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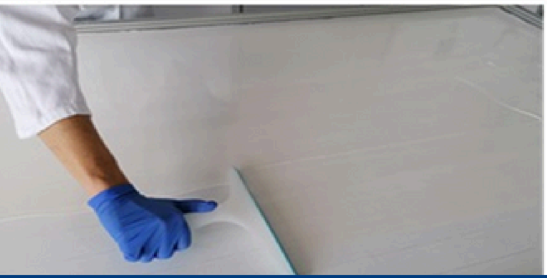

Task 13 Reliability and Performance of Photovoltaic Systems

PVPS

Performance and Reliability Aspects of 2nd Life Photovoltaic Modules

2026

Report IEA-PVPS T13-37:2026

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCPs within the IEA and was established in 1993. The mission of the programme is to “enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems.” To achieve this, the Programme’s participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct ‘Tasks,’ that may be research projects or activity areas.

The 28 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Lithuania, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Türkiye, the United Kingdom and the United States of America. The European Commission, Solar Power Europe and the Solar Energy Research Institute of Singapore are also members.

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What is IEA PVPS Task 13?

Within the framework of IEA PVPS, Task 13 aims to provide support to market actors working to improve the operation, the reliability and the quality of PV components and systems. Operational data from PV systems in different climate zones compiled within the project will help provide the basis for estimates of the current situation regarding PV reliability and performance.

The general setting of Task 13 provides a common platform to summarize and report on technical aspects affecting the quality, performance, reliability and lifetime of PV systems in a wide variety of environments and applications. By working together across national boundaries, we can all take advantage of research and experience from each member country and combine and integrate this knowledge into valuable summaries of best practices and methods for ensuring PV systems perform at their optimum and continue to provide competitive return on investment.

Task 13 has so far managed to create the right framework for the calculations of various parameters that can give an indication of the quality of PV components and systems. The framework is now there and can be used by the industry who has expressed appreciation towards the results included in the high-quality reports.

The IEA PVPS countries participating in Task 13 are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, Thailand, and the United States of America, and the Solar Energy Research Institute.

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COVER PICTURE

Top: Second-life PV system installed on the rooftop of the Waasland demo building; Bottom: PV system with repaired backsheet

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Performance and Reliability Aspects of 2nd Life PV Modules

IEA PVPS

Task 13

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
BS	Backsheet
BOM	Bill of Materials
CEA-INES	Commissariat à l'énergie atomique et aux énergies alternatives - Institut National de l'Énergie Solaire
CIGS	Copper Indium Gallium Selenide
CPV	Concentrating Photovoltaics
DH	Damp Heat
DfD	Design for Disassembly
DfR	Design for Recycling
EG	Expandable Graphite
EL	Electroluminescence
EOL	End of Life
EU PVSEC	European Photovoltaic Solar Energy Conference
EVA	Ethylene Vinyl Acetate
IEC	International Electrotechnical Commission
IEA	International Energy Agency
IEA PVPS	International Energy Agency Photovoltaic Power Systems Programme
IR	Infrared
ISO	International Organization for Standardization
IV (I–V)	Current–Voltage
LID	Light Induced Degradation
LIT	Lock-in Thermography
MC	Microcracks
Mo	Molybdenum
MST	Module Safety Test
NIR	Near Infrared
OECD	Organisation for Economic Co-operation and Development

PA	Polyamide
PAS	Publicly Available Specification
PIB	Polyisobutylene
PID	Potential Induced Degradation
PLR	Performance Loss Rate
PMMA	Poly-Methyl Methacrylate
PSS	Product-Service Systems
PV	Photovoltaic
Riso wet	Wet Insulation Resistance
RSB	Resistive Solder Bond
SEPA	Smart Electric Power Alliance
STC	Standard Test Conditions
TCP	Technology Collaboration Programme
TEM	Thermally Expandable Microspheres
TR	Technical Report
TRL	Technology Readiness Level
UV	Ultraviolet
WEEE	Waste Electrical and Electronic Equipment

LIST OF FIGURES

EXECUTIVE SUMMARY

This report, prepared within the framework of IEA PVPS Task 13, addresses the performance, reliability, and practical feasibility of second-life photovoltaic (PV) modules, with a specific focus on repair, refurbishment, and reuse strategies. In the context of rapidly increasing global PV deployment, sustainable approaches to extend module lifetimes and manage end-of-life flows are essential to limit future waste streams and to support circular economy's objectives. The intended audience of this report is broad and includes policymakers, PV system owners and operators, manufacturers, insurers, researchers, and other stakeholders with varying levels of technical expertise.

Key Insights

The report consolidates technical findings, process developments, and field experience related to second-life PV. A comprehensive review of PV module repair strategies is provided, covering a wide range of defect types such as backsheet cracking, solder bond and interconnect failures, junction box and bypass diode issues, and localized glass damage. Repair approaches discussed in the report span laboratory-scale concepts, pilot implementations, and multi-year field demonstrations.

A key distinction is made between repair technologies that have undergone extended reliability testing or long-term field validation and those that have so far demonstrated feasibility primarily through process development or short-term post-repair performance measurements. While many repair techniques are technically feasible, the review highlights that repair remains labor-intensive and difficult to scale economically, particularly when defects are rooted in intrinsic design or manufacturing weaknesses.

Beyond repair, the report places strong emphasis on reuse pathways based on systematic testing, sorting, and qualification of decommissioned modules. Visual inspection, I–V characterization, electroluminescence imaging, and insulation resistance testing form the technical backbone of reuse-oriented triage frameworks. Automated and semi-automated testing solutions, mobile laboratories, and AI-assisted diagnostics are identified as key enablers for increasing throughput, consistency, and cost efficiency, allowing modules to be reliably classified into reuse, repair, or recycling streams.

Economic and Policy Perspectives

Economic considerations are addressed throughout the report in a qualitative manner. In many market contexts, the declining cost of new PV modules constrains the competitiveness of labor-intensive repair approaches. Nevertheless, second-life PV can be viable in specific situations, including logistics-constrained or remote installations, repowering projects, and regions with supportive regulatory or financial frameworks. Policy instruments such as eco-contribution schemes are highlighted as effective mechanisms to stimulate reuse markets and help bridge cost gaps between new and second-life products.

From a policy and market perspective, the lack of harmonized requalification criteria, standardized testing protocols, and clear repair guidelines remains a major barrier to broader adoption of second-life PV. Ongoing standardization activities within IEC technical committees and PV quality assurance initiatives are therefore critical to improving transparency, comparability, safety, and bankability of reused PV modules.

Field Experience and Demonstration Projects

Field experience and demonstration projects presented in the report confirm that second-life PV systems can deliver tangible benefits, including stable energy yields, reduced

environmental impact, and contributions to local energy autonomy. At the same time, these case studies highlight persistent challenges related to module heterogeneity, certification and requalification, insurance and bankability, logistics, and regulatory compliance. The reported experiences underline the importance of robust qualification procedures and clear system integration guidelines.

Scope and Limitations

This report does not aim to provide a comprehensive quantitative performance or reliability assessment of all repair technologies. Instead, it offers a structured overview of existing practices, emerging solutions, and key knowledge gaps in testing, standardization, and market frameworks. By consolidating current experience and clearly stating limitations alongside opportunities, the report seeks to inform future research, standardization activities, and policy development for second-life PV.

Conclusions and Recommendations

Repair, refurbishment, and reuse of PV modules represent technically viable and environmentally beneficial pathways to extend the operational life of solar assets and reduce waste. The review presented in this report demonstrates that a wide range of PV module defects can be addressed through repair; however, the maturity, scalability, and long-term reliability of these solutions vary significantly. Only a limited subset of repair approaches has been supported by multi-year field data or extended reliability testing, and repair should therefore be applied selectively, with careful consideration of defect type, module age, and underlying failure mechanisms.

Testing- and sorting-based reuse strategies emerge as the most robust and scalable option for second-life PV deployment. Standardized inspection and qualification procedures—prioritizing safety and traceability over marginal performance gains—are essential to ensure confidence among system owners, insurers, and investors. The absence of harmonized requalification protocols and clear pass/fail criteria remains a major barrier to market uptake and bankability of second-life PV products.

Economic feasibility remains a decisive constraint. In many regions, the low and continuously declining cost of new PV modules makes replacement more attractive than labor-intensive repair. Nevertheless, reuse and selective repair can be economically justified in specific contexts, including repowering projects, remote or hard-to-access installations, and policy-supported reuse schemes. Case studies included in this report demonstrate both the potential value of second-life PV and the practical challenges encountered in real-world implementation, including technical compatibility, logistics, regulatory uncertainty, and market acceptance.

Progress toward broader adoption of second-life PV will require coordinated advances in technology, standardization, and policy. Improved design-for-repairability, increased transparency of bills of materials, and the development of internationally harmonized standards for testing, requalification, and certification are critical enablers. Policy measures such as eco-contributions, incentives, and reporting requirements can play a key role in creating a level playing field for second-life products.

In summary, second-life PV has clear potential but is not a universal solution. Its successful deployment depends on rigorous qualification procedures, scalable testing and reuse infrastructure, and supportive regulatory frameworks. Continued collaboration between industry, research organizations, and policymakers is essential to transition second-life PV from isolated pilot projects toward a mature, reliable, and trusted market segment.

1 INTRODUCTION

As the global deployment of photovoltaic (PV) systems continues to grow, increasing attention is being directed towards the repair, refurbishment, and extended use of PV modules to support circular economy principles and reduce environmental impact. This report presents the outcomes of a collaborative activity aimed at reviewing the technical and practical aspects of enabling a viable second life for PV modules.

The objectives of this activity are twofold:

1.	To provide a comprehensive review of existing repair strategies and approaches for enhancing the reparability of PV modules, both immediately post-production and after field aging.
2.	To explore and evaluate current practices, challenges, and opportunities related to the re-qualification, standardization, and bankability of second-life PV modules, including insights from real-world field experiences.

The report is structured into two main parts:

Part 1: Review of PV Module Repair Strategies: This section describes and evaluates current repair methods for PV modules, considering their effectiveness and long-term stability. It covers repair scenarios both immediately after production and for field-aged modules. Detailed discussions include the replacement of broken cells, repair of cracked backsheets or front glass, correction of defective solder joints, and the exchange of exterior module components such as frames, junction boxes, and bypass diodes.

Furthermore, this part includes a review of measures to improve reparability through alternative module designs and bills of materials aligned with current and future eco-design and circular economy design requirements.

Part 2: Re-qualification, Standardization, Bankability, and Field Experience of Second-Life PV**:** This section focuses on two core aspects:

> **Part 2.1: Re-qualification and Standardization**: It discusses best practices and technical challenges in reliability testing, selection, and quality/safety control for second-life PV modules. It also proposes a framework and recommendations for future (inter)national standardization, including contributions towards new IEC Technical Specifications for second-life PV modules. The – sometimes contradictory - interplay between design-for-repairability and design-for-reliability is also addressed.
> **Part 2.2: Bankability and Field Experience:** This part evaluates the cost implications of second-life PV services, covering the complete process chain from testing and sorting to transport and system integration. It provides recommendations for optimizing the cost-performance ratio of second-life PV systems and shares real-world data and lessons learned from installed and operational second-life PV installations, with a focus on performance, reliability, and maintenance requirements.

By consolidating current knowledge and practical experiences, this report aims to support the broader adoption of repairable and second-life PV technologies and inform future technical and policy developments in the field.

Parts of this report have previously been presented at the European Photovoltaic Solar Energy Conference (EU PVSEC) [1] and published in a peer-reviewed scientific journal [2]. The publication originated from the initial planning and collection of contributions for this report, serving as a focused summary of selected findings and early insights. As a result, some sections and figures may appear like those found in the earlier publications. However, this report significantly extends the scope of the original work. It provides a more comprehensive treatment of the subject, incorporates additional data and analysis, and includes a review of the most recent literature and developments in the field up to mid-2025.

2 REVIEW OF PV MODULE REPAIR STRATEGIES

Extending the operational lifetime of PV modules is one of the most pressing challenges facing the PV industry. Numerous studies regard the repair of PV modules as a promising approach to ensure their continued functionality and safety, both up to and beyond the expiration of their warranty period [3–6].

Nevertheless, repair of damaged or degraded PV modules remains a relatively new and underexplored topic. A comprehensive internet and literature survey conducted in October 2024 identified only **16 scientific contributions** dealing with PV module repair and a small number of commercial repair services. The results of this survey are summarized in Table 1.

This chapter focuses primarily on repair, refurbishment, and reuse strategies for PV modules. Repair and reuse of balance-of-system (BOS) components, such as inverters, cabling, and storage systems, are acknowledged as important topics but are not addressed in detail in this report.

While repair has the potential to extend service life, field observations indicate that the majority of PV modules already possess an inherently long lifetime, provided they are manufactured with robust bills of materials (BOMs) and sound production processes [3,4]. In contrast, modules that suffer from premature failures often do so due to inferior component selection or substandard manufacturing practices [3–6]. In such cases, repair may not be technically or economically prudent, as the underlying quality and reliability issues are embedded in the original manufacturing process.

In this context, it is critical to distinguish between damage caused by external factors and damage stemming from intrinsic design or material weaknesses [3]:

- **External damage** – such as cracks, delamination, or junction box detachment caused by transportation mishandling, improper installation, or localized impact
- **Intrinsic material or design failures** – such as degradation or failure of poorly selected components or structural failure resulting from inappropriate module dimensions or improper racking design and installation.

It is debatable whether repairing modules with intrinsic failures arising from poor design or substandard manufacturing practices is technically or economically justifiable [7–9] . However, assumedly due to interests of certain stakeholders, most of the research and development efforts have focused on this specific area.

