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TOWARDS REUSE-READY PV: A PERSPECTIVE ON RECENT ADVANCES, PRACTICES AND FUTURE CHALLENGES

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ABSTRACT: Despite its rapid expansion, PV industry confronts challenges (and questions) in end-of-life management (EoL) as the cumulative PV waste is projected to escalate exponentially in the next two decades. The surge in revamping and repowering activities, notably in early PV fleets, accentuates the imperative of refining EoL strategies, emphasizing the need for higher PV reuse-readiness. In the transition from PV operations to EoL, streamlined PV triage/qualification and efficient PV repair strategies become indispensable, to ensure reuse-ready PV and a bankable second-life PV market. In this perspective study, we attempt to shed light on recent research, innovations, practices and future challenges towards higher reuse-readiness in the PV industry; encompassing qualification/triage methods, PV repair strategies, and standardization. An exemplary triage-for-reuse framework is discussed, involving four steps (off-site eligibility checks; on-site inspections and functionality tests; sorting for collection and transportation; and deeper technical checks) and emphasizing the importance of digitalization and advanced inspection, as well as the need for a defined functionality threshold in the absence of standardized regulations for second-life PV. Further, the study reviews recent advances and research in repair strategies for reuse – addressing notably reliability issues of glass-backsheet PV modules – as well as ongoing standardization efforts, underscoring their key role to address the pressing need for resource-efficiency in the entire PV products' lifecycle: from design/material level to system, operations and maintenance (O&M) and EoL.

Keywords: PV reuse; PV repair; circular economy; PV sustainability; PV O&M for reuse.

1 RATIONALE and AIM

The crossing of the 1 TW mark of global installed PV capacity in 2022, was followed by an over 50% year-over-year (YoY) growth of newly added PV installations in 2023; hence a further impressive 43% YoY growth of global cumulative PV, based on latest market data [1]. Despite the recent rise in PVs levelized cost of electricity (LCOE), for the first time this decade, such numbers clearly indicate that solar PV is on an increasingly fast track. This, in turn, raises important questions – if not concerns – regarding the preparedness of the PV industry towards resource-efficiency and streamlined end-of-life management (EoL), from design up to operation and maintenance (O&M) level.

According to current figures, approximately 2.7 to 3.3 million PV modules are installed every day around the world. Considering an average annual in-field failure rate of 0.2% in the field [2], we can anticipate at least 7 to 9 million PV modules (including those already installed) to fail on annual basis, contributing to a potential annual 162 kt of PV waste resulting solely from failures. Accounting then for the rest of PV waste sources/streams, e.g. decommissioning by the end of PV service lifetime, revamping and repowering efforts, insurance or contractual claims, etc., the cumulative PV waste is well on track to escalate from at least 4 Mt by 2030 to almost 50 Mt in 2040 and more than 200 Mt by 2050, should the early loss scenarios unfold, according to the recent reports [3].

Notably in the case of the very first PV fleets installed during the boom of feed-in tariff schemes, which have now passed mid-life (10+ years old), we are witnessing an unprecedented wave of revamping and repowering activities, involving the replacement of well-functioning 10-

15 years old PV modules in utility-scale PV power plants. In this context, it is estimated that up to 80% of the PV waste stream concerns replaced products and premature failures, instead of PV modules reaching the end of their designed service life. Tsanakas et al. [4] and H2020 CIRCUSOL experts estimated that about 2/3 of these PV modules can be repaired/refurbished and reused. Therefore, about 50% of the PV waste can be diverted from the recycling path, today's default strategy for decommissioned PV modules in Europe.

This paradigm shift underscores the growing need for optimizing EoL management strategies in PV industry, towards higher reuse readiness. Besides, there are certain key metrics/differentiators to assess the techno-economic bankability of PV reuse [4]:

1. The addressable volume and costs for functionality testing/repair, directly influencing the profitability of the PV reuse (second-life) market.
2. The reliability, safety and residual efficiency of the post-repair PV product for reuse, having a direct impact on the “confidence” of the second-life PV market.

