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Toward Reuse-Ready PV: A Perspective on Recent Advances, Practices, and Future Challenges

Ioannis (John) A. Tsanakas, Gernot Oreski, Gabriele Eder, Anika Gassner, Arvid van der Heide, Daniela M. Godinho Ariolli, Guillermo Oviedo Hernandez, David Moser, and Karsten Wambach*

Photovoltaic (PV) industry is facing challenges in end-of-life (EoL) management, as cumulative PV waste is expected to increase exponentially over the next two decades. The increase in revamping and repowering activities, especially of older PV fleets, underscores the need to refine EoL strategies and increase the reuse readiness of PV modules and other components. As PV systems transition from operational to the EoL regime, streamlined PV qualification and repair strategies become indispensable. This is the only way to ensure reusable PV systems and a bankable second-life PV market. This perspective study sheds light on current research, innovations, practices, and future challenges toward higher PV reuse readiness in the PV industry, highlighting qualification methods, repair strategies, and standardization for PV reuse. An exemplary triage-for-reuse framework is discussed, involving four steps: 1) off-site eligibility checks; 2) on-site inspections and functionality tests; 3) collection and transportation; 4) deeper technical checks. The study also reviews recent advances and research in repair strategies for reuse—addressing notably reliability issues of backsheet, glass and interconnection components—as well as ongoing standardization efforts. Conclusions underscore the the pressing need for circularity in the entire PV products' lifecycle: from design/material level to system, operations and maintenance, and EoL.

1. Introduction—Rationale of the Study

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, is expected for 2024.[1] Despite the recent rise in PVs levelized cost of electricity, for the first time in this decade,[1] 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 toward resource-efficiency and streamlined end-of-life management (EoL), from design up to operation and maintenance (O&M) level.

According to current figures, ≈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%,[2] we can anticipate at least 7–9 million PV modules (including those already installed) to fail on an 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.,

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I. (John) A. Tsanakas
CEA
Liten
Univ. Grenoble Alpes Campus INES
73375 Le Bourget du Lac, France
E-mail: ioannis.tsanakas@cea.fr

G. Oreski
PCCL – Polymer Competence Center Leoben GmbH
8700 Leoben, Austria

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/aesr.202400237.

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G. Eder, A. Gassner
OFI – Österreichisches Forschungsinstitut für Chemie und Technik
1030 Vienna, Austria

A. van der Heide
imec/EnergyVille
imo-imomec
Thor Park 8320, 3600 Genk, Belgium

D. M. G. Ariolli, G. O. Hernandez
BayWa r.e. Operation Services S.r.l.
20122 Milan, Italy

D. Moser
Eurac Research
Institute for Renewable Energy
39100 Bolzano, Italy

K. Wambach
Wambach-Consulting
86574 Petersdorf, Germany

decommissioning by the end of PV service lifetime, revamping and repowering efforts, etc., the PV module waste from global cumulative solar PV projects 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.[3,4]

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.[5] 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, into a second-life cycle.

This paradigm shift underscores the growing need for optimizing EoL management strategies in the PV industry, toward higher reuse readiness. Besides, there are certain key metrics/differentiators to assess the techno-economic bankability of PV reuse[5]: 1) the addressable volume and costs for functionality testing/repair which are directly influencing the profitability of the PV reuse (second-life) market and 2) the reliability, safety, and residual efficiency of the post-repair PV product for reuse, having a direct impact on the "confidence" in the second-life PV market.

In this context, for the transition from PV operations to EoL, streamlined PV triage and 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. However, industry practices and knowledge on these two topics are still inconsistent and scarce today and the standardization efforts (IEC TC82, EC level, VDI, ASTM) are at a relatively early stage.

In this perspective study, we attempt to shed light on recent research, innovations, practices, and future challenges toward higher reuse-readiness in the PV community. In the next three sections, we review, discuss, and assess the state-of-play in: 1) qualification/triage methods for PV reuse; 2) PV repair strategies; and 3) 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 selection of PV modules for reuse comprise health assessment and functionality tests. They are typically based on inspection and characterization methods, adhering to the principles of established technical criteria and standards. To enable the reuse of PV modules and prevent their premature entry into the waste stream, PV module should undergo functionality testing that is technically feasible, cost-effective, and tailored to the second-life market, with a prioritized focus on safety rather than performance. Consequently, replicating the qualification procedures used for new modules (such as those outlined in the IEC 61215) should be avoided, as this would be financially impractical and pose significant technical and practical challenges.

In recent years, research and industry programs introduced technical advances and best practices of PV preparedness for reuse. Several PV actors from the SolarPower Europe's Lifecycle Quality Workstream and from the TRUST-PV research project[6,7] have recently outlined a qualification and triage framework for PV reuse (**Figure 1**). This framework aims at a technically feasible and cost-effective procedure, giving priority to safety over performance. A key question that needs to be answered upfront is whether every single module of a given PV plant must undergo all quality assurance tests, or whether a sampling approach can be used instead. The framework is divided into four steps (Figure 1): 1) off-site eligibility checks; 2) on-site inspections and functionality tests; 3) sorting for collection and transportation; and 4) deeper technical checks.

Off-site ("desktop") eligibility checks can be based on recent advances in PV data monitoring analytics,[8,9] to assess PV plants' health state, pinpoint underperforming components (e.g., in terms of power loss rate (PLR)), 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 electroluminescence (EL), photoluminescence (PL) inspections, and/or isolation resistance measurements ($R_{\text{iso wet}}$) are favored when precise selection, classification, and root-cause analysis are required.

For such eligibility checks, two different (yet complementary) criteria are suggested: 1) the performance loss rate (PLR) and 2) the residual value. Upon eligibility check, a PV module should present an annual power output loss in line with the expected (intrinsic) performance degradation. Therefore, PLR can be considered as a pass/fail criterion, in contrast to the residual value, which is a rather use/business case-specific criterion, i.e., depending on how "value-for-reuse" is defined and justified (technically and economically) per case.

