.g. type of inverter, DC/AC ratio etc).

Figure 10

Various periods of time for the calculation of the Technical Availability



Technical Availability should be measured also at inverter level. Individual inverters' Technical Availability $A_{t\,k}$ should be weighted according to their respective installed DC power P_k. In this case, the Technical Availability of the total solar PV power plant $A_{t\,total}$ with a total installed DC power of P_0 can be defined in the box below.

Technical Availability

weighted by individual inverters' installed DC power:

$$A_{t\,total} = 100 \times \sum \left(A_{t\,k} \times \frac{P_k}{P_0}\right)$$

Where:

- $A_{t\,total}$ = Technical Availability of the plant (%)
- $A_{t\,k}$ = Technical Availability of the inverter *k*
- P_k = Installed DC power of the inverter *k*
- P_0 = Plant Peak DC power (nominal power) (kW_p)

For the calculation of Technical Availability, typically up to 15 minutes of irradiation and power production data should be taken as a basis if granularity of components remains at the level of inverter or higher. Anything below the level of inverter is then captured with the PR calculation presented above.

Technical Tracker Availability or Tracker Uptime

Similar to Technical Availability, Technical Tracker Availability is simply a ratio of the useful time compared to the uptime or downtime of the tracker. This measurement is a purely technical parameter and would not allow for any agreed exclusions in the availability. To calculate the technical tracker availability, the following formula in the box below can be used.

Technical Tracker Availability

is calculated as:

$$A_{t\,tracker} = \frac{T_{t\,useful} - T_{t\,down}}{T_{t\,useful}} \times 100$$

Where:

- $A_{t\,tracker}$ = Technical Tracker Availability (%)
- $T_{t\,down}$ = Period when the tracker is down (h)
- $T_{t\,useful}$ = Period when the tracker is functional (h)

Tracking Performance Availability

Functional failure of a tracker can count as inaccurate, or out of sync tracking compared to the set point. This failure can often lead to shading or small performance deviations, based on the deviation from the sun path. The formula for the tracker's performance availability is like the technical availability. $T_{t\,down}$ is defined as the period during which deviation of the tracker's tilt is higher than the accepted deviation angle (e.g. greater than 5° of angle deviation). This metric can help to improve single-or dual-axis tracking performance.

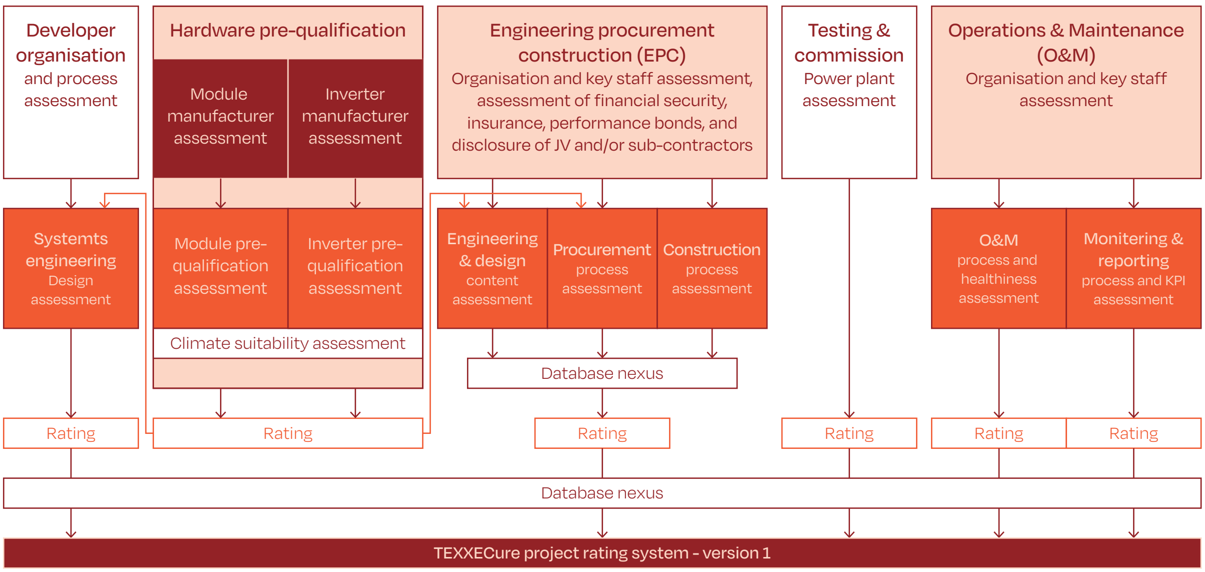
Solar PV power plant healthiness KPI

As opposed to raw data and power plant KPIs, healthiness KPI are essential to provide an overview of the physical status of a PV power plant. Healthiness KPI can be established following physical third-party reviews verifying and validating the physical state of a PV power plant in regular intervals. A PV power plant physical health review can include the entire system, including state of components such as e. g. modules (incl. IR measurements, EL measurements), inverters, cables, connectors, junction boxes, fixed tilt or tracked substructures, and ultimately, by connecting the information and resulting data streams from these individual items, of the entire PV power plant.

Such inspections result in KPI that can be established by using a comprehensive technical rating system. One such example is the expected upcoming IECRE rating system, of which the concept is currently in the voting process at the IEC Conformity Assessment Board (IEC CAB). A rating contains a comprehensive weighted points system to differentiate the relevance of the various check points. The result is valid for a defined period, and a re-rating can be performed in regular intervals (e. g. annually). The final points are correlated with previous rating results e. g. from the inception phase and previous (annual) assessments, and linked with a nexus by using algorithms. The results serve as an indicator of the healthiness of a PV power plant as well as of the to be expected performance related to the physical condition of a PV power plant for the released validity period. The O&M part of the rating assessment is illustrated on the righthand side of Figure 11.

Figure 11

Modular rating system schematic



Source:

10.2 O&M service provider KPIs

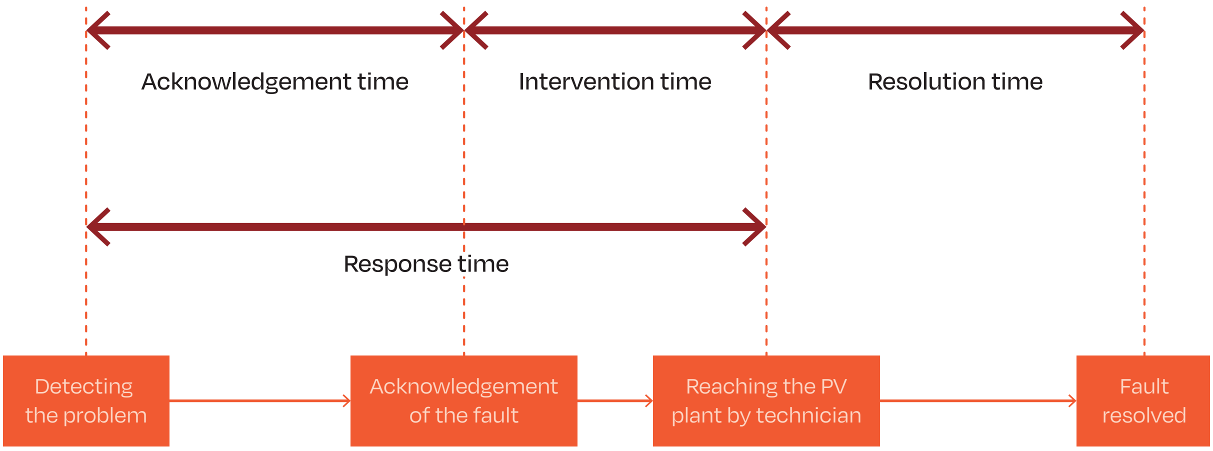
As opposed to power plant KPIs, which provide the Asset Owner with information about the performance of their asset, O&M service provider KPIs assess the performance of the O&M service.

The expected IECRE rating system outlined above is as well available for rating the O&M service provider as well as the O&M service KPI.

The following time KPIs are illustrated in Figure 12 below.

Figure 12

Acknowledgement Time, Intervention Time, Response Time, Resolution Time



Acknowledgement Time

The Acknowledgement Time (also called Reaction Time) is the time between detecting the problem (receipt of the alarm or noticing a fault) and the acknowledgement of the fault by the O&M service provider by dispatching a technician. The Acknowledgement Time reflects the O&M service provider's operational ability.

Intervention Time

The Intervention Time is the time between the acknowledgment of a fault and the arrival of a service technician or a subcontractor at the plant. Intervention Time assesses the capacity of the O&M service provider, and how fast they can mobilise and be on site. It is worth noting that, in certain cases remote repair is possible, or the O&M service provider is not able to repair the fault and third-party involvement is necessary.

Response Time

The Response Time is the Acknowledgement Time plus the Intervention time. Used for contractual purposes, minimum Response Times are guaranteed based on fault classes, classified on the basis of the unavailable power, the consequent potential loss of energy generation, and the relevance of the failure in terms of their safety impact.

Resolution Time

Resolution Time (or Repair Time) is the time taken to resolve a fault, starting from arrival at the solar PV power plant. Resolution Time is generally not guaranteed as resolution often does not fully controlled by the O&M service provider.

Reporting

It is very important for the O&M service provider to comply with reporting requirements and reporting timelines. The Asset Owner may only obtain operational updates from the plant through this reporting, and therefore this is a major contribution to assessing the performance of the O&M contractor. Content and timing of the reporting is generally agreed by the parties in the Contract agreement. Content of the reporting is expected to be consistent and any change in content or format needs to be explained by the O&M service provider. Delivery of reports per the agreed upon timeline is an important indicator for reliability and process adherence within the O&M service provider's organisation. For more information see Chapter 6.1 in Solarpower Europe's report *Asset Management Best Practices Guidelines V.2* (www.solarpowereurope.org).

O&M service provider experience

Experience of the O&M service provider with solar PV power plants in a particular country, region, grid environment and/or with solar PV power plants equipped with certain technology or size can play an important role. This is relevant for the selection of the O&M service provider and can be tracked by the Owner over time (track record).

Schedule Attainment

Schedule Attainment (or Schedule Compliance) is the ability of the O&M service provider to execute the Preventive Maintenance schedule within the required timeframes (typically across a period of a week or month).

O&M service providers who adhere to the schedule ensure accomplishing as much preventive maintenance and other timely corrective work as possible. Schedule Attainment provides a measure of accountability.

Low Schedule Attainment can provide key warning signs to the Asset Owner regarding the O&M service provider:

- That preventive maintenance is not done which will lead to equipment failures over time
- The O&M service provider might not have sufficient numbers of qualified technical staff to performance maintenance
- The O&M service provider systems such as the management of stores and spares, procurement processes are not effective
- There may be high levels of corrective maintenance work – which could be due to unsolved technical issues
- Notifying proactively and providing remediation plans to the technical asset manager in times of low schedule attainment will contribute in managing expectations.

Best practice

requires > 90%, based on the following formula:

$$\text{Schedule Attainment} = \frac{\text{Number of completed schedules in the period}}{\text{Total number of schedules for the period}} \times 100$$

Preventive vs. Corrective Maintenance ratio

This metric measures the reactive nature of the plant maintenance work. Asset Owners and AMs prefer a higher proportion of Preventive maintenance than Corrective Maintenance. This indicator is based on the actual hours technicians spend on jobs. The actual hours are measured regardless of the originally estimated hours of the planners.

When the O&M service provider has control over the equipment, the O&M service provider decides when to take certain actions to preserve equipment. When the equipment has control over the O&M service provider, the equipment drives the efforts of maintenance. A more reactive plant environment has more circumstances of the equipment experiencing problems and causing the O&M service provider to break the weekly schedule. A more proactive one experiences few circumstances of sudden equipment problems interrupting scheduled work.

Best practice requires that the ratio of Preventive vs. Corrective Maintenance is 80/20.

10.3 Solar PV power plant/O&M service provider KPIs

Contractual Availability

Contractual Availability is Technical Availability with certain contractually agreed exclusion factors (see below) applied in the calculation; It is used as a basis for evaluating the general Contractual Availability guarantees provided by the O&M service provider and included in the O&M Contract. A best practice is a Minimum Guaranteed Contractual Availability of 98% over a year. (For more details on Availability guarantee provided by the O&M service provider, see *Section Availability Guarantee*).

Contractual Availability is the parameter that represents the time in which the plant is operating over the total possible time it is able to operate, taking into account the number of hours the plant is not operating for reasons contractually not attributable to the O&M service provider (listed below in the same section).

Contractual Availability
is therefore defined and calculated as:

$$A_c = \frac{T_{useful} - T_{down} + T_{excluded}}{T_{useful}} \times 100$$

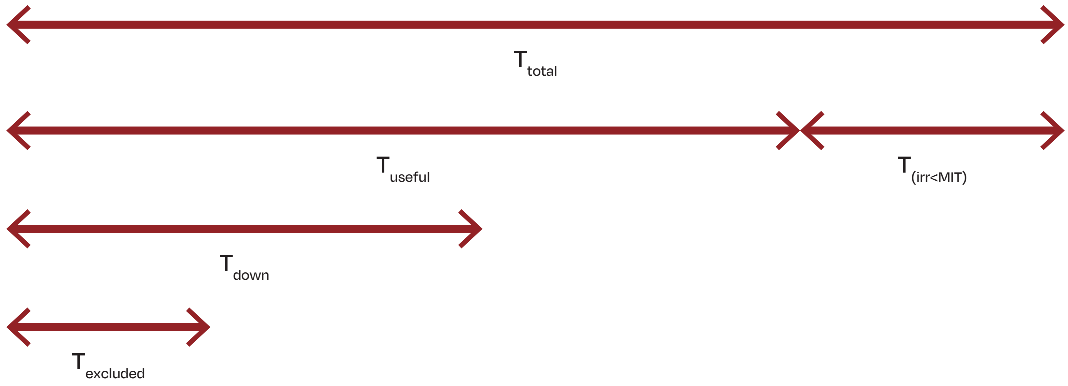
Where:

- A_c = Contractual Availability (%)
- T_{useful} = period of time with in-plane irradiation above MIT (h)
- T_{down} = period of T_{useful} when the system is down (no production) (h)
- $T_{excluded}$ = part of T_{down} to be excluded because of presence of an exclusion factor (see below) (h)

Figure 13 on the following page illustrates the various periods in time mentioned above.

Figure 13

Various periods of time for the calculation of Contractual Availability[7]



Like Technical Availability, Contractual Availability is also calculated for irradiance levels above the MIT and measured at inverter level. Individual inverters' Contractual Availabilities AC_k should be weighted according to their respective installed DC power P_k. In this case the Contractual Availability of the total solar PV power plant $A_{c\ total}$ with an installed total DC power of P_0 can be defined as show in the box below.

Contractual Availability

weighted by individual inverters' installed DC power:

$$A_{c\ total} = 100 \times \sum (A_{c\ k} \times \frac{P_k}{P_0})$$

Where:

- $A_{c\ total}$ = Contractual Availability of the plant (%)
- $A_{c\ k}$ = Contractual Availability of the inverter *k*
- P_k = Installed DC power of the inverter *k*
- P_0 = Plant Peak DC power (nominal power) (kW_p)

For the calculation of Contractual Availability, typically up to 15 minutes of irradiation and power production data should be taken as a basis if granularity of components remains at the level of inverter or higher. Anything below the level of inverter is then captured with the PR calculation presented earlier.

As Contractual Availability is used for contractual purposes, any failure time should only begin to run when the O&M service provider receives the error message. If the data connection to the site was not available due to an external issue that is beyond the O&M service provider's responsibility, failure time should only begin after re-establishment of the link. However, if the data connection was lost due to the unavailability of the monitoring system, the failure time should count. In general, the O&M service provider should immediately look at the root cause of the communication loss and resolve it.

7 The T_{down} represents the whole downtime, before the exclusions are applied. Therefore, $T_{excluded}$ is a part of T_{down} in the diagram. In practice you often first see that a plant is down (= measurement of T_{down}) and only in the course of troubleshooting one gets the information whether you can exclude part of the downtime.