In general, any field repair process should be developed, managed, and validated with the same rigor as the original manufacturing process, including adherence to relevant quality assurance protocols and safety standards. Without such rigor, repairs may only mask deeper defects rather than restoring long-term reliability. It is also important to evaluate whether cell-level damage has already occurred before attempting a repair. In some cases, restoring external integrity may only conceal an already compromised product, leading to premature secondary failures and potential safety hazards.

Most work on repair of PV modules so far has been done on the repair of damaged/cracked backsheets, with first results being published in 2020 [10–12]. Two different approaches have been investigated, the application of an additional coating or of an adhesive tape/foil [13] on top of the existing backsheet. One work from 2023 dealt with the repair of glass defects [14]. First works on repair strategies for broken interconnects have been published from 2022 onwards [9,15–17].

Several companies list repair of PV modules as a commercial service [18–21]. Amongst others, repair procedures are offered for the following components: bypass diodes, junction boxes, frames, backsheets, cables and connectors. Despite listing repair services on their websites, most of these companies do not provide detailed descriptions of their repair approaches or procedures. This could be due to a variety of reasons such as proprietary methods, competitive advantage, or simply an oversight in providing comprehensive information to potential customers. However, the lack of detailed information can be a barrier for customers considering using these services. They may be unsure about the quality, reliability, and longevity of the repairs performed. Detailed descriptions of repair procedures can build trust and ensure customers understand what they are getting. The lack of transparency might also indicate a broader industry issue where standard practices for repairing 2nd life photovoltaics are not well established or documented yet.

Nieto-Morone et al. [9] investigated 23 partially repaired modules obtained from a Spanish company specializing in photovoltaic module repairs. Repairable defects considered include damaged diodes, junction box replacements, minor backsheet damage, and broken or burnt cells. Unfortunately, no details on the repair procedures are given, also the company who did the repair is not named. The objective was to assess the restored power capacity achieved through partial repairs, providing insights into the technical and cost-effectiveness of module repair as compared to replacement. The study's significant finding suggests that the repaired modules meet the manufacturer's warranty criteria, indicating their potential for reuse.

In recent years, the topic of PV module repair has gained increasing attention beyond the limited scope of earlier scientific publications and specialized repair services. A growing number of projects, working groups, and standardization bodies are now actively addressing the subject, reflecting its growing importance in the context of sustainability and circular economy principles [22]. Within the IEA-PVPS Task 12 framework, which focuses on the sustainability of photovoltaic systems, the repair of PV modules has been officially introduced as a new activity under Subtask 1 (Circular Economy) [23]. This inclusion highlights the recognition of repair as a key element in extending the lifespan of PV systems, reducing waste, and improving resource efficiency. The PVQAT Working Group 15 (WG15) is also dedicated to topics closely linked to repair, specifically Repair, Reuse, Recertification, and Recycling of PV modules. This group aims to establish quality assurance guidelines and best practices to ensure that repaired and reused modules meet reliable performance and safety standards over their extended service life [24]. Additionally, within the IEC Technical Committee 82 (IEC-TC82), a specialized working group is addressing the reuse of PV modules in alignment with circular economy strategies [25]. Their work includes the development of international standards that define technical requirements, testing procedures, and certification pathways for second-life PV modules, ensuring that they can be reintegrated into the market without compromising quality or safety.

Table 1: Overview of repair approaches for mainstream crystalline silicon PV modules (and their technology readiness level, TRL) reported in the literature and in the market. All repairs except for cables and connectors require wet leakage testing to confirm safety.

Compo-nent	Failure modes	Mode	Field repair possible without dismantling	Automatable	TRL	Reference
Backsheet	Chalking; Cracks; Microcracks; Insulation issues	Coating	Yes*	Yes	7	[10,11]
		Tapes	Yes	No	9	[20,26,27]
		New Backsheet	No	Yes	9	
Glass	Cracks	Coating / Adhesive	Yes	Yes	3-4	[14]
Inter-connect	Broken soldering; Broken ribbons	Invasive Repair	No	No	3-4	[15,16]
Junction box	Delamination; Water ingress; Failed bypass diodes	Replace	Yes	No	9	[19,21]
Frame	Delamination	Replace	No	No	9	[19]
Cables & Connectors	Torn cables and connectors	Replace	Yes	No	9	[19]

** Sometimes, but in many cases, the module must be removed from the rack*

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

2.1 Repair of PV modules after production

In general, there is a noticeable lack of comprehensive literature and technical guidance on the repair of PV modules or their individual components after production. This includes modules affected by damages incurred during manufacturing, the use of defective or sub-standard components, or irregularities resulting from process fluctuations - such as variations in temperature during soldering or lamination. Such repairs are typically carried out within the manufacturing facility before the modules are shipped to customers, ensuring that they meet minimum performance and safety criteria prior to market release.

Anecdotally, certain repair techniques are/were used, such as re-soldering electrical connections and re-laminating modules in cases where the curing of the original encapsulant was insufficient. These corrective actions typically served to restore mechanical integrity or improve moisture resistance. In earlier years of module production, it was also not uncommon to manually replace defective or damaged solar cells within the module. Such modules, which often exhibited minor optical or electrical deviations from standard specifications, were subsequently marketed and sold as B-stock.

Reported work on repair during and directly after production include the automated detection of faulty silicon solar cells [28] and the repair of scribing lines in Cu(In,Ga)Se_2 (CIGS) cells [29,30].

Crystalline silicon cells

Rodriguez-Araujo et al. [28] developed a system for the use in solar cell production lines that can automatically identify, locate, and repair defects. The system isolates and removes defective sections, allowing the salvage of reusable pieces from faulty solar cells (see Figure 1). This method is estimated to reduce waste by 69%. A key feature of the system is its ability to simultaneously segment and classify different types of defects, such as shunts and cracks, in solar cells. This marks an advancement over current methods, which typically detect only one defect type or fail to differentiate between defects. Recognizing specific defect types is essential, as each requires a unique repair approach. Despite this advancement, no further publications or evidence of market readiness or commercial uptake of the proposed system could be found.

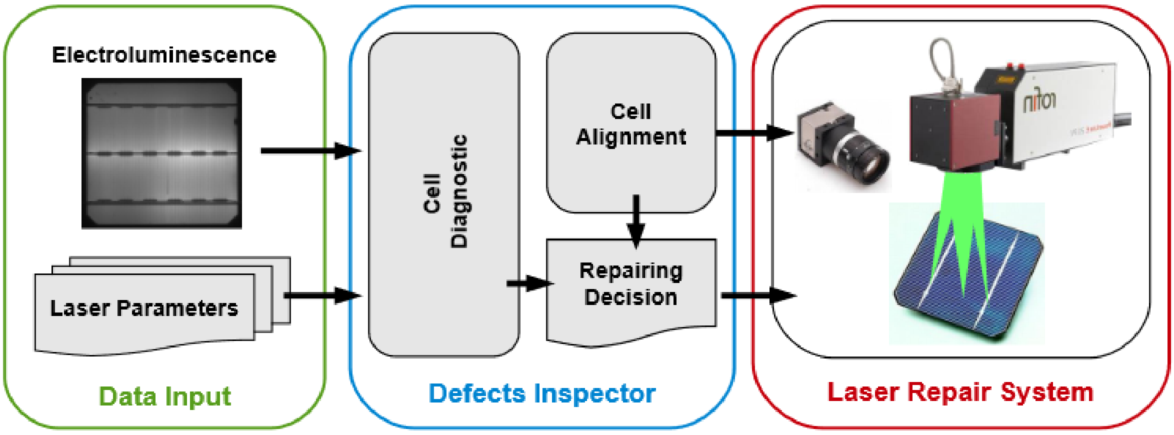

Figure 1: Block diagram of the automatic laser based solar cell repair system as proposed in 2014 [28]

Thin-film technologies

Misic et al. developed a simple method to repair broken P1 scribe lines early in the production of CIGS (Copper Indium Gallium Selenide) solar modules [29]. Scribe lines are thin cuts used to separate and connect layers in the solar cell—P1 specifically separates the back contact layer. Their method uses voltage ramps to create current through the molybdenum layer, allowing it to find and fix defects without needing detailed imaging. It works regardless of the defect's size or location. By monitoring the repair current, the system also gathers useful data on where and how often defects occur, helping improve the scribing process. This approach has been successfully used in real production, but no further studies or commercial tools based on it have been reported.

In another approach Misic et al. [30] examined the repair of interruptions in the back contact (P1) scribing line between two Mo back electrodes through thermally induced fractures. These fractures occur during the co-evaporation of the absorber, a process used in CIGS thin-film module manufacturing and can effectively repair line interruptions up to approximately 70 µm. Additionally, they demonstrated that a thermal treatment applied after P1 laser scribing and before CIGS co-evaporation can repair interruptions as large as 1 mm.

2.2 Repair of PV modules in the field

2.2.1 Junction Box / Cable / bypass diodes

No scientific or technical publications have been found on this topic. However, the authors could get information of procedures from Suncycle (https://www.suncycle.eu/), a company specialized on operation and maintenance of PV systems.

Suncycle follows defined technical procedures and safety protocols for the repair of substring failures in PV modules within operational solar plants. The primary objective is to establish a safe, efficient, and standardized methodology for diagnosing and repairing modules with electrical faults, particularly those involving bypass diodes and interconnection failures, to restore performance and ensure long-term reliability.

A key focus of the process is the diagnosis of failures, which begins with a visual and electrical inspection of each module. Technicians assess signs of damage, such as discoloured or deformed junction boxes, and use a multimeter to measure DC voltage. This allows the identification of defective substrings: a full V_{oc} indicates all substrings are intact, while readings of 2/3, 1/3, or 0 V_{oc} suggest one, two, or all substrings are disconnected or bypassed. Detailed diode testing in forward and reverse directions is used to confirm functionality, helping to differentiate between diode failure and circuit interruptions.

Based on the diagnostic outcome, the procedure provides three main corrective approaches: (i) resoldering faulty contacts, (ii) replacing damaged bypass diodes, or, when necessary, (iii) installing a new junction box. All repair actions are carried out in a mobile workshop set up onsite (Figure 2), ensuring minimal disruption and quick intervention. Post-repair, the modules are re-tested to confirm recovery of nominal electrical parameters, and the junction box is resealed; all steps are documented. The procedure emphasizes maintaining high safety standards, ensuring environmental protection (including waste collection and habitat preservation), and ensuring legal compliance with national labour and risk prevention laws.

The implemented repair process has demonstrated a high-throughput industrial capacity, enabling the reworking of up to 120 modules per day. Field data show a rework success rate of approximately 90% for recently installed modules, indicating strong effectiveness for modules with low degree of degradation. Even for modules that have been exposed to environmental conditions for a long time, the process achieves a success rate of around 75%, highlighting its robustness and value in extending module lifespan across a range of aging profiles [26]. However, no investigations assessing the long-term electrical performance, reliability, or degradation behaviour of these repaired modules have been reported to date.

Figure 2: Mobile repair workshop © Suncycle Iberica [31].

2.2.2 Interconnect & solder failures

Two different research groups proposed repair procedures for failures of cell interconnections. Lee et al. presented [15] a method for the recovery of resistive solder bond (RSB) hotspots caused by poor soldering. Rosillo et al. [16] proposed a method for repairing busbar interruptions in PV modules.

The proposed repair method [15] for RSB hotspot modules involves several detailed steps to ensure minimal damage and effective recovery, see Figure 3. The team compared a new on-site repair approach with a more comprehensive factory recovery process. In the factory process, the frame is separated, and adhesive materials such as tape or sealant are removed. The EVA is then heated and softened using a hot plate, allowing the backsheet to be peeled off and to be completely removed, the EVA and busbar in the damaged area are also removed. Then the EVA encapsulant is re-layered along the interface of the upper and lower cells. The cell tab to be connected to the new busbar is fluxed for re-soldering. After cooling the module to room temperature, flux is applied to the new bus bar, which is then soldered to connect it. The first EVA is inserted between the glass and bus bar with high accuracy to avoid bubbles and ensure a perfect connection. A second EVA layer, slightly larger than the restored area, is overlapped and fixed using an iron tip to prevent shifting during lamination. It is crucial to maintain an overlap margin of about 5 mm to avoid visible repair signs post-lamination. Finally, the entire module is covered with new EVA and a new backsheet, the electrical connections are checked, and the module is placed into the lamination process.

With on-site recovery, all restoration processes are performed directly in the field, reducing the steps from 22 in factory settings to 8 on-site. This approach allows for immediate installation and inspection of the post-recovery without the need for repacking or transferring modules. In the 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. Field validation over a defined monitoring period is recommended to assess the long-term performance and effectiveness of the proposed repair solutions."