In cases where PLR estimation is ambiguous or doubtful, existing data from field inspections could be used as complementary (typically I–V tracing and IR imagery). Further, it must be added that the residual value criterion naturally depends on the second market value of that specific type of PV module under consideration for repair/reuse. For instance, a second-life PV module could be highly priced if used as spare part or replacement due to its electrical compatibility within a string. In contrast, the value could be low if the PV module's technology is obsolete and limited to a very small application-specific market (off-grid applications).

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. 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 (rarely available by default, yet identifiable by means of near-infrared (NIR) spectroscopy), etc.[10] Recent studies[11] and reports[12] outline the main methods, test protocols,

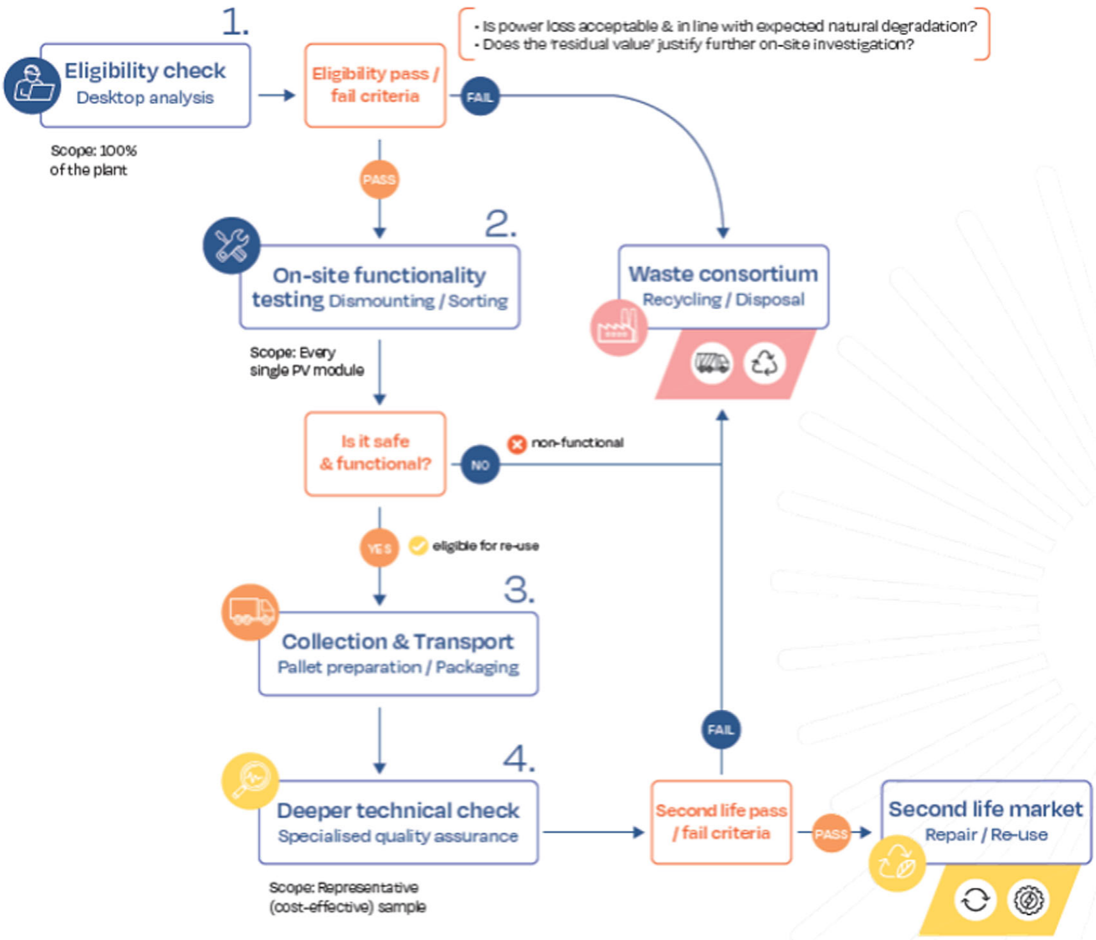


Figure 1. Workflow of the qualification and triage framework for PV reuse, as introduced and proposed by TRUST-PV and SolarPower Europe's Lifecycle Quality Workstream experts. Reproduced (Adapted) with permission.[6] Copyright 2024, SolarPower Europe.

and latest innovations for on-site inspections suitable for qualification/selection of PV modules for reuse, primarily on the basis of visual inspections and *I*–*V* tracing (IEC 62446-1), as well as ground and/or aerial IR imagery (IEC TS 62446-3).

Following all eligibility and safety checks, as well as the inspections-based qualification of PV modules, proper logistics—including dismounting, packaging, and pallet shipping—is crucial to prevent handling and transportation damage and to ensure that PV modules eligible for reuse are not mistaken for e-waste. Collection and transportation should comply to the minimum requirements for shipments of used products as specified in the Waste Electrical and Electronic Equipment Directive-Annex VI (Minimum Requirements for Shipment), which aims to prevent the unwanted transportation of e-waste to countries with inadequate reuse schemes, such as repair hubs, recycling facilities, etc.[13]

The last step of the proposed qualification and triage framework will provide definitive and accurate evidence on the health status of the modules that were categorized as eligible for repair/reuse in the previous steps. Comprehensive and costly quality control carried out in specialized test laboratories is meant to be complementary and applied only to a representative sample of PV modules.[14] Laboratory tests might include but are not limited to *I*–*V* characterization (flash) tests, lock-in thermography (LIT), EL imaging, diode tests, wet insulation testing, aging tests in climatic chambers, etc.