The Asset Owner and the O&M service provider should agree on certain failure situations that are not included **(exclusion factors)** in the calculation of Contractual Availability. Evidence should be provided by the O&M service provider for any exclusion factor and the reason for excluding the event must not be due to an O&M service provider fault. Some good examples for exclusion factors are:

- Force majeure
- Snow and ice on the solar PV modules
- Damage to the solar PV power plant (including the cables up to the feed-in point) by the customer or third parties who are not sub-contractors of O&M service provider, including, but not limited to, vandalism
- Disconnection or reduction of energy generation by the customer or as a result of an order issued to the customer by a court or public authority
- Operational disruption by grid disconnections or disruptions caused by the grid operator
- Disconnections or power regulation by the grid operator or their control devices
- Downtimes resulting from failures of the inverter or MV voltage components (for example, transformer, switchgear), if this requires
  - Technical support of the manufacturer and/or
  - Logistical support (for example supply of spare parts) by the manufacturer
- Outages of the communication system due to an external issue that is beyond the O&M service provider's responsibility. Any failure time only begins to run when the O&M service provider receives the error message. If the data connection to the site was not available, failure time shall only begin after re-establishment of the link
- Delays of approval by the customer to conduct necessary works
- Downtimes for implementation of measures to improve the solar PV power plant, if this is agreed between the parties
- Downtimes caused by the fact that the customer has commissioned third parties with the implementation of technical work on the solar PV power plant
- Downtimes caused by Serial Defects on Plant components
- Depending on the O&M contract, time spent waiting for some spare parts to arrive can be excluded from the calculation of Contractual Availability. However, this is not considered a best practice

Contractual Tracker Availability

Like Contractual Availability, Contractual Tracker Availability also makes allowance for pre-defined exclusions, like maintenance, panel cleaning, etc. A similar formula is used to the technical availability with provision made for any predefined contractual exclusions (see above). The formula can be seen in the box on the following page.

Contractual Availability
is therefore defined and calculated as:

$$A_{c\ tracker} = \frac{T_{t\ useful} - T_{t\ down} + T_{t\ excluded}}{T_{t\ useful}} \times 100$$

Where:

- $A_{t\ tracker}$ = Technical Tracker Availability (%)
- $T_{t\ down}$ = Period when the tracker is down (h)
- $T_{t\ useful}$ = Period when the tracker is functional (h)
- $T_{t\ excluded}$ = part of $T_{t\ down}$ to be excluded because of presence of an exclusion factor (see above) (h)

Energy-based Availability

Energy-based Availability takes into consideration that an hour in a period of high irradiance is more valuable than in a period of low irradiance. Therefore, its calculation uses energy (and lost energy), instead of time, for its basis:

Energy-based Availability
is defined as:

$$A_{e\ i} = \frac{E_i}{E_i + E_{loss\ i}} \times 100$$

Where:

- $A_e(i)$ = Energy-based Availability for the period *i* (%)
- $E_{loss}(i)$ = Calculated lost energy in the period *i* (kWh)
- $E(i)$ = Plant energy production or Plant energy metered in the period *i* (kWh)

Generally, the Energy Based Availability is used within the O&M Contract in the Availability guarantee chapter and the exclusion factors defined for Contractual Availability tend to apply for Energy-based Availability too.

The following table provides an overview of different types of KPIs and their main purposes.

Table 14

Overview of different types of Key Performance Indicators and their purposes

	Solar PV Power plant KPI	O&M service provider KPI	Quantitative	Qualitative[8]	To be monitored within the O&M contract	Guaranteed in the O&M contract	Usage main purpose
Reference Yield	●	X	●	X	●	X	Useful during plant designing and economic valuation
Expected Yield	●	X	●	X	●	X	Useful during plant designing and economic valuation
Specific Yield	●	X	●	X	●	X	Useful during plant designing and economic valuation
Performance Ratio	●	X	●	X	●	X	Useful during plant life for assessing plant performance over time
Temperature-corrected Performance Ratio	●	X	●	X	●	X	Useful FAC and PAC or in other specific moment in plant life to assess plant PR starting point
Energy Performance Index	●	X	●	X	●	X	Useful during plant life for assessing plant performance over time, against plant expected performance at plant designing
Technical Availability (Uptime)	●	X	●	X	●	X	Useful during plant life for assessing how much time, during the time frame under analysis, the plant is ready to produce power
Technical Tracker Availability (Tracker Uptime)	●	X	●	X	●	X	Useful during plant life for assessing how much time, during the time frame under analysis, the trackers are functioning properly
Acknowledge-ment Time	X	●	●	X	●	●	Useful during plant operation for assessing readiness of the O&M service provider to "realise" (detected by the monitoring system and acknowledge by the O&M service provider) plant failures
Intervention Time	X	●	●	X	●	●	Useful during plant operation for assessing readiness of the O&M service provider to reach the plant once a failure is "realised"

8 Qualitative data is concerned with descriptions, i.e. information that can be observed but not computed (e.g. service experience). In contrast, quantitative is measured on a numerical scale (e.g. Performance Ratio).

Table 14 - continued

Overview of different types of Key Performance Indicators and their purposes

	Solar PV Power plant KPI	O&M service provider KPI	Quantitative	Qualitative	To be monitored within the O&M contract	Guaranteed in the O&M contract	Usage main purpose
Response Time	X	●	●	X	●	●	Useful during plant operation for assessing readiness of the O&M service provider from acknowledging a failure and subsequently reaching the site
Resolution Time	X	●	●	X	X	●	Useful during plant operation for assessing the time used to solve a fault from when the plant is reached
Contractual Availability	●	●	●	X	●	●	Useful during plant life for assessing how much time during the time frame under analysis, the O&M service provider keeps the plant ready to produce power
Contractual Tracker Availability	●	●	●	X	●	●	Useful during plant life for assessing how much time, during the time frame under analysis, the O&M service provider keeps the trackers functioning properly
Energy Based Availability	●	●	●	X	●	●	Useful during plant life for assessing how much energy has been lost due to causes attributable to the O&M service provider, during the time frame under analysis
Reporting	X	●	●	●	●	●	Useful during plant operation for assessing reliability of reporting services
O&M service provider experience	X	●	X	●	●	X	Useful during O&M Contract awarding/tendering for assessing O&M service provider reliability from a purely document-based analysis
Schedule Attainment	X	●	●	X	●	X	Useful during O&M Contract awarding/tendering for assessing O&M service provider reliability
Preventive vs. Corrective Maintenance ratio	X	●	●	X	●	X	Useful during O&M Contract awarding/tendering to assess O&M service provider reliability and effectiveness

Contractual Framework

This section contains a set of considerations for the contractual framework of O&M services for the utility-scale segment, and more specifically, systems above 1 MWp. A complement to the technical specifications detailed in the previous chapters, the contractual framework described in this chapter is considered best practice.

11.1 Contractual Framework

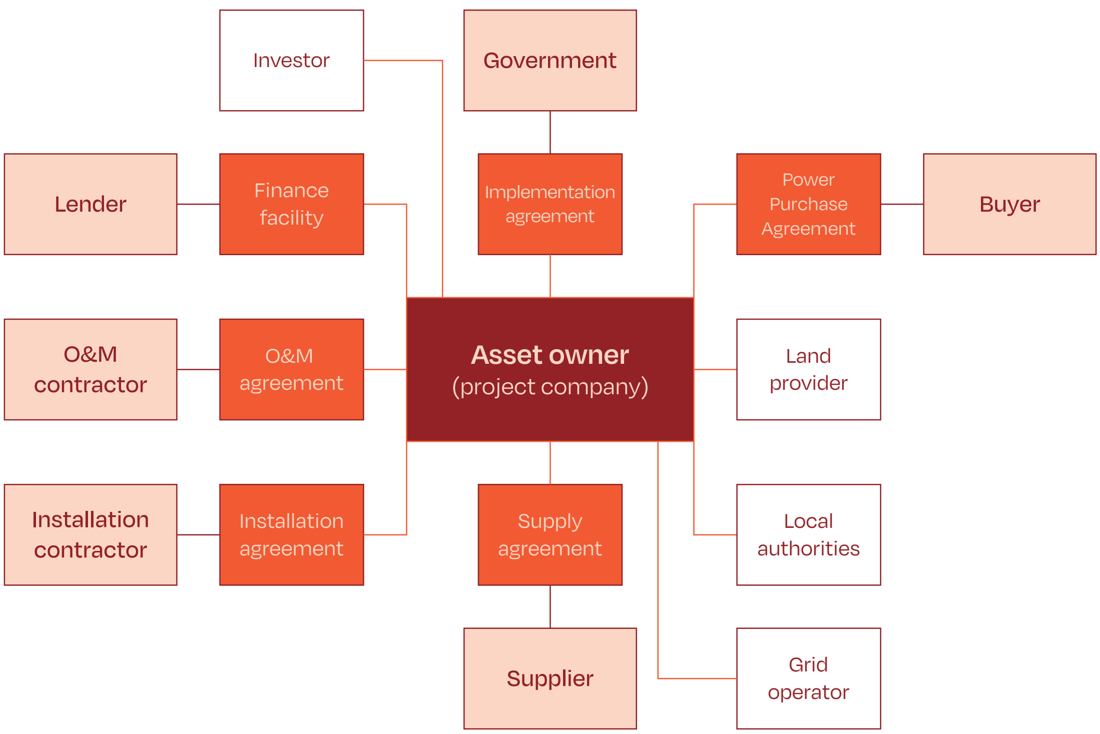
We recommend using the O&M template contract developed as part of the Open Solar Contracts suite of template contracts. Formerly known as the Global Solar Energy Standardisation Initiative (SESI) this is a joint effort of the Terrawatt Initiative and the International Renewable Energy Agency (IRENA). SolarPower Europe contributed to the drafting of the template O&M contract. There are a total of six templates in a suite of contracts, designed to be used as a package to streamline the procurement of solar projects and make it simpler to aggregate projects using standard terms. Aside from the O&M contract, the other templates include:

- Implementation Agreement
- Power Purchase Agreement
- Finance Facility Agreement term sheet
- Supply Agreement
- Installation Agreement
- Asset Management Agreement

A common contractual framework for solar PV O&M is the "fixed price" model for a specified scope of work that can include administrative, operational, and Preventive Maintenance tasks. A "cost plus" element can then be added for Corrective Maintenance or additional services. The "cost plus" element requires, labour rates, equipment markup, overheads and profits to be negotiated in the contract and added to the actual equipment costs incurred in correcting unexpected problems.

Figure 14

Overview of the six template contracts developed under the Open Solar Contracts[9] initiative



9 Copies of each contract and explanatory guidance can be found at the Open Solar Contracts website: www.opensolarcontracts.org.

11.2 Contractual Risk Allocation

The O&M contract is a project agreement between the Asset Owner and the O&M service provider for the purpose of managing, operating, and maintaining the solar PV power plant. The O&M contract, together with the EPC contract, is a key document in any project finance transaction. Its provisions should stem financial risks associated with the failure of the O&M service provider to keep the solar PV power plant operating properly. In general, an O&M contract should minimise financial risks through appropriate operational risk allocation. Financial risks posed to the Asset Owner from operational failures include (i) shortage of actual revenues in comparison with expected ones - displayed in the base case, (ii) inability of the Asset Owner to meet their debt service obligations to the lenders, (iii) Asset Owner's liabilities under other agreements with third parties, including any PPA; and ultimately, (iv) the risk of depreciation of the project assets. As for the EPC contracts, the Asset Owner may choose between entering into a fully wrapped O&M agreement, which provides the lenders with a single recourse party for fulfilment of all obligations and responsibilities in relation to the O&M of the Plant. Another option is to have several agreements that, together, cover the O&M of the plant. If some of the O&M services are allocated to third-parties under different agreements, the Asset Owner should clearly define the obligations and responsibilities of each contractual party to ensure the absence of risk allocation "gaps".

A balance between the lenders' demands and the Asset Owner's interests can be struck by aligning key clauses in the contract regarding timing, cost and quality of the works, and market standards. In this regard, the main drivers are:

- A detailed list of Ordinary and Extraordinary services to be performed by the O&M service provider, both before and after commercial operation of the project. To prevent confusion over risk allocation the operator's obligations may be defined as general performance requirements and closely linked to performance results

- Availability or Performance Guarantees: in a power project, performance requirements typically include availability, output, outages, emissions, and other performance-related standards. Penalties for non-fulfilment of the performance obligations should also be included. At their most severe, this can mean termination of the O&M contract. These performance guarantees are usually supported by Bonus Schemes and backed-up by Liquidated Damages (LDs)

- Spare Parts warranties: management and availability of spare parts is a key aspect of minimising the impact of both scheduled and unscheduled outages on the project's revenue stream

- O&M service provider's limited liability in respect of consequential loss, loss of revenue, loss of profit and other financial losses

- Incentives for the O&M on forecasting and planning outages during low radiation hours. Financial incentive and penalties can help align interests between the Asset Owners and the O&M.

11.3 Scope of the O&M contract

Services to be provided by the O&M service provider include:

Technical Asset Management (either O&M service provider or Asset Manager)

Technical asset management of a PV plant typically provides reporting to the Asset Owner through a "Monitoring Services" (as per Open Solar Contracts templates) as a key activity. This involves providing detailed reports on plant performance, evaluating the effectiveness of O&M activities, and documenting any incidents that occur.

Regulatory compliance is another cornerstone of effective TAM. This includes adhering to the legal requirements for solar PV plant operations, meeting obligations under PPAs and Interconnection Agreements, and maintaining compliance with power generation license agreements. Additionally, it involves ensuring that all necessary building and environmental permits are in orders.

Beyond these operational aspects, TAM also involves overseeing warranty management, handling insurance claims and managing various contracts.

Power Plant Operations

To ensure the smooth operation of a PV power plant, it is crucial to ensure the documentation of the plant is well managed, to be able to easily access relevant data and information to address potential issues, technical or otherwise. The supervision of the plant notably needs to make sure that there is proper monitoring and documentation of activities, deliver analysis of performance and identify areas and actions for improvements, ensure a proper detection and diagnosis of issues and faults in the various areas of the plant operation. Moreover it is crucial to ensure proper service dispatch, with relevant supervision of workers and activities. Plant supervision may also include the security monitoring interface, notably related to security systems such as cameras etc.

More generally, it is crucial for proper operation of a solar power plant to have operational and sufficient plant controls tools and instruments. Plant operators are also in charge of managing the interface with the grid operator and ensure compliance with grid codes, as well as maintenance scheduling. Moreover, they may be in charge of power generation forecasting (especially for plants not subject to feed in tariffs).

Plant operation also covers change management on the site, as well as reporting to the technical asset manager, especially in the case when the O&M service provider is not the technical asset manager of the site.

Power Plant Maintenance

Solar PV power plant Maintenance is essential to prevent cascading failures and minimise degradation over the asset operating lifetime. It may notably include:

- Preventive Maintenance (which is referred to in the Open Solar Contracts as "Scheduled Maintenance")
- Corrective Maintenance in accordance with agreed Response Time guarantees (some types of maintenance activities may be beyond the scope of the contract, for more information, see *Section 5.2. Corrective Maintenance*)
- Extraordinary Maintenance (generally not included in the O&M fixed fee but it is advisable that the O&M contract includes the rules to prepare the quotation and to execute Extraordinary Maintenance works, for more information, see *Section 5.4. Extraordinary maintenance*). In the Open Solar Contracts O&M template, this would fall within "Additional Services".

Additional maintenance services

In the Open Solar Contracts O&M template, there are also various additional "Additional Services" which are optional (see *Additional services*).

Below is a non-exhaustive list of Additional services and general market trends with regards to whether these Additional services are generally included in the O&M agreement or not.

Table 15

Examples for additional maintenance services and general market trends

	Additional services	General behaviour
Solar PV site maintenance	Module cleaning	Generally included, or as a priced option
	Vegetation management	Generally included, but need to specify perimetral vegetation management and management of possible environmental compensation measures
	Snow or sand removal	Generally, not included and also generally not easy to provide
General site maintenance	Pest control	Generally included
	Waste disposal	Generally included with reference to waste generated during O&M activities
	Road management	Generally not included
	Perimeter fencing repair	Generally not included and often caused by force majeure (i.e.: theft)
	Maintenance of buildings	Generally not included
	Maintenance of Security Equipment	Generally not included, these activities are performed by a separate surveillance and security provider in order to have clearly defined responsibilities (see *Section Power plant security*)
On-site measurement	Meter weekly/monthly readings	Generally included since it feeds the periodic performance reporting to the Asset Owner. However, these readings are now generally automated from the site SCADA system
	Data entry on fiscal registers or in authority web portals for FIT tariff assessment (where applicable)	Generally this activity is the responsibility of the AM. However, it can be included in O&M scope of work
	String measurements – to the extent exceeding the agreed level of Preventive Maintenance	Generally not included but a price could be agreed in advance in the O&M contract
	Thermal inspections – to the extent exceeding the agreed level of Preventive Maintenance	Generally not included but a price could be agreed in advance in the O&M contract

All the services not included in the scope and in the fixed fee such as Extraordinary Maintenance (See *Section 5.4 Extraordinary Maintenance*) and Additional services (See *Section 5.1 Additional services*) should be regulated within the contract. A dedicated clause should indicate the procedure and should include: (i) a proposal by the O&M service provider within a fixed time frame, (ii) a fixed period for the Asset Owner to accept it or request modification, (iii) a final approval. Pre-agreed tariffs for personnel, machinery renting etc. could be agreed and a specific table could be attached as Contract Annex. This is provided for in the Open Solar Contract O&M template, with reference to "Standard Rates", which can be pre-agreed for Additional services.