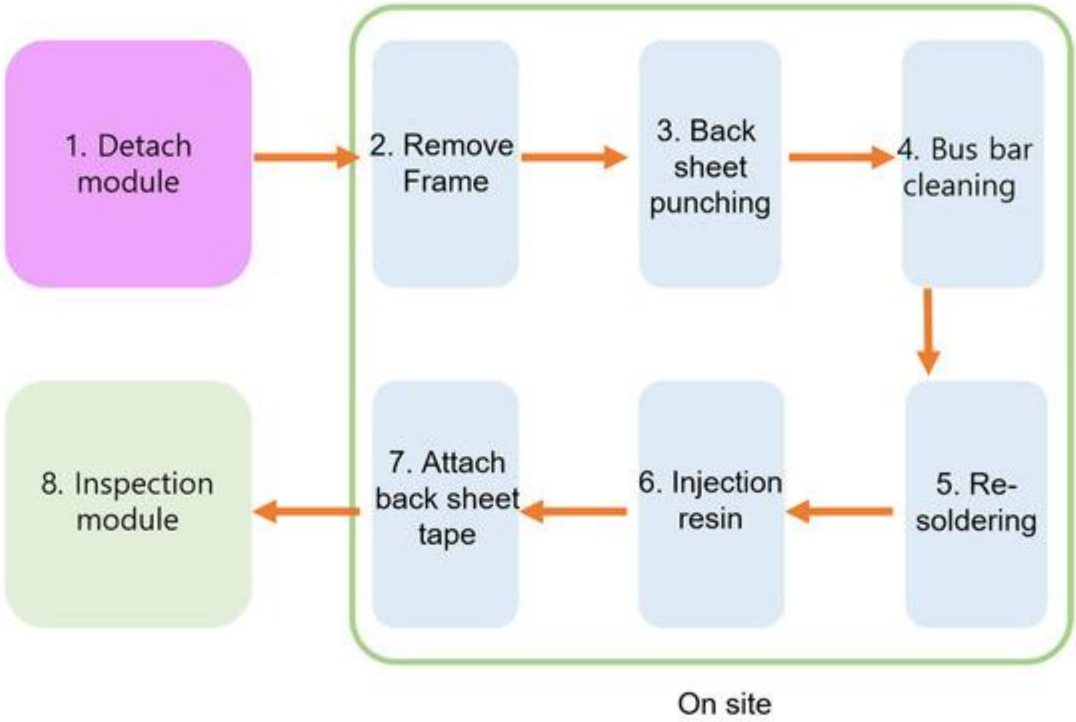

Figure 3: Scheme of on-site interconnect repair as proposed by Lee et al.; reproduced (adapted) with permission. Copyright 2022, MDPI. [15].

The process proposed in [16] involves marking the work area and removing the backsheet and EVA at the module part to be repaired. Sanding band accessories, as well as various polishing and cleaning tools were used. The critical steps involve carefully separating and lifting the bus bar sections, applying flux, and inserting a complementary bus bar piece (see Figure 4). Soldering is done with a specific soldering iron temperature (183°C) to ensure secure connection. After checking continuity with a multimeter or tone tester, the hole is filled with a silicone sealant to ensure proper sealing. Each ribbon interruption repair takes about 5 to 10 minutes. The procedure was tested on three different modules, labelled M1, M2, and M3. Before repairing, M1 and M2 generated around 50W, while M3 was unable to produce power. After repair, all modules produced about 200W of electricity; no additional damage due to the repair process has been found.

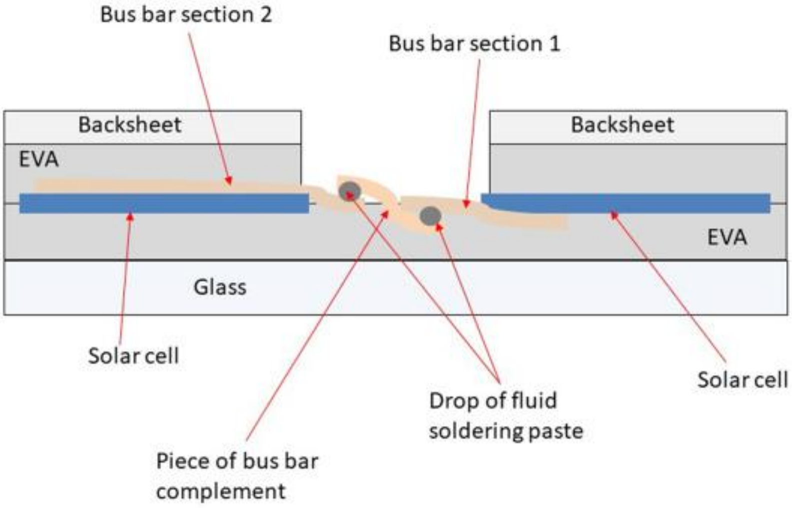

Figure 4: Scheme of interconnect repair as proposed by Rosillo et al. Reproduced (Adapted) with permission. Copyright 2024, Elsevier [16].

In a follow-up paper Rosillo et al. [17] investigate the repair of ribbon interruptions - both twin (affecting both ribbons on a cell) and single (affecting only one) - in PV modules with two-ribbon cell interconnections. Twin interruptions were found to cause significant power loss, and their repair can recover power in multiples of one-third of the module nominal power, while single interruptions can yield additional gains of up to 6%. A simple, low-cost method using a magnetic compass for locating single interruptions was proposed, with results matching those from EL imaging and current sensors. The study highlights the benefits of full repair (twin and single interruptions), which led to power gains of up to 320% and a fill factor improvement of up to 25% in the tested modules.

2.2.3 Module packaging

Glass repair

Tas and Van Sark [14] explored an experimental repair technique for glass defects in glass-glass PV modules, assessing its effectiveness through performance and reliability tests post accelerated ageing tests (DH). The experimental repair technique for glass defects in double-glass PV modules is adapted from methods used for windshield repairs in cars. Materials required include repair and pit resins, a UV lamp, and supplementary cleaning tools. It involves seven steps:

(1) Inspection: Assessing the fracture's freshness and extent.
(2) Temperature Control: Maintaining the module between 5°C and 29°C, ideally 20°C, and ensuring the fracture is dry.
(3) Preparation: Cleaning the module and positioning it horizontally.
(4) Resin Application: Inserting repair resin into fractures and using a paintbrush to ensure it flows in, then removing excess resin.
(5) Pit Resin Application: Applying pit resin on larger pits and fractures as a sealant.
(6) Curing: Using a UV lamp or sunlight to cure the resin.
(7) Finishing: Verifying the repair and cleaning of the module.

The study inspected PV modules with glass defects, confirming no initial defects other than the glass fractures. Initial EL imaging revealed no internal irregularities. 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. After DH exposure, five out of six specimens had similar performance, with a 4.0-4.7% decrease. Only the not repaired module exhibited a significant 7.8% performance decrease due to the formation of additional large cracks upon DH storage. Tas and Van Sark [14] used the Cost Priority Number approach [8] to compare economic benefits comparing local repair and substitution. They found that energetically, repair is significantly more desirable than substitution, with economic benefits dependent on repair scale and frequency. In a follow-up project [32], new resins and foils are being tested, combining indoor accelerated tests and outdoor testing, however, no results are available at the moment.

Backsheet repair

Field experience clearly shows that the lifetime of glass/backsheet modules often depends on the reliability of the polymer backsheets. A significant proportion (over 40%) of material defects in PV modules are due to cracking, delamination, and material degradation/yellowing of the backsheet. The most serious consequence is the possible resulting decrease in the electrical insulation resistance (R_{iso} wet) of the backsheets, which can have a significant impact on the safe operation and, in the long term, also on the yield of the PV system. 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 [10–12]. Two different repair strategies have been addressed: repairing BACKSHEET damage of deep cracks by applying coatings (i) to restore electrical insulation properties, and (ii) preventing further growth of the surface near microcracks. A repair process (see Figure 5) has been developed that comprises the following steps [11]: (i) cleaning, (ii) pretreatment (if necessary) and (iii) coating (crack filling and sealing).

From a technical point of view, several of the repair solutions examined met the defined requirements for compatibility and applicability. On the one hand, repair tapes/films sealed the surface perfectly, but crack filling was only successful if the adhesive could penetrate the cavities that had formed due to the cracks in the backing material, such as in the case of microcracks close to the surface. On the other hand, 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. The required insulation resistance (R_{iso} wet) 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. Accelerated aging tests and natural weathering tests of repaired modules were/are performed. PV-plants with repaired modules with deep longitudinal cracks and microcracks are in operation now since August 2021 and June 2020, respectively, as shown in Figure 6.

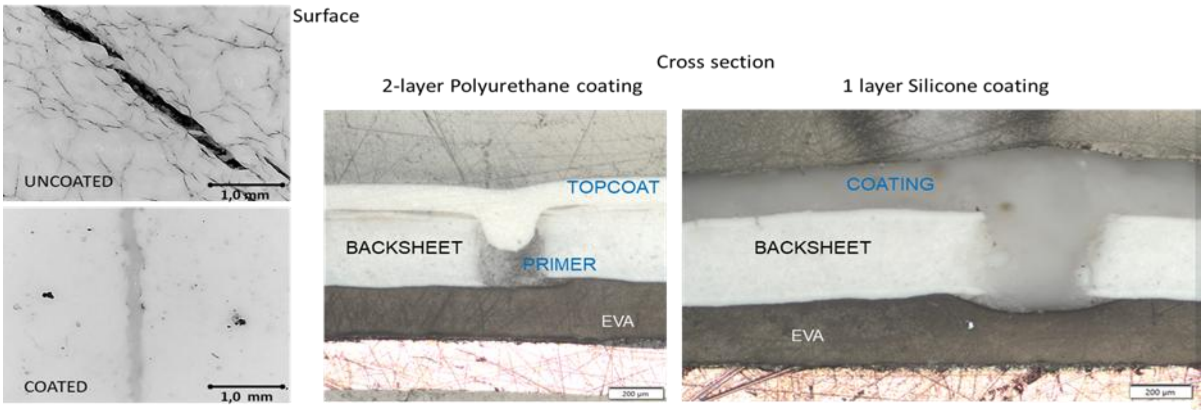

Figure 5: Microscopic images of a Polyamide backsheet surface (left) with microcracks (MC) and deep, longitudinal cracks (LC); and of cross sections (middle and right) of the coated samples [11].

Figure 6: Foto of the coating process of an aged module with cracked backsheet (left), on-site material and adhesion tests (middle) and of the test-site operating successfully with repaired/coated PV modules since 2021 (right). As repair coatings flowable silicone and a two component Polyurethane-coating were used [10,11,33].

Based on these results it can be concluded that for a successful repair of modules with deeply cracked backsheets, complete sealing of the deep cracks and the entire weathered and often micro-cracked backsheet surface is necessary to stop further material degradation of the backsheet and regain its electrical insulation. The long-term performance of the repaired PV-system was followed (electrically and material wise) under operating conditions. After coating and 30 months of natural weathering (modules in operation) (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 behaviour of the repair and its life-extending effect of PV modules. Repair coatings for backsheets can thus be applied in four different scenarios, see Figure 7.

Local backsheet defects caused by mechanical damage during installation or handling of the modules, can be easily repaired with coatings or tapes/films [11]. Defects caused by physical cracking in the backsheet, such as (i) microcracks in the outer layer or (ii) deep longitudinal cracks (through the entire cross-section of the backsheet) beneath the busbars, can also be repaired by applying coatings capable to fill the crack voids. This also restores the insulation resistance of the backsheets/modules [11].

In the case that backsheet cracking is accompanied by chemical degradation of the polymer layers (like for the squared cracks observed in PA backsheets, see references [10,11]), which leads to delamination, [28,29] repair with coatings or tapes is not possible.

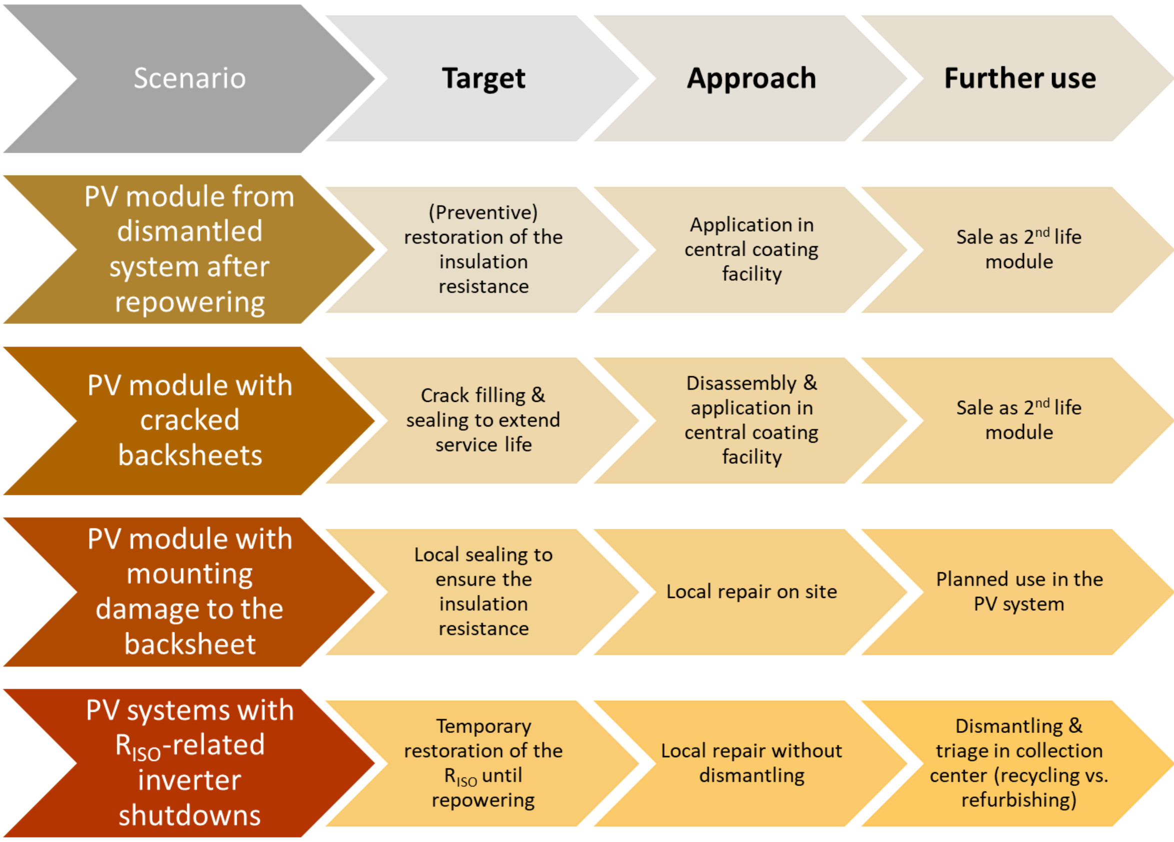

Figure 7: Repair scenarios for 2nd life PV modules with backsheet issues, as identified by the ReNew PV Project [34].