Steps 2–4 are meant to be applied when a major campaign of PV modules' substitution is carried out. Replacing PV modules is very CAPEX (capital expenditures) and labor intensive and therefore it is suggested that these activities are done only during PV plant revamping, repowering, or EoL decommissioning of the entire plant. In contrast, Step 1 (eligibility checks), which is a desktop analysis, can be typically done periodically as part of scope of work of an O&M service provider, at a very low cost, since it does not imply additional activities in the field.[6,7,11]

In addition to the above eligibility and qualification tests, a minimum set of follow-up 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). 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).[10] In contrast, the wet leakage insulation testing remains an insuperable challenge, as it is practically almost impossible to be applied to every PV module-candidate for reuse. Instead, the dry insulation test is applied. The idea is to accept modules with lower insulation resistance for lower system voltage, as aforementioned.

Following all above steps, the actual (residual) power output of the sample test is established, as percentage of the original of the original (nameplate) value. On this basis, the PV module is placed on the second-life PV market at a discounted price tag to be then sold, for instance, to a local installer that specializes in small rooftop and carport applications, as per the example given in ref. [14].

After applying the Steps 1–4 mentioned above in a real case study within the TRUST-PV project, some key takeaways are important to highlight[14]: 1) on-site dry insulation testing might not be conclusive for reuse purposes and it is advised to perform wet insulation tests only when in doubt of safety (because it is time consuming). It has been proven that even broken modules with evident compromised electric insulation can yield positive insulation results without the presence of water; and 2) sampling is possible, but a criterion for maximum spread in module power could be necessary. A final basic visual inspection of each PV module is needed.

It should be underlined that, so far, there little to no real-life data of post-triage PV reuse rates, from field-exposed PV modules. The statistics from an ongoing (nondisclosable) study of triage–repair–reuse of several decommissioned PV modules, carried out by CEA-INES, indicate that repairability and reuse rates can range from a little over 10% for batches of decommissioned PV modules with cracks and soldering defects, to up to 95% for PV modules with bypass diode failures. In the latter case, with deeper technical checks in laboratory, by means of *I–V* characterization, EL imagery (**Figure 2**), and LIT, it was possible to confirm a residual (postrepair) power output ranging from 93% to nearly 100% of the original nameplate power output of the repaired PV modules. Considering such dispersion of residual power output to a larger volume of repaired PV modules, it would probably be necessary to separate the modules into different "power output batches," which highlights the need of an additional triage step as well as more complex palletization management.[15]

In refs. [5,10], researchers have proposed a classification matrix for PV modules' eligibility for reuse, based on three main criteria: 1) technical feasibility of repair; 2) economic feasibility of repair; and 3) postrepair safety (including warranty) and residual value/power ratio. In such a matrix, three distinct "reuse eligibility classes" have been identified (**Figure 3**): 1) Class 1 (A and B): reuse without further handling is possible; 2) Class 2 (C to G or H): deeper technical checks and/or repair are needed (e.g., modules with insufficient $R_{\text{iso wet}}$); and 3) Class 3 (H and I): nonfunctional, nonrepairable, enter recycling stream.

To support the need for rapid on-site fault classification, recent innovations introduced in the EU-funded H2020 projects SERENDI-PV and TRUST-PV can be further exploited.[7,16–18] (Aerial) imagery, especially IR and visual data, can be used to enable rapid diagnostic assessments of PV systems and subsequently to qualify/select PV modules for repair and reuse (**Figure 4**).

Despite the emergence of qualification/reuse programs for PV devices and the technological advances in recent years, the inherent ambiguity of the proposed eligibility criteria/measures for qualification and triage of PV modules remains a stumbling block. While functional testing and qualification for repair/reuse are in principle straightforward for ordinary electronic devices (i.e., "it works/it doesn't work"), in case of sufficient functionality of PV modules, a lower limit for the remaining power or PLR needs to be set. Such a functionality "threshold" is crucial for waste legislation, as nonfunctional products are considered waste. To date, H2020 CIRCUSOL experts have proposed a threshold of at least 70% of the (original) nominal power of the PV module.[10] However, as the regulatory framework for second-life PV systems remains uncertain and inconsistent and there is currently a lack of standardization of testing/triage procedures for reuse, a threshold for PV system functionality may be somewhat arbitrary.

3. State-of-Play in Repair Strategies for PV Reuse

In many studies, repair of PV modules is seen as a way to extend and ensure function and safety of PV modules.[5,14,19,20] However, repair of damaged or degraded PV modules is a relatively new topic. The current PV module design and packaging concept, with interconnected solar cells in between two