Spare Parts Management

Contracts for operation and maintenance typically include various provisions on spare parts, considering there is a continuous need for monitoring, update and replacement of components in PV systems. These notably cover: spare parts maintenance, replenishment and storage (which is an optional in O&M contracts). For more information on this specific items, please view the respective sections and chapters of the present Guidelines (see *Chapter 8. Spare Parts Management*).

O&M contract fee

As a best practice, O&M services should be provided on a fixed fee plus escalation basis. See the section *Spare Parts Management* further on in this chapter which discusses how spare parts management may impact on the contract fee.

Contractual guarantees and price adjustments

Although some O&M service providers still provide PR guarantees, recent developments, including the recommendations of the Open Solar Contracts initiative, show that eliminating PR guarantees and only using Availability guarantees and Response Time price adjustments has several advantages.

PR is to a large extent a result of equipment choice, design and construction, over which a (third-party) O&M service provider has little influence, beyond vegetation control and module cleaning. Moreover, removing PR as an O&M service provider KPI makes power plant handover between EPC and O&M service providers or between O&M service providers simpler. Generally, the PR warranties are applied on projects where the O&M and EPC service providers are the same company (or an affiliate). Here the O&M service provider carries forward the risk of the technology made by its sister company.

Availability guarantees and Response Time price adjustments protects Asset Owners from poor performance on the part of O&M service providers. Availability is the KPI that best reflects an O&M service provider's service. Thanks to the Response Time price adjustment, the O&M service provider has to intervene within a pre-agreed timeframe (dependant on the fault) when events that effect plant performance are not covered by the Availability guarantee. Moreover, the O&M service provider is obliged to intervene during incidents that do not affect performance, referring to good industry practices in general. A further upside is that it makes the transition to a new O&M service provider much smoother and allows Lenders and Owners to pick a service provider based solely on of quality of services. Availability guarantees and Response Time price adjustments avoid burdensome change management processes resulting from the need to recalculate the guaranteed PRon the event of a plant handover.

PR warranties are no longer standard in the independent/third-party O&M market. However, it is possible to set a PR target that, if not fulfilled, can trigger a joint analysis between the Asset Owner and the O&M service provider, to identify causes and agree on possible corrective actions, including revamping projects.

Availability guarantee

A best practice is a Minimum Guaranteed Contractual Availability of 99%+ over a year at least at inverter level. In certain jurisdictions, such as in Mexico, where labour legislation and the requirements of the network operator stipulate the presence of full-time technical staff on-site, a Minimum Guaranteed Availability of 99% can be provided. This should be reflected in the O&M agreement's price.

For contractual KPI reasons, Availability should be calculated at inverter level, on an annual basis. For more information on this, see *Section Contractual Availability.*

The Availability achieved by the O&M service provider is translated into Bonus Schemes and LDs. For more information on this, see *Section Bonus Schemes and Liquidated Damages (LDs).*

Response Time price adjustment

The O&M service provider should be obliged to react to alarms received from the plant within a certain period, 7 days a week. This translates in a minimum guaranteed Response Time with the consequence of an adjustment to the contract price (the O&M fee) payable to the O&M service provider in the event of failure to meet the Response Times. For a definition of Response Time, see *Section Response Time.*

When setting a Response Time price adjustment, periods with high and low irradiance levels, and fault classes should be differentiated. This accounts for the (potential) loss of energy generation capacity or relevance in terms of safety impact of the failure.

An example for response times according to fault classes can be seen below in Table 16.

Table 16

Examples for Fault classes and corresponding minimum Response Times.

Fault class	Fault class definition	Response time guarantee
Fault class 1	The entire plant is off, 100% power loss	4 daytime hours
Fault class 2	More than 30% power loss or more than 300 kW_p down	24 hours
Fault class 3	0%-30% power loss	36 hours

Note: Fault classes and the corresponding Response Time guarantees applied even if the duration of the respective power loss is less than the corresponding Response Time guarantee, provided that the power loss may occur again

In case an equipment replacement is needed, the O&M service provider should commit to doing this within 8 business hours from the end of the Response Time, if the spare part is included in the portfolio of minimum spare parts list. If the spare part is not included in the minimum spare parts list, the O&M service provider should commit to ordering the spare part within 8 business hours from the end of the Response Time and to carrying out the replacement as soon as possible.

In case the fault cannot be fixed by the O&M service provider and the equipment supplier's intervention is required, the following actions are necessary:

- If the intervention requires spare parts beneath the O&M cost responsibility (see *Section Spare Parts Management*), the O&M service provider may proceed without separate approval (insurance aspects to be considered)

- If the costs exceed the budget limit mentioned above, the O&M service provider should communicate the issue in writing to the Asset Owner within 8 business hours from the end of the Response Time

Force Majeure events are excluded from Response Time obligations.

In the Open Solar Contracts O&M template, failure to comply with a Response Time guarantee by more than five business days entitles an Asset Owner to terminate the O&M contract.

Bonus Schemes and Liquidated Damages (LDs)

The Availability guarantees provided by the O&M service provider can be translated into Bonus Schemes and LDs. The Bonus Scheme concept is referred to in the Open Solar Contract O&M template as the "Availability Bonus". These ensure that the Asset Owner is compensated for losses due to lower-than-guaranteed Availability and that the O&M service provider is motivated to improve their service to achieve higher Availability. Higher Availability usually leads to higher power generation and an increase of revenues for the Owner. Hence, the Bonus Scheme agreements lead to a win-win situation for both parties and ensures that the O&M service provider is highly motivated. The Open Solar Contracts O&M template provides for a list of "Excusable Events".

Since the O&M service provider's responsibility are the O&M works for the solar PV asset, they should be exempted from other influencing factors like force majeure events, grid operator activities to reduce the plant output, grid instability, or offline periods, and any related LDs. (See exclusion factors in the section *Contractual Availability*)

An example for Availability Bonus Schemes and LDs can be found below:

- Bonus Schemes: if the measured availability exceeds the Minimum Guaranteed Availability, the additional revenue will be divided between the Asset Owner and the O&M service provider per previously agreed shares. In this case additional revenue should be calculated against the expected annual revenue in the base case scenario. Targets for overall plant production constitute minimum thresholds for bonuses

- Liquidated Damages: if the Minimum Guaranteed Availability is less than the measured availability, all the revenue lost due to the availability shortfall should be reimbursed to the Asset Owner by the O&M service provider. In this case revenue lost should be calculated against the expected annual revenue in the base case scenario. This is usually invoiced by the Asset Owner to the O&M service provider

- Bonuses can be offset against LDs and vice versa

- The amount of yearly LDs should be capped at 100% of the O&M annual fee. Reaching this cap usually results in termination rights for the Asset Owner and the O&M service provider. In the Open Solar Contracts O&M template, the right is only given to the Asset Owner

Service standards

The O&M service provider must act in accordance with all laws, authorisations, good industry practice, planning consents, manufacturer's warranties and operating manuals, and to the standard of a reasonable and prudent operator. Compliance with adequate H&S standards, is also a critical requirement and expectation within the standard of the services.

The Asset Owner should be entitled to instruct a third-party to provide any services that the O&M service provider cannot at the O&M service provider's cost. This entitlement should only be triggered if the O&M service provider fails to follow a corrective maintenance programme.

O&M service providers' qualification

The O&M service provider must have the means, skills and capabilities to operate and maintain the plant in accordance with the contractual obligations. Experience and professionalism, H&S capabilities, skilled teams, and access to spare parts are criteria for the selection of the O&M service provider. As O&M services are a combination of remote operations services and local maintenance activities, the Asset Owner should make sure that both components are well managed and interfaces between the two are well defined. This is especially important should the O&M service provider subcontract any aspect of the work, as each entity will need to be held accountable for the overall O&M performance.

Responsibility and accountability

The responsibility of the O&M service provider is usually defined in the Scope of work, which forms a part of the O&M contract. In the Open Solar Contract O&M template, this is set out in the O&M Services Schedule. A detailed description of the O&M scope items ensure clarity on what the O&M service provider will do during the term of the contract. In addition to the Scope of work, the Annual Maintenance Plan (AMP) and Annual Maintenance Schedule (AMS) (please refer to attachment "Annual Maintenance Plan") outline the granularity and frequency of (predominantly) Preventive Maintenance works. The execution of the activities should be regularly reported to the Asset Owner– this forms the minimum requirements. Best practice in reporting is to compare the executed activities with the AMP and AMS, and outlines deviations and reasoning.

Corrective Maintenance activities performed in cases of component failure or energy generation shortfall, are controlled by performance commitments signed by the O&M service provider. In the Open Solar Contracts O&M template, these are set out as "Corrective Maintenance Services".

Moreover, the Availability Guarantee and Response Time price adjustment explained in *Section Contractual Guarantees and price adjustments* of the present chapter also represent a level of accountability for the O&M service provider.

In most countries there are strict legal requirements for security service providers. Therefore, solar PV power plant security should be ensured by specialised security service providers, directly contracted by the Asset Owner or, exceptionally, subcontracted by the O&M service provider. The security service provider should also assume liability for the services provided. For more information on this, see *Section Power plant security.*

Spare Parts Management

The Open Solar Contracts O&M template takes two approaches to Spare Parts management. Either the O&M service provider takes full responsibility for Spare Parts or there is a distinction between "Included Spare Parts" (included in the O&M service provider's fee), and "Excluded Spare Parts" (payable in addition to the O&M service provider's fee within a pre-agreed margin). In either case, replenishing Spare Parts stock will be the O&M service provider's responsibility, although at the Asset Owner's cost in relation to Excluded Spare Parts. This guidance considers it best practice to take the second approach of clearly identifying Included and Excluded Spare Parts, in order to find an appropriate balance between the amount of risk that the Asset Owner is willing to accept against the cost of the O&M fee.

There should be a component, materials, and spare parts defects warranty for 12 months from the date of installation, which should continue to apply even after expiry or termination of the O&M contract.

For more information on Spare Parts Management, see the *Chapter 8. Spare Parts Management*.

Power plant remote monitoring

The O&M service provider should operate and maintain the metering system according to local regulations and norms. In some countries there are two metering systems: one that measures power injection in the grid, owned and operated by the grid operator, and one that measures power production, owned by the Asset Owner and operated by the O&M service provider.

The O&M service provider will also make sure that performance monitoring and reporting is operated and maintained according to the monitoring specifications and best practices (see *Chapter 9. Data and Monitoring Requirements*).

The Asset Owner has the right to carry out the verification of the metering system to evaluate and control the exactness of the measured data.

Reporting

Reporting should be done periodically, as contractually agreed between the O&M service provider (the Technical Asset Manager) and the Asset Owner. The Asset Owner should have the right to contest the report within a certain timeframe.

For more information on industry best practices regarding reporting, see SolarPower Europe's report *Asset Management Best Practices Guidelines V.2* at (*www.solarpowereurope.org*).

Innovations and Trends

O&M service providers face growing pressure to increase efficiency while reducing human intervention. Key trends include the use of data-driven techniques, Industry 4.0 solutions, and robotics, such as drones, to streamline operations. Innovative practices leverage data from both field experience and monitoring, feeding into digital platforms or digital twins to support decision-making. The rise of AI and language-based models is automating analysis and reporting, saving valuable time. Additionally, with the increasing frequency of severe weather events, tailored planning and mitigation measures are essential. This chapter highlights important technologies being developed, some close to mainstream adoption, others still in early stages.

O&M service providers are under increasing pressure to do more with less. Increasing human resource efficiency through the use of data-driven and Industry 4.0 techniques are key themes for O&M as the industry works to reduce the number of human interventions and embraces digitisation. New trends include more and more the use of robotic solutions with a new wave of in field robotics to integrate the work carried out by the use of drones. Innovative O&M practices will include data-driven measures coming from both field experience and monitoring. All of the information collected along the whole value chain, must be streamlined into digital platforms (or digital twins) in order to avoid information loss that can act as decision support system for the best actions to follow in case of deviations. Processes are aided by the incredible acceleration we have seen in the use of AI introducing language-based models that will free valuable time in terms of automated analysis, actions, reporting, etc. Finally, severe weather events are increasing in frequency and bespoke planning, and dedicated mitigation measures must be put in place.

The following chapter lists important technology areas being developed by several innovative industry service providers. Many of these new technologies are becoming close to mainstream adoption, others are in early-stage development.

Drone in a box

Purpose and description

A "drone in a box" system for solar PV involves an autonomous drone that resides in a secure, weather-resistant docking station when not in use. These systems are designed for automated deployment, operation, and data collection, requiring minimal human intervention. Equipped with advanced sensors, these drones can perform various tasks like thermal imaging for fault detection, visual inspections for cleanliness or damage, and even monitoring vegetation growth near panels. The "box" serves as a charging station and a safe storage unit, enabling frequent, programmed flights to optimise operations and maintenance efficiency on large solar farms.

State of play

The "drone-in-a-box" system for solar PV operations is gaining traction as a cutting-edge solution for automated inspections and monitoring. While regulatory challenges, such as BVLOS operation restrictions persist, ongoing legislative progress and advancements in solar-powered docking stations are enhancing their feasibility. Despite high initial costs, their potential for ROI through operational efficiency makes them a promising technology for the solar industry.

In field robotic solutions

Purpose and description

Field inspection is typically carried out manually and is time consuming, preventing the deployment of novel characterisation techniques in a cost-effective way. Using aerial inspection increases throughput, however in some cases this is impeded due to restrictions and current legislation which requires the presence of a pilot. In addition to this, aerial inspections cannot visualise faults such as loose/faulty bypass diodes or connectors, or back sheet cracking/chalking, as they are located on the underside of the modules. In field robotic solutions can have a multipurpose: continuous field inspection, check as built vs. drawings, etc.

State of play

In field robotic solutions are coming to the market, starting from the inclusion of sensing solutions in cleaning robots/mowing robots. Rovers are being developed to transfer the cleaning robots from one array to another and while not used as a carrier, they can provide services such as continuous field inspection.

Photoluminescence

Purpose and description

Daylight photoluminescence (DPL) is a relatively novel imaging technique utilised in photovoltaic (PV) system inspection, using the sun as excitation source. Filtering the luminescence signal from the strong sun irradiation is its main challenge. Images acquired at two different operating points (OPs) of the module, allow the subtraction of the background radiation while maintaining the luminescence signal. To avoid strong variation in the sunlight conditions, images of these two operating points (OPs) must be taken within a short time interval, and to decrease noise, several images of each OP must be taken and averaged. Contrary to EL, PL does not require cables disconnection.

State of play

Different methods have been developed to switch between the two different OPs of a PV module. Recently, researchers have focused on inverters' features that allow for an automatic switching. For example, in the project TRUST-PV, a DPL-ready inverter has been developed with the capability of toggling between manually selectable OPs of connected PV modules. The synchronisation of image acquisition and OP switching becomes particularly challenging if the camera is applied to unmanned aerial vehicles. To overcome this challenge, algorithms are developed to identify OP switches in a set of images taken in the field by investigating image intensities. The integration of PL in field robotics is currently ongoing, for example in the Horizon Europe project SUPERNOVA.

UV Fluorescence imaging

Purpose & Description

UV-Fluorescence imaging is a non-destructive imaging technique for failure analysis of solar PV-modules. The development of the technique started around 2010 with first publications in 2012 (Köngtes et al., 2012; Schlothauer et al., 2012; Eder et al., 2017; Muehleisen et al., 2018).