In this context, for the transition from PV operations to EoL, streamlined **PV triage/qualification methods** and efficient **PV repair strategies** become indispensable in the “prepare-for-reuse” scheme, to ensure PV reuse readiness and (ultimately) a bankable second-life PV market. Still, today, industry practices and insights into these two topics are yet inconsistent and scarce, whereas there is standardization efforts (IEC TC82, EC level, VDI, ASTM) are at a relatively infant stage.

In this perspective study, we attempt to shed light on recent research, innovations, practices and future challenges towards higher reuse-readiness in the PV industry. In the next three sections, in particular, we review, discuss and assess the state-of-play in: i) qualification/triage methods for PV reuse, ii) PV repair strategies and iii) efforts on repair/reuse standardization and integration in the current PV (and O&M) value chain.

2 STATE-OF-PLAY IN QUALIFICATION/TRIAGE FOR PV REUSE

The qualification and triage of PV modules for reuse comprise health assessment and functionality tests, typically based on inspection and characterization methods, adhering to the principles of established technical criteria and standards such as the IEC 61215. In the recent years, research and industry programs introduced technical advances and best practices of PV preparedness for reuse. BayWa and other actors from the PV sector, have recently outlined a qualification and triage framework for PV reuse in four steps (Fig. 1): i) off-site eligibility checks, ii) on-site inspections and functionality tests, iii) sorting for collection and transportation, iv) deeper technical checks [5].