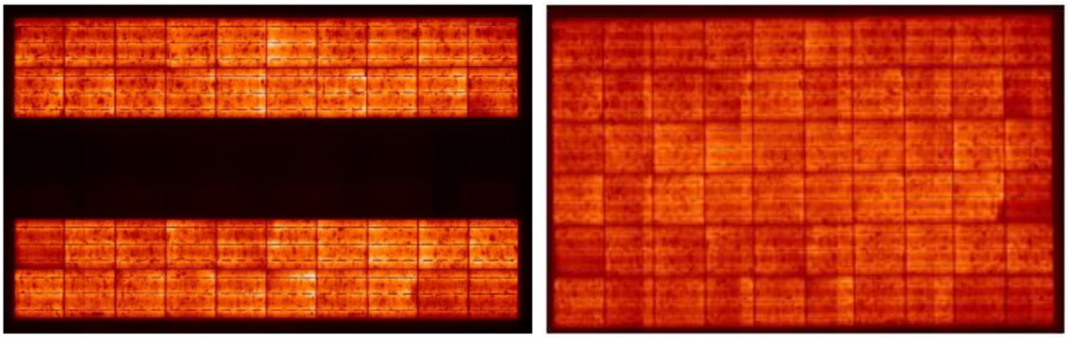
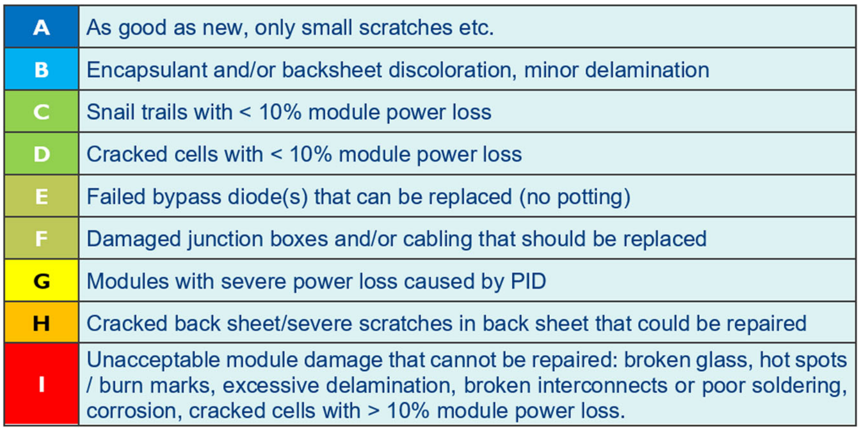


Figure 2. Left: Example of EL image characterization of a first-life PV module with a bypass diode failure (corresponding to an open-circuited submodule). Right: EL image of the same PV module postrepair, ready to enter the reuse stream.



A	As good as new, only small scratches etc.
B	Encapsulant and/or backsheet discoloration, minor delamination
C	Snail trails with < 10% module power loss
D	Cracked cells with < 10% module power loss
E	Failed bypass diode(s) that can be replaced (no potting)
F	Damaged junction boxes and/or cabling that should be replaced
G	Modules with severe power loss caused by PID
H	Cracked back sheet/severe scratches in back sheet that could be repaired
I	Unacceptable module damage that cannot be repaired: broken glass, hot spots / burn marks, excessive delamination, broken interconnects or poor soldering, corrosion, cracked cells with > 10% module power loss.

Figure 3. Classification matrix for PV modules triage and eligibility for repair/reuse.

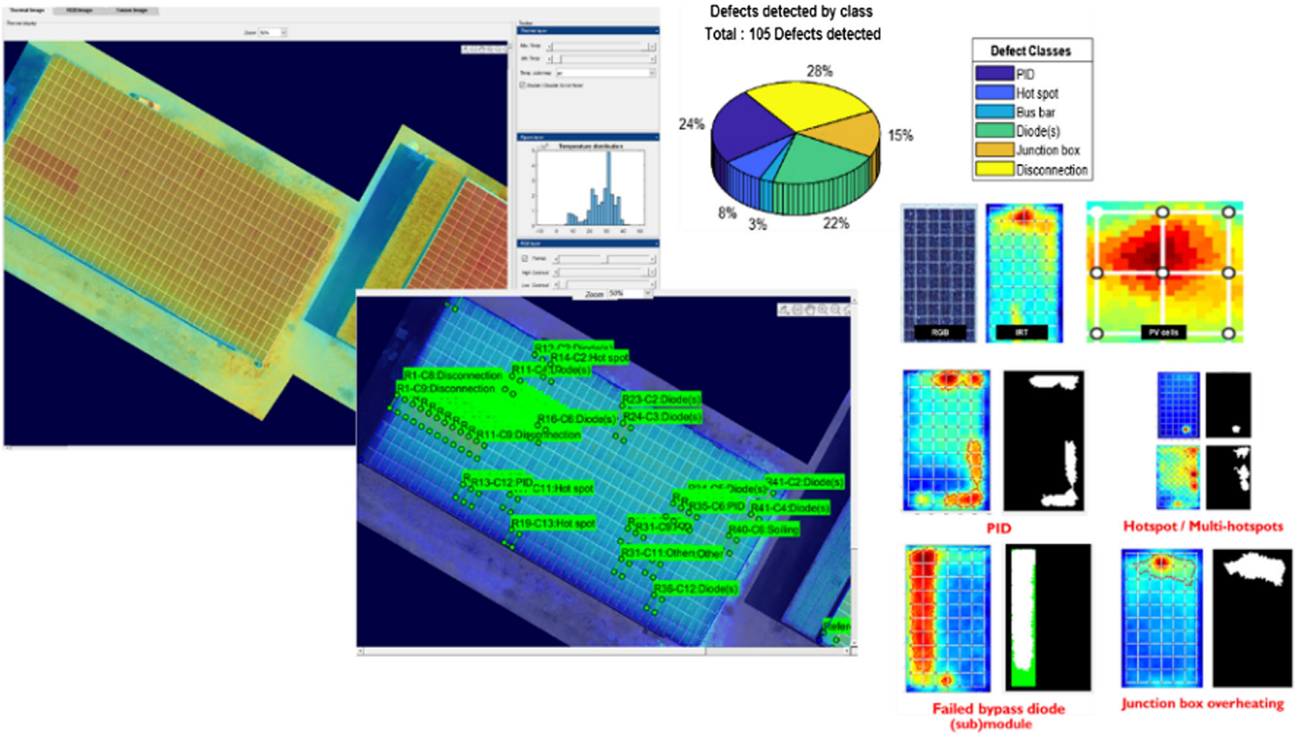


Figure 4. Example dashboard outputs from ASPIRE, a software prototype introduced by CEA, aimed for image-based detection and classification of PV failures allowing for selecting PV modules for reuse.[17,18]

