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TOWARDS CLIMATE-SPECIFIC O&M FOR PV PLANTS: GUIDELINES AND BEST PRACTICES

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ABSTRACT: Considering that nearly half (40%-50%) of the photovoltaic (PV) plants are less than just 5 years old, the cumulative knowledge and return-of-experience (REX) from PV operations and maintenance (O&M) are at their relative infancy; particularly where it relates to the impact of different climatic profiles on the budgeting, technical risks and customization of PV O&M. Besides, one of the main challenges in tailoring O&M for a specific PV application in a certain climate zone is the present scarcity of comprehensive guidelines and/or standards, which only clarify the minimum requirements of climate-specific O&M and their implementation. Recently, experts of the IEA PVPS Task 13 have gleaned best practices and guidelines for O&M in different climate zones/profiles, covering all key aspects of the typical PV O&M agenda, based on field experiences of the contributing PV and O&M experts from multiple countries representing the climate zones addressed. In this paper, we provide the key findings of this work: a comprehensive guide on setting up a customized O&M practice for PV plants in seven different climate zones, four of which are general (moderate, hot and dry, hot and humid, desert in high elevation), and three which are more specific to extreme conditions (flood-prone region, cyclonic region, snowy region). In terms of novelty, we particularly emphasize on (existing and new) knowledge and practices for PV O&M in the last three climatic profiles/regions, which present distinct challenges from a PV performance and reliability point of view. As such, the climate-specific O&M guidelines presented in this report aim to serve different functions to various stakeholders depending on their roles in the entire value chain of PV.

Keywords: *PV systems; Operations & Maintenance (O&M); PV field experience; PV systems reliability.*

1 INTRODUCTION – RATIONALE

In view of the (ongoing) rapid growth of photovoltaic (PV) installations worldwide, nearly 60% of the PV plants are less than just 5 years old [1], with more GW-scale PV markets in different climatic regions each year. With PV technical (service) lifetimes expected to reach 25 to 40 years or more, it becomes clear that the cumulative knowledge and return-of-experience (REX) from PV operations and maintenance (O&M) are at their relative infancy; particularly where it relates to different climatic regions, i.e. climate-specific O&M. For instance, multiple (individual or combined) stress factors such as temperature, humidity, exposure to UV light, rain, and wind would indeed contribute differently to the occurrence of PV degradation or failures in diverse climate zones and conditions worldwide; consequently, dictating different strategies for PV O&M.

Given that O&M costs constitute a large portion of

total Operational Expenditures (OPEX) at 30%-70% [2] and that future O&M costs are inherently uncertain, much uncertainty in the real versus modelled Levelized Cost of Electricity (LCOE) remains. In a globalised world where investors and owners, O&M providers and installers (EPCs) operate in multiple countries with varying climates, it pays to understand and apply general best practices for O&M, supplemented or modified with climate- and site-specific practices.

Typically, PV plant operators adopt a rather standard scope of O&M services (Fig. 1) that could be replicated easily across to reach an optimal point between minimizing O&M efforts (and therefore OPEX), while maximizing PV plant uptime, performance and durability. However, a shift from the one-size-fits-all approach to a customized O&M approach could offer an advantage that the O&M activities are adapted for the needs of the PV plant, focusing on what maintenance activities are necessary for that specific plant and climate zone [1].