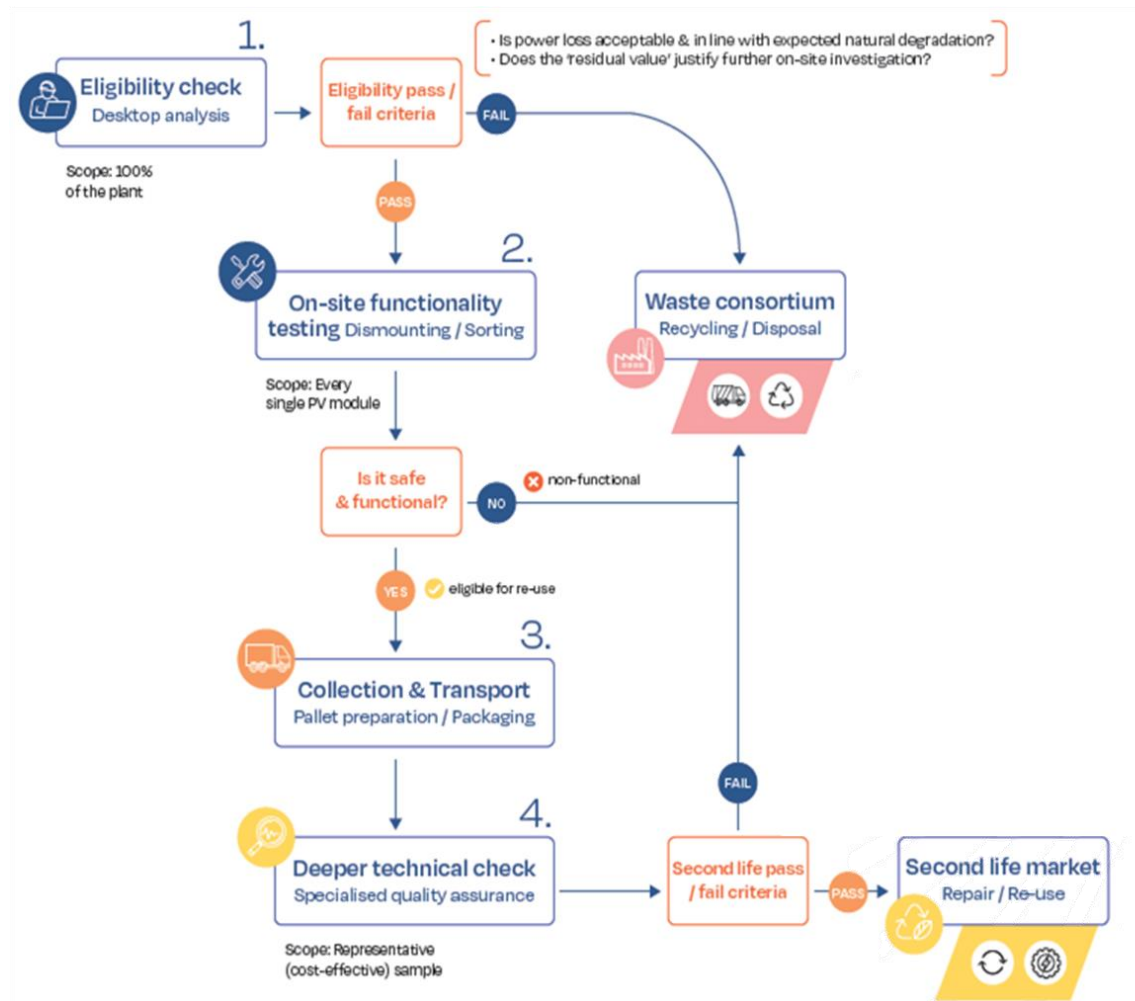


Figure 1: A four-step scheme suggested for PV qualification for reuse [5]. ©SolarPower Europe

Off-site (“desktop”) eligibility checks can be based on recent advances in PV data monitoring analytics [6,7], to assess PV plants’ health state, pinpoint underperforming components (e.g. in terms of power loss rate) and therefore determine the necessity of follow-up on-site inspection(s). The latter may include infrared (IR) imagery and I-V tracing campaigns on at least annual basis, while EL inspections are favored when precise triage, classification and root-cause analysis are necessary.

On-site inspections and functionality checks for reuse are carried out either at the decommissioning site or at a treatment site with suitable inspection and repairing facilities. Yet, priority is given to mobile test labs and/or on-site inspections, to allow swift assessments and minimize risks of further damage during transportation.

Besides, before removing and verifying the individual modules of a PV plant, general input data should be collected, e.g. PV module serial numbers, nameplate electrical parameters, bill of materials (BOM), etc [8].

Recent studies [9] and reports [10] outline the main methods, test protocols and latest innovations for on-site inspections suitable for triage/qualification of PV modules for reuse, primarily on the basis of visual inspections and I-V tracing, per IEC 61215, as well as ground and/or aerial IR imagery, per IEC TS 62446-3. In addition to these, follow-up a minimum set of safety testing and associated triage criteria are recommended, including the IEC 61730-2 MST 13 (ground continuity, to check if all frame parts are electrically connected) and MST 16 (isolation resistance, determination if the module is sufficiently well-

insulated between current-carrying parts and the frame or the outside world). PV modules failing these safety tests should be diverted to the recycling stream, or alternatively be considered for PV configurations of lower system voltages (<60 V) [8].

In [4] and [8] researchers have proposed a classification matrix for PV modules' eligibility for reuse, based on three main criteria: i) technical feasibility of repair, ii) economic feasibility of repair, iii) post-repair safety (including warranty) and residual value/power ratio. In such matrix three distinct "reuse eligibility classes" have been identified (Fig. 2, left):

- Class 1 (A and B): Reuse without further handling is possible.
- Class 2 (C to G or H): Deeper technical checks and/or repair are needed.
- Class 3 (H and I) Non-functional, non-repairable, enter recycling stream.

In support of such need for swift on-site faults classification, particularly in the field of image-based inspections, recent innovations introduced in EU-funded H2020 projects SERENDI-PV and TRUST-PV use from (aerial) imagery data, notably IR and visual ones, to yield

rapid diagnostic assessments of PV plants, can be further leveraged for qualification/triage of PV modules for repair and reuse (Fig. 2, right).

Although such emergence of PV qualification/reuse schemes and technical advances over the last years, the intrinsic ambiguity of the eligibility criteria/metrics proposed for the qualification and triage of PV modules, remains a stumbling block. While for common electronic equipment, functionality tests and qualification for repair/reuse are, in principle, straightforward (i.e. "it works / it does not work"), for the case of PV modules, to answer the question "When should a PV module be considered as not (sufficiently) functional?", a lower limit for the remaining power or the performance loss rate (PLR) is needed to be set. Such functionality "threshold", is crucial for the waste legislation, since non-functional products are considered as waste. As of today, a threshold of at least 70% of the PV module's (original) nominal power was proposed by H2020 CIRCUSOL experts [7]. Yet, as far as the regulatory landscape for second-life PV remains uncertain and inconsistent, with the current lack of standardization in testing/triage procedures for reuse, a PV functionality threshold may be somewhat arbitrary.