transparent polymer films, a frontglass, and a backsheet or backglass were developed over 40 years ago (between the end of 1970 and beginning of 1980 decades).[21] The main development goals have been increasing the efficiency and durability of the modules, which was achieved with the basically inseparable multilayer composite structure. So far, no comprehensive concepts considering the Right for Repair[22] have been published for PV modules. However, few research groups and startup companies have presented approaches for increasing recyclability of PV modules or PV module components. And most of these approaches would also increase the reparability of PV modules. Wanghofer et al. investigated different reversible adhesives for frames and junction boxes.[23] Reversible bonding would considerably facilitate repairs. Schnatman et al. concluded that thermoplastic encapsulation films would increase the sustainability of PV modules.[24] Erhardt et al. proposed a self-healing mechanism for solar cell encapsulants.[25] The Dutch Startup company Biosphere Solar developed recently a modular PV module design that allows disassembly and therefore repair or refurbishment[26]; whereas, earlier research work[27] introduced the N.I.C.E. PV module concept, which follows a similar approach, avoiding polymer encapsulants. However, so far none of these approaches reached market readiness. In this context, on policy-making level, the recent "Preparatory Study for solar PV modules, inverters and systems," a Science for Policy report published by the European Commission's Joint Research Centre (JRC), has introduced—among others—design recommendations for promoting and enhancing the reparability (and eventually reuse) of PV modules.[28]

A comprehensive survey carried out in March 2024 resulted in only 13 scientific contributions (journal articles and publications in conference proceedings) as well as several industry actors offering "PV module repair" as a service. The results are summarized in **Table 1** and will be published in further details in an upcoming report of the IEA PVPS Task 13 experts group.

Most work so far has been done on the repair of damaged/cracked backsheets with first results being published in 2020.[29] Two different approaches have been investigated in this topic, i.e., 1) the application of an additional coating[30,31] or 2) a tape[32] or full-deck foil adhered on top of the existing backsheet. Beyond backsheet repair, recent research efforts dealt with strategies for the repair of glass defects[33] and broken interconnects.[34,35]

Nieto-Morone et al.[36] investigated twenty-three partially repaired modules obtained from an undisclosed Spanish company specialized in PV module refurbishment including repair of damaged bypass diodes, junction box replacements, and minor backsheet damage. The objective of the study was to assess the restored power capacity achieved through these partial repairs and provide insights into the effectiveness and cost-effectiveness of module repair as compared to replacement. The most significant finding achieved was that the repaired modules meet the manufacturer's warranty criteria, indicating their potential for reuse. This shows that it is possible to fix various problems that lead to PV module failures through repairs and thus restore the modules' power generation. Information on the stability and reliability of the repairs, however, was not provided.

On the commercial side, a handful of industrial players offer "repair of PV modules" as a commercial service, amongst others, for bypass diodes, junction boxes, frames, backsheets, cables, and connectors; yet, without disclosing details on their repair approaches or procedures. This could be due to a number of reasons, such as proprietary methods that provide competitive advantages or simply a shortfall to inform prospective end-users. Such lack of detailed and transparent information can be a barrier toward the market uptake of such solutions, whereas resulting in reluctance from the end-use the quality of the repairs performed and the postrepair reliability and safety of postrepair PV modules. The lack of transparency may also indicate a broader problem in the PV community, as standard procedures for repairing second-life PV systems are not yet well established or documented. Further discussion on the latter aspect is given in Section 4.

In the following subsections, several repair strategies as described in literature, are presented in more detail.

3.1. Backsheet Repair

Field experience clearly shows that the reliability of glass/backsheet 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.[37–39] Most serious is the potential resulting drop in electrical insulation resistance ($R_{\text{iso wet}}$) of the backsheets (BS), which can have a significant impact on PV system yield.

Local backsheet defects caused by mechanical damage during installation or handling of the PV modules, can be easily repaired with coatings or tapes/films. Defects caused by physical cracking in the backsheet, such as 1) microcracks in the outer layer or 2) deep longitudinal cracks (LC) (through the entire sheet cross-section) beneath the busbars, can also be repaired by applying coatings, provided that they can fill the crack voids. This also restores the insulation resistance of the backsheets. In the case that a backsheet cracking is accompanied by chemical degradation of the polymers of the backsheet layers or the adhesive between them—which leads to delamination—repair with coatings or tapes is no further possible.

A repair coating can address the moisture sensitivity of the aged and often cracked backsheets. An Austrian research team therefore investigated possible strategies for repairing backsheets, using cracked polyamide-based backsheets as the first test case.[30,31,40–42] Two different repair strategies have been addressed: 1) repairing BS damage of deep cracks by coating to restore electrical insulation properties and 2) preventing further growth of the surface near microcracks in mostly strongly chalking backsheets. A repair process has been developed that

Table 1. Overview of PV module repair approaches (and their technology readiness level, TRL) reported in the literature or in the market.

Component	Failure modes	Mode	Field repair possible without dismantling	Automatable	TRL	References
Backsheet	Chalking; cracks; microcracks; insulation issues	Coating	Yes	Yes	7	[30,31]
		Tapes	Yes	No	9	[50,51]
–	–	New backsheet	No	Yes	9	
Glass	Cracks	Coating/adhesive	Yes	Yes	3–4	[33]
Interconnect	Broken soldering; broken ribbons	Invasive repair	No	No	3–4	[34,35]
Junction box	Delamination; water ingress; failed bypass diodes	Exchange	Yes	No	9	[52]
Frame	Delamination	Exchange	No	No	9	[43]
Cables and connectors	Torn cables and connectors	Exchange	Yes	No	9	[43]