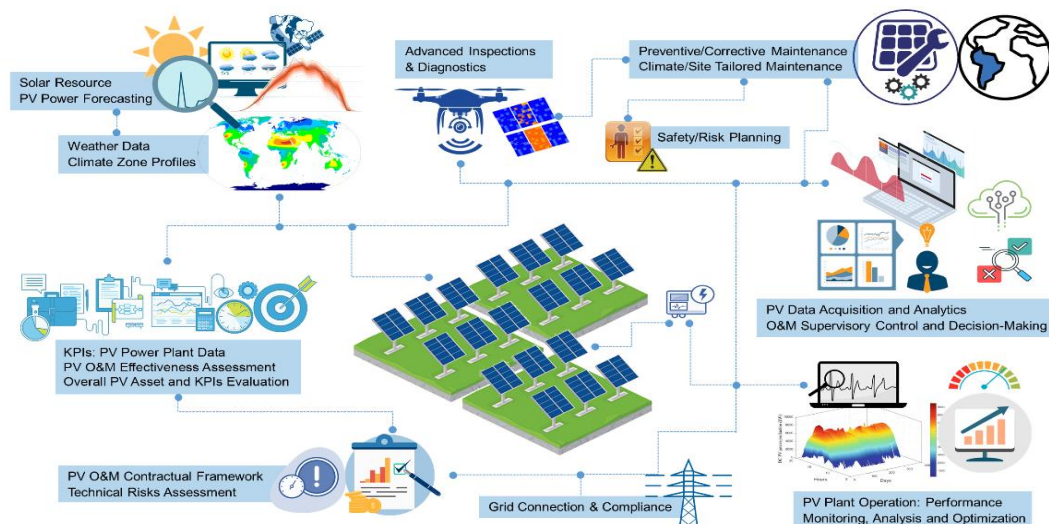


Figure 1: Overview of the different O&M aspects and services for PV power systems [2].

2 SCIENTIFIC RELEVANCE – APPROACH

The keystone towards PV O&M tailored to specific climate zone(s) lies upon comprehensive REX from PV developers and O&M service providers on worldwide scale. At present, insights into climate-specific PV O&M remain scarce, sporadically reported, and therefore relevant guidelines have yet to be developed. To this end, and with these “knowledge gaps” in mind, experts of the IEA PVPS Task 13 have gleaned best practices and guidelines for O&M in different climate zones/profiles, covering all key aspects of a typical PV O&M agenda (Fig. 1), ranging from the regulatory, risk/safety and asset management level, up to the operational level (notably the monitoring/inspections, data analytics, maintenance, and optimization).

This paper presents the key findings of this work, the basis of which is formed by O&M guidelines recommended for all PV plants and illustrated for moderate climates, with an additional six climate types or regions selected for their specific characteristics and PV installation (and penetration) potential. The selected

climatic regions and their Köppen-Geiger classification are given in Fig.2. The first four refer to conditions which broadly prevail in large parts of the world (moderate, hot and dry, hot and humid, desert at high elevation), while the latter three refer to extreme conditions (flood-prone, cyclonic and snowy regions).

These guidelines and best practices can assist PV plant engineers and designers, financing parties, and investors in designing and maintaining PV plants, as well as in determining operational risk related to investment decisions. The O&M provider must aim to perform its contractual duties within the context that certain system design choices have been previously fixed at the design and EPC stages, subject to the knowledge at that time, which includes assumptions about climate change and the likelihood of extreme weather events (EWEs). O&M providers may have different levels of sophistication and provide different strata of quality, based on the agreed-upon contractual framework and fees.

Region and climate profile	Köppen-Geiger classification
Moderate (e.g. mainland Europe)	Csa-Csb-Cfa-Cfb-Cfc
Hot and dry (deserts, e.g. Israel, Australia)	BWh or BWk
Deserts in High Altitudes (e.g. Atacama)	BWn-BWk-BWk'-ETH
Hot and Humid (e.g. South-East Asia)	Af
Flood-prone (e.g. monsoons India)	Am
Cyclonic (e.g. Japan, Caribbean)	Cfa, Aw
Alpine/Snow-prone (e.g. Alaska)	Dfb-Dfc-Dfd-ET-EF

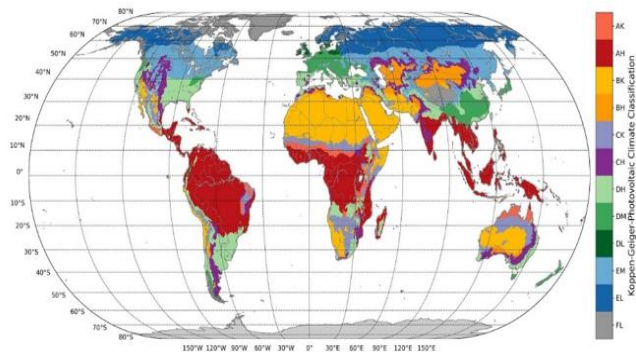


Figure 2: Left: Regions investigated for the climate-specific O&M guidelines. Right: Climate classification and implications to worldwide mapping for PV O&M [3].

3 KEY FINDINGS – DISCUSSION

3.1 Maintenance actions and cost considerations for PV

Preventive maintenance (PM) action plans that exclude redundant activities can bring costs down. The PM plan should seek to optimize the overall PV plant and O&M budgeting, depending on the plant's size, design, complexity, and environment. In overall, the most important – commonly reported – maintenance actions include periodic sampling of individual electrical measurements at module level, soiling and snow mitigation, site and vegetation management as well as upkeeping of balance of systems (BOS) and SCADA (supervision control and data acquisition) monitoring systems.