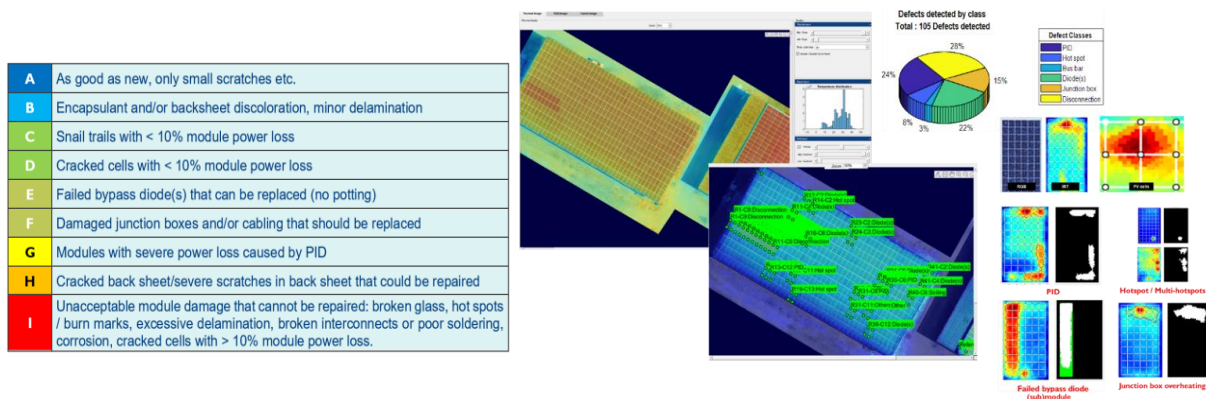


Figure 2: Left: Classification matrix for PV modules triage and eligibility for repair/reuse. Right: Example dashboard outputs from ASPIRE, a software prototype introduced by CEA, aimed for image-based detection, classification and triage of PV failures [11].

3 STATE-OF-PLAY IN REPAIR STRATEGIES FOR PV REUSE

Extending the lifetime of PV modules is one of the most pressing challenges facing the PV industry. Field experience clearly shows that the reliability of glass/backsheets modules often depends on the lifetime of the polymer backsheets, with a significant portion (over 40%) of material failures in PV modules due to cracking, delamination, and material degradation/yellowing of the backsheet film. Most serious is the potential resulting drop in electrical insulation resistance (R_{iso}) of the backsheets, which can have a significant impact on PV system yield. A repair coating can address the moisture sensitivity of the aged backsheets. An Austrian research team therefore investigated possible strategies for repairing backsheets, using cracked polyamide-based backsheets as the first test case [12-16]. Two different repair strategies have been addressed: (i) repairing BS damage of deep cracks by coating to restore electrical insulation properties, and (ii) preventing further growth of the surface near microcracks. A repair process has been developed that comprises the following steps [13]: (i) cleaning, (ii) pretreatment (if

necessary) and (iii) repair process (crack filling and sealing) (Fig. 3).

From a technical point of view, several of the repair solutions examined met the defined requirements for compatibility and applicability. On the one side, repair tapes / films perfectly sealed the surface but filling of the cracks was only achieved when the adhesive could penetrate into the cavities that had opened through the cracks in the backsheet material (PSA). On the other side, several repair coatings based on polyurethane, epoxy, silicone and synthetic rubber were identified which, after a two-step application process, showed complete crack filling and sealing of the surface. The required insulation resistance of the aged modules could be restored. The important topic of long-term reliability of the repaired modules and the effectiveness in stopping crack-propagation were also addressed [14-16]. Artificial reliability tests were performed and natural weathering test were/are performed. PV-plants with repaired modules with deep longitudinal cracks and microcracks are in operation now since August 2021 [15] and June 2020 [16], respectively.