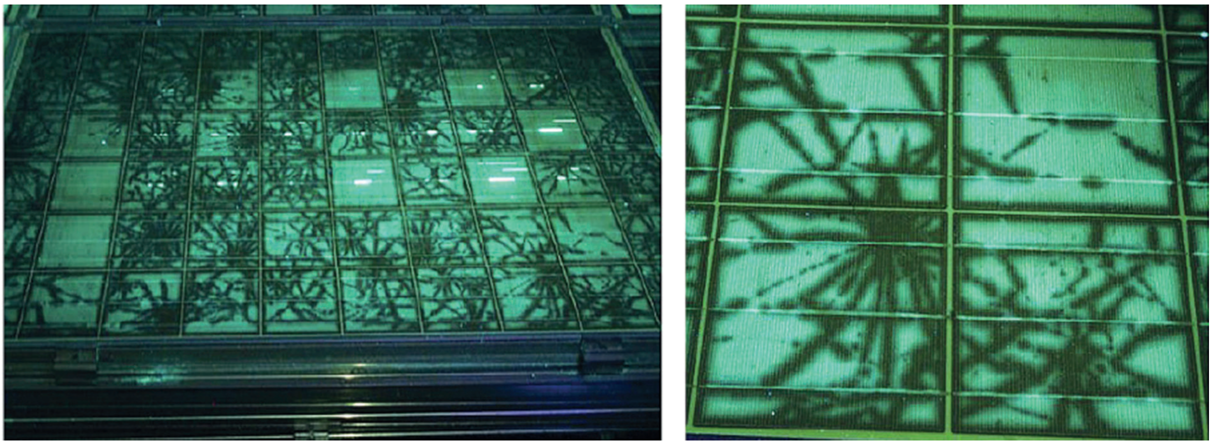
UV-Fluorescence measurements must be performed in a dark environment (typically at night) by illuminating the solar PV-modules with UV-light (<400nm). Most encapsulants show fluorescence in the visible region and thus the material's response can be captured with a photographic camera. Modules do not need to be disconnected or powered during this procedure.

The observed fluorescence of the encapsulation above the cells with respect to (i) spatial distribution, (ii) intensity and (iii) spectral shift of the fluorescent light is dependent on operation time in the field, climatic conditions, and the type of encapsulant and backsheet used. Furthermore, the fluorescence signal depends on the type of defect (micro cracks in c-Si cells, hotspots, or glass breakage).

Imaging of solar PV modules typically takes less than 60 seconds. An example of UV-fluorescence is given in Figure 15. The advantages of the technique are that no modifications are necessary to the solar PV systems and, when used in combination with EL, an evaluation of timelines for various instances of damage becomes possible as the fluorescence signal is a function of time. New cracks for instance are only visible in EL because there was no time to "bleach" the fluorescence signal.

Figure 15

Example UV-Fluorescence images after a severe hailstorm



Source: Taken from W. Muehleisen (2018)

State of Play

There are several things to consider when performing drone-based UV Fluorescence (UVF) Imaging inspections. The cost of drones and trained pilots can be a prohibitive factor in using UVF technology. Similarly, conditions must be stable enough to take images in the dark with a 0.1 second exposure time and the drone needs to be powerful enough to support the extra weight of a camera and a UV lamp.

A minimum of two trained people are required for a UVF inspection, one being the pilot and the other being the photographer. The extra weight of the camera and the UV lamp on the drone means that batteries drain quicker and poses limits on inspections. These constraints are increased further by the UV lamp drawing power from the battery as well. This means that a 4.5 Ah battery can provide a flight time of 8-10 minutes. Moreover, the drone's flight path must be relatively low to be able to capture quality images.

Estimates predict that it is possible to inspect 720 modules per hour (including time for six battery changes) if conditions are perfect. However, there are several other factors that can affect inspection time, such as project design and weather conditions. To be most effective UVF inspections must be done in the dark and in calm conditions, both of which are far from guaranteed. Working in the dark risks damage to the drone from increased operating difficulty, secondly finding staff willing to work at night comes with added costs to the project (paying overtime or taking on more staff). Moreover, new modules with UVA transparent EVA technology reduce the effectiveness of drone based UVF inspection. Despite these drawbacks, using drones to perform UVF inspections can save time, particularly when inspecting rooftop installations as staff do not need to get up onto roofs.

As this technology is still emerging, many O&M service providers lack the in-house expertise to interpret the findings of UVF inspections. This adds an extra layer of cost to the process and has prevented the technology being mainstreamed for solar PV power plant inspection.

Predictive Maintenance for optimised hardware replacement

Purpose and description

Preventive Maintenance occurs periodically according to contractually agreed schedules and based on expert knowledge. In addition, Preventive Maintenance may be scheduled when the operator identifies an unexpected deviation in performance through the monitoring system. Different maintenance optimisation models are employed to find the optimal cost to benefit balance between maintenance interventions. These models count on the probability of failure of each component of the solar PV system and the impact of that failure on the entire system. For example, the actual lifetime of solar PV inverters under different operating conditions is still uncertain. In practice, inverters will not fail in a predictable way, after a certain period of time, as usually modelled in business plans. Moreover, failure-based maintenance i.e., replacing inverters as they fail may not be the most efficient solution.

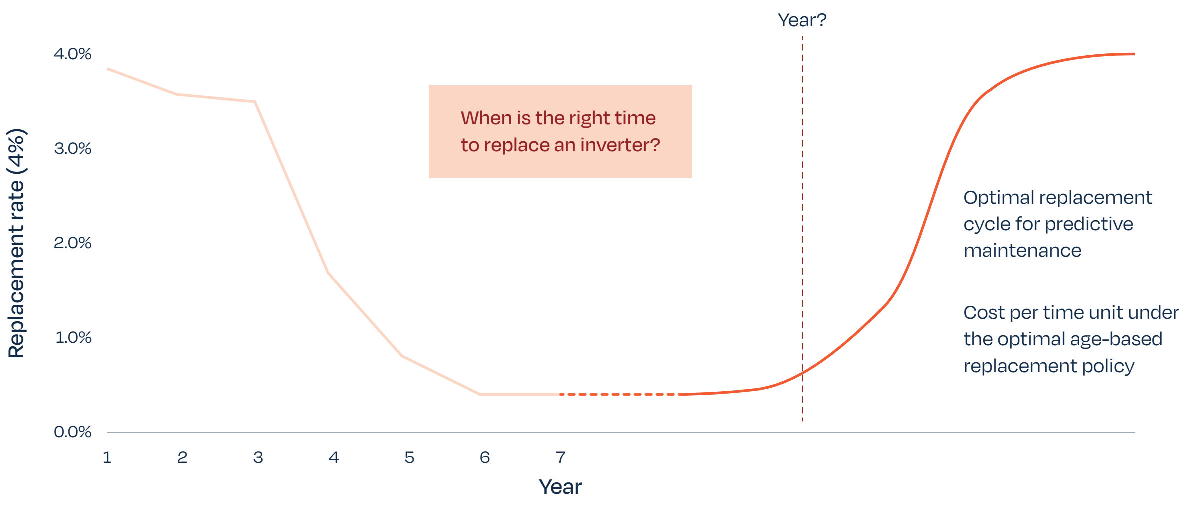
A good predictive monitoring system could help with assessing the optimal hardware replacement cycle by modelling the uncertainty in the time-to-failure with a known probability distribution function. Maintenance optimisation models use the output of root cause analyses and remaining useful lifetime analyses to predict future asset failures. This can be used to optimise planning of maintenance and related resource allocation.

Big data analytics can bring added value at any stage of O&M objectives: analysis from observation of collected information, fault detection, fault diagnosis, and optimisation through recommendations issued from the advanced monitoring system. Today different approaches are proposed. Whereas classic Artificial Intelligence (AI) proposes an advanced diagnostic through knowledge-based models, unsupervised and supervised learning methods offer different approaches (e.g. neural networks) using statistics.

The advantages of these Predictive Maintenance optimisation models are that they lower the cost of maintenance by scheduling it more effectively. The diagnostic element of the models also helps to reduce plant downtime. However, the methods are sensitive to device models and brands, making them hard to generalise.

Figure 16

Predictive maintenance for optimised hardware replacement



Source: Achim Woyte, 3E

State of play

Today, no model has been proven to be completely reliable. Big-data analysis allows easy recognition of a fault and, in some cases, provides a clear diagnosis and recommendations on the short-term actions to take to avoid probable upcoming issues. The trend is to model the behaviour of the entire system and to plan optimal maintenance and hardware replacement programmes in the medium to long-term. This will of course reduce the overall risk of a solar PV project and, increase investment attractiveness.

Augmented Reality | Smart Glasses

Purpose and Description

Virtual or augmented reality refers to digital elements of interactions using cameras on e.g. smartphones, tablets, or special devices such as smart glasses. Specifically, virtual reality is a computer-generated simulation of a three-dimensional environment that can be interacted with by a person using special electronic equipment. Augmented reality refers to an enhanced version of the real world achieved through using digital elements. For the sake of simplification, the term augmented reality is used in the following referring to the use of smart glasses in O&M.

O&M service providers and their operations teams face the recurring challenge of working with a considerable variety of hardware and software from different manufacturers at various sites (at sometimes remote locations). This heterogeneity requires broad knowledge, skill transfer, and good cross-departmental communication. New technologies based on augmented reality can support O&M service providers with these challenges by easing the collaboration between offices and field engineers.

Corresponding software applications combined with smart glasses enable users to interact visually and acoustically to support works on site. The field engineer using the smart glasses is connected to a supervising (desktop) user who will be able to guide them through working steps, using the desktop version of the respective software. The smart glasses user is connected to the supervisory user via an integrated headset. Visually, conditions on site are recorded by an integrated camera. The recordings are then displayed live for the supervisory user who can add explanatory diagrams, screenshots, comments, etc. These additions are then displayed on the lens of the smart glasses. This ensures secure working in line with common H&S requirements (hands free) while the field engineer is guided through working procedures. Furthermore, holograms can be used to enable access to animated maintenance instructions.

State of Play

Smart glasses and corresponding software solutions are becoming more popular in the O&M segment. Decreasing price levels for O&M services require improved service/cost efficiency. Augmented reality can support O&M service providers ‘operations by easing skills and information transfer and ad hoc solutions which can positively affect service efficiency.

There are many advantages to this technology, including: increased efficiency in O&M service provision; more fluid knowledge transfer between senior and junior colleagues; and effective upskilling of O&M personnel, resulting in fewer resourcing challenges and generating savings on internal costs for O&M service providers.

However, there are still limitations on the technology’s usefulness. A stable internet connection is required to maintain contact between the field engineer and the supervisor. This can be problematic for solar PV power plants in more remote locations. At present the technology is also expensive. However, as it becomes more mainstreamed, cost competitiveness should improve.

Internet of Things (IoT) and auto-configuration

Purpose and description

Internet of Things (IoT) in solar PV systems represents an interoperability environment where all devices in the field are connected to each other and show themselves as available to be connected to the system. This can improve integrated, secure communication and efficiency. Each connecting device should provide the following information:

- Device parameters (brand, type, Serial Number, internal datasheet specifications)
- Device status and conditions (operational status, temperature, etc.)
- Connection with other devices & mapping (strings connected, inverter, sensor position, etc.)
- Any other relevant information

Standardisation efforts (e.g. SunSpec Alliance's Orange Button initiative) are taking place throughout the solar PV market and will help to improve on configuration costs for solar monitoring. However, the solar monitoring industry will also benefit heavily from the emerging Internet-of-things technologies that further improves plug-and-play behaviour of device communication, improves the quality and the security of the communication, and reduces the cost of hardware.

State of play

There are several advantages to this technology. Principally, it can reduce the costs of monitoring hardware and infrastructure. Similarly, it eases the configuration and maintenance of monitoring systems, whilst improving the quality and stability of data. It also provides for improved secure communications.

However, there is a risk that existing hardware and monitoring equipment will not be compatible with the new technology, resulting in expensive hybrid solutions until it becomes more mainstreamed.

Many Internet-of-Things (IoT) technologies have passed the prototype phase and are available for massive deployment. However, many different technological solutions and approaches are still available in the market and no final best practice approach has emerged.

Again, this leads to a standardisation issue for the industry-wide adoption of Internet-of-Things technology within the solar industry and, as such benefits from its advantages will be reduced when considering solar PV on a larger scale.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Solar PV Monitoring-Imagery Data fusion

Purpose and description

Current solar PV monitoring solutions track key parameters of solar PV assets (e.g. energy production, irradiance, performance ratios, etc.), with high temporal resolution (e.g. up to 1-10 minutes) and trigger alarms when deviations form expected performance occur. However, there are no specific optimisation objectives linked to the detection of underperformance. This method, which relies solely on solar PV monitoring data, presents two significant intrinsic limitations:

- **Expert-dependence:** As such, a misconfiguration of (manually defined) expected performance data often leads to misdetection (or misinterpretation) of deviations from the monitored performance data (i.e. false negatives/positives)

- **Insufficient spatial granularity:** solar PV monitoring data alone is insufficient for identifying the root-causes and locations of energy losses within solar PV systems, as their best spatial resolution is typically down to string level (i.e. 10-30 solar PV modules combined). As a result, several underperformance issues – especially at solar PV array, module, and submodule level – may remain undetected or unidentified

Currently, root cause analysis at higher granularity is carried out through various aerial imaging inspection techniques, some of which are described earlier in the chapter). Although these methods have impressive time-efficiency and spatial resolution of aerial imagery data analytics (inspection rates of several MW/hour; detection down to submodule/cell level), there are also considerable drawbacks:

- **Practically inexistent temporal granularity:** Aerial imagery inspections/scans of solar PV power plants are carried out per-schedule (e.g. bi-annually), rather than as part of preventive maintenance. This means they can, at best, only offer a qualitative "instant picture" of the condition of a solar PV power plant and its components

- **Decoupled from solar PV monitoring:** There is no real-time communication or correlation with crucial solar PV monitoring data (inverter outputs, PR, weather data, etc.), preventing precise determination of the causes of underperformance and power losses with image data (fault) signatures

From this perspective, enabling fusion (and interoperability) between heterogeneous solar PV monitoring and imagery data/sensors, will be a key functionality and differentiator for next generation "integrated" solar PV monitoring solutions. Indeed, this concept offers key advantages: i) solar PV performance monitoring data becomes more actionable, leveraging the diagnostic capacity and accuracy of image data with high spatial granularity; ii) the solar PV imagery data gain a temporal and quantitative dimension, being coupled and correlated with real-time monitoring data and power gain/loss analytics.

Other innovation pathways towards solar PV monitoring-image data fusion solutions can include their interfacing with solar PV digital twins, for example, or the integration of BIM and GIS data, and the replacement of (aerial) IR image data by hyperspectral or multispectral image data of solar PV power plants.

State of play

Several commercial solutions of advanced solar PV monitoring exist, offering software-driven quantification and classification of string/inverter-level failures, data analytics for soiling rates and performance degradation, and weather and energy flow analytics. On the other hand, turnkey commercial aerial-IR imagery services offer AI-based data analytics, fault diagnostics and reporting, as well as recommendations for corrective maintenance actions. Yet, in practice, solar PV monitoring platforms are decoupled from IR imagery diagnostics and not optimally aligned in today's solar PV O&M.

Concepts towards aggregation and fusion of solar PV monitoring and inspection/imagery data are under development and being patented, in ongoing international R&D projects. The aim is to gain validation by 2024. Over the last 5 years, there have been efforts and patented methodologies that couple solar PV monitoring and/or IR imaging data with physics-based solar PV yield simulations and loss analytics.

Use of Generative AI in workflow's automatisation

Purpose and description

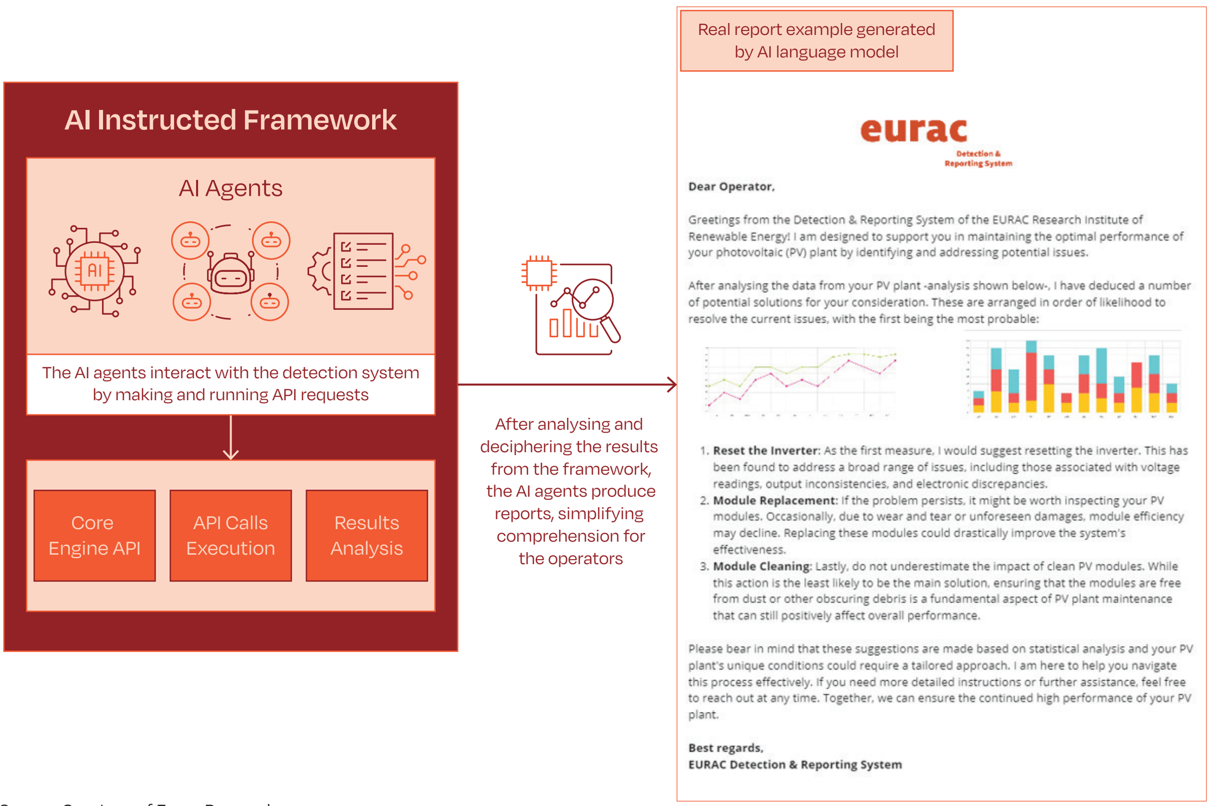
In the coming years, large language-based AI models (LLM) will reshape engineering software for renewable energy asset operations, driven by the urgency to enhance human-computer interaction. These models, adept at comprehending instructions and configuring settings seamlessly, promise significant time savings by expediting data queries and contextual data visualisation. As the PV sector grows in complexity, these models are set to become indispensable tools, streamlining operations, and ensuring efficient asset management. Through language models the user will be able in the future to automatically generate or bypass dashboards. The use of natural language will reduce barriers created by the need of having programming skills.