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 BACKSHEET 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.

2.2.4 Frame

A comprehensive review of available resources indicates that a dedicated, standalone field procedure for replacing only the frame is not commonly documented or standardized. In most cases, when structural damage is present, the prevailing recommendation is to replace the entire module rather than attempt repairs. However, repair of damaged frames is listed as service of some companies, e.g., Suncycle (www.suncycle.eu), without listing any further information about the repair procedure itself.

2.3 Refurbishment of PV modules for 2nd life

If PV systems are dismantled upon modernization or repowering, the modules have sometimes only reached half of their possible service life and still have 90% or more of their original output. Such modules can be tested for their electrical performance and safety aspects and then - if necessary - be refurbished for a second lifecycle. The Austrian start-up 2ndCycle FlexCo (https://www.2ndcycle.at/en) builds an upcycling plant for this purpose (see case study 2 in chapter 3.2). They are developing a fully automated and scalable solution to process used, dismantled solar modules cost-efficiently for a second life cycle. In the upcycling plant (see Figure 8), the PV modules are cleaned, the Bill of Materials (BOM) identified, electrically tested (EL-images, IV-curves, R_{ISOwet}) and damaged components (e.g., connectors) replaced where possible. After passing through all test stations, a test report is created based on the data measured.

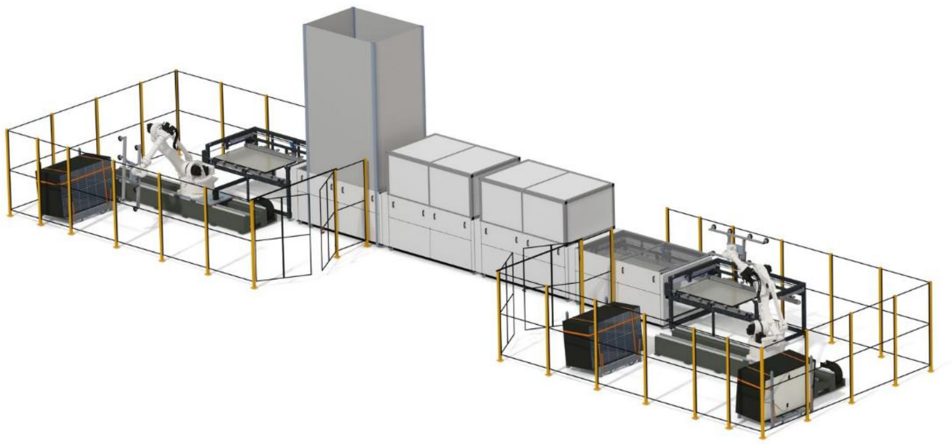

Figure 8: Schematic of the upcycling plant of 2nd Cycle (https://www.2ndcycle.at/en).

2.4 Methods for assessment of repair measures / safety aspects

The aim of repair/refurbishment measures is to restore the full functionality of all PV components in a PV module; the safety requirements as given in IEC 61730-2 [35] must be met at all times during operation. IEC 61730-2 is the internationally recognized standard defining safety test sequences for photovoltaic modules, covering electrical, mechanical, and fire safety aspects. It became the consensus method through long-term international collaboration within IEC technical committees, where manufacturers, test laboratories, and researchers aligned laboratory testing with field experience. Its global adoption was reinforced by interlaboratory validation, formal IEC voting, and widespread acceptance by certification bodies, regulators, and the PV industry. Thus, the most adequate methods to assess the success of a repair process is to test according to the module safety test (MST) procedures of the standard and evaluate according to the pass/fail criteria given there.

One example: after repairing a PV module with cracked backsheet with a coating or adhesive foil [27], the wet leakage current test (MST17) has to be passed which is equivalent to MQT 15 in IEC 61215-2 [36]. The requirements for the insulation resistance of modules in wet environment are $R_{iso,wet}$ > 40 MW/m^2. Studies have shown that this is met in the long-term, when complete crack filling is achieved [10,11,37]. This can be checked on a cross-section of the module as already described and depicted in Figure 5 in Section 2.2.3.

2.5 Measures to increase repairability of PV modules

In many studies, repair of PV modules is seen as a way to extend and ensure function and safety of PV modules [1,2,38–41]. The current PV module design and packaging concept, with interconnected solar cells in between two transparent polymer films, a front glass and a back-sheet or back glass was developed over 40 years ago (between the end of 1970s and beginning of 1980s) [42]. The innovation and relevance of “Design for Repair" in PV modules lies in its potential to extend the functional lifespan of modules, reduce waste, and enhance sustainability in the solar energy sector. Relevance stems from the need to address challenges posed by the Durability-Repairability Paradox of traditional PV module designs, which prioritize durability but limit reparability. As a rule, the more permanently you attach materials the stronger and more durable it is, but the more difficult it is to repair and replace.

So far, no comprehensive strategies addressing “Design for Repair” or the “Right for Repair” [43] have been published for PV modules. However, a few research groups and start-up companies have introduced approaches aiming at improving the recyclability of PV modules and their components. Many of these advancements could also enhance the reparability of PV modules.

Wanghofer et al. explored the use of reversible adhesives for frames and junction boxes, highlighting their potential to significantly simplify repairs [44]. This study evaluated dismantlable adhesive connections for PV modules using silicone adhesive containing thermally expandable fillers, such as thermally expandable microspheres (TEM) and expandable graphite (EG). TEM samples showed rapid expansion at lower temperatures, while EG samples required longer heating times but demonstrated effective debonding properties.

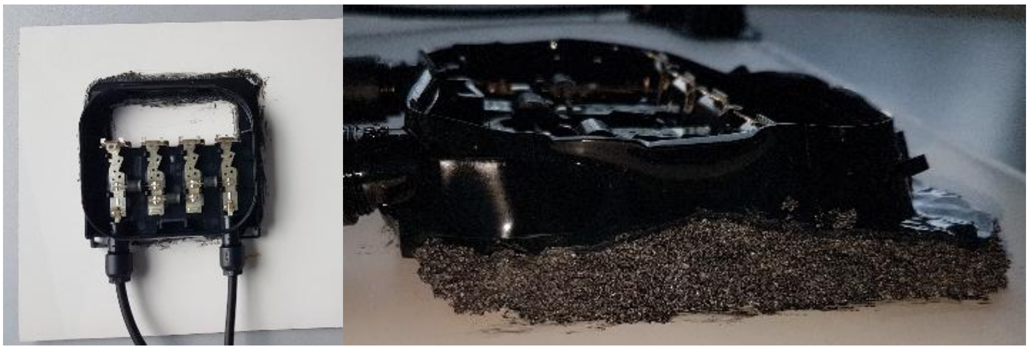

Figure 9: Adhesively connected junction boxes on PV module before (left) and after (right) expansion of the expandable graphite (see also [44]).

The mechanical properties and aging stability of the adhesives were tested, revealing that EG significantly reduced bond strength due to its structure, whereas TEM slightly improved it. Aging tests indicated no significant influence of filler content on stability, though TEM degraded under damp heat conditions. Overall, EG proved effective for creating dismantlable adhesive connections, though lower expansion temperatures remain a challenge due to limited commercially available materials. Figure 9 illustrates the module before and after thermal expansion. Prior to heat treatment, both junction boxes could support the module’s weight. After heating, the reference junction box remained firmly attached and intact, while the adhesive containing expandable graphite expanded significantly, allowing the junction box to be easily detached, demonstrating the potential of expandable graphite for externally triggered de-bonding.

Ehrhardt et al. [45] proposed a self-healing mechanism for solar cell encapsulants, offering another innovative approach to improving module longevity. Thermal stress-induced micro-defects in encapsulant layers can be repaired using thermally responsive polymers. Two model polymer systems were tested, showing repeated thermal reversibility and effective self-healing capabilities while maintaining structural integrity across application temperatures (-40°C to 85°C). Overall, these materials show promise for improving PV module durability by leveraging daily temperature fluctuations for self-repair.

Recently, the Dutch startup Biosphere Solar developed an encapsulant-free modular PV module design inherently enabling disassembly, repair, refurbishment, and component reuse [46]. Biosphere Solar's modules feature a lamination-free, glass–glass construction sealed using a double edge-seal system, combining polyisobutylene (PIB) and silicone to protect against moisture and oxygen ingress. The absence of traditional encapsulants like EVA eliminates common degradation issues such as yellowing and delamination. An inert internal atmosphere, maintained using desiccants and oxygen absorbers, further enhances durability and long-term stability. Biosphere Solar's module design is fully modular and repairable, allowing for the replacement of individual components such as solar cells and junction boxes without damaging the entire unit. Each cell is mounted in a removable "bed," making targeted repairs straightforward and non-destructive. The edge-seal system is designed for controlled disassembly, enabling field-level access for maintenance and upgrades. This modular approach supports extended product lifetimes, facilitates reuse, and aligns with circular design principles. However, so far, no results on reliability testing or outdoor performance have been published.

Earlier research introduced the N.I.C.E. (New Industrial Solar Cell Encapsulation) PV module concept, primarily developed by Apollon Solar, which follows a similar modular approach by avoiding the use of polymer encapsulants [47]. The core concept of N.I.C.E. PV module technology centers on a disruptive manufacturing process that eliminates traditional soldering and lamination. Instead of using EVA encapsulants and high-temperature processes, N.I.C.E. modules employ a double-glass structure with a polyisobutylene (PIB) edge seal and achieve electrical interconnection through pressure-based contact between copper ribbons and cell busbars. Unfortunately, Apollon Solar ceased its activity in 2022 due to lack of success with the module concept.

From a regulatory and governance perspective, policymakers are increasingly recognizing the need to incorporate design-for-repairability and design-for-circularity principles into regulatory frameworks. The European Commission's Joint Research Centre (JRC) recently published the "Preparatory Study for Solar PV Modules, Inverters, and Systems" [48], in which key areas are identified, where improved PV module design could enhance long-term durability, ease of maintenance, and end-of-life (EoL) recycling. One major focus is on component accessibility, particularly in junction boxes, where bypass diodes are increasingly soldered instead of plug-in types, limiting the possibility of replacement. The study suggests that manufacturers should be required to report on the accessibility and replaceability of junction box components, and, where diode replacement is hindered, the entire junction box should be replaceable without damaging the module's integrity. Additionally, EN 45554, a standard that defines generic assessment methods for repairability and upgradability of energy-related products, could serve as a foundation for developing product-specific repairability indexes for PV modules. These indexes could quantify factors such as access to maintenance information, type of fasteners used, required tools for repair, and the skill level needed for disassembly [48,49].

Beyond repairability, design-for-disassembly (DfD) and design-for-recycling (DfR) are also critical considerations. The preparatory study stresses the need for modular PV construction, which would facilitate the separation of individual components for targeted repair and easier recycling at EoL. Disassembly trials by manufacturers could provide valuable insights into optimal fastening and joining methods to improve recyclability while maintaining structural integrity during operation. Despite low module failure rates (~0.5%), long-term sustainability concerns necessitate proactive design measures to prevent future environmental burdens associated with growing PV waste streams. Policymakers are therefore encouraged to introduce both compulsory information disclosure and semi-quantitative eco-design requirements that promote circularity, ensuring that future PV modules are not only high-performing but also designed for longevity, repair, and resource recovery.

2.6 Economic considerations of repair

The economic viability of repair versus replacement hinges on a detailed cost-benefit analysis [7]:

Repair is often the preferred option when the damage is localized to only a few panels, and the rest of the system remains functional. This approach is also suitable if the problem originates from external components such as the inverter or wiring, rather than the core module itself. Furthermore, if the panels are still under warranty, if the physical damage is minimal and confined to surface components, or if issues are detected and addressed early, repair tends to be the more practical choice. However, if defects are found in many modules from the same production lot, this typically points to deeper root causes—such as material degradation or systemic manufacturing issues—which should be addressed at their source rather than temporarily patched in the field.

Replacement is frequently the superior option when the PV system is over 20 years old, as panel efficiency naturally declines over time. Replacement is also advisable if the energy demands of the property have increased, or if the damage is widespread, affecting multiple panels (e.g., extensive cracking or delamination). If both the inverter and panels are simultaneously nearing their end-of-life or failing, replacing both components at once can be a sensible strategy as well.

Current methods for repairing modules as described before requiring significant manual labour. This often involves diagnosing the issue, disassembling the unit, replacing or fixing the faulty component, and reassembling the module. This process can be time-consuming and requires skilled technicians. Given the high labour costs and the time required for repairs, it can be more cost-effective and less risky 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. However, in regions where labour costs are comparatively lower, such as India, the economic viability of repair and reuse could be further enhanced; for instance, preliminary estimates from the Indian Council on Energy, Environment and Water (CEEW) indicate that repairing junction box and bypass diode failures costs approximately 50–60% of a new 350 Wp module.

The choice between repairing and replacing a module often depends on several factors, including the cost of labour, 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 of damaged modules is possible, it is often more practical and economically viable to replace them with new ones due to the high labour costs and potential for improved performance with new modules.