Based on these results it can be concluded that for a

successful repair of modules with deeply cracked BSs, complete sealing of the deep cracks and the entire weathered and often microcracked backsheet surface is necessary to stop further material degradation of the backsheet regain its electrical insulation and avoid electrical power loss. The long-term performance of the repaired PV-system was followed (electrically and material wise) under real conditions. After coating and 30

M natural weathering (i) no changes in electrical characteristics, (ii) no inverter tripping events due to leakage current as well as (iii) high stability of the coating in the spectroscopic (IR, NIR, Raman) measurements and adhesion tests was found. Therefore, initial positive predictions can be made about the long-term behavior of the repair and its life-extending effect of PV modules.

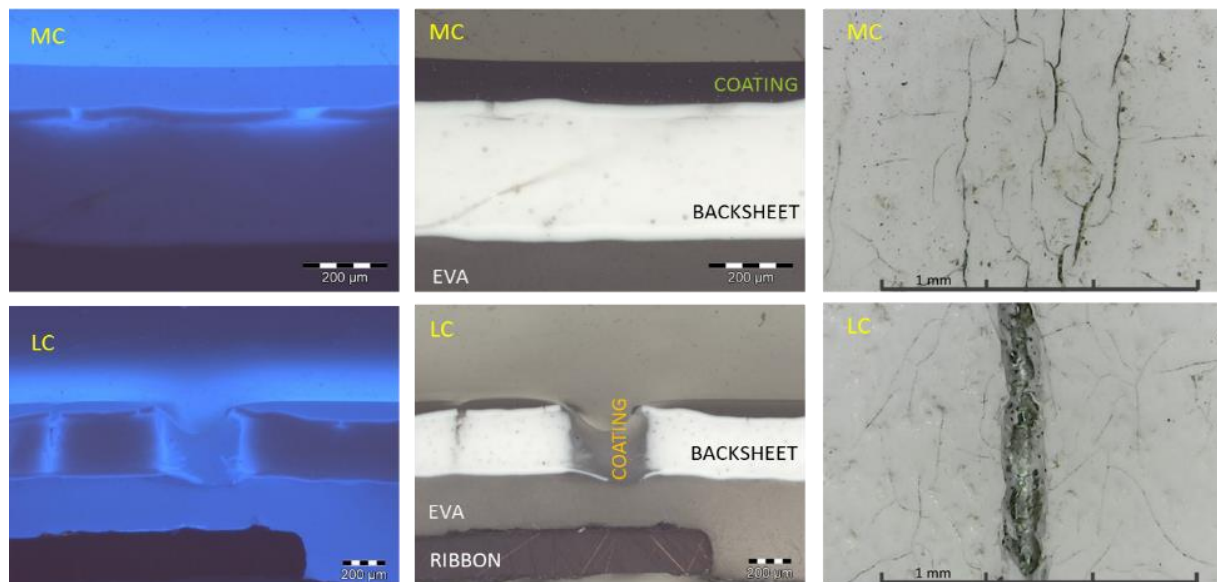


Fig. 3 : Microscopic images of BS surface (right) of microcracks (MC) and deep, longitudinal cracks (LC) in Polyamide BSs ; and cross sections (left and middle) of the coated samples [13].

Repair coatings for backsheets can thus be applied in three different scenarios:

- repair of defective backsheets (cracks)
- (preventive) restoration of insulation resistance of PV modules
- repair of mechanical damage due to transport or assembly

Reliable repair solutions can bring cost benefits to PV asset owners due to longer service life and more stable energy yields. Operational safety is restored on-site as a retrofit action, by applying a coating to mechanically damaged BS films. Another advantage of extending the service life is the reduction in PV waste and the associated protection of the resources used. In addition, a repair in the field reduces additional costs for logistics and, as a result, reduces CO₂ emissions.