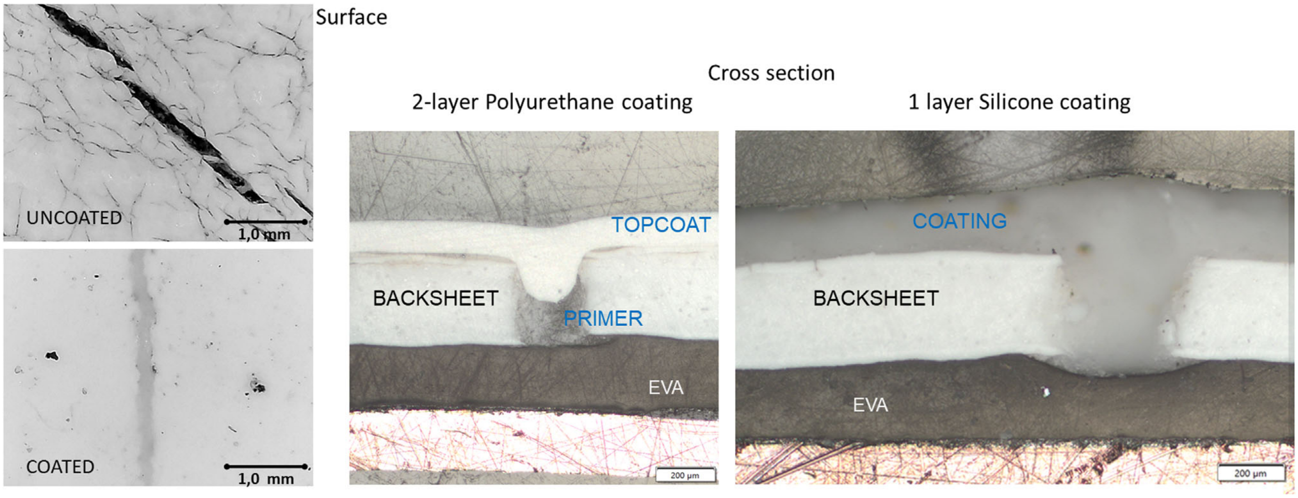


Figure 5. Microscopic images of a BS surface (left) with deep, LC in polyamide BSs before and after coating; and cross-sections of the coated samples (left-silicone and middle-PU-coating).[44]

comprises the following steps[31]: 1) cleaning; 2) pretreatment (if necessary); and 3) repair coating application (crack filling and sealing) (**Figure 5**).

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 (pressure sensitive adhesive, PSA) could penetrate into the cavities that had opened through the cracks in the backsheet material—which was the case for surface-near microcracks.[31,39] On the other side, several repair coatings based on polyurethane, epoxy, silicone, and synthetic rubber were identified which, after a one- or two-step application process, showed complete crack filling and sealing of the surface even for deep LC (backsheet completely thrown).[31,43] The required $R_{\text{iso wet}}$ of the aged modules could be restored upon coating. The important topic of long-term reliability of the repaired modules and the effectiveness in stopping crack-propagation were also addressed.[30,41,44] Artificial accelerated tests (damp heat and temperature cycling tests) were performed on coated microcracked backsheets/modules and natural weathering tests of modules with coated microcracks[42] and with coated deep LC were/are performed since 2020 and 2021, respectively, as shown in **Figure 6**.

Based on these results, it can be concluded that a successful repair of modules with deeply cracked backsheets requires a complete sealing of the cracks (first coating step = crack filler, primer) and the entire weathered and often microcracked surface of the backsheet (second coating step = barrier layer, top coat). This stops further material degradation of the backsheet, avoids moisture ingress into the encapsulant, and restores the electrical insulation. As a result, these effects avoid long-term electrical performance losses. The long-term performance of the repaired PV system was followed (electrically and material wise) under real conditions (Figure 6). After coating and 30 months of natural weathering 1) no changes in the electrical characteristics; 2) no inverter tripping events due to leakage current as well as 3) high stability of the coating in the spectroscopic (IR, NIR, Raman) measurements and adhesion tests were found. Therefore, initial positive predictions can be made about the long-term behavior of the repair and its life-extending effect of PV modules.

Repair coatings for backsheets can thus be applied in three different scenarios: 1) repair of defective backsheets (cracks);

Figure 6. Picture of the coating of cracked backsheets (left), on-site coating tests (middle), and the test-site operating successfully with repaired/coated PV modules since 2021 (right). As repair coating flowable silicone and a two-component polyurethane-coating were used.[30,41]

2) (preventive) restoration of insulation resistance of PV modules; and 3) 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 CO_2 emissions.

3.2. Repair of Interconnection

The developed repair method of Lee et al.[34] for resistive solder bond (RSB) hotspot modules involves several detailed steps to ensure minimal invasion and effective recovery. The new on-site repair approach was compared to a more comprehensive factory recovery process where the frame is separated, and the adhesive materials (tape or sealant) are removed. The Ethylene Vinyl Acetate (EVA) is then heated and softened using a hot plate, allowing the backsheet to be peeled off/completely removed, along with the EVA and busbar of the damaged area. After cooling the module to room temperature, flux is applied to the new bus bar, which is then soldered. The first EVA is inserted between the glass and bus bar, while a second EVA layer, slightly larger than the restored area, is overlapped and fixed. Finally, the entire module is covered with a new EVA and a new backsheet, the electrical connections are checked, and the module is placed into the lamination process.

On-site recovery involves performing all restoration processes directly in the field, reducing the steps from 22 in factory settings to 8 on-site (**Figure 7**). This approach allows for immediate installation and inspection postrecovery without the need for repacking or transferring modules. In case of the on-site repair procedure, the backsheet is just punched to expose the affected soldering joint. After repair, the module was sealed using resin and a backsheet tape. The on-site recovery method using resin demonstrated comparable reliability to the factory method, with the added advantages of reduced time, cost, and logistical complexity.