State of play

The use of generative AI in PV operation and maintenance workflows is advancing, supported by EU initiatives such as Horizon Europe's SUPERNOVA project. AI-driven solutions, including language-based models and large language models (LLMs), are automating tasks like reporting and data analysis while providing actionable insights tailored to operators. These tools reduce manual workload, enhance decision-making, and shift the focus from traditional analytics to more advanced "insight as a service." By integrating established industry KPIs, such as the Cost Priority Number (CPN), these innovations improve efficiency and profitability in PV asset management.

Figure 17

Example of AI agents based framework for the automated report generation



Source: Courtesy of Eurac Research

Chapter 13

O&M for Rooftop Solar

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This chapter aims to assist in the application of established utility-scale best practices, detailed in the previous chapters of the document, to rooftop solar projects. It also highlights where rooftop solar projects are distinctively different from utility-scale projects, and where they may require specific O&M best practices that may not be present or applicable to utility-scale projects.

A rooftop solar PV system has its electricity-generating solar panels mounted on the rooftop of a residential or commercial building or structure. On residential buildings they have typically a power of about 5 to 20 kWp, while those mounted on commercial buildings often reach 100 kWp to 1 MWp. Large roofs can house industrial scale solar PV systems in the range of 1-10 MWp. Since O&M organisation depends on size and structure of the asset we distinguish between:

- C&I (commercial and industrial) rooftop solar and
- Distributed solar portfolios (Large portfolios of residential systems)

13.1 C&I Rooftop Solar

C&I rooftop solar systems are designed and installed for commercial or industrial applications. They are either built, owned, and operated by an IPP who then sells electricity to a company or institution via a PPA.

There are also cases in which C&I rooftop solar systems are designed to generate electricity for on-site use. In fact, business owners opt to sing a long-term operational lease contract with the IPP; this guarantees price certainty and long-term contracts for the energy producers while reducing dependence on grid power and lowering energy costs for business owners.

Recently, C&I rooftop solar systems are being paired increasingly with on-site energy storage solutions to enhance energy independence and efficiency for the site.

Due to the relatively significant size of C&I rooftop systems (1MWp -10+ MWp), the best practices highlighted in these Guidelines should be applied to these installations. However, their location on roofs and their situation in commercial/industrial environments require additional guidelines to address these factors.

Regarding H&S considerations for C&I rooftop solar, the necessary precautions outlined in *Chapter 2. Health, Safety, Security, and Environment* should be taken into account, but need to be complemented to address the dangers associated with working at height (see for example Best practice guidelines for working at height in New Zealand, HSA Guide to the Safety, Health and Welfare at Work or IACS Guidelines for Working at Height). These additional precautions include:

- Presence of permanent guardrails or other forms of edge protection
- Presence of maintenance corridors
- Use of mobile elevating work platforms, forklift platforms, etc.
- Use of safety mesh
- Use of temporary work platforms (also to avoid damage of modules)
- Marking of dangerous areas (for example, fragile roof material)
- Correct use of harness systems and lifelines
- Correct use of ladders

Beside the above HSE measures to be taken into account by technicians, inspectors, business owners etc, it is becoming more common to implement HSE measure to the building itself as insurance requirement. In the Netherlands, for example, Scope 12 inspection is periodically requested by insurers to guarantee that the photovoltaic installations comply with the technical regulations and the safety standards.

Operations

An asset-centric approach to operations that promotes the free flow of data and transparency between all stakeholders for the entire lifecycle of the asset should be followed. This is made possible by using a monitoring and asset management platform.

Operating a C&I rooftop solar asset is similar in principle to the guidelines mentioned in *Chapter 4. Power Plant Operation*. To recap, it should include:

- A Document Management system
- Plant performance monitoring and supervision
- Performance analysis and improvement
- Optimisation of O&M
- Maintenance scheduling
- Spare part Management
- Decommissioning

Major KPIs that drive the operation of C&I rooftop solar systems are Performance Ratio or Energy performance Index and Availability.

To accurately calculate these KPIs, collection of Irradiation and temperature data locally is required.

The following table shows methods that can be applied for data collection.

Table 17

Methods suggested for the collection of reference yield

Reference yield source	Accuracy	Hardware Cost	Comment
Onsite pyranometer	High*	High	For more information, see *Section Irradiance Sensors* Public pyranometers may be used if available
Module level sensor	High	High	For more information, see *Section Irradiance Sensors*
Satellite data	Medium-High**	None	
Cell sensors	Medium	Low	For more information, see *Section Irradiance Sensors*

*Pyranometers and cell sensors need periodical cleaning and recalibration to keep the highest level of accuracy. If this cannot be sustained, a good satellite irradiation data set is preferable.
** Satellite data accuracy depends on type of source. However, the best references have a granularity of 3x3 km^2 and do not include local shades. It is also worth noting that real-time satellite data provision comes at a cost. Another alternative is comparing the performance of neighbouring systems.

The variety of conditions leads to a higher incidence of uncertainty: greater shade, lower data accuracy, lower comparability between assets.

For example, greater and more variable shade profiles, due to significant roof obstacles, require that expected yields used in the PR and EPI are adjusted based on shade expectation for the KPI interval.

As shading and vegetation control tend to be an ongoing problem for smaller-scale C&I given their relative size, and proximity to trees and gardens, as well as ongoing construction of neighbouring buildings that could affect the shading profile of the solar PV installation site, drones can be considered as a fast, accurate, safe and non-intrusive method of delivering shading analysis and vegetation management inspections at regular intervals appropriate to the site.

As a recommendation, horizon and obstacle plotting should be included in all yield modelling.

Maintenance

C&I O&M service providers should provide a yearly Preventive Maintenance Plan to the Asset Owner.

Roofs under warranty require annual preventive roof maintenance to maintain the roof warranty. It is best practice for the retailer/installer and O&M service provider to meet with the roof maintenance provider to make sure both teams understand their roles and responsibilities and respect each other's needs.

The preventive maintenance of the solar system is performed at least once a year for visual inspections, repairs, minor replacements and cleaning of parts of those systems whose failure can statistically be predicted and/or scheduled.

Such services are carried out in accordance with the instructions given by the or by the manufacturers or the suppliers of the respective equipment and systems.

The services include:

- Maintenance of the electrical installation (earthing/leakage/insulation resistance checks, fuses, circuit breaker, switchgear.)
- Visual inspection of equipment
- Follow up on failures or messages that do not require corrective maintenance
- Follow up on minor defects, issues that were detected during visual inspection
- Cleaning and maintenance of the weather stations
- Recalibration of irradiance sensors (every two years)
- Full maintenance of all inverters according to manufacturer's standards and intervals.
- Recording of the maintenance operations with identifying information about the maintenance personnel and defining of actions for issues that were detected but that could not be resolved immediately

Part of the scope of preventive maintenance is the thermographic inspection of the equipment. Due to the scale and particularity of the components, this is performed in different ways, all being according to the IEC62446 Standard.

- Modules will receive a thermographic inspection soon after cleaning is performed with the irradiation over 600 W/m^2. Following this, the images will be processed, and the failures will be mapped and classified based on severity and type. The outcome will result in corrective maintenance actions.

- Inverters, combiner boxes and AC equipment will be inspected with a thermographic camera on days where the average irradiation is higher than 400W/m^2 and several hours after the installation has been running at full capacity. This way helps identifying if the heating inside the equipment is distributed according to the design specifications.

As a result of the yearly preventive maintenance and the close monitoring of the performance of the solar systems, **corrective maintenance** is also required on site. This involves scheduling of on-site interventions to solve any problem such as repairing or replacing any defective/malfunctioning part of the relevant PV Park.

This service includes:

- Analysis of the problem and notification of the necessary actions
- Work, transportation, the removal or elimination of the defective equipment or components, their reconditioning or replacement, their packaging and delivery, until return to operation

The time for the interventions are set by the SLA (Service Level agreement) which depends on level of criticality of the malfunction remotely detected.

All the preventive inspections and corrective interventions need to be logged in a form of report which will be sent to the Asset Owner within 5 working days

The report will include:

- Date and time of the inspection/incident/intervention
- Description, root cause analysis with photos and videos (if applicable)
- Name of person who carried out the intervention
- Date and time of repair and, if necessary, of service reboot

Table 18

Incidents covered by O&M service agreements for rooftop solar systems

Incident	Comment
HSSE/trafo shutdown	Disruptions related to fire and/or HSSE risks, PV Park/transformer- level resulting in loss of income, future loss of income require action within 12 hours.
Inverter alarms	Alarms generated by the inverter should be acknowledged at least daily. The personnel responsible for maintenance should take necessary actions within 2 days.
Module - String/inverter level alerts	For commercial projects with more than one inverter, reporting should be at the inverter level as a minimum. String or MPPT level reporting to enable string failure alerts is recommended where possible.
Monitoring failure	As monitoring failure is often caused by inverter failures or DC issues, this diagnosis must be done quickly to determine if the failure is limited to monitoring or if yield production is impacted. As a rule of thumb is always important to cross check meter data to exclude potential downtime. Resolution of monitoring failure (without yield losses) should be completed within 5 days.

Spare Parts Management

If economically feasible, the O&M service provider should have basic spare parts in stock. Failing this, care should be taken to select component manufacturers which can provide local service and fast replacement of faulty goods in Europe.

The inverter is the most important spare part as energy production and most monitoring processes rely on it.

13.2 Distributed Residential Solar Portfolios

Distributed solar portfolios refer to portfolios comprising multiple, small assets installed on residential rooftops. Distributed energy systems can be part of a microgrid that offers a degree of crucial power independence from the main grid in cases such as mains electricity outages during extreme climate events.

Ownership of assets varies from country to country and is based on the bilateral agreement between the constructor/operator and the roof owner. Generally, there are three kinds of owners:

- Homeowners that own the installations on their homes. These type of owners, have paid for the installation themselves and usually have a bilateral net- metering agreement with the local utility for the energy produced.

- Depending on the size, third-party companies that own the installations and usually lease the rooftop or sell the electricity produced to the owner of the rooftop at a discounted price from the one offered by utilities one (similarly to C&I rooftops)

- Local councils or private and social housing associations that have equipped their properties with solar panels

Apart from the general aspects of rooftop solar systems, main challenges of large distributed solar portfolios are:

- The multitude of assets: portfolios of 10,000+ installations are common

- The variety of conditions (for example, shading, inclination, orientation, etc.)

- The variety of equipment used: multiple inverter brands (including monitoring systems) and panels

- The common presence of stakeholders who are not solar professionals

- Getting access to the house for maintenance activities requires making appointments with the tenants

Operations

Since physical site inspections and callouts at multiple sites mean higher costs, it is economically cheaper to invest into monitoring hardware (temperature/irradiance) on top of inverter monitoring, and implement automatic root cause analyses, where this is possible. Therefore, monitoring equipment accounts for a greater percentage of the total investment.

For large portfolios of small installations extra monitoring hardware might be too expensive. Automated analysis methodologies comparing neighbouring installations can be used in combination with irradiation data coming from meteorological stations and satellites, or theoretical clear-sky irradiation data.

Monitoring of a large portfolio of residential installations requires a different approach to monitoring an individual installation. For the latter, the inverter built-in monitoring system via Wi-Fi might be sufficient, making the tenant responsible for communication with the server.

When performing long-term monitoring of a high number of installations, using a communication channel independent from the house Internet connection, i.e., cellular communication is advised. This largely decreases the number of support calls and local interventions to resolve communications issues. It also decreases the installation cost (cabling, configuration) and the risk of cyber security issues.

For local data acquisition, three approaches can be followed:

- **Inverter manufacturer built-in system:** This is often free-of-charge including access to a portal for the installer and end-user. The disadvantage is that, when multiple inverter brands are used, different monitoring systems need to be managed which makes it more complex and time consuming

- **Independent data logger:** These are compatible with multiple inverter brands decreasing the dependency on a single manufacturer

- **External energy meter:** These are easy to install and often have an integrated communication module. It is the only solution when a calibrated measurement is required following the European Measurement Instrument Directive (MiD)

In case only an energy meter is used in the monitoring systems, the following parameters need to be measured at the minimum:

- **AC Energy production:** This is the basis for yield calculations. A resolution of minimum 15 minutes is advised for further intra-day performance analysis.

- **AC voltage:** In areas with a lot of local production, AC voltage can rise to a level that sends the inverter into safety mode. The level is dependent on local legislation.

In case more detailed inverter data is acquired, the following parameters provide useful information:

- Inverter alarms

- Inverter temperature: This can give an indication of an upcoming problem or clogged ventilation holes

When monitoring large portfolios of solar PV installations, the following challenges can occur:

- High volumes of different installations with very different characteristics
- Base parameters (Wp, orientation, tilt) are often incorrect or missing in the monitoring database
- Shading effects (trees, chimneys, etc.) which are season dependent resulting in errors in yield analysis
- Local irradiation measurement is too expensive
- Errors in yield analysis due to clipping effects

The following best practices should be adopted:

- Apply robust procedures during installation to start from correct parameters. Installer technicians need to provide the correct information as part of the commissioning process
- Avoid a high variety of data acquisition methods and monitoring systems
- Apply performance index calculations that are immune from the effects of shading (e.g. part of the day, clear sky index)
- Compare with a pool of nearby installations to neutralise temperature, wind, and pollution effects on performance indexes

Maintenance

Also small residential solar rooftop do require maintenance. As best practice, the Installer should educate their clients about the necessity and benefits of a regular, high-quality O&M practice for the lifetime of their solar assets. This should include a minimum yearly inspection and maintenance as well as cleaning based on the environmental conditions. This will ensure the continuous safe operation of the asset and minimise H&S risks to building users. It will also maximise the energy production capability of their asset throughout its lifetime. It needs to be clarified to homeowners or tenants that they should not clean the panels themselves using high pressure systems. This would void the warranty.

In areas with a high density of residential solar PV installations, collective drone inspection should be considered. In a short period, thermographic data of lots of installations can be collected.

Corrective Maintenance of large residential portfolios relies heavily on a good monitoring system. Besides detecting and communicating alarms it should be able to detect decreasing performance trends. Once an anomaly is detected, it would be wise to group interventions in a certain geographical area.

Depending on the familiarity of the tenants with electrical systems, it could be an option to train the tenants to perform certain actions such as removing dust from ventilators and resetting an installation (switch off/on). However, the O&M service providers should always considers themselves responsible of any HSE hazards even when the tenants is instructed to perform these types of tasks.

Annex A List of international standards for PV O&M

Find below a non-exhaustive list of Standards applicable and relevant the implement of best O&M practices for the photovoltaic sector.