During PV operational years, it is important to consider vegetation growing on adjacent PV assets, especially if these will cause shading on PV arrays, which can then result in hot spots (Fig. 3). Site and vegetation management, depending on the site/climatic conditions and the size of the PV plant, can be both challenging and labour/cost intensive, particularly in moderate and tropical

(hot, humid) climatic profiles. On the other hand, in arid or alpine areas for instance, mowing may be unnecessary with proper soil stabilization. For areas where mowing is required, there is the added risk of projectiles damaging modules. In the latter case, vegetation management “strategies” that have gained increasing popularity in the last years include the collaboration with local farmers in using certain species of grazing animals.

Similarly, regular cleaning of modules from dust (soiling) or snow is an imperative PM action in PV plants installed in certain geographical locations and climates, e.g. hot arid, desert and alpine regions. As well known, soiling (Fig. 4) can result in considerable losses in the PV energy yield on both seasonal and annual scale. Also, as in the case of unwanted shading from vegetation, cases of uneven, localized soiling (dirt e.g. from bird droppings, Fig. 3, right) can lead to hot-spot effects on PV modules and risks of follow-up failures or even fire hazards. Upon cleaning of PV arrays, care should be taken, in compliance with manufacturer's recommendations, to avoid damaging the different PV components. For instance, cleaning solutions shall be based on plain demineralized water and mild detergents.

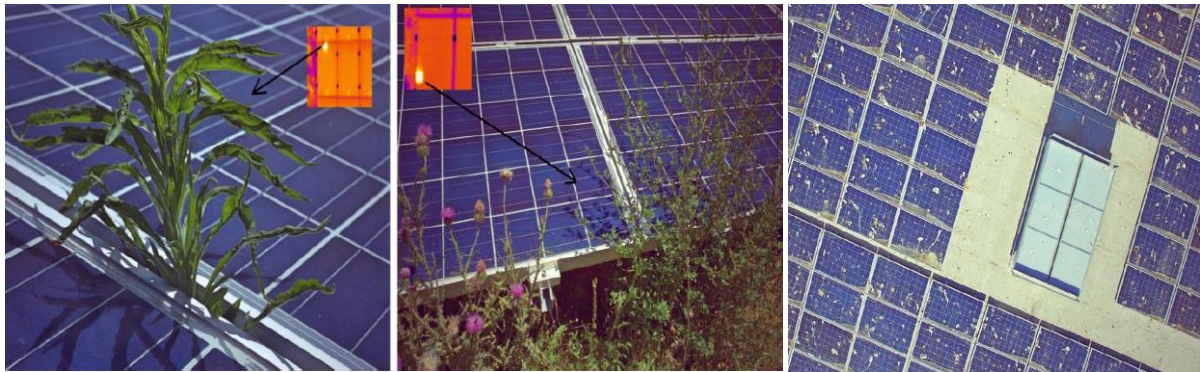


Figure 3 : Examples of shading (left, middle) and excessive soiling from bird droppings (right) caused by poorly managed vegetation and absence of cleaning respectively, in PV plants installed in Europe (moderate climate) [4].

Independently of the climatic zone of a PV plant is installed, O&M service providers tend to overestimate PV O&M budgets to offset both their own margins and uncertainties or technical assumptions. On the other hand, PV plant developers typically follow a more moderate or underestimating budgeting approach for PV O&M, to allow higher PV plant valuations, more “motivating” revenue prospects.

As aptly noted by Enbar et al. [5], such contrasting O&M budgeting viewpoints can ultimately undermine a PV plant’s lifecycle performance economics. In Table 1, we provide a non-exhaustive list of representative costs and remarks associated with the main PM tasks, as publicly reported in the years 2021/2022, specific for utility-scale PV plants.

Table 1: Representative costs of main preventive maintenance tasks in PV plants [2].

PM Task	Costs	Remarks
Base O&M scope	6 - 14 €/ kWp/ year	Includes: full preventive maintenance scope, regular module cleanings, security (remote or on-site); excl. IR and EL scans. Varying highly with the site characteristics, labor, and frequency of activity.
Cleaning/washing of PV modules [83]	0.5 - 2.5 €/ kWp/ year	Varying with the module technology, labor, cleaning solution and method, climatic conditions (affecting the frequency), etc.
IR scans	0.5 – 3.0 €/ module	Includes drone inspections, analysis, and reporting
EL scans	3.0 – 10.0 €/ module	



Figure 4: Example of (sources of) soiling in PV installations [2].