Another essential consideration in determining whether to repair or replace a PV module is obtaining explicit approval from the original manufacturer. Manufacturer authorization ensures that the proposed repair aligns with product design specifications, maintains safety and performance certifications, and does not inadvertently void existing warranties.

Table 2 summarizes key factors for repair vs. replacement decisions. A COST PRIORITY NUMBER approach [8] can assist in making the most economic decision. Potential exceptions to the general practice of replacing defective photovoltaic modules rather than repairing them are found in remote or hard-to-access installations, where the logistics of transporting new modules involve significant effort, cost, or risk. A notable example includes PV systems installed in high-altitude or mountainous regions, where conventional transportation is not feasible and replacement modules must be delivered by helicopter. In such cases, on-site repair of damaged modules may become a more practical and economically viable solution, especially when accessibility, weather conditions, and transportation constraints make regular maintenance or component replacement extremely challenging.

Table 2: Key Factors for Repair vs. Replacement Decisions.

Factor	Consideration for Repair	Consideration for Replacement
Damage severity	Minor issues (small cracks, chips, surface damage)	Severe damage (glass breakage, delamination, twisted frames, water ingress, deep backsheet cracks)
Module age	Relatively new panels (within warranty period or early in lifespan)	Nearing or exceeding 20–25-year lifespan
Warranty coverage	Damage covered by manufacturer or installer warranty	Damage not covered by warranty (e.g., weather, pests)
Cost effectiveness	Repair cost significantly less than new module + labour	Repair cost comparable to or exceeding new module + labour
Performance impact	Minor dip in output, expected significant recovery post-repair	Significant, persistent dip in output; no substantial improvement expected from repair
Widespread damage	Only a few panels affected: rest of system healthy	Multiple panels extensively damaged, delaminated, or failing
System needs	Current system meets energy needs; no desire for upgrade	Energy needs have changed; desire for more efficient, modern technology
Component failure	Problem isolated to external components (e.g., inverter, wiring)	Both inverter and panels are aging/failing concurrently

3 RE-QUALIFICATION, STANDARDIZATION, BANKABILITY AND FIELD EXPERIENCES OF 2ND LIFE PV

3.1 Re-qualification for 2nd life PV

Re-qualification for second-life PV modules typically begins with visual inspection, followed by electrical performance measurements and, in some cases, safety testing. These steps are essential to classify modules according to their remaining performance potential and safety compliance before they are reintroduced into the market.

In practice, evidence of requalification is usually provided through traceability records and test documentation (e.g., I–V data, insulation results, EL images) issued by the entity performing the assessment. At present, a harmonized and widely recognized consumer-facing label is still emerging, which can make it difficult for non-expert buyers to verify requalification status without accompanying documentation.

However, it should be noted that there are currently online platforms actively selling second-life PV modules without evidence of having performed such tests. While these marketplaces provide an accessible channel for module resale, the absence of standardized inspection, classification, and safety verification protocols raises serious concerns regarding the reliability and long-term performance of the products offered. Inadequately tested second-life modules may present risks including accelerated degradation, electrical faults, or safety hazards, particularly when deployed in systems without additional quality assurance oversight.

In the following, the requalification procedure for second-life PV modules is described in detail, outlining the necessary inspection, testing, and classification steps to ensure safety, reliability, and performance compliance.

3.1.1 In-field sorting: from inspection to classification

The qualification and selection of PV modules for reuse comprise module health assessment and functionality tests. They are typically based on inspection and characterization methods, adhering to the principles of established technical criteria and standards. 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 [50,51], have recently outlined a qualification and triage framework for PV reuse (Figure 10) [1,2].

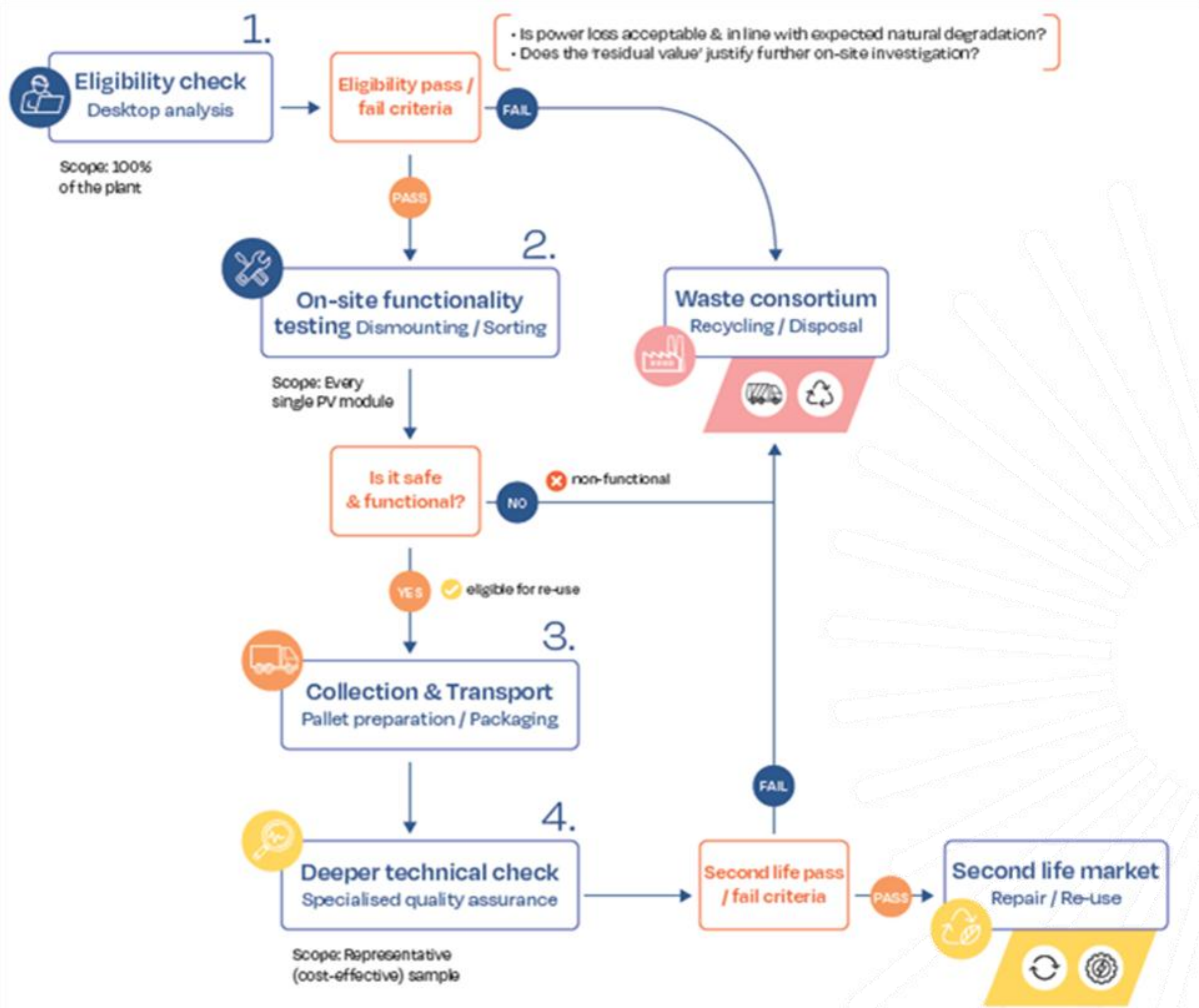

Figure 10: Workflow of the qualification and triage framework for PV reuse, as introduced and proposed by TRUST-PV and SolarPower Europe's Lifecycle Quality Workstream experts. ©SolarPower Europe [2].

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: i) off-site eligibility checks, ii) on-site inspections and functionality tests, iii) sorting for collection and transportation, iv) deeper technical checks [2].

1) Off-site ("desktop") eligibility checks can be based on recent advances in PV data monitoring analytics [52,53], 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 electroluminescence (EL), photoluminescence (PL) inspections and/or isolation resistance measurements ($R_{iso\ wet}$) are favored when precise selection, classification and root-cause analysis are required.
2) For such eligibility checks, two different (yet complementary) criteria are suggested: i) the performance loss rate (PLR) and ii) 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.

3) On-site inspections and functionality check 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 (BOM) (rarely available by default, yet identifiable by means of near-infrared (NIR) spectroscopy), etc. [54–56]. Recent studies and reports [39,57,58] outline the main methods, test protocols 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).
4) Following all eligibility and safety checks, as well as the inspections-based qualification of PV modules, proper logistics – including dismounting, packaging, and pallet shipping – are 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 WEEE 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. [59].
5) 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 [39]. Laboratory tests might include but are not limited to I-V characterization (flash) tests, lock-in thermography (LIT), EL imaging, diode tests, wet leakage insulation testing, aging tests in climatic chambers, etc.

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) [54]. On the other hand, the wet leakage insulation testing remains an insuperable challenge, as it is practically almost impossible to apply to every PV module-candidate for reuse. Instead, the dry insulation test is applied. The idea is to accept modules with lower insulation resistance values 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 [39].

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 [39]: (i) on-site dry insulation testing might not be conclusive for reuse purposes and it is advised to perform wet leakage 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; (ii) 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 is little to no real-life data of post-triage PV reuse rates, from field exposed PV modules. The statistics from an ongoing (non-disclosable) 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, wither deeper technical checks in laboratory, by means of I-V characterization, EL imagery (Figure 11) and LIT, it was possible to confirm a residual (post-repair) 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.

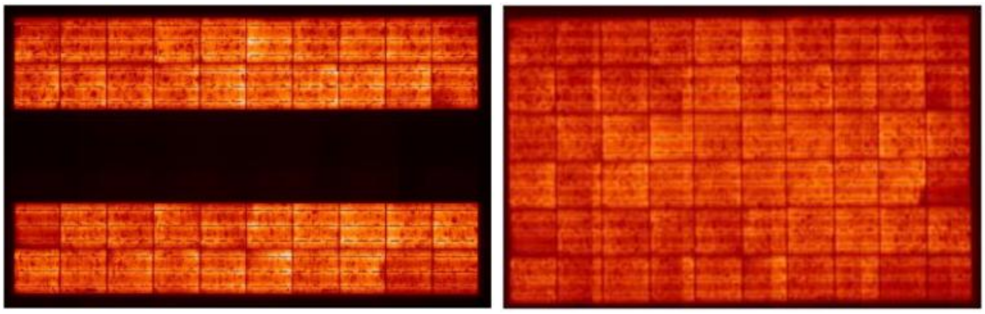

Figure 11: Left: Example of EL image characterization of a first-life PV module with a bypass diode failure (corresponding to an open-circuited submodule). Right: EL image of the same PV module post-repair, ready to enter the reuse stream [2].

In references [38] and [54] 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 a matrix three distinct "reuse eligibility classes" have been identified (Figure 12):

- 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 (e.g., modules with insufficient R_{iso} wet)
- Class 3 (H and I): Non-functional, non-repairable, enter recycling 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 12: Classification matrix for PV module triage and eligibility for repair/reuse [2].

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 [50,60,61]. 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 (see Figure 13).

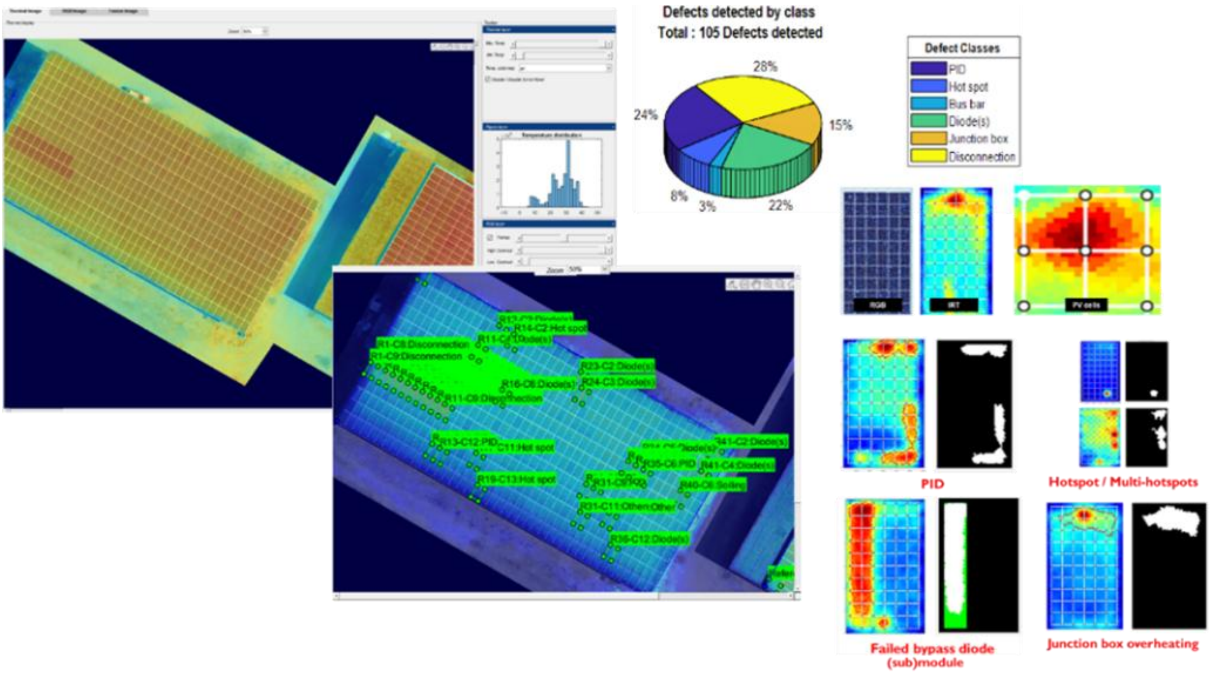

Figure 13: Example dashboard outputs from ASPIRE, a software prototype introduced by CEA, aimed for image-based detection and classification of PV failures allowing for selecting PV modules for reuse [2,61].

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 power loss rate (PLR) needs to be set. Such a functionality “threshold” is crucial for waste legislation, as non-functional 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 [54]. 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, the threshold for PV system functionality may be somewhat arbitrary.

These qualification thresholds also influence how modules are routed in practice: modules that fail safety or performance criteria typically enter regulated waste streams and should be handled in accordance with applicable WEEE and national requirements. Early separation of reuse-eligible modules, careful handling during dismantling and transport, and appropriate routing of non-reusable components to recycling channels are therefore important operational best practices, although detailed recycling process assessment is outside the scope of this report.

3.1.2 Quality assurance for 2nd life PV: recommendations and (future) standardization

As mentioned above, so far there has been a lack of international standardization for the qualification of PV modules for reuse. To change this, a project team has been created within the IEC Technical Committee 82 WG 2 at the end of 2021, that had the task to write an IEC Technical Report (TR) on the reuse of PV modules as a first step towards the creation of a worldwide standard. The project team involved around 30 IEC experts from different continents. A Technical Report is not allowed to be normative, but recommendations for test procedures and suggestions for future limit specification can be provided. In this way, it could serve as a basis for an IEC Technical Specification or Standard on the reuse of PV modules in the future. The draft TR has been finished in September 2025, but the IEC office has now (October 2025) recommended to go with this document for a Publicly Available Specification (PAS) since the draft TR was considered to be not only informative. The countries in IEC TC82 now still need to decide about the proposed change from a TR into a PAS and after that, would need to approve the text of the draft for the PAS. The publication of the PAS is expected close to the end of 2025.

Some terms and definitions in draft Technical Report on reuse of PV

Before discussing the draft PAS contents in more detail, some of the most important terms and definitions in the world of end-of-life, waste and reuse are listed for clarification in

Table 3. Most of the original formal definitions have been revised and adapted to the PV sector common nomenclature for a better understanding.

Table 3: Important terms and definitions.

Decommissioning	Process of removing a PV system or component from an active status. For a complete PV system, it means that it is deconstructed, and the land is made ready for redevelopment or returned to its original use.
End-of-life (EoL)	Natural or planned end of a PV system or component service lifetime
Performance Loss Rate (PLR)	Parameter indicating the decline of PV module power over time (in % per year)
Preparing for re-use	Checking, cleaning and/or repairing operations by which PV components are prepared so that they can be reused.

Recycling	Any recovery operation by which PV waste materials are reprocessed into products, materials or substances whether for the original or other purposes
Repowering	Increasing the nominal power of the PV system by replacement of old components (mainly modules and inverters) by new ones, to enhance its overall performance.
Revamping	Replacement of old components of a PV system (mainly modules and inverters) by new ones, to enhance its overall performance without substantially changing its nominal power and without compromising new land.
Reuse	Extending the lifetime of a product or a product component that has reached the end of its first use, by using it again for the same purpose for which it was conceived.
Reused PV module	PV module having reached the end of an operational phase being used again to generate electrical energy for the purpose of lifetime extension.
Waste	Any substance or object which the holder discards or intends or is required to discard.
E-waste	Electrical or electronic equipment which is waste, more formally '*waste electrical and electronic equipment (WEEE)'*

Discussion on different reuse testing approaches

The general PV module testing strategy targeted is to minimise the testing as much as possible while promoting module safety and quality. 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. Indeed, all modules from a utility-scale PV plant can be assumed to be similar in their remaining quality and it might be sufficient to use a sample. Such an approach would be limited to large plants that are still operational, and where all modules have degraded in a similar way, excluding of course any damage by extreme weather events before decommissioning. Furthermore, to justify sampling, it is necessary to first make a general assessment of a PV plant based on historical monitoring and maintenance data (e.g., tickets, IR thermography reports, insulation errors reported by the inverters, etc.). For PV modules from a (weather-) damaged plant or that are already stacked in a warehouse, individual module testing is considered inevitable.

Module qualification based on sampling approach

The sampling approach would be intended for PV plants in which the modules can be assumed to be all in similar condition. The clear benefit would be that the number of PV modules to be tested would be much smaller, reducing time and costs significantly. On the other hand, this is the most difficult approach, since it requires a procedure that will provide sufficient guarantee concerning module safety, quality and performance to a customer, without measuring every single module. It is also more difficult to check whether the sampling approach has been used in the correct way, and for a case where it was justified. It is different when sampling would be used "internally" for qualification of reuse modules from a PV plant, so when the modules are to be used in another location/application from the same owner.

The procedure should (as always) start with a visual inspection in the PV plant and an analysis of the monitoring data to check for the approximate PLR, possible outlier strings and possible insulation failures detected by the inverters. Based on this, and possible I-V and insulation checks for a few module strings (or modules), the decision about re-using the PV modules can be taken, before decommissioning.

The current recommendation for the module sampling is to base its partly on the checking of new plants in the "Engineering, & Construction Procurement Best Practice Guidelines" [62]. In Table 4, the different tests to be applied for new modules are listed with their sample rates.

Table 4: Sampling rates for checking PV plants (adapted from ref [39]).

Type of testing	Sampling rate (ISO 2859-1)		
	For new PV modules	Modules for re-use	
		On-site testing	Deeper technical check
Performance characterisation testing			
Maximum power determination at Standard Test Conditions (STC)	G 1	G 1	G 1
Efficiency loss at low irradiance	S 1	--	(S 1)
Electroluminescence inspection	G I	G 1	G 1
Qualification testing			
Visual Inspection	S 3	S 3	S 3
Insulation test under wetting (wet leakage test)	S 3	S 3	S 3
Degree of ethylene-vinyl acetate (EVA) cross linking	S 1	--	(S 1)
Adhesion strength EVA/backsheet	S 1	--	(S 1)
Power loss due to light induced degradation (LID)*	S 1	--	--
Power loss due to power induced degradation (PID)**	2 modules per BOM and test	--	--
Power loss due to light and elevated temperature induced degradation (LeTID)	2 modules per BOM and test	--	--
Reliability testing			
Design suitability (extended stress testing i. e. damp heat, thermal cycling, humidity freeze, UV exposure, mechanical load), relevant for all BOM used	2 modules per BOM and test	--	(2 modules per BOM and test)

*Can be less considered for n-type technology.

**Can be less considered for systems that have anti-PID solutions.

These are based on the Acceptance Quality Limit (AQL) system, with sample rates defined in ISO2859-1. From this list, the maximum power determination at STC, electroluminescence inspection, (detailed) visual inspection and insulation test under wetting should be done at least. These tests can in principle all be done on-site, but for EL and module power testing during cloudy weather, a mobile indoor test set-up is required. The deeper technical checks can be done when desired, most of them will typically not be possible on-site. The sampling rates with a G (general) are higher than the S (special) rates. As an example, G1 means 200 for a 125,000 modules plant, while S3 would mean only 32 modules. These rates could of course be adapted/increased for modules to be reused. The modules should of course be sampled across the area of the plant to obtain a representative sample. For the maximum power determination at STC, measurements can be done on module strings or modules with a handheld tool, or otherwise in the mobile PV test setup mentioned before.

Concerning the module powers, it is still open which variation should be the upper limit for sampling to be still justified. Concerning the visual test mentioned in the table above, in this case it is meant to be a detailed one, while a visual inspection on major issues should still be performed for each module during the decommissioning of the plant. Finally, the insulation test under wetting can be done with a hand-held insulation tester while spraying water onto the rear side of the module.

Module qualification according to the individual testing approach

When a PV plant has been (partly) damaged, typically by a weather event like hail or strong winds, modules will not be in similar condition (also monitoring date from the past are useless due to the damage) so that measuring every single module is the only option. This is also the case when modules have already been stacked on piles in a warehouse. In this case, the approach is to perform first a visual check on major issues, followed by performing the following indoor tests: I-V curve tracing, dry insulation test, bypass diodes test and EL (with automatic evaluation). It should be mentioned that the dry insulation test should be performed in a faster way than in the IEC61215 standard (that mentions a voltage ramp rate of maximum 500 V/s and dwell times of 1-2 minutes) to increase the throughput.

To allow for the reuse of modules that do not meet the (dry) insulation requirements for the original system voltage (typically 1000 V or 1500 V), or maybe also for certain types of defects and repairs, the draft PAS recommends introducing also a “reduced maximum system voltage” for these modules.

The labelling of the modules for reuse should be done in addition to the original one, not covering the original label. On this label, it should be indicated that it is a module for reuse, which company has checked the module for reuse, which is the (possibly reduced) maximum system voltage, and which repair(s) have taken place (if any). In addition, it is advised to add the obtained I-V parameters to the label.

A factory test line performing the measurements listed above can reach a throughput of around 60 modules/h (or 200 MW/y), while a mobile test setup can reach only 20 modules/h. For this reason, testing each module on-site is not a viable option.

Recently some companies have started using such a test line. They apply this individual testing also for modules from large PV plants that could have been suitable for a sampling approach. However, it is still unclear if this testing of every single module for all cases will be economically viable.

Approach recommendation in draft PAS and remarks for future standardization

Both testing approaches that have been described above have been included in the final draft of the PAS. However, for the moment the draft PAS recommends to still use the evaluation of every module when modules are meant to be sold on the market. For the future, it will probably be the best to create different standards for the different approaches, since it is to be expected that the sampling approach will require (much) more time and discussions than the every-module approach.

Concerning repair, different options are mentioned and discussed in the draft PAS (replacing bypass diodes, cables, connectors, junction box, etc.). While the replacement of connectors is a relatively straightforward subject, other repairs like replacement of a junction box are more difficult issues and will have to be addressed carefully in future normative documents.

3.2 Field experience and bankability: Case studies

3.2.1 Case Study 1: SOLARCYCLE (USA)

SOLARCYCLE, a prominent PV recycling company, has established an approach to sustainability by powering its Odessa, Texas recycling facility with a 500 kW “second life” PV system. This system, consisting of approximately 1,000 decommissioned solar panels, meets about 50% of the facility’s electricity demand. The panels used in this PV system were sourced from retired PV installations, i.e., a mix of residential, commercial and utility-scale PV projects by Ørsted and Sunrun, all installed nationwide (USA). A unique aspect of designing and building such a PV system from reused PV modules is that the PV modules have various power and form factors.

Figure 14: Overview of SOLARCYCLE’s second-life PV installation, made of retired PV modules, after evaluating their residual power output. Bottom-right photo of the PV1 array of the installation, shows example of reused PV module with broken glass, that is still producing energy.

Each of the decommissioned PV modules, arriving at SOLARCYCLE's facility, undergoes a rigorous evaluation process. The company tests the power output, structural durability, and overall functionality of each PV module for reuse. In addition, visual inspections to all PV modules are carried out to ensure that key components (glass, frame or connectors/junction boxes) are fit. The company discloses that no repair tasks are performed in this case study. On the other hand, flash (I-V) tests and electroluminescence (EL) tests were performed on every PV module to be reused/installed. Acknowledging that, currently, such comprehensive tests are cost prohibitive at scale, SOLARCYCLE team aimed to still gather as much information as possible, regarding the reused PV modules' residual performance and reliability. On this basis, PV modules that are still operational are repurposed for direct use in the on-site PV system. The PV modules deemed unfit for reuse due to performance issues, safety issues or faults/damage beyond repair are instead processed through SOLARCYCLE's advanced recycling stream.

SOLARCYCLE has developed a recycling method capable of recovering up to 95% of the value of a solar panel and returning it to the supply chain. These include:

- Silicon: Essential for creating new solar cells.
- Silver: A critical and valuable component in solar panel manufacturing.
- Copper and Aluminum: Reused in various industrial applications.

The materials extracted are reintroduced into the supply chain, reinforcing domestic production capabilities and reducing the industry's dependence on imported resources. This dual approach of reuse and recycling aligns with the principles of a circular economy, extending the lifespan of solar panel materials and significantly reducing waste. SOLARCYCLE is actively expanding its operations to bolster its impact.

3. Cedartown, Georgia Facility: Recycling site operational since July 2024. The same site, from 2027 onwards, is expected to produce 5–6 GW of solar glass annually using materials recovered from recycled panels. Enhances the domestic supply chain for photovoltaic manufacturing.
4. Mesa, Arizona Facility: Positioned to increase the company's processing capacity. Targeted at managing increasing demand for recycling services as more panels are being decommissioned nationwide.

The 500-kW reused PV system installed at the Odessa facility not only does it reduce operational costs by offsetting energy consumption, but it also demonstrates the viability of reused or second-life PV modules for commercial and industrial energy solutions.

Figure 15: Another view of SOLARCYCLE's second-life PV installation next to its PV recycling facility.

In five to ten years, once the power production of this PV system shrinks, SOLARCYCLE intends to transfer the reused PV modules right into their nearby recycling lines and replace the PV modules with future feedstock, using the existing balance of system and continue to generate power for their facility. As the company scales the Odessa facility's recycling capacity to one million panels a year, SOLARCYCLE's plan is to expand this reused PV power plant to continue to generate more of their energy demands.

The company has plans to replicate its Odessa model across more facilities, demonstrating how recycling and reuse can co-exist to enhance resource efficiency. SOLARCYCLE also envisions contributing to policy discussions around circular economy practices and recycling mandates for renewable energy systems.

3.2.2 Case Study 2: 2nd-Cycle (Austria)

2nd Cycle is addressing the growing challenge of managing end-of-first-lifecycle (EoL) PV modules through innovative and automated solutions. With the volume of EoL PV modules increasing rapidly, there is a pressing need for processes that extend the lifespan of these modules while optimizing resource efficiency. To meet this need, the company is developing a fully automated refurbishment system for PV modules, encompassing cleaning and a comprehensive condition assessment through advanced testing methodologies (see Fig. 16).

The refurbishment process begins with the cleaning and careful handling of used PV modules, an essential step for ensuring accurate assessments. During this phase, an innovative integration of the insulation (ISO) test into the cleaning station allows for the assessment of each module's electrical insulation while it is being cleaned, thereby saving time and streamlining operations.

Figure 16: Pilot Upcycling-Line from 2nd Cycle in Amstetten, Austria (https://www.2ndcycle.at/en).

Following the cleaning stage, modules undergo a series of inspection and testing procedures to evaluate their condition. These include:

- **Optical inspections:** Cameras are used to identify visible surface defects such as cracks or discoloration.
- **UV Fluorescence testing:** This detects subtle surface anomalies that could impact the module's long-term performance.
- **Electroluminescence (EL) testing:** EL testing identifies internal defects such as micro-cracks and degradation within PV cells, offering a detailed analysis of the module's structural integrity.
- **Electrical performance tests:** These include IV curve measurements to determine power output and efficiency, frame continuity tests to ensure proper grounding, and bypass diode checks to confirm correct functionality and prevent overheating during operation.

Through this automated and precise evaluation, the suitability of each module for reuse or recycling is determined. This approach not only maximizes the recovery of valuable materials but also ensures that only high-quality modules are reused, supporting both economic and environmental sustainability. The concepts of reuse and recycling are viewed as complementary strategies essential for maximizing the value of the increasing stream of EoL PV modules. Modules that retain a substantial portion of their original efficiency, typically around 85-95%, are prioritized for reuse. Recycling, on the other hand, provides an effective solution for damaged or non-viable modules. By adopting a dual approach, it becomes possible to efficiently separate viable modules for restoration while recovering valuable materials from those that cannot be reused. This combined strategy enhances the value creation from the PV module stream and improves the competitiveness of recycling operations that integrate these processes effectively (Fig. 17).

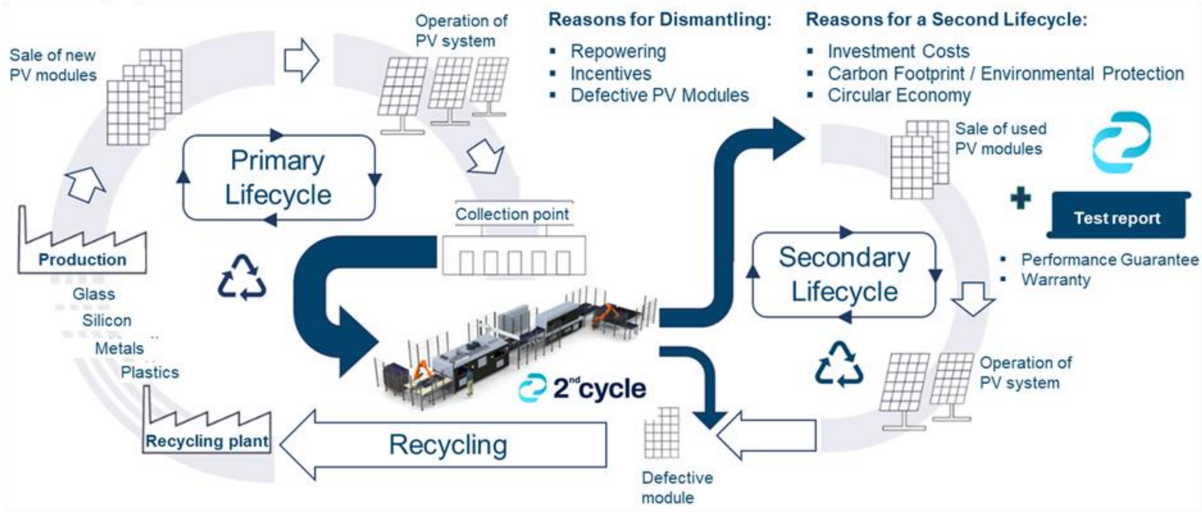

Figure 17: Business approach of 2nd Cycle.

The industry is shifting away from general shredding methods towards component-specific recycling processes. Shredding often makes it challenging to separate particles composed of different materials, leading to downcycling or thermal processing where valuable resources are lost. This limits both the environmental and economic benefits of solar technology.

2nd Cycle's approach addresses this issue by developing individualized handling systems for PV modules. Their automated system integrates PV-type identification and precise condition assessment, enabling treatment tailored to the unique characteristics of each module. This shift from bulk processing to individualized assessment represents a significant advancement in the second-life management of PV modules, emphasizing the role of upcycling in maximizing environmental and economic value.

3.2.3 Case Study 3: Solreed (France)

Solreed is a French start-up formally established in September 2024, through CEA's Magellan startup accelerator programme. Solreed focuses on the diagnosis, repair and requalification of PV modules for reuse, aiming ultimately to extend their lifespan and reduce the environmental impact. Instead of replacing defective panels with costly new imports (typically custom-made in Asia) Solreed introduces a sustainable, localized and economically viable alternative by refurbishing and reintegrating PV modules into the energy market, as second-life PV products. This approach not only decreases waste but also strengthens Europe's energy sovereignty by reducing dependence on foreign manufacturers.

Solreed's mission is to establish an innovative and sustainable circular economy model for PV modules. Through ongoing R&D activities, the company seeks to stablish an innovative and sustainable circular economy model for PV modules, based on the following actions:

- Develop high-precision diagnostic tools capable of real-time failure detection, improving maintenance efficiency and reducing downtime in large-scale solar farms;
- Implement industrial-scale repair processes that restore the operational reliability and longevity of PV modules;
- Validate and standardize a comprehensive quality assurance framework for requalified PV modules for reuse, ensuring compliance with stringent industry standards;

- Establish strategic partnerships with energy providers, policymakers, and sustainability organizations to advance regulatory recognition of PV modules for reuse.

Solreed claims to potentially cover PV module repairs of at least 80% of common PV faults, leveraging from novel tools for real-time PV monitoring and diagnostics of PV plants, that locate and classify module failures as soon as they occur. Unlike conventional methods that rely on annual drone inspections to identify faulty PV modules, Solreed's PV diagnostic framework focuses on continuous performance tracking powered by artificial intelligence and a growing database of electrical failure signatures, allowing for remote diagnosis and intervention.

Once modules are diagnosed, Solreed employs pilot-scale (at this stage) repair and characterization steps to restore them to operational efficiency. These, so far, include: i) Replacement of defective bypass diodes and junction boxes; ii) sealing and structural reinforcement, preventing further degradation from environmental exposure; iii) I-V characterization and EL/LIT imagery, to verify that repaired PV modules meet performance and safety standards or identify and quantify residual physical/performance degradation. In addition, Solreed is developing on-site repair units, eliminating the need for costly module transport, with two pilot operations planned within 2025.

Solreed has already demonstrated its capabilities in real-world conditions, repairing modules in partnership with ENGIE Green and deploying the first solar reuse pilot plant with the city of Grenoble. A key milestone was the recent establishment of a pilot repair line at CEA INES facilities, experiments in which have shown that the proposed detect-repair-reuse approach can extend the lifespan of PV module by another at least 10 years.

In a recent region-funded project, Solreed, ENGIE Green and CEA, along with Envie (a French social enterprise network specializing in the collection, refurbishment, and resale of household appliances and electronic equipment), aimed to assess the feasibility of reuse of decommissioned PV modules by diagnosing failures, applying standardized repair protocols, and testing large-scale refurbishment processes. The initiative was divided into three main phases. The first phase involved identifying sources of used PV modules, including decommissioned PV modules from PV and storage sites operated by energy companies and recycling organizations. The second phase consisted of a detailed pre-study to characterize module defects and establish a repair methodology. The third and final phase was a full-scale processing campaign lasting three weeks, during which 158 modules were inspected, repaired, and tested. The results provided insights into the technical feasibility of such processes, as well as the logistical and economic considerations involved in scaling up this approach.

The identification of decommissioned PV modules took place across several PV sites. One of the main sources was a utility-scale PV plant where defective modules were removed periodically based on IR inspections. The most common failures included bypass diode shunts and structural damage, particularly in areas affected by a past fire incident. Another key source was a facility collecting PV modules, from various PV plants, for recycling. Some PV modules had been exposed to severe hail, which caused micro-cracks in the cells, visible only under EL imaging. In some cases, long-term outdoor storage of first-life PV modules had led to significant degradation, including water infiltration, corrosion of connectors, and frame damage.

Following this initial assessment, two specific types/models of PV modules were selected for detailed study. The first type exhibited a recurring issue with diode failures, leading to partial loss of voltage and power output. The second type showed more severe defects, particularly under-dimensioned bypass diodes that overheated and, in many cases, caused melting of plastic components inside the junction boxes. The pre-study confirmed that diode replacement could restore electrical performance in the first module type (Figure 18), although additional IR imaging revealed potential risks related to excessive heat generation at certain solder joints. The second module type required a more comprehensive repair strategy, replacing faulty diodes with higher-rated components to prevent future overheating.

During the large-scale processing campaign, the first module type demonstrated a high repair success rate. Out of 105 units processed, 101 were successfully restored to nominal working conditions, representing a **96% reuse rate**. These refurbished modules passed all electrical and safety tests and were subsequently approved for reuse in a municipal PV energy project. The second module type, however, presented a major challenge. Only 19 out of 104 processed modules (approximately 11%) could be validated for reuse. A widespread defect in the solder joints near the junction box caused frequent electrical disconnections and potential overheating risks. Although a repair approach was attempted, thermal cycling tests demonstrated that the defect could reappear under operational conditions. As a result, the majority of these modules were set aside pending re-evaluation of the repair approach and further eligibility/safety checks. Based on statistical analysis of the pre-repair and post-repair electrical characteristics of the PV modules, the former type of PV modules has also demonstrated lower variation in its residual power output, also indicative of the high reproducibility of its repair (Figure 19).

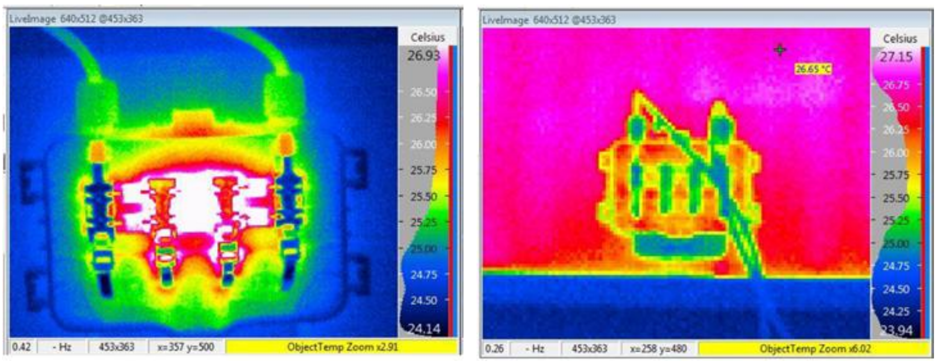

Figure 18: Example of LIT images before (left) and (after) repair of bypass diodes' failure, suggestive of full recovery of normal thermal and electrical performance of the repaired PV module.

The testing and validation process relied on a combination of flash-testing (IV characterization), EL/LIT imaging, and leakage current measurements under humid conditions. This multi-step characterization approach proved effective in ensuring the reliability and performance of the refurbished modules. Additionally, a digital tracking system developed by the refurbishment team allowed each module's repair history and electrical characteristics to be logged systematically, ensuring traceability throughout the process.

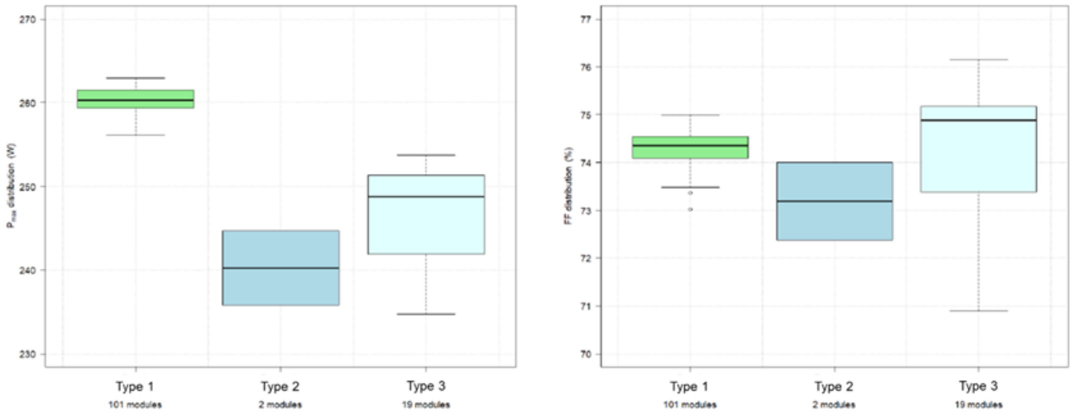

Figure 19: Statistical distribution of post-repair (residual) PV power output and fill factor for the three types of PV modules of the case study, indicating that Type 1 modules exhibited highly consistent electrical performance after repair, while Types 2 and 3 showed significant variability, underscoring the challenges posed by soldering defects.

The specific project/case study successfully validated a methodology for refurbishing PV modules. The high success rate for one module type suggests that large-scale reuse of decommissioned solar panels is feasible, provided that suitable batches are identified in advance. However, the study also highlighted challenges that must be addressed before scaling up this approach. The quality of module storage and transportation played a crucial role in refurbishment success, as poorly handled panels suffered additional damage, reducing their repair potential. Furthermore, the widespread solder defect observed in the second module type demonstrated that certain failure modes require more advanced repair techniques than initially anticipated.

From an operational perspective, the protocol (Figure 20) demonstrated the importance of structured workflows and proper training for personnel. The repair and testing process was successfully implemented, but additional measures may be needed to optimize efficiency in a future commercial setting. The study also reaffirmed the value of involving individuals from professional reintegration programs in the refurbishment process. With adequate training, personnel without prior experience in PV technology were able to contribute effectively to module inspection, repair, and testing. Further research is needed to determine whether the modules affected by soldering defects can be reliably repaired. If a viable solution is found, it could significantly improve the overall recovery rate for used PV modules. Discussions with industry partners are ongoing, and a follow-up technical study may be launched to explore potential repair strategies.

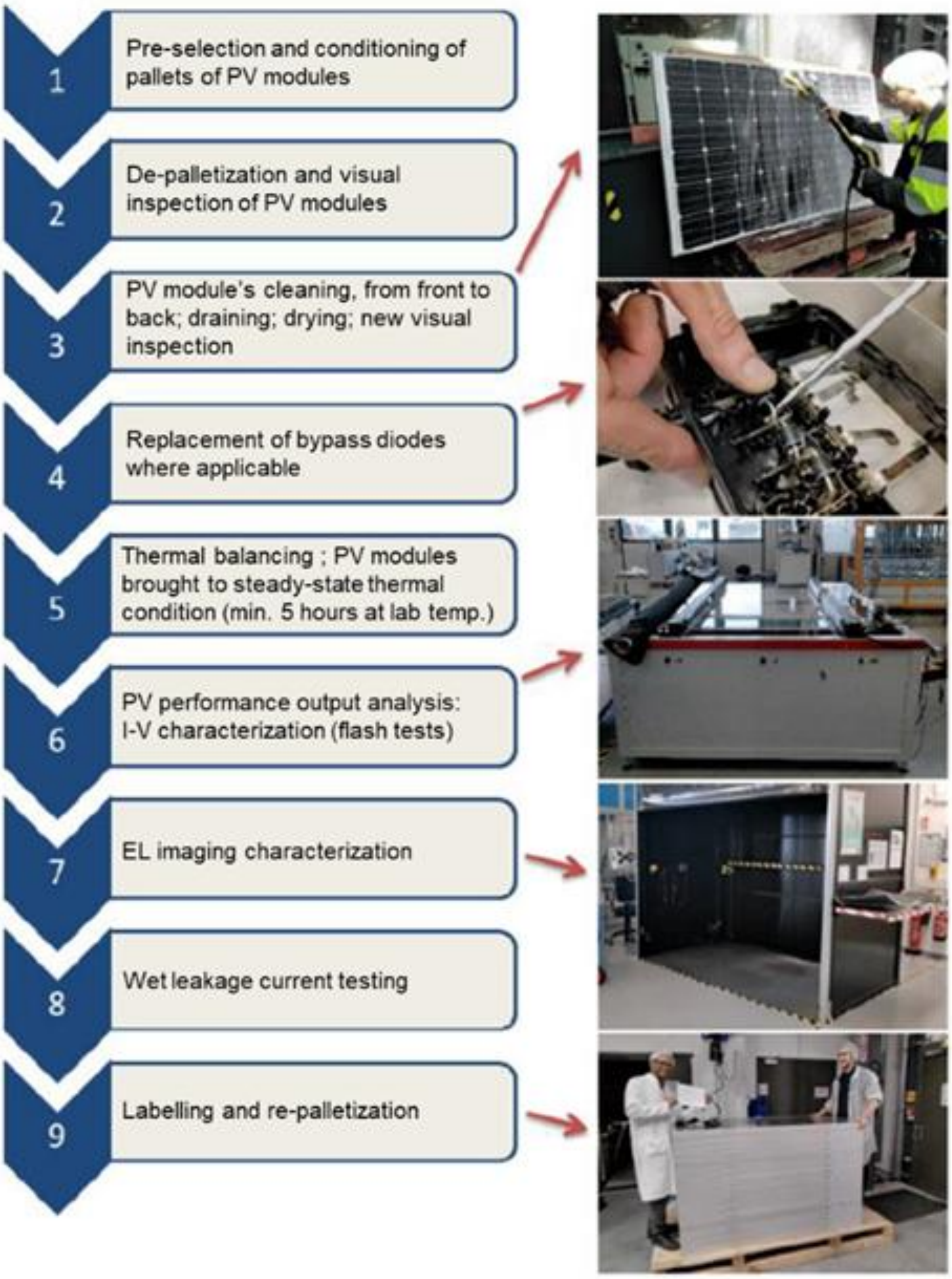

Figure 20: Overview of the PV reuse protocol explored by Solreed and CEA researchers, including PV triage, classification, diagnosis, repair and testing/characterization steps.

3.2.4 Case Study 4: CIRCUSOL demo Waasland (Belgium)

In the framework of CIRCUSOL (Circular Business Models for the Solar Power Industry) project, funded by the European Union's Horizon 2020 programme, several demonstrators (demo sites) were implemented to showcase real-life scenarios of implementing Product-Service Systems (PSS) business models for the PV and battery sectors. The underlying idea of the PSS concept proposed in CIRCUSOL, is to extend the lifecycle of PV system components, particularly PV modules and batteries, through reuse, refurbishment, and improved resource efficiency. Instead of selling solar equipment, the project provides solar PV energy as a service, reducing financial barriers and increasing accessibility.

Among its demonstrator sites, the Waasland co-housing project in Belgium has been employing and testing second-life PV modules and battery storage in a residential setting, evaluating their technical feasibility and economic viability (Fig. 21). The Waasland co-housing project consists of 22 housing units, including apartments and terraced houses, with a focus on collective solar energy production and consumption. Instead of individual rooftop installations, a **centralized second-life PV system** was implemented, reducing installation complexity and ensuring efficient energy distribution. The project's objective is to maximize self-sufficiency in renewable energy, minimize waste through reuse of decommissioned PV modules, and explore the feasibility of a service-based solar energy model operated by Futech (CIRCUSOL partner), where residents pay for the electricity produced rather than owning the equipment.

Figure 21: Left: Satellite view of the Waasland demo building, and the second-life PV system on its rooftop. Right: external views of the building hosting the second-life PV and storage system.

The Waasland second-life PV system consists of 231 second-life PV modules repurposed from decommissioned commercial PV installations (see Figure 22). These panels underwent EL testing to detect defects and confirm their continued efficiency and safety. The total installed capacity is 59.91 kWp, sufficient to cover a large portion of the community's electricity needs.

One major challenge was the variation in electrical characteristics of the second-life panels, as they originated from different sources. This required additional Maximum Power Point Tracking (MPPT) controls, allowing the inverter to optimize performance despite differences in module voltage and output.

The original inverter capacity was 10 kVA, limited by Flemish regulations at the time of installation. However, a recent regulatory update allowed for expansion, leading to the replacement of the original inverter with a 20 kVA hybrid inverter, improving system performance and energy distribution.

To optimize energy use, a real-time monitoring system provides 15-minute interval data on energy consumption and solar production. This helps end users track performance and adjust usage patterns for maximum efficiency.

Figure 22: Views of the second-life PV system installed on the rooftop of the Waasland demo building, showing the diversity of the reused PV modules, in terms of PV technology and power output.

To increase self-consumption for the Waasland second-life PV system, the installation includes a 21 kWh second-life lithium-ion battery, sourced from SNAM (Société Nouvelle d'Affinage des Métaux). This battery stores excess solar energy for use during low-generation periods, enhancing energy independence and reducing reliance on the grid. Grid integration required approval from Fluvius, the regional grid operator. A feasibility study confirmed that the expanded 20 kVA hybrid inverter complied with grid stability requirements, allowing the battery storage and PV system to function optimally together. The battery system supports multiple key functions, including: i) Increased solar self-consumption, reducing the need to purchase electricity from the grid; ii) Energy arbitrage, allowing stored solar power to be used when electricity prices are high and iii) Grid stability, through controlled charging and discharging.

The reuse of second-life PV modules and batteries significantly reduces electronic waste, minimizes resource extraction, and lowers CO_2 emissions associated with manufacturing new components. This circular approach extends the lifespan of solar technologies, improving sustainability. Financially, the PSS model stabilizes electricity costs for residents, protecting them from market price fluctuations. Additionally, centralized management improves system efficiency, maximizing the return on investment for both users and service providers.

Key performance indicators for the first phase of the project:

- Annual solar energy production: ~28.2 MWh
- Total electricity consumption: 84 MWh
- Grid injection: 3.5 MWh
- Self-consumption rate: 88%
- Autonomy level: 29%

The Waasland demonstrator project highlighted several key challenges in the implementation of second-life solar technologies. One major issue is **technical compatibility**, as integrating second-life photovoltaic panels often requires sophisticated power management systems to handle the variability in their electrical performance. Additionally, **legislative barriers** pose a significant hurdle; adapting to evolving regulations is essential to allow for larger inverter capacities and ensure compliance with grid standards. Finally, the **economics of second-life batteries** remain a concern, as the cost difference between new and refurbished batteries is still relatively small—underscoring the need for targeted incentives to support the adoption of second-life energy storage solutions.

4 MAIN CONCLUSIONS

This section outlines the technical conclusions derived from the assessment of 2nd life photovoltaic modules, with specific attention to repair procedures, requalification practices, emerging reuse business models, and policy incentives. The findings aim to support structured discussions and forward planning within the IEA-PVPS Task 13 framework.

Status of the Second Life PV Market

The second-life PV market remains fragmented and underdeveloped. The lack of harmonized qualification criteria, standardized testing protocols, and repair guidelines significantly limits transparency, comparability, and trust in reused products. Without clear technical standards, second-life PV modules face barriers to large-scale adoption, insurance coverage, and bankability. Moving forward, alignment with international frameworks (e.g., IEC standards) and the development of robust pass/fail criteria are essential to ensure safety, reliability, and traceability.

Repair Feasibility and Limitations

Repair of PV modules—whether addressing solder bond failures, cracked backsheets, or junction box issues—has been demonstrated as technically feasible. However, field experience shows that repair is often labour-intensive, costly, and difficult to scale without automation. Case studies revealed widely varying reuse success rates: while certain defects such as bypass diode failures achieved >90% restoration rates, modules with systemic soldering defects had success rates as low as 10–15%. Thus, repair is best reserved for specific contexts such as remote areas or where logistics make replacement prohibitive. For the broader market, testing- and sorting-based reuse strategies are generally more cost-effective.

Testing and Automated Triage as Enablers

Automated testing systems capable of IV characterization, electroluminescence imaging, and insulation resistance testing provide a scalable path for large-volume triage. This approach allows efficient classification into “reuse,” “repair,” or “recycle” streams, minimizing labour costs and ensuring greater consistency. Advances in aerial inspection, AI-based diagnostics, and mobile test labs can further reduce costs and risks, while increasing throughput. The creation of centralized or semi-automated reuse hubs is a promising strategy to strengthen the economic viability of second-life PV.

Requalification

Requalification emerges as a cornerstone for the large-scale deployment and economic viability of second-life PV modules. Robust, transparent, and standardized requalification procedures are essential to ensure safety, performance predictability, and market confidence. Beyond technical assurance, requalification enables the development of new value chains by reducing uncertainty for investors, insurers, and system owners, thereby improving bankability. Automated and scalable requalification frameworks, combined with clear classification and documentation of residual performance, are key enablers for transforming second-life PV from niche applications into a mature market segment with tangible economic and employment opportunities.

Field Experience and Demonstration Projects

Pilot projects, such as the Waasland demonstrator, confirm that second-life PV and battery systems can deliver tangible benefits in energy autonomy, reduced emissions, and protection against electricity price volatility. However, they also underline persistent challenges: technical compatibility of heterogeneous module batches, evolving grid compliance requirements, and the limited economic advantage of second-life batteries compared to new ones. These experiences highlight the need for robust system integration guidelines and regulatory flexibility to unlock wider adoption.

Policy and Economic Drivers

Economic viability is still a decisive bottleneck. Repair and reuse compete with the rapidly declining cost of new PV modules, making financial incentives or eco-contributions crucial to establish a reuse market. The French model, coordinated by Soren and supported by eco-funding, demonstrates that policy frameworks can increase reuse rates significantly—from ~1% today to 5–7% of collected modules within a few years. This underlines that regulatory clarity, funding schemes, and circular economy mandates will be central to scaling second-life PV solutions.

Recommendations for Future Actions

1. **Standardization:** Fast-track IEC-based technical specifications for requalification and safety of reused modules.
2. **Infrastructure:** Support investments in automated testing hubs and logistics networks for efficient collection and redistribution.
3. **Market Incentives:** Introduce financial instruments (eco-fees, subsidies, tax benefits) to close the cost gap between new and second-life modules and batteries.
4. **Targeted Repair:** Encourage selective repair for high-yield cases while prioritizing automated triage for scalability.
5. **Collaboration:** Promote international cooperation among research institutes, industry, and policymakers to accelerate learning and harmonization.

In summary, 2nd PV has clear potential to contribute to circular economy goals, reduce waste, and extend the value of existing solar assets. Realizing this potential will require **coordinated advances in technical qualification, scalable reuse infrastructure, and supportive policy frameworks**. Without these, the reuse market risks remaining niche and fragmented.

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