Annex A

List of international standards for PV O&M

Standard Code	Topic	Description	Category
EN 13306	Maintenance terminology	Defines general terms for maintenance	General O&M activities
EN 50380	Marking and documentation requirements for photovoltaic modules	Mandatory information that needs to be included in the product documentation or affixed to the product to ensure safe and proper use	PV components & BOS
EN 50618	Solar cable standards	Specifies cable requirements for PV systems to ensure safety and reliability	PV components & BOS
IEC 60364-7-712:2017	Electrical installations	Safety and operational aspects for PV system installations	General O&M activities
IEC 60891:2021	Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics	Procedures to be followed for temperature and irradiance corrections to the measured I-V curves	Other supporting standards
IEC 60904 Series	Measurement techniques	Measurement of module and cell performance for inspections	Specialised technical inspections
IEC 61215 Series	PV module durability	Design qualification and type approval for module durability	PV components & BOS
IEC 61439-1:2020	Low-voltage switchgear assembly	Describes the design verification for control gear assemblies and the responsibilities of the manufacturer and switchboard manufacturer	PV components & BOS
IEC 61557	Electrical safety in low voltage distribution systems	Specifies safety requirements for electricity distribution systems with a 1,000 V AC and/or 1,500 V DC	PV components & BOS
IEC 61724 Series	Performance monitoring	Guidelines for monitoring performance, data exchange, and analysis	System performance & monitoring
IEC 61730 Series	PV module safety	Safety-related design and testing standards for modules	PV components & BOS
IEC 61853 Series	Performance testing of modules	Defines PV module performance under various environmental conditions	System performance & monitoring
IEC 62093:2021	Balance-of-System components	Design qualification for non-module components such as inverters and cabling	PV components & BOS
IEC 62109-1 & 62109-2	Safety of power converters	Safety requirements for inverters and power conversion equipment	PV components & BOS
IEC 62446-1:2016	Documentation and testing	Testing, documentation, and inspection for grid-connected PV systems	General O&M activities
IEC 62548:2016	Photovoltaic (PV) arrays – Design requirements	Guidelines for the design & installation of PV systems	Other supporting standards
IEC 62790:2020	Junction boxes for photovoltaic modules - Safety requirements and tests	Definition of standards for safety requirements & testing regarding junction boxes for PV modules	PV components & BOS

List of international standards for PV O&M

Standard Code	Topic	Description	Category
IEC 62817:2014	Design of solar trackers	Standards for maintaining and testing solar tracking systems	PV components & BOS
IEC 63049:2017	Reliability of PV modules	Metrics for reliability and predictive maintenance of modules	General O&M activities
IEC TR 63149:2018	Land usage of PV farms	Mathematical models for calculation of the distance between arrays to avoid shading & optimise land use	Other supporting standards
IEC TS 61836	Solar Photovoltaic Energy Systems – Terms, definition & symbols	Provides terms, definitions & symbols in line with IEC TC 82	Other supporting standards
IEC TS 62446-2:2020	Maintenance of PV systems	Maintenance requirements and test procedures for grid-connected PV systems	General O&M activities
IEC TS 62446-3:2017	Requirements for testing, documentation and - Part 3	Defines outdoor thermographic (infrared) inspection of PV modules and plants in operation	Specialised technical inspections
IEC TS 62738:2018	Ground-mounted photovoltaic power plants - Design guidelines and recommendations	General guidelines & recommendations for the design of ground mounted PV plants	Other supporting standards
IEC TS 62804	Test methods for the detection of potential-induced degradation	Defines procedures to test and evaluate the durability of PV modules for c-Si and thin films	PV components & BOS
IEC TS 62915:2023	PV modules retesting	Uniform approach to maintain type approval, design and safety qualification of terrestrial PV modules when modification from their originally assessed design	PV components & BOS
IEC TS 62930:2017	Photovoltaic cables	Standards for reliable DC cables under various conditions	PV components & BOS
IEC TS 62941:2019	Quality Assurance for PV modules	Enhancing quality assurance in PV module manufacturing and maintenance	Other supporting standards
IEC TS 63019-2019	Photovoltaic power systems (PVPS) - Information model for availability	Categorisation of data for system availability and production	System performance & monitoring
IEC TS 63126: 2020/	Guidelines for qualifying PV modules, components and materials for operation at high temperatures	Defines additional testing requirements for modules deployed under conditions leading to higher module temperature	PV components & BOS
IEC61829: 2015	PV Array onsite measurement of current voltage characteristics	Specifies procedures for on-site measurement of flat-plate photovoltaic (PV) array characteristics	Specialised technical inspections
ISO 14001:2015	Environmental management	Framework for incorporating environmental considerations in O&M	Other supporting standards
ISO 31000:2018	Risk management	Guidelines for operational risk assessment and management in PV systems	Other supporting standards
ISO 50001:2018	Energy management	Framework for optimising energy use, including PV systems	General O&M activities
ISO 9847:1992	Calibration of field pyranometers	Specifies calibration requirements for solar radiation measurement equipment	System performance & monitoring

Annex B

Skill Matrix Operations Phase

Standard Code	Electrical	Solar Specific	Mechanical	Work Safety	SCADA	Analytics	Electrical Safety	Processes & Quality Control
Field Worker	1	0	2	1	0	0	1	1
Field Service Technician = O&M Technician	2	1	2	2	1	0	2	2
Field Service Manager	2	2	2	3	1	1	3	3
Site Manager	1	1	1	3	1	0	2	3
Remote Support Technician	2	2	1	1	2	1	1	2
Monitoring Specialist	3	3	1	1	2	2	1	2
SCADA Operator	2	1	1	1	3	2	1	1
SCADA Specialist	3	2	1	1	E	3	1	2
O&M Manager	3	3	2	3	1	3	3	E
Installation and Work Responsible	E	1	1	E	1	1	E	3
Technical Asset Manager	2	2	1	3	2	3	3	3
Data Analyst	3	3	0	0	3	E	1	2
Asset Manager	2	2	0	3	1	3	2	3

0 **Level 0:** Untrained person that has vague notions of the domain

1 **Level 1:** Basic or entry level training allowed to performed works supervised

2 **Level 2:** Junior technician level training with partial autonomy in performing the tasks

3 **Level 3:** Senior technician level with full autonomy in performing the tasks

E **Expert:** Highly trained and experienced with deep know-how of the domain

Domains

- **Electrical:** The electrical power generation system from DC current working principles to AC working principles. It includes solid bases of power electronics
- **Solar Specific:** The working principles and technologies specific to PV modules, inverters and relevant modeling and calculations. It includes operations specific to PV installations such as cleaning, greenkeeping, thermography
- **Mechanical:** The support and mounting systems of the PV installation, including the use of appropriate tools and power tools. Operating heavy machinery during Operational phase is included
- **Work Safety:** The general principles of working safely according to the national and sector's guidelines. It ranges from being able to receive instructions using specific terminology to using the appropriate documentation such as LMRA, TRA, HSE plan etc
- **SCADA:** The technologies used to connect the data generating devices in a PV installation with the monitoring platforms. From Modbus configuration to IoT network setup, including cybersecurity and infrastructure specific knowledge
- **Analytics:** Using the monitoring platforms to extract insights and value from data. KPI analysis, dashboard setup and ad-hoc data validation are part of the domain
- **Electrical Safety:** The specific guidelines and procedures according to national law on working safely on electrical systems based on type and voltage range
- **Processes & Quality Control:** The techniques and know-how in ensuring quality work combined with the ability to work according to processes. It goes from following at higher level the stage gateway life-cycle for a PV plant to following the corrective maintenance steps from monitoring to reporting at lower level

Annex C Documentation set accompanying the solar PV power plant

(Download it from www.solarpowereurope.org)

Annex C

Documentation set accompanying the solar PV power plant

Information type and depth of detail/as-built documents			
No.	Minimum Requirements	Description	Comments
1.	Site information	• Location/map/GPS coordinates • Plant access/keys • Access roads • O&M building • Spare parts storage/warehouse • Site security information • Stakeholder list and contact information (for example, owner of the site, administration contacts, firefighters, subcontractors/service providers, ...)	For the plants already in operation: • Previous monthly reports • Previous preventive maintenance report • Previous corrective maintenance report • Previous opened warranty claims • Previous revamping/repowering documents
2.	Project drawings, including main components and equipment O&M manuals	• Plant layout and general arrangement • Cable routing drawings • Cable list • Cable schedule/ cable interconnection document • Single Line Diagram • Configuration of strings (string numbers, in order to identify where the strings are in relation to each connection box and inverter) • Earthing/grounding system layout drawing • Lightning protection system layout drawing • Lighting system layout drawing (optional) • Topographic drawing • O&M manuals	"Lightning Protection System layout drawing" obligatory by most of insurance companies to be handed over as As-built
3.	Project studies	• Shading study/simulation • Energy yield study/simulation • Inverter sizing study • Full geotechnical assessment • Drainage studies	
4.	Power control system studies according to national regulation requirements	• Voltage drop calculations • Protection coordination study • Short circuit study • Grounding study • Cable sizing calculations • Lightning protection study	
5.	Solar PV modules	• Datasheets • Flash list with solar PV modules positioning on the field • (reference to string numbers and positioning in the string) • Warranties & certificates • Factory inspection report • Quality assurance reports, if available	
6.	Inverters	• O&M manual • Commissioning teport • Warranties & certificates • Factory acceptance test • Inverter settings • Dimensional drawings • Quality assurance report	If the plant is in operation: • Thermography reports • OEM intervention reports

Documentation set accompanying the solar PV power plant

Information type and depth of detail/as-built documents			
No.	Minimum Requirements	Description	Comments
7.	Medium Voltage/ Inverter Cabin	• Medium voltage/inverter cabin layout and general arrangement drawing • Medium voltage/inverter cabin foundation drawing • Erection procedure • Internal normal/emergency lighting layout drawing • Fire detection and fire fighting system layout drawing (if required) • HVAC system layout drawing • HVAC system installation & O&M manual • HVAC study (according to national regulations) • HVAC air flow study according site temperatures • Earthing system layout drawing • Cable list	
8.	MV/LV Transformer	• O&M manual • Commissioning report • Factory acceptance test report • Type test reports • Routine test reports • Warranties & certificates • Dimensional drawing with parts list	If the plant is in operation: • Oil preventive maintenance report • Thermograph reports • OEM intervention reports
9.	Cables	• Datasheets • Type & routine test reports	
10.	LV & MV Switchgear	• Single Line Diagram • Switchgear wiring diagrams • Equipment datasheets and manuals • Factory acceptance test report • Type test reports • Routine test reports • Dimensional drawings • Warranties & certificates • Protection relays settings • Switching procedure (according to national regulations)	"Protection relays settings" and "Switching procedure" are considerations for the MV Switchgear If the plant is in operation: • Thermograph reports • OEM intervention reports
11.	HV Switchgear	• Single Line Diagram • Steel structures assembly drawings • HV switchyard general arrangement drawing • HV equipment datasheets and manuals (CTs, VTs, circuit breakers, disconnectors, surge arresters, post insulators) • Protection & metering Single Line Diagram • HV equipment type & routine test reports • Interlock study • Switching procedure (according to national regulations) • Warranties & certificates	If the plant is in operation: • Thermograph reports • OEM intervention reports
12.	UPS & Batteries	• Installation & O&M manual • Commissioning report • Warranties & certificates • Datasheets • Dimensional drawings	
13.	Mounting Structure	• Mechanical assembly drawings • Warranties & certificates	

Documentation set accompanying the solar PV power plant

Information type and depth of detail/as-built documents			
No.	Minimum Requirements	Description	Comments
14.	Trackers	• Mechanical assembly drawings • Electrical schematic diagrams • Block diagram • Equipment certificates, manuals and datasheets (Motors, encoders) • PLC list of inputs and outputs (I/O) by type (Digital, analog or bus) • Commissioning reports • Warranties & certificates • Wind tunnel testing references • Functional validation tests, stow position	
15.	Security, anti-intrusion and alarm system	• Security system layout/general arrangement drawing • Security system block diagram • Alarm system schematic diagram • Equipment manuals and datasheets • Access to security credentials (e.g. passwords, instructions, keys etc) • Warranties & certificates	
16.	Monitoring/ SCADA system	• Installation & O&M manual • List of inputs by type (Digital, analog or bus) • Electrical schematic diagram • Block diagram (including network addresses) • Detailed flow diagram with IP address and passwords, if applicable according to the company policy • Equipment datasheets	
17.	Plant controls	• Power plant control system description • Control room (if applicable) • Plant controls instructions • Breaker control functionality (remote/on-site) and instructions • List of inputs and outputs	
18.	Communication system	• Installation and O&M manual • System internal communication • External communication to monitoring system or Operations Centre • IP network plan • Bus network plans	

Annex D Electrical Safety

Electrical safety in solar photovoltaic (PV) plants is paramount, governed by stringent European standards such as IEC 60364 and EN 50110. A robust safety framework is essential for ensuring the well-being of personnel and the efficient operation of the plant.

Roles and Responsibilities

Ensuring electrical safety in solar PV plants requires a well-structured team of qualified personnel, with clear distinctions between those responsible for Low Voltage (LV) and High Voltage (HV) systems. This structure is crucial for maintaining the highest safety standards across all voltage levels present in the plant.

Electrically Responsible Personnel Structure

The electrical safety team must be organised to reflect the distinct requirements of LV and HV systems:

1. **LV Responsible Person:** Oversees all aspects of LV system safety, including maintenance, operations, and personnel management for LV equipment
2. **HV Responsible Person:** Manages safety concerns related to HV systems, including switchgear, transformers, and grid connection points
3. **Overall Electrical Safety Manager (often the QEPIC):** Coordinates between LV and HV teams, ensuring cohesive safety practices across the entire plant

Best practice for utility-scale and commercial & industrial (C&I) solar PV plants is to have technicians certified in both LV and HV operations. This dual certification ensures flexibility and a comprehensive understanding of the plant's electrical systems. However, the minimum requirement is to have separate appointments for HV and LV responsibilities, even if these roles are fulfilled by the same individual in smaller installations.

Appointment Procedure and Chain of Custody

The appointment of personnel responsible for electrical safety must adhere to national regulations and follow a strict procedure:

1. **Identification of Qualified Candidates:** Management identifies individuals with appropriate qualifications and experience for LV and HV roles
2. **Formal Nomination:** Candidates are formally nominated for their respective roles (LV, HV, or both)
3. **Regulatory Compliance Check:** Ensure that the nominations comply with national electrical safety regulations and any specific requirements for solar PV installations
4. **Official Appointment:** Upon verification of qualifications and compliance, the plant manager or designated authority officially appoints the individuals to their roles
5. **Documentation:** The appointments are documented, including specific responsibilities, areas of authority, and duration of the appointment
6. **Notification:** Relevant authorities and all plant personnel are notified of the appointments
7. **Periodic Review:** Appointments are reviewed annually or as required by national regulations to ensure continued competence and compliance

The chain of custody for electrical safety responsibilities should be clearly defined:

- **Plant Manager/Owner:** Ultimate responsibility for safety compliance
- **QEPIC:** Overall management of electrical safety
- **HV and LV Responsible Persons:** Direct oversight of their respective systems
- **Shift Supervisors:** Day-to-day implementation of safety protocols
- **Individual Technicians:** Adherence to safety procedures in all operations

This structured approach ensures that at every level of operation, there is a clear understanding of who is responsible for electrical safety, facilitating quick decision-making and effective risk management.

Qualified Electrical Person in Charge (QEPIC)

The QEPIC plays a crucial role in overseeing all electrical operations within the solar PV plant. This position carries significant responsibility and requires specific qualifications and experience.

Appointment and Approval Hierarchy

1. The QEPIC is nominated by the solar PV plant management.
2. The nomination must be approved by the plant's Safety Director or equivalent senior management role.
3. Final approval is typically given by a regulatory body or certified electrical safety organisation, depending on local regulations.

Minimum Requirements for QEPIC

1. Certification:
    - Electrical Engineering degree from an accredited institution
    - Professional certification as a Chartered Electrical Engineer or equivalent national certification
    - Specific certifications in solar PV systems and high-voltage installations
2. Experience:
    - Minimum of 5 years of hands-on experience in electrical systems, with at least 3 years specifically in solar PV or similar renewable energy plants
    - Demonstrated experience in managing electrical safety programmes and teams
3. Additional Qualifications:
    - Up-to-date knowledge of relevant electrical codes and standards (e.g. IEC, EN)
    - Certified training in advanced electrical safety practices and risk assessment
    - First aid and CPR certification with specific training in electrical injury response

Responsibilities of the QEPIC

- Develop and maintain electrical safety protocols and procedures
- Conduct regular safety audits and risk assessments
- Approve switching procedures and oversee high-risk electrical operations
- Provide technical guidance on electrical safety matters to all staff
- Ensure compliance with all relevant electrical safety standards and regulations
- Coordinate with external safety auditors and regulatory bodies

Qualified Person Responsible for Electrical Works (QPREW)

The QPREW plays a vital role in ensuring the safety and quality of electrical work execution, particularly focusing on switching procedures. This role complements the QEPIC, providing hands-on oversight of electrical operations.