3.2 O&M best practices and recommendations in different climates/regions

O&M in flood prone regions

To date, few if any such plants have been designed with repeated flood endurance in mind. Yet, climate change and extreme weather events, combined with limited availability of land in certain parts of the world, mean that in some areas nowadays, PV plants may be subjected to flooding on an annual or even quarterly basis.

PV plants are yet to be flood-hardened through the design and orientation of the mounting system to likely water flow direction, selection of equipment (e.g. PV

modules with IP68 rated junction boxes) and raising of inverters and transformers above likely flood levels. Floods can damage module mounting clips, PV modules, the lamination on panels, and even uproot foundations (Fig. 5). Soiling damage is particularly difficult to repair when water has been standing on the PV modules for a long time. Inverters connected to flooded systems may see repeated arcing and have increased fire risks, despite not being submerged; submerged inverters typically see short-circuits and require significant repairs. Fast flowing water can also cause debris impact because most PV mounting systems present a high resistance to flowing water.

Consequently, O&M activities for flooding events may have a proactive nature (shutting a PV plant down before a flood arrives, if enough time is available), as well as a potentially large reactive set of actions. Once flood waters recede, the plant must be inspected. O&M staff must be given appropriate Personal Protective Equipment (PPE) and training for post-flood site visits, and repair and

cleaning activities. Depending on the scale or nature of the flooding event, and the degree of insurance coverage, different approaches can be taken. For “light” flooding events and/or self-insured systems, the O&M provider will have to look to restore the system to its operational state. For this, spares management may be key, and the location of storage of spares a flow-on risk.

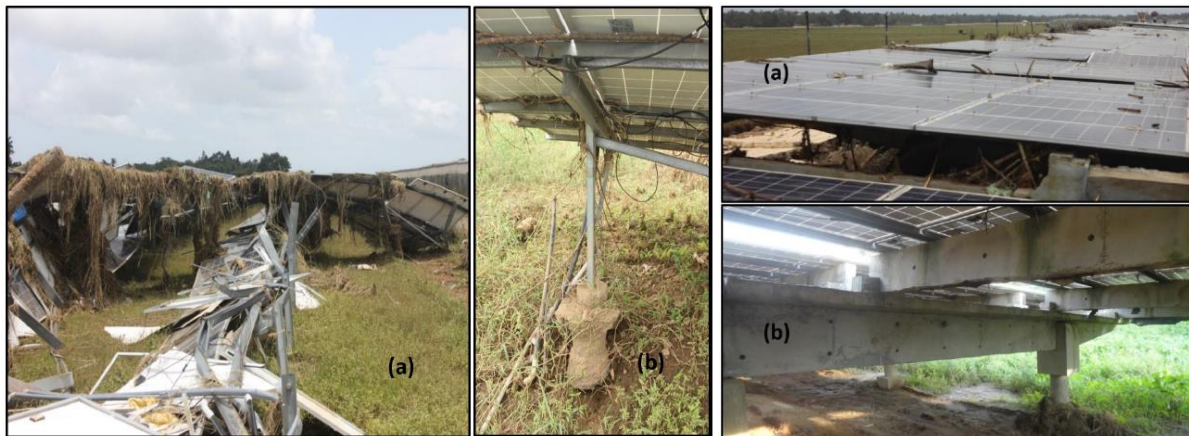


Figure 5: Damage to modules and structures (a-left) and structures' foundations (b-left) due to submersion with fast-flowing waters [2]. Another case of a PV plant after having been submerged under fast flowing water, showing limited damage on the upper part of its PV arrays (a-right), with a view of its all-concrete structure underneath (b-right).

O&M in snow prone regions

PV systems in snowy regions may be subjected to significant electrical mismatches (shading) and snow loads that exceed the module qualifications according to IEC 61215. A suggested limit for snow accumulation on panels is 0.7m. PV racking systems can also be damaged by extremes between winter and summer temperatures. In this case steel racking is preferred over aluminium racking. Even for systems where snow loads are below the module threshold, issues may appear.