The process proposed by Rosillo et al.[35] involves marking the work area, removing the backsheet and EVA with a sanding band accessory, and using various polishing and cleaning tools. The critical steps involve carefully separating and lifting the bus bar sections, applying flux, and inserting a complementary bus bar piece (**Figure 8**). Soldering is done with a specific soldering iron temperature (183 °C) to ensure a secure connection. After checking continuity with a multimeter or tone tester, the hole is filled with silicone to ensure proper sealing. Each ribbon interruption repair takes about 5–10 min. The procedure was tested on three different modules, labeled M1, M2, and M3. Before repairs, M1 and M2 generated around 50 W, while M3 was unable to produce power. After repairs, all modules had a power output of 200 W, and additional damages due to the repair process have been found. Unfortunately, the long-term behavior of repaired modules has not been investigated in this study.

3.3. Repair of Glass

Tas et al.[33] explored an experimental repair technique for glass defects in glass-glass PV modules, assessing its effectiveness through performance and reliability tests after accelerated lifetime simulation. This experimental repair technique for glass defects in double-glass PV modules is adapted from methods used for windshield repairs in cars.[45,46] Materials required include repair and pit resins, a UV lamp, and supplementary cleaning tools. Unfortunately, the type of resin is not mentioned in the article.

This study inspected PV modules with glass defects, confirming no initial defects other than the glass fractures. Initial EL imaging revealed no internal cell or connector irregularities.

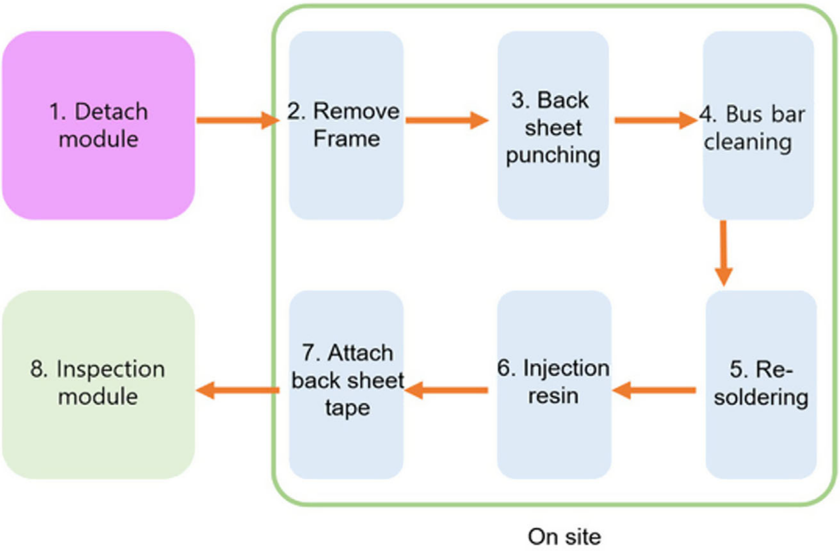


Figure 7. Scheme of on-site interconnect repair as proposed by Lee et al. Reproduced (Adapted) with permission.[34] Copyright 2022, MDPI.

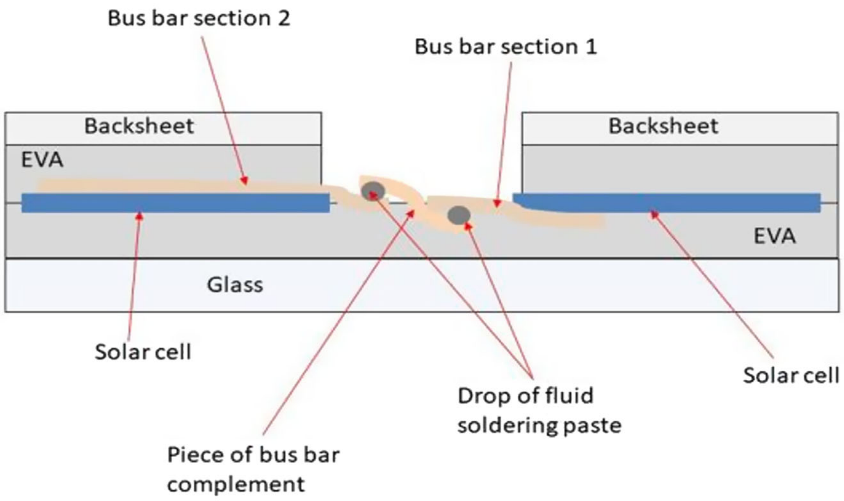


Figure 8. Scheme of interconnect repair as proposed by Rosillo et al. Reproduced (Adapted) with permission.[35] Copyright 2024, Elsevier.

After the experimental repair, visual inspections and EL imaging showed no additional defects or internal deformities. This indicates that the repair process does not negatively impact the PV modules, confirming the expected durability and resilience of double-glass PV modules. Despite the initial glass defects, all specimens remained within acceptable performance ranges. Repaired specimens showed no negative impact from the repair and even a slight performance increase. Post-DH test, five out of six specimens had similar performance, with a 4.0–4.7% decrease aligns with IEC standards. Only the not repaired exhibited a significant 7.8% performance decrease due to additional large cracks. Energetically, repair is significantly more desirable than substitution, with economic benefits dependent on repair scale and frequency.

3.4. Economic Feasibility

Current methods for repairing modules as described before require significant manual labor. This often involves diagnosing the issue, disassembling the unit, replacing or fixing the faulty component, and reassembling the multimaterial composite PV module. This process can be time-consuming and requires skilled technicians. Given the high labor costs and the time required for repairs, it can be more cost-effective to replace the entire module with a new one. This is especially true when considering the downtime associated with repairs and the potential for future failures in a repaired module. New modules come with warranties and are expected to perform optimally without immediate risk of failure. They can also integrate newer technologies or improvements that might not be present in older units, providing better performance and efficiency. The choice between repairing and replacing a module often depends on several factors, including the cost of labor, the availability and cost of new modules, the critical nature of the module to the overall system, and the long-term reliability considerations. In summary, while repairing damaged modules is possible, it is often more practical and economically viable to replace them with new ones due to the high labor costs and potential for improved performance with new modules. Sustainability considerations, however, often support refurbishment and reuse of aged modules.