Appointment and Reporting Structure

1. The QPREW is appointed by the QEPIC or plant management.
2. Reports directly to the QEPIC on matters of electrical work safety and quality.
3. May oversee a team of electrical technicians and operators.

Minimum Requirements for QPREW

1. Certification:
    - Electrical Engineering degree or equivalent technical qualification
    - Specific certifications in electrical safety and switching procedures
    - Training in solar PV systems and high-voltage installations
2. Experience:
    - Minimum of 3 years of hands-on experience in electrical systems, with at least 2 years in solar PV or similar renewable energy plants
    - Demonstrated proficiency in executing and supervising switching procedures
3. Additional Qualifications:
    - Thorough knowledge of relevant electrical codes and standards
    - Certified training in risk assessment and safe work practices
    - First aid and CPR certification

Responsibilities of the QPREW

- Oversee the execution of electrical works, ensuring adherence to safety protocols
- Conduct and supervise switching procedures, following the five golden rules
- Perform risk assessments before commencing electrical works
- Ensure proper use of PPE and safety equipment during electrical operations

- Conduct on-site safety briefings and toolbox talks
- Monitor and report on the quality and safety of electrical work execution
- Assist in the development and review of electrical work procedures
- Serve as the primary point of contact for electrical technicians on safety matters
- Collaborate with the QEPIC to continuously improve electrical safety practices

Interaction between QEPIC and QPREW

- QEPIC develops overall safety strategies and protocols; QPREW ensures their proper implementation
- QPREW provides feedback to QEPIC on the practicality and effectiveness of safety procedures
- Both roles collaborate in incident investigations and safety audits
- QPREW escalates significant safety concerns or complex technical issues to the QEPIC

Other Key Roles

- Clearly define roles and responsibilities for all personnel involved in electrical work, including technicians, operators, and maintenance staff
- Establish a clear chain of command for electrical safety decisions

Work Permits and Switching Procedures

A crucial component of electrical safety in solar PV plants is the implementation of a robust work permit system, particularly for high-risk electrical works. Work permits serve as a formal, documented authorisation for specific tasks, ensuring that all safety precautions have been considered and implemented before work begins. For electrical works, the permit should detail the scope of work, identified hazards, required precautions, and the specific switching procedures necessary to create a safe working environment.

The work permit process directly links to the execution of switching procedures. Once a permit is issued, it triggers a carefully planned sequence of switching operations designed to isolate the work area electrically. This switching procedure, overseen by the QPREW and approved by the QEPIC, typically involves the following steps:

1. Identification of all potential sources of electrical energy
2. Sequential de-energisation of circuits
3. Lockout/Tagout (LOTO) application to prevent unauthorised re-energisation
4. Verification of zero-energy state using appropriate measurement equipment
5. Installation of temporary protective earthing where necessary

Only after the completion and verification of these switching procedures, as outlined in the work permit, can the authorised work begin. This systematic approach ensures that every electrical task is preceded by a comprehensive safety assessment and the implementation of necessary precautions, significantly reducing the risk of electrical accidents.

Maintenance and Inspection Regimes

Maintenance and inspection regimes in solar PV plants play a crucial role in ensuring electrical safety. While specific maintenance procedures are detailed elsewhere, it's important to emphasise that all maintenance activities must prioritise electrical safety. This involves adhering to a strict schedule of inspections and maintenance for both low voltage (LV) and high voltage (HV) equipment, with frequencies ranging from daily visual checks to annual comprehensive evaluations. The primary focus of these activities, from an electrical safety perspective, is to identify and mitigate potential hazards such as damaged insulation, loose connections, or signs of overheating that could lead to electrical accidents.

A clear distinction between LV and HV systems must be maintained throughout all maintenance operations. This separation is not just physical but extends to personnel qualifications and procedures. Only technicians with appropriate certifications and up-to-date training should perform maintenance on LV systems, while HV maintenance must be restricted to highly qualified HV specialists. This segregation of duties ensures that all work is carried out by personnel with the specific expertise required to maintain safety standards. Regular safety audits, thorough documentation of all maintenance activities, and continuous review of procedures by the QEPIC and QPREW are essential to identify trends, address recurring issues, and continuously improve the electrical safety aspects of the maintenance regime. It is best practice that every 2 years all personnel involved in performing O&M works on solar plants refresh their certifications for electrical safety. The minimum requirement is at least every 5 years or upon a new release of the national applicable electrical safety standard.

Personal Protective Equipment (PPE)

Non-negotiable PPE includes:

- Insulating gloves rated for the appropriate voltage
- S3 shoes or S5 boots with electrically insulated soles
- Arc-rated face shields
- Flame-resistant clothing appropriate for the specific arc flash hazard category

The quality and compliance of the PPE must be reviewed regularly and if any degradation is noticed, it must be exchanged immediately to prevent life-threatening accidents. The QPREW has to regularly perform checks on the technical service team and organise toolbox meetings to continuously review and improve both the state and the use of PPE.

Measurement Equipment and Safety Validation

Proper selection, maintenance, and use of measurement equipment is critical for ensuring electrical safety during maintenance and operations in solar PV plants. The following best practices should be adhered to:

Equipment Selection

1. **Voltage Rating:** Choose equipment rated for the highest voltage present in the system. For utility-scale solar PV plants, this often means equipment rated for up to 1,500V DC and 1,000V AC
2. **Measurement Category:** Use CAT III or CAT IV rated equipment
    - CAT III for measurements on LV distribution circuits and solar inverters
    - CAT IV for measurements at the utility connection point or HV side of transformers

3. **Multimeters:** Select true-RMS meters for accurate AC measurements in the presence of harmonics common in solar PV systems
4. **Current Measurements:** Use clamp meters or flexible current probes to avoid breaking circuits for current measurements
5. **Insulation Testers:** Choose models with test voltages up to 1000V or 1500V for testing PV arrays and cables
6. **Earth/Ground Testers:** Essential for verifying proper grounding of PV arrays and equipment

Usage Best Practices

1. **Pre-use Inspection:** Always inspect equipment, leads, and probes for damage before use
2. **Calibration:** Maintain a regular calibration schedule as per manufacturer recommendations, typically annually
3. **Proper Technique:**
    - Use the "one hand rule" when possible to reduce the risk of current passing through the heart
    - Stand on an insulating mat when making measurements in wet or damp conditions
4. **Voltage Testing Sequence:**
    - Step 1: Test the meter on a known live circuit
    - Step 2: Test the circuit to be worked on
    - Step 3: Retest the meter on the known live circuit to confirm it's still functioning correctly
5. **Remote Measurement:** Where possible, use equipment that allows for remote reading or wireless data transmission to increase distance from potential arc flash zones
6. **Documentation:** Record all measurements in a log, noting any unexpected readings for further investigation

By rigorously adhering to these best practices and properly utilising appropriate measurement equipment, technicians can significantly enhance electrical safety during maintenance and operational activities in solar PV plants. Regular training on the correct use of measurement equipment should be provided to all relevant personnel, emphasising that these tools are the first line of defence in preventing electrical accidents.

Training and Safety Culture

EU electrical safety hinges on a skilled workforce achieved through:

- **Skills Matrix:** This maps competencies for roles like LV/HV qualified personnel (up to 1000V AC/1500V DC or above) and protection system technicians. It aligns with European electrical certifications (e.g. IEC 60417 for low voltage)
- **Certifications:** The European Qualifications Framework (EQF) provides standardised assessment. Examples:
    - EQF Level 3: Basic electrical skills for safe work near electrical installations (e.g. non-conductive tools, arc flash hazards)
    - EQF Level 4: Advanced skills for solar PV installers and maintenance technicians (LV systems) - includes DC isolation procedures, string inverter operation, and module-level safety devices
    - Higher EQF levels for specialised roles (e.g. EQF Level 5 for EUREM-certified energy managers overseeing plant operations and grid interconnection)

Effective Training Programmes: Training should be:

- Comprehensive: Covering theory (e.g. arc flash calculations, DC arc fault protection) and practical skills (e.g. safe hot work procedures, proper use of multimeters and insulation testers for DC systems)
- Role-specific: Tailored to job responsibilities. For instance, HV technicians might receive training on high voltage isolation techniques and SCADA system operation
- Regular: Including initial training, annual refreshers, and updates on new technologies (e.g. safe handling of bifacial modules) and regulations (e.g. IEC standards revisions)
- Assessed: Verifying competence through practical assessments (e.g. safe isolation of a DC combiner box) and theoretical exams

Fostering a Learning Safety Culture: Continuous improvement is achieved by:

- Encouraging Reporting: Implementing a non-punitive system for incident and near-miss reporting (e.g. unsafe work practices observed, potential electrical hazards identified)
- Lessons Learned Sessions: Regularly conducting sessions to share insights from incidents, audits, and industry best practices (e.g. learnings from a DC ground fault incident)
- Knowledge Sharing Platforms: Utilising internal platforms or forums for staff to exchange experiences and ask questions (e.g. best practices for safe cleaning of high voltage insulators)
- Cross-training & Mentorship: Encouraging broader understanding through cross-training (e.g. operations staff learning about inverter maintenance) and pairing experienced staff with new employees for knowledge transfer (e.g. senior technician mentoring a new installer on safe cable termination techniques)

Safety Culture Assessment: Regularly evaluate the safety culture maturity using:

- Safety Climate Surveys & Behavioural Observations (e.g. observing safe work practices during routine maintenance tasks)
- Incident Report Analysis & Corrective Actions (e.g. analysing root causes of electrical incidents and implementing corrective actions to prevent recurrence)
- Participation in Safety Initiatives & Training Programmes (e.g. monitoring participation rates in safety drills and specialised training workshops)

By integrating these elements, solar PV plants ensure a competent workforce that proactively champions electrical safety. This fosters a resilient safety culture, adapting to new challenges and continuously striving for excellence in electrical safety practices.

Documentation

Comprehensive electrical safety documentation is a cornerstone of effective operations and maintenance (O&M) for solar photovoltaic (PV) plants. This document outlines the minimum regulatory requirements, best practices, and innovative recommendations for electrical safety documentation within the solar PV industry.

Minimum Requirements

International Electrotechnical Commission (IEC) standards and national regulations establish the minimum requirements for electrical safety documentation in solar PV plants. These essential elements ensure a baseline level of worker safety and regulatory compliance:

- **Training Records:** Documented training programmes verify worker competency in electrical safety principles (e.g. arc flash hazard awareness, Lockout/Tagout procedures) aligned with their specific roles within the solar PV plant (e.g. LV/HV qualified personnel).
- **Risk Assessments:** Detailed evaluations of electrical hazards at the facility are crucial. These assessments consider equipment types (presence of DC arc fault protection, high voltage transformers) and specific work activities (cable terminations, inverter maintenance). Mitigation strategies and safe work procedures must be clearly documented within the risk assessment.
- **Inspection & Maintenance Logs (Including Lone Worker Devices):** Regular inspections by qualified personnel ensure timely identification of electrical deficiencies. Logs document inspection findings, corrective actions taken (e.g. replacement of faulty insulation testers), and retest results. Lone worker devices are now considered a minimum requirement, enhancing safety by providing immediate assistance and real-time documentation for personnel working in remote locations on the solar PV site.

Best Practices

Building upon the minimum requirements, best practices foster a culture of continuous improvement in electrical safety:

- **Pre-Job Briefings & Sign-offs:** Tailored briefings for each task ensure clear communication of hazards, safe work procedures specific to the solar PV environment, and emergency response plans. Workers acknowledge their understanding by signing off on the briefing document.
- **Detailed Maintenance Logs:** Logs capture not only corrective actions but also preventive maintenance activities crucial for solar PV systems (e.g. thermal imaging of switchgear panels, cleaning of high voltage insulators). This comprehensive record facilitates trend analysis and proactive identification of potential issues before they escalate.

Recommendations for Innovation

The solar PV industry can leverage cutting-edge technologies to propel electrical safety documentation further:

- **Cloud-Connected Mobile Apps:** Real-time data capture through mobile apps streamlines safety compliance within the solar PV plant. Workers can access risk assessments, pre-filled inspection checklists specific to solar PV equipment, and record corrective actions directly on-site. This data readily integrates with a central safety framework for centralised analysis and reporting, enhancing overall safety oversight.
- **Advanced Lone Worker Devices:** These devices go beyond the minimum requirements, offering features like real-time communication with support teams specifically trained in solar PV safety protocols. Additionally, they can provide automatic logging of worker location and environmental data during electrical work on the solar field, and even trigger alerts during emergencies.

Adhering to minimum requirements, implementing best practices, and embracing innovative technologies, solar PV plant operators can create a data-driven safety culture that prioritises worker well-being and continuously evolves to meet the challenges of the ever-changing solar PV industry.

By adopting these best practices and fostering a culture of continuous improvement, solar PV plant operators can create a data-driven electrical safety programme that prioritises the well-being of personnel, minimises equipment damage, and ensures the long-term success of their solar PV operations.

Annex E Annual Maintenance Plan (Download it from www.solarpowereurope.org)

The utility maintenance plan is conceived for a 3-5 MW site (land-locked site far from seashore). The distributed maintenance plan is conceived for a 50 kW to 1 MW fixed mount rooftop installation with secure access. The maintenance plan applies for both utility and distributed solar plants.

The abbreviations describe the importance and frequency of the maintenance tasks related to each component of the solar plant:

D: Daily
M: Monthly
Q: Quarterly
SA: Semi-annual
Y: Yearly

nYr: Every n years
T: Total installation
S: Defined subset
R: Random subset

Annex E

Annual Maintenance Plan

Equipment	Task	Importance	Frequency	Extent
Modules	Integrity inspection & replacement	Minimum requirement	SA	T
	Thermography inspection	Recommendation	SA	T
	Measurements inspection	If required	Y	S
	Check tightening of clamps	Minimum requirement	Y	R
	Modules cleaning	According to local conditions	Y*	T
	Inspection and tightening the screws of the modules and fix substructure with proper torque	Minimum requirement	SA	R
	Sample internal inspection of junction boxes (if possible)	Recommendation	Y	R
Stock of spare parts	Inventory of stock	Minimum requirement	Q	T
	Visual inspection of stock conditions	Minimum requirement	Q	T
	Stock replenishment	Minimum requirement	M	T
Site Maintenance (Bifacial configurations)	Terrain Cleaning	Minimum requirement	M	T
	Visual inspection of ground conditions	Minimum requirement	Q	T
Buildings	Integrity inspection of O&M Buildings	Minimum requirement	SA	T
PV SCADA and PPC	Equipment fans cleaning	If required	SA	T
	General cleaning	Minimum requirement	Y	T
	PLC's power consumption checking	Minimum requirement	Y	T
	Equipment fans cleaning	Minimum requirement	Y	T
	Cables visual inspection	Minimum requirement	Y	T
	Check cables terminals	Minimum requirement	Y	T
Tracker	Battery replacement	Minimum requirement	Y	S
	Tracker meteo station POA pyranometers	Minimum requirement	Y	T
	Tracker meteo station thermocouples inspection and calibration	Minimum requirement	Y	T
	Check for corrosion, deformation or misalignments in the structure components.	Minimum requirement	Y	T
	General visual checks (fixings torque, earthing connections, status of modules fixings)	Minimum requirement	Y	T
Transformer	Check the torque mark of respective screw joints (visual inspection of the reference sign to avoid disconnections)	Minimum requirement	Y	T

*: SA if automated cleaning is not considered)