To minimize such snow-load associated risks, appropriate PV array design strategies can be beneficial for “passive” snow mitigation, such as in the case of high tilted or vertical installations (Figure 6, left) [6]. If active cleaning measures such as mechanical cleaning (brushing or similar) are implemented, care must be taken not to scratch the glass as well. As an example, Fig. 6-right

shows how inappropriate cleaning techniques can damage PV modules [7]. Similarly, (micro-) cracks can be initiated by snow loads, which can be then detected using electroluminescence (EL) inspections. This thus requires a different or additional set of skills and equipment by the O&M provider or their subcontractors.

Recent research and in-field experiments have been conducted to heat PV modules by applying a controlled forward voltage to melt the snow [8]. This would require careful load control and the use of weather forecasts. In this study, the forward biased PV modules' abilities to melt snow was assessed both in a climate chamber as well as in an operating rooftop PV system covered with snow. The main purpose of the PV system investigated was to mitigate snow from under-dimensioned roofs before, during, or after heavy snowfalls, and to keep the roof from collapsing from snow loads.



Figure 6: Left: Test site in Piteå, Northern Sweden (65°N) showing the impact of PV array tilt angle on the snow accumulation, for the studied case of frameless bifacial PV modules [6]; Middle and Right: PV module damage due to inappropriate snow cleaning of a PV array [7].

O&M in remote PV plants in hot arid regions

PV plants in such regions are routinely subjected to high temperatures and high irradiance (with high UV

content); and, in some cases, high temperature variations between day and night hours. Typical risks and failures include increased soiling losses, cell cracks, optical degradation, damages to equipment such as cables (e.g.

due to termites). Adequate ventilation during hot months is crucial for good operating conditions of the inverters installed in such sites.

Inspections and site management are typically scheduled in the early morning hours and must consider numerous risks e.g. heat strokes, the presence of stray wild livestock, venomous insects, etc. Vegetation management is typically reactive and implemented together with fire breaks to facilitate access to the PV arrays.

When vegetation is present, soiling of PV modules is usually less of a problem in hot and dry climates; instead, yield losses due to rapid crop growth after rain events are possible. On another note, fire risks can also be posed by agricultural activities, e.g. field clearing, in the proximity of such PV plants. In view of these risks, in these areas, vegetation management is also implemented together with fire breaks (physical barriers that impede the spread of bushfires, such as cleared roads at the edges of PV plants)

to facilitate access to the PV arrays. Besides, vegetation management is often reactive, i.e. following rapid vegetation growth after rainfall events, and the contracts often reflect these reactive activities.

With regard to soiling mitigation, due to the relative remoteness of such PV sites and their impact on the system maintainability, combined with relatively low pollution losses, the use of automatic soiling management systems (e.g. cleaning robots) has been limited to date. On the other hand, on hot and dry climates without vegetation, soiling losses are usually higher, and therefore the need for automated module cleaning solutions has increased, particularly with fully automated dry brushing (in view of high costs and low availability of appropriate low-mineral water). Cleaning schemes can decrease production losses of PV modules by as much as 6-8% during summer months in these PV sites.



Figure 7: Left: Vegetation management of PV plant in Central Australia [2]; Middle: PV module (from a PV array in Central Australia) damaged during vegetation management due to pebbles [2]; Right: Automated cleaning of soiled PV modules in the Negev Desert, Israel [2].

4 CONCLUDING REMARKS – OUTLOOK

Through this study, Task 13 experts shed light on PV O&M best practices and guidelines, which are indispensable for reaching (or even exceeding) the expected service lifetime of PV systems in different climatic profiles and site characteristics.

A combination of well-designed O&M specifications, proactive monitoring systems and a flexible and tailored O&M regime that considers both climatic impact on PV systems as well as possible changes to grid requirements are good practices to ensure that PV systems reach or even exceed the expected lifetime. Taking these recommendations into account in operating a PV power plant e.g. in flood-prone conditions, hot arid (and remote) regions or in sites subjected to significant snowfalls will help proactive asset owners and O&M providers in identifying problems before they become serious and help prevent losses from avoidable circumstances.

Overall, calculating the risk profile of PV power plants in different climates may prove beneficial. On that note, we reckon that PV asset owners need to re-evaluate their risk appetite and the willingness to pay for higher resilience of PV systems (e.g. physical elevation of inverters, installing flood barriers, installing hardware and software to proactively shut down PV plants in case of extreme weather events).

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