4 OUTLOOK: STANDARDIZATION, TECHNOLOGY ROADMAP and FUTURE CHALLENGES

As pointed out in Sections 1 and 2, standardization and a consistent regulatory framework are of vital importance for the reuse of PV modules to establish end users' trust in the safety, reliability and residual performance of such modules. Activities towards standardization (IEC TC82, VDI, ASTM etc) are underway [17]. By mid-2024 a Technical Report (TR) is expected to be concluded and published by the IEC Technical Committee 82 (Working Group 2). Although the incoming TR remains entirely informative in nature (it is not allowed to contain any normative text, e.g. pass/fail criteria), it will outline recommendations for the reuse of PV modules, thus

serving as a basis for the further development of the normative/standardization framework in the topic. A major challenge, among others, faced in the effort for PV reuse (second-life) standardization is the diversity and uncertainty of field exposure (environmental and operational) conditions and application scenarios of PV modules over their first-life; which, in turn, means that it cannot always be assumed that their testing/repair for reuse is representative for all PV modules. For this reason, the current concept text of the TR describes two approaches: i) testing every PV module on some basic aspects of safety and performance when it is necessary and ii) some first recommendation for a sampling approach when it can be justified. Considering the very low prices of new PV modules (currently reaching below 0.15 US\$/W), testing/repair for reuse should be cost- and time-efficient. In this respect, the module sampling approach could be a much more attractive option, yet a challenge is to determine the right and commonly accepted criteria, for the sampling approach to be justified. It is also understood that, for detailed testing and qualification of PV modules for reuse, a dedicated off-site test line is required to enable reasonable throughput (~150 modules/hour). Such a test line would be employed for I-V characterization, dry insulation and bypass diode tests, as well as EL imagery (evaluation protocol still under discussion). Performing such tests sequence on-site would be overly time-consuming, whereas even for the testing line, the economic viability of the approach remains today rather questionable.

On another note, in order to justify sustainable PV reuse business models and overall solidify a successful PV reuse market, while considering current very low prices of new PV modules, a major focus should also be drawn, at policy-making level, on avoiding that healthy modules are

prematurely sent to waste simply due to a very short financial life. In this direction, the authors advocate for a policy that, for instance, enforces PV module state-of-health (SOH) analysis in case of PV modules reaching the end of their first life ten years earlier than their warranty period. For example, for modules with 30 years warranty, SOH check is enforced if owners want to perform repowering/revamping before 20 years of lifetime. The authors reckon that such policy could become relevant and come into action as early as by 2030. By then, the type of performance and safety checks of PV for reuse will be clear and standardized, while their cost would be considered at the planning phase of a PV plant and included in the OPEX and asset management budget of the PV project.

Apart from the settling regulatory framework, looking further into the next 10-15 years, there are important changes anticipated that could boost PV reuse-readiness; therefore, the potential and market uptake of repair/reuse technologies in the value chain of second-life PV. The shares of decommissioned modules of glass-glass type and multi-wire interconnection technology will be increasing and progressively dominate. Glass-glass PV modules are free of backsheet issues and required repairs, typically less prone to non-repairable failures such as cell cracks, while they exhibit lower degradation rates (thus, potentially, higher post-repair residual efficiency and value). Besides, multi-wire based PV modules feature higher reuse potential and lower post-repair risks, being less sensitive to cell cracks and hotspots. In addition, digitalisation and automation in PV O&M emerge as major catalysts in preparation for reuse. From PV systems and regulatory perspective, in the coming years, most decommissioned or EoL PV modules will originate from PV systems without feed-in tariff; therefore, there will be no need to wait 20 years before repowering. In parallel, with higher incoming volumes, streamlined O&M-integrated procedures for reuse (a subject that will be closely investigated in the newly EU-funded project SUPERNOVA), we anticipate that second-life PV modules will render more attractive, with steadily lowering costs (end price) compared to future new PV modules. On the other hand, while the better quality and reliability of decommissioned modules are positive for PV “reusers”, such advantages may slow down the (urgency for) deployment of repowering schemes. Finally, an increasing number of national and European incentives consider the environmental footprint of PV modules, which can further encourage reuse of PV modules.

A more detailed discussion and critical review of recent advances, literature, industry practices, future challenges and obstacles (e.g. economic challenges with decreasing module prices) towards reuse-ready PV, are given in the peer-reviewed extensive version of this paper, to be published in the Advanced Energy and Sustainability Research journal's Special Issue “EUPVSEC 2024”.

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