4. Outlook: Standardization, Cost Considerations, Technology Roadmap, and Future Challenges

As pointed out earlier, 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 toward standardization (IEC TC82, VDI, ASTM, etc.) are underway.[14,47] By Q4 of 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.

One of the main challenges related to the standardization of requirements for reuse (second-life) of PV modules is the diversity and uncertainty of the (environmental and operational) conditions and application scenarios of the PV modules during their first life. This in turn means that their testing/repair for reuse cannot always be assumed to be representative of all PV modules. For this reason, the current concept text of the TR describes two approaches: 1) testing every PV module on some basic aspects of safety and performance, where necessary; and 2) a sampling approach, where this can be justified. Considering the very low prices of new PV modules (reaching below 0.15 US$ W^{-1} in 2024), 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. It is also understood that, for the "testing every module" approach, i.e., for detailed testing and qualification of each PV module for reuse, a dedicated off-site test line is required to enable reasonable throughput (≈150 modules h^{-1}). 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). In this direction, earlier this year (2024), an Austrian startup developed a dedicated test line for preparation-for-reuse services,[48] whereas a French startup is introducing an all-in-one pipeline for monitoring, maintenance, and repair for PV reuse.[49] In contrast, performing such tests sequence on-site would be very time-consuming, whereas even for the testing line, the economic viability of the approach is currently rather questionable and must first be proven. Nevertheless, on-site testing with the aforementioned "sampling" approach can be technically and economically feasible with the deployment of mobile test-labs.

From the perspective of large O&M service providers, the application of the triage methods for PV reuse is usually only financially viable when done in large scale during major decommissioning activities (revamping and repowering), in view of the high probability of finding functional modules. The application at small scale does not usually make sense in cost and operational terms, since—in such cases—most PV modules are directly entering the disposal or (at best) the recycling waste streams, without any further investigation.

Table 2 provides an overview of costs for specific O&M activities linked to the overall "preparation-for-reuse" scheme (i.e., triage, testing, and repair of PV modules, described in Sections 2 and 3). For most of the listed activities, personnel costs (which have a significant impact in such budgeting) were unfortunately not disclosed by any of our sources. Due to the relative infancy of the market in this field, these cost figures, although relatively up-to-date (reported with the last 3 years), are market-specific and noncomprehensive. Therefore, they should only be considered as indicative and subject to deviations.

Table 2. Breakdown of key costs for O&M "preparation-for-reuse" activities, as compiled by IEA PVPS Task 13 and TRUST-PV experts.

Description	Action or element involved	Unit	Cost
Pre-evaluation and classification (in-house)	Visual inspection	€ kW^{-1}	0.26
	Insulation resistance (R_{iso}) test	€ kW^{-1}	0.26
	I–V tracing	€ kW^{-1}	0.26
	IR Thermography	€ kW^{-1}	0.3
Certified quality test (3rd party)	Visual inspection + IV tracing + EL + R_{iso}	€ kW^{-1}	4.25
Packaging materials	Pallets	€ nit^{-1}	20
	Cardboard/Cellular rubber	€ kg^{-1}	–
	Cardboard box	€ unit^{-1}	30
	Stretch wrap	€ m^{-1}	0.0042
Logistics	PV modules transportation	€ km^{-1}	–
Warehouse	Storage costs	€	–
Repair	Material/component	€ m^{-2}	3–4
	Personnel (dismounting process)	€ module^{-1}	6
	Personnel (repair process)	€ m^{-2}	2
Exchange	Material/component	€ W$_p{}^{-1}$	0.3
	Transport	€ module^{-1}	2.27
	Personnel (dismounting process)	€ module^{-1}	6

On another note, 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 10 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 is important. The shares of decommissioned modules of glass-glass type and multiwire interconnection technology will be increasing and progressively dominate. Glass–glass PV modules are free of backsheet issues and required repairs, typically less prone to nonrepairable failures such as cell cracks, while they exhibit lower degradation rates (thus, potentially, higher postrepair residual efficiency, and value). Besides, multiwire-based PV modules feature higher reuse potential and lower postrepair risks, being less sensitive to cell cracks and hotspots. In addition, digitalization and automation in PV O&M are proving to be important catalysts in preparing 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. Thus, there will be no need to wait 20 years before repowering. In parallel, with higher incoming volumes and 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. In contrast, 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.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Ioannis (John) A. Tsanakas: Conceptualization (lead); Formal analysis (equal); Supervision (lead); Writing—original draft (equal); Writing—review & editing (equal). **Gernot Oreski**: Formal analysis (equal); Investigation (equal); Methodology (equal); Supervision (supporting); Validation (equal); Writing—original draft (equal); Writing—review & editing (equal). **Gabriele Eder**: Conceptualization (supporting); Formal analysis (equal); Investigation (equal); Methodology (equal); Supervision (supporting); Writing—original draft (equal); Writing—review & editing (equal). **Anika Gassner**: Formal analysis (equal); Investigation (equal); Methodology (equal); Writing—original draft (equal); Writing—review & editing (equal). **Arvid van der Heide**: Conceptualization (supporting); Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Writing—original draft (equal); Writing—review & editing (equal). **Daniela M. Godinho Ariolli**: Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (supporting); Writing—original draft (equal); Writing—review & editing (equal). **Guillermo Oviedo Hernandez**: Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (supporting); Writing—original draft (equal); Writing—review & editing (equal). **David Moser**: Formal analysis (equal); Investigation (equal); Methodology (equal); Supervision (equal); Validation (equal); Writing—original draft (equal); Writing—review & editing (equal). **Karsten Wambach**: Validation (supporting); Writing—original draft (supporting); Writing—review & editing (supporting).

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