Annual Maintenance Plan

Equipment	Task	Importance	Frequency	Extent
Electrical cabinets and switchboards • Array/string junction box • Generator junction box • AC switchboards • AUX switchboard • General utilities switchboard • Weather station's cabinet • Monitoring system cabinet • Communication cabinet • Security system board • Other cabinets	Integrity check & cleaning	Minimum requirement	Y	T
	Documents inspection	if required	Y	T
	Check labelling and idenitifcation	Minimum requirement	Y	R
	Electrical protections visual inspection & functional test	Minimum requirement	Y	T
	Check fuse status	Minimum requirement	SA	T
	Check surge protection status (if applicable)	Minimum requirement	SA	T
	Check integrity of cables & state of terminals	Minimum requirement	SA	T
	Sensor functional verification (if applicable)	Recommendation	Y	T
	Meaurements inspection	Best practice	Y	T
	Thermographical inspection	Recommendation	Y	T
	Check tightening of clamps	Minimum requirement	Y	T
	Lubrification of locks	Minimum requirement	Y	T
	Monitoring operation tests (if applicable)	Recommendation	Y	T
Cables • DC/AC cables • Cables in switchboards, cabinets, inverters	Integrity inspection	Minimum requirement	Y	R
	Check labelling and identification	Minimum requirement	Y	R
	Check cable termianls	Minimum requirement	Y	R
	Insulation resistance measurement in the stretch between string box and panels	Minimum requirement	Y	R
	Measurements inspection	Recommendation	Y	R
Inverters • Central inverters • String inverters	Integrity check & cleaning	Minimum requirement	Y	T
	Documents inspection	Best practice	Y	T
	Check labelling and identification	Minimum requirement	Y	R
	Electrical protections visual inspection, check correct operations	Minimum requirement	Y	T
	Check fuses	Minimum requirement	SA	T
	Check surge protections	Minimum requirement	SA	T
	Thermographical inspection	Best practice	Y	T
	Sensors functional verification	Minimum requirement	Y	R
	Measurements inspection	Minimum requirement	Y	T
	Check parameters	Minimum requirement	Y	T
	Functional test of ventilation system	Minimum requirement	SA	T
	Check batteries	According to manufacturer's recommendations	(Y)	T
	Replace batteries		(3yr)	T
	Replace fans		(5yr)	T
	Safety equipment inspection	Minimum requirement	Y	T
	Clean filters	Minimum requirement	SA	T
	Replace filters	Minimum requirement	2yr	T
	Functional tests according to manufacturer (e.g., Insulance resistance, gorunding, fans functioning, etc)	Minimum requirement	Y	T
	General Visual checks to all switchgear, foundations, housing structure, connections, earthing points, etc.	Minimum requirement	SA	T
	Check temperature and humidity readings are within operational limits	Recommendation	M	T
	Thermographic measurements of bypass diodes (manually)	Minimum requirement	SA	T

Annual Maintenance Plan

Equipment	Task	Importance	Frequency	Extent
Transformer • Power transformer • AUX transformer	Integrity check & cleaning	According to local conditions	(Y)	T
	Check labelling and identification	Minimum requirement	Y	R
	Thermographical inspection	Best practice	Y	T
	Functional verification of sensors & relais	Minimum requirement	Y	T
	Check parameters	Minimum requirement	Y	T
	Check oil level (if applicable) and max. temperature	Minimum requirement	Y	T
	Check of coding system (fans) if applicable	Minimum requirement	Y	T
	Check of MV surge discharger devices (if applicable)	Minimum requirement	Y	T
	Oil analysis (if applicable)	Best practice	Y	T
MV switchgear incl. protection devices	Integrity check & cleaning	According tolocal conditions	(Y)	T
	Safety equipment inspection	Minimum requirement	Y	T
	Check labelling and identificcation	Minimum requirement	Y	R
	Electrical protections visual inspection	Minimum requirement	Y	T
	Thermographical inspection; if possible	Recommendation	Y	T
	Sensors functional verification	Minimum requirement	Y	T
	Measurements inspection	Minimum requirement	Y	T
	Check correct operation	Minimum requirement	SA	T
	Check fuse status	Minimum requirement	SA	T
	Check cables terminals	Minimum requirement	SA	T
	Battery / UPS check	Minimum requirement	Y	
	Mechanical lubrication	According to manufacturer's recommendations and necessity	(5yr)	T
	Replace certain mechanical parts		(5yr)	T
	Battery / UPS replacement		(3yr)	T
	Check protection parameters	According to local grid code	(3-5yr)	T
	Functional check of protection devices	According to local grid code	(3-5yr)	T
Power analyser	Integrity check & cleaning	Minimum requirement	Y	T
	Check labelling and identification	Minimum requirement	Y	R
	Measurements inspection	Minimum requirement	SA	T
	Software maintenance	Recommendation	Y	T
	Monitoring operation test	Minimum requirement	SA	T
	Check parameters	Minimum requirement	Y	T
Energy meter	Integrity check & cleaning	Minimum requirement	Y	T
	Functional certification and calibration	According to local code	3y	T
	Check labelling and identification	Minimum requirement	Y	R
	Check values and parameters	Recommendation	Y	T
	Check of communication devices (modern converters) if applicable	Recommendation	Y	T

Annual Maintenance Plan

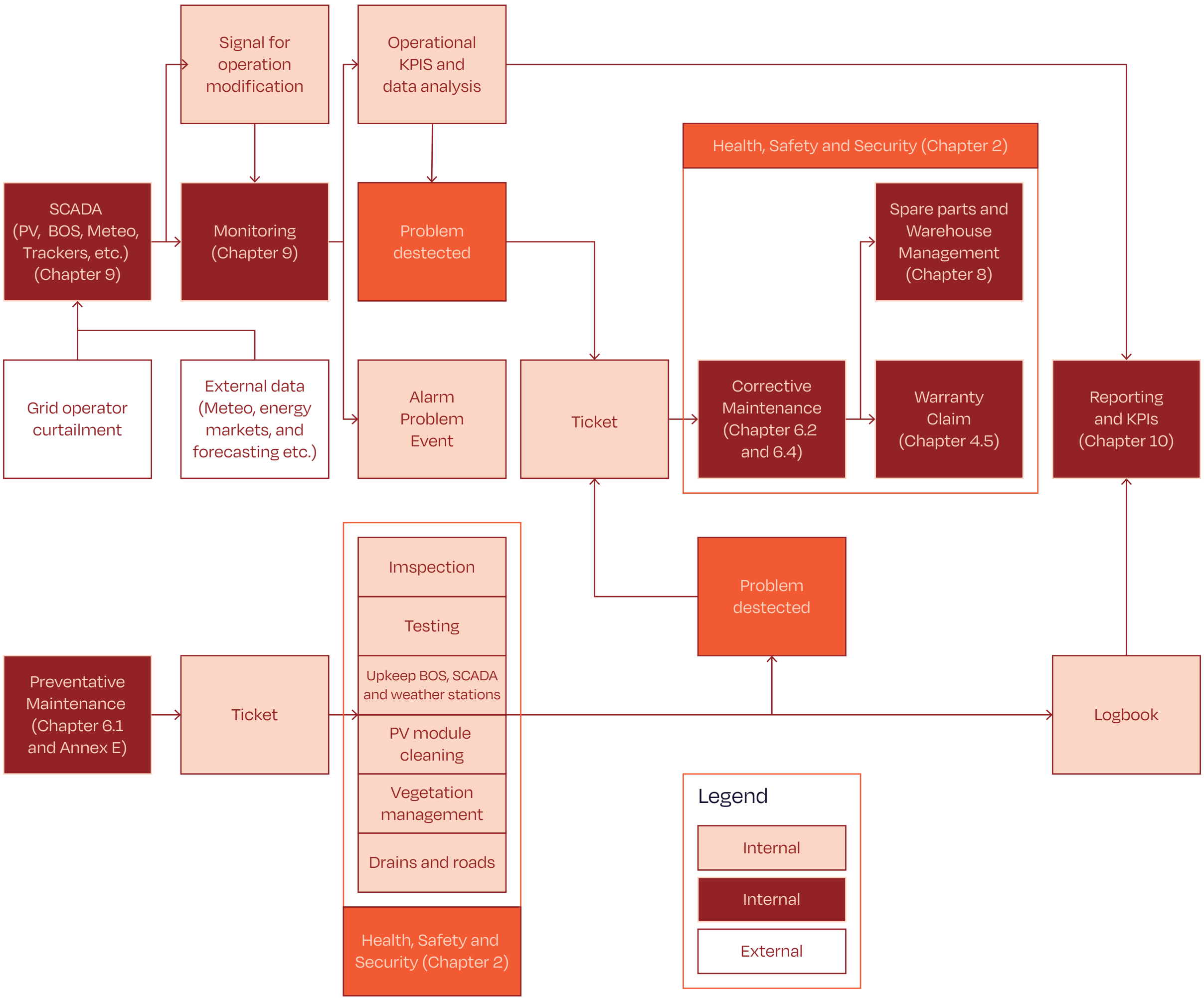
Equipment	Task	Importance	Frequency	Extent
Power control unit	Check batteries	According to manufacturer's recommendations	(Y)	T
	Replace batteries		(3yr)	T
	Functional verification		Y	T
	Integirty check & cleaning	Minimum requirement	Y	T
UPS	According to manufacturer's recommendations	Minimum requirement	Y	T
	Check batteries	According to manufacturer's recommendations	(Y)	T
	Replace batteries		(3yr)	T
	Functional test of ventilation system (if applicable)	Best practice	Y	T
Emergency generator (If applicable)	Integrity check & cleaning	According to manufacturer's recommendations	(Y)	T
	General maintenance		(Y)	T
	Check correct operation		(Y)	T
	Replacement of filters		(5yr)	T
Lights and electric sockets	Integrity check & cleaning	Minimum requirement	Y	T
	Check correct operation	Minimum requirement	Y	T
	Check conformity to local security standards	Minimum requirement	3yr	T
HVAC (if applicable)	Integrity check & cleaning	According to manufacturer's recommendations	(Y)	T
	Functional verification		(Y)	T
	Change of air filters		(Y)	T
Water supply system (if applicable)	Integrity inspection	If applicable	Y	T
Fire detection central (if applicable)	Integrity check & cleaning	According to manufacturer's recommendations and local requirements	(Y)	T
	Check correct operation		(Y)	T
	Battery inspection		(Y)	T
	Sensors functional verification		(Y)	T
	Cleaning of cameras & sensors		(Y)	T
Lightning protection (if applicable)	Integrity inspection	Minimum requirement	Y	R
Fences and gates	Integrity inspection	Minimum requirement	SA	T
	Lubrication of locks	Minimum requirement	SA	T
Vegetation	Vegetation clearing	According to local conditions	(Q)	T
Paths	Integrity inspection	Best practice	Y	T
	Vegetation clearing	Recommendation	Y	T
Drainage System	General cleaning	Minimum requirement	SA	T
Manholes	Integrity inspection	Best practice	Y	T
Buildings	Integrity check & cleaning	According to local requirements	(Y)	T
	Lubrication of locks	Minimum requirement	SA	T
	Documents inspection	According to local requirements	(Y)	T
	Check fire extinguishers		SA	T
	Check earthing		(3yr)	T

Annual Maintenance Plan

Equipment	Task	Importance	Frequency	Extent
Safety equipment	Integrity check & cleaning	Minimum requirement	Y	T
	Check correct operation	Minimum requirement	Y	T
PV support structure	Integrity inspection	Minimum requirement	Y	R
	Check tightening	Minimum requirement	Y	R
	Check potential equalization	Minimum requirement	2yr	T
Tracker system	Integrity check & cleaning	Minimum requirement	Y	T
	Check correct operation	According to ma0nufacturer's recommendations	SA	T
	Check tightening		(Y)	R
	General maintenance		(Y)	T
	Mechanical lubrication		SA	T
Weather station	Integrity check & cleaning	According to manufacturer's recommendations	M	T
	Functional test of sensors		SA	T
	Check correct operation		SA	T
	Check batteries (if applicable)		Y	T
	Monitoring operation test		Q	T
Irradiation sensors	Integrity check & cleaning	According to manufacturer's recommendations and local requirements	Q	T
	Calibration		2yr	T
	Monitoring operational test		D	T
Communication Board	Functional communications test	Minimum requirement	SA	T
Intrusion detection and verification system	Integrity check & cleaning	Minimum requirement	Y	T
	Functional verification of intrusion detection	According to manufacturer's recommendations	Y	T
	Functional verification of alarming		Y	T
	Functional verification of cameras		M	T
	Specific maintenance		Y	S
Stock of spare parts	Inventory of stock	Minimum requirement	Q	T
	Visual inspection of stock conditions	Minimum requirement	Q	T
	Stock replenishment	Minimum requirement	M	T

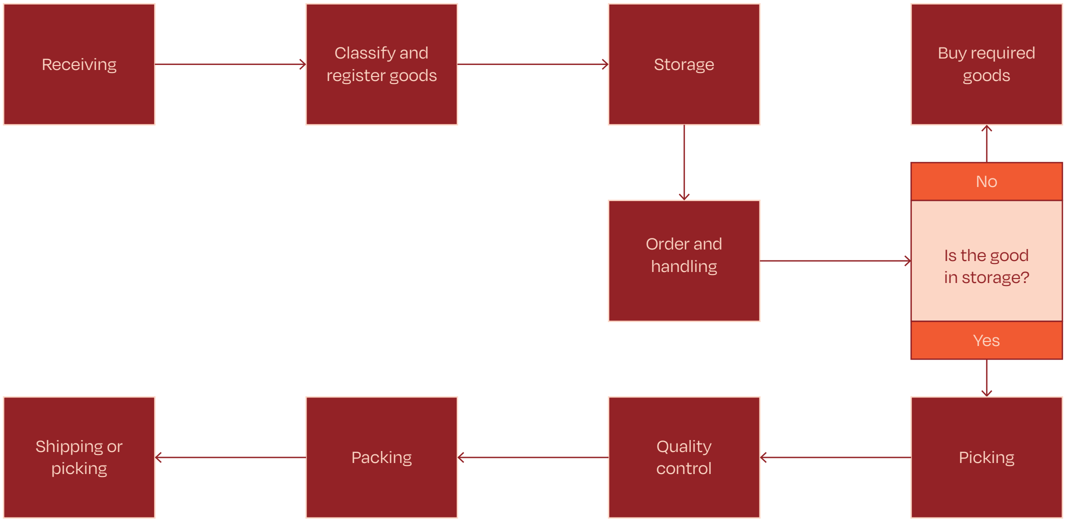
Annex figure 1

O&M Workflow



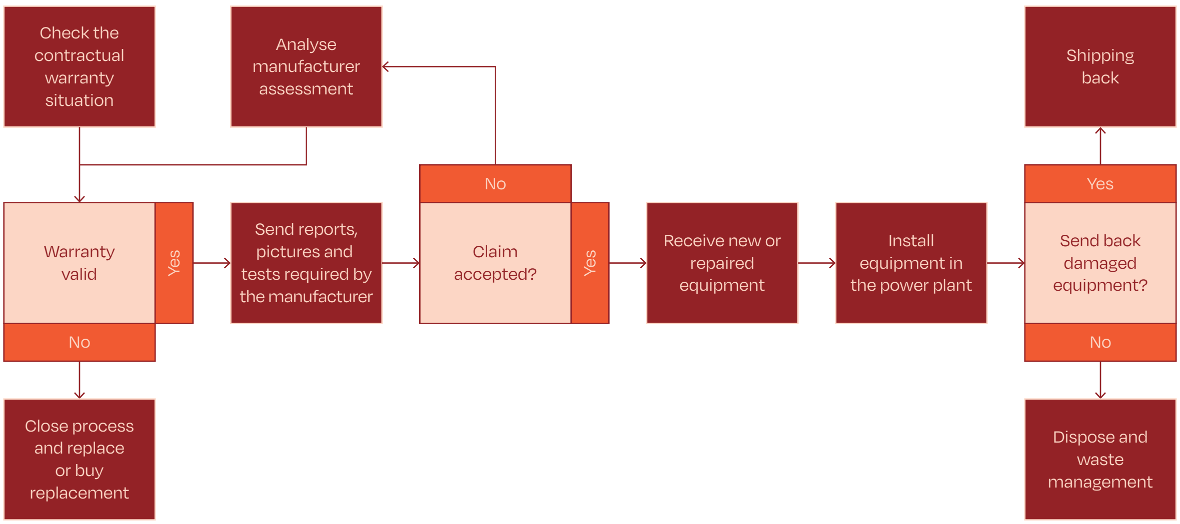
Annex figure 2

O&M Workflow - Warehouse Management



Annex figure 3

O&M Workflow - Warranty claim



SolarPower Europe

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SolarPower Europe

Leading the Energy Transition

SolarPower Europe, the premier association for the European solar PV sector, unites 320+ organisations. Collaborating with members, we shape regulations and business landscapes for solar's growth.

Our dedicated policy experts lead focused workstreams, addressing key issues and influencing legislation. Based in Brussels, we build strong relationships, ensuring solar's pivotal role in the European energy transition.

As co-founders of the RE-Source Platform, Renewable Hydrogen Coalition, and the European Solar Initiative, we actively engage in EU and international projects, fostering partnerships with 40+ organisations globally.

SolarPower Europe's top analysts provide market intelligence through reports like the Global Market Outlook for Solar Power and EU Solar Jobs Report. Our events, including the SolarPower Summit and RE-Source, bring policymakers and stakeholders together for networking and business opportunities.

Quick Facts

SolarPower Europe was established in April 1985 – we will celebrate our 40th anniversary in 2025!

Almost 90% of our members are European headquartered companies

SolarPower Europe represents over 40 national solar energy associations across Europe

SolarPower Europe won 'European Association of the Year' at the International & European Association Success Awards 2024

Rond-point Robert Schuman 3,
1040 Brussels, Belgium

info@solarpowereurope.org
www.solarpowereurope.org