HORIZON EUROPE PROGRAMME
TOPIC HORIZON-CL5-2023-D3-01-02

GA No. 101136094

Sustainable Photovoltaics Integration in buildings and Infrastructure for multiple applications



SPHINX - Deliverable report

D6.3 – Report on 3R's of IPV products: Repair, reuse, recycle

Funded by
the European Union

Deliverable No.	D6.3	
Related WP	WP6	
Deliverable Title	Report on 3R's of IPV products: Repair, reuse, recycle - Public version	
Deliverable Date	30/08/2026	
Deliverable Type	Report	
Dissemination level	Public	
Author(s)	• Becquerel Institute France: Melodie de l'Epine • Becquerel Institute Spain : Jose M. Vega de Seoane • Becquerel Institute: Elina Bosch	
Checked by	Jose M. Vega de Seoane	
Reviewed by (if applicable)	All Partners	
Approved by		
Status	Public version	

Public Summary

This deliverable assesses the framework and barriers for repair, re-use and recycling of integrated photovoltaic (IPV) and building-integrated photovoltaic (BIPV) systems. The public analysis draws on scientific and technical literature, standards and regulatory sources, public manufacturer and service documentation, stakeholder questionnaires and targeted practitioner evidence.

Repairability must be considered at **system level as well as component level**. A defective module or other component may not itself be repairable, while the wider installation remains repairable if the faulty element can be diagnosed, accessed and replaced without disproportionate disturbance. For BIPV, this distinction is especially important because the PV product may simultaneously perform roofing, waterproofing, façade, glazing, acoustic or other building and infrastructure functions.

Repair is a multi-factor decision. Technical feasibility interacts with product architecture, access, component compatibility, labour and occupational coordination, warranty and service conditions, regulatory requirements, documentation, cost and responsibility allocation. Within the reviewed commercial documents, replacement, exchange and substitution are more consistently formalised than independent field repair, although this does not mean that replacement is always the preferred technical or economic solution.

Repair is also directly connected to deconstruction, re-use and recycling. Selective replacement may require partial deconstruction of a roof, façade or infrastructure assembly. The removed product may then be repaired, prepared for re-use or routed to recycling while the wider system is returned to service. The three pathways are therefore interconnected value-retention routes rather than separate end-of-life stages.

For re-use, the main enabling conditions are controlled deconstruction, preservation of product integrity and traceability, appropriate testing and qualification, and restoration of any affected building function. Evidence on actual BIPV dismantling costs remains limited, so the report uses a cost-accounting framework rather than a predictive cost model.

For recycling, material value depends not only on the mass recovered but also on the quality and purity of recovered fractions. Glass represents most module mass but may have limited value where recovered as contaminated cullet, while clean aluminium and copper retain higher market value. Higher-value recovery of silicon and silver requires more advanced separation and treatment.

Across the three pathways, the most important common enabling conditions are accessible and reversible design, long-term technical documentation, component traceability, compatible replacement strategies, clearly allocated responsibility and planning for intervention throughout the system lifetime. The findings are qualitative and should be interpreted as recurring mechanisms within the evidence reviewed rather than as statistically representative estimates of European market practice.

Use of artificial intelligence

Generative artificial intelligence tools were used to support the preparation of this deliverable, including the translation of source documents, the preliminary organisation and analysis of information, and linguistic and editorial assistance during drafting. All AI-generated outputs were reviewed, verified and, where necessary, corrected by the authors against the original sources and project evidence. The interpretation of results, scientific conclusions and final wording remain the responsibility of the authors.

Table of Contents

1 Introduction 7
2 Methodology 8
2.1 Literature and documentary review 8
2.2 Questionnaires and stakeholder input 9
2.3 Data analysis framework 9
2.4 Limitations 10
3 The 3R principles 11
4 PV system repairability 12
4.1 System-level repairability and dual functional lifetime 12
4.1.1 Component vs system repairability 12
4.1.2 Dual functional lifetime of integrated PV systems 13
4.1.3 Scope of the assessment 14
4.2 Repair Decision Framework 14
4.2.1 Decision stages 15
4.3 Commercial strategies 16
4.3.1 Product warranty conditions 17
4.3.2 Service and other commercial conditions 18
4.3.3 BIPV-specific commercial constraints 19
4.3.4 Conclusions on commercial strategies 20
4.4 Labour competency 20
4.4.1 Occupational competency interfaces 20
4.4.2 Survey of maintainers 20
4.5 Regulatory barriers to repair 23
4.5.1 Regulatory decision framework 24
4.5.2 Regulatory and compliance mechanisms 25
4.6 BIPV type sensitivity to repairability 25
4.7 Consolidated assessment of barriers and recommendations for improving system repairability 26
4.7.1 Assessment method 26
4.7.2 Consolidated barrier assessment 28
4.7.3 Recommendations for repairability 31
5 Deconstruction and re-use 32

5.1 Deconstruction conditions and economics 32
5.2 Re-use conditions 32
5.3 Recommendations 32
6 Recycling and contribution to the circular economy 33
6.1 Mass recovery and value recovery 33
6.2 Implications for higher-value recycling 33
7 Conclusions and recommendations 34
References 35

List of Tables

Table 1 - Criteria favouring repair, replacement or repowering 16

Table 2 - Three elements to commercial strategies examined: warranty, O&M and other commercial conditions 17

Table 3 -Summary of warranty conditions relevant to system repairability 18

Table 4 – Non warranty linked elements of commercial strategies affecting repair vs replacement decisions 19

Table 5 - BIPV repair vs architectural and competency interfaces as evaluated by the authors 22

Table 6 -Regulatory layers that can impact repair. The effects depend on the intervention, original documentation, national implementation, product architecture and contractual arrangements 24

1 Introduction

D6.3 addresses the framework and barriers of repair, re-use and recycling of IPV and BIPV products developed or studied in the SPHINX project and more broadly available in Europe. Its purpose is to translate technical knowledge, market evidence and stakeholder input into recommendations for system lifetime extension, resource conservation and circular-economy pathways.

The 3R assessment is at the intersection of PV performance, building-product functionality and circularity. This is particularly important for BIPV products because they are not only electricity-generating components; they may also function as roof elements, facade elements, glazing, cladding, waterproofing-adjacent components, shading elements or infrastructure elements. Repair and re-use decisions therefore affect electrical safety, building safety, aesthetics, insurance, construction compliance and end-user acceptance.

2 Methodology

The methodology combines scientific and technical literature, standards and regulation, public manufacturer and service documentation, stakeholder questionnaires and targeted practitioner evidence. It is a qualitative, evidence-led approach designed not to produce a statistically representative model of the European IPV/BIPV market, but to identify traceable decision conditions, recurring barriers, practical circularity pathways and recommendations across the evidence reviewed.

Repair of IPV/BIPV systems is examined in greatest depth because system-level repair is less directly addressed in the literature, particularly where a PV product also performs a building or infrastructure function. Deconstruction, second-life qualification and recycling are treated more frequently in the circular-PV and end-of-life literature, so the corresponding chapters synthesise and apply that evidence rather than repeat the more extensive repair-barrier analysis.

2.1 Literature and documentary review

The first phase of the study consisted of a review of existing literature related to:

- IPV and BIPV systems;
- PV module repair, refurbishment and second-life qualification;
- re-use and recycling of PV modules;
- deconstruction and end-of-life management;
- market and regulatory barriers;
- warranty, insurance, certification and compliance constraints.

The objective was to establish the technical, regulatory and circular-economy baseline needed to assess repair, re-use and recycling pathways for integrated PV. The review distinguishes repair, replacement, re-use, recycling, revamping and repowering, and identifies where general PV frameworks can be transferred to BIPV and where the additional building function requires caution.

The review included EU directives and national regulations, scientific articles, technical reports, standards, commercial documents, European project publications and conference material. The main source families were:

- PV repair and second-life sources, including IEA PVPS Task 13, Trust-PV, CIEMAT repair studies and studies on reuse-ready PV; [1] [2] [3] [4] [5] [6] [7] [8]
- BIPV and building-integration sources, including IEA PVPS Task 15 standardisation, technical guidebook and training reports; [9] [10] [11] [12] [13]
- circularity and LCA sources on PV re-use and recycling; [4] [5] [6] [7] [14]
- warranty and commercial documents from manufacturers and maintenance actors; [15] [16]
- EU directives and national regulations; [17] [18] [19] [20] [21] [22] [23] [24] [25] [26]

The review confirmed that repair and re-use are increasingly recognised as circularity pathways, but that it predominantly addresses conventional PV modules and systems, not BIPV and IPV products. Literature on PV reuse emphasises that many decommissioned modules may retain functional value, but re-use requires testing to identify safety-critical defects and degradation.

The literature also shows that recycling alone does not capture the full circular potential of PV modules. One circularity study found that the production stage dominates life-cycle impacts, while the solar cell layer represents a small share of module mass but a very large share of production emissions. This means that recycling heavy fractions such as glass and aluminium is useful, but re-use can preserve a larger share of embedded environmental value where modules remain functional and safe. [7]

2.2 Questionnaires and stakeholder input

Two online questionnaires were developed.

The first questionnaire targeted **maintenance professionals and installers**. Its purpose was to understand how actors involved in operation and maintenance approach repair, replacement and intervention decisions for PV systems on buildings. The survey addressed the scope of maintenance activities, experience with repair and replacement, constraints limiting interventions, the role of warranties and insurance, and skills and training needs. It was distributed primarily in France and collected 40 responses. Because of the sample size, the analysis was not intended to establish statistically robust correlations, but to identify recurring patterns and converging constraints.

The second questionnaire targeted **PV professionals with experience or knowledge of deconstruction and end-of-life operations**. Its purpose was to understand the economics and practical constraints of deconstruction, including labour, access, dismantling, logistics, sorting and the destination of recovered components. The number of responses from professionals directly practising deconstruction was limited, so this evidence was treated as qualitative and anecdotal. It was used to identify practical deconstruction issues rather than to calculate representative costs.

2.3 Data analysis framework

The data analysis framework combines different aspects:

- technical feasibility;
- regulatory and compliance subjects;
- commercial and warranty impacts;
- operational and labour feasibility;

For each 3R pathway, the analysis asks a different but connected question.

- For repair, the question is whether the system or component can be restored to safe and acceptable operation without full system replacement.
- For re-use, the question is whether the product or component can be removed, tested, documented and redeployed while retaining functional, safety and regulatory value.
- For recycling, the question is whether materials can be separated and recovered through available pathways, and whether product design supports higher-value recovery rather than only bulk recovery.

The framework distinguishes between system-level and component-level repairability. A technically repairable fault may still be impracticable where access, economics, warranty conditions, compliance requirements or responsibility allocation prevent intervention; conversely, targeted replacement can constitute successful system repair where overall functionality is restored.

The framework also distinguishes between product families. Product architecture is treated as an important determinant because bonded, tiled, framed, glazed and infrastructure-integrated configurations have different access conditions, removal risks, compatibility constraints and compliance exposure.

The analysis synthesises literature and standards, public commercial and warranty documentation, maintainer questionnaire responses, regulatory screening, deconstruction evidence and re-use/recycling literature. Barriers are prioritised according to severity, recurrence in the reviewed evidence and changeability.

2.4 Limitations

The study has several limitations. First, the scientific and technical literature on PV module repair, re-use and second-life qualification is growing, but the literature specifically addressing BIPV and IPV repairability remains limited. Much of the available evidence concerns conventional PV modules. It must therefore be transferred cautiously to products that also act as roofing, façade, glazing, cladding, waterproofing or infrastructure elements.

Second, the maintainer survey was distributed primarily in France and collected 40 responses. The results provide useful insight into repair and replacement practices, but they are not statistically representative of all European maintenance actors. The analysis identifies recurring patterns rather than quantified market-wide conclusions.

Third, the deconstruction questionnaire produced only a limited number of responses from professionals directly practising deconstruction. The information is therefore treated as qualitative and anecdotal and is not used to estimate representative costs or market prevalence.

Fourth, commercial-document analysis is constrained by uneven public availability. Some manufacturers provide detailed warranty and service documents, while others provide only summary information. Insurance clauses, installer contracts, procurement obligations and end-user service agreements are often unavailable outside a real project discussion, even though they can strongly influence real repair and re-use outcomes.

Finally, the report uses existing evidence to identify decision conditions, barriers and recommendations. Quantitative LCA and cost modelling remain complementary tools, particularly for comparing reuse and recycling under specific product and market conditions, but outside the scope of the current investigation.

3 The 3R principles

The 3R principles treat repair, re-use and recycling as linked value-retention pathways rather than as three independent end-of-life options.

- Repair seeks to preserve the installed system and its associated building or infrastructure function.
- Re-use seeks to preserve the function of a removed product or component in a second application.
- Recycling is considered when functional value can no longer reasonably be retained and the remaining objective is recovery of materials at the highest practicable quality.

The pathways are related, but not necessarily sequenced. A critical or irreparable defect may bypass repair; a component removed during a system-level repair may be suitable for refurbishment or re-use; and a product intended for re-use may ultimately be routed to recycling if inspection or qualification shows that safe second-life use cannot be demonstrated. The relevant decision (which of the 3 R's to activate) is therefore the highest-value pathway that remains technically feasible, legally acceptable and economically proportionate for the specific product and intervention.

For BIPV and IPV, this decision must consider two different functions at the same time: The PV element has an electrical function, but it may also provide roofing, weather protection, façade, glazing, cladding, shading, acoustic or structural functions. A repair that restores power generation but compromises the building envelope is not a successful lifetime-extension intervention. Likewise, deconstruction that damages an otherwise reusable product, or leaves the building without an equivalent function, can eliminate the practical benefit of re-use. Product architecture and the reversibility of interfaces therefore connect all three 3R pathways.

Economic considerations differ across the three pathways. For repair, the relevant question is whether intervention remains economically preferable to replacement or broader system renewal once labour, access, downtime, diagnostics, logistics and expected remaining life are considered. For deconstruction and re-use, the cost factors are varied – they determine whether products can be removed, handled, tested and prepared for a second life, including labour, access, transport, storage, testing and any necessary reinstatement of the building envelope. For recycling, an economic assessment would examine the quantity of material recovered as well as the quality and value of the recovered fractions, which depend strongly on pre-treatment, separation and material purity.

Any analysis should reflect the maturity and availability of evidence. Repair of integrated PV systems remains comparatively under-documented and often requires evidence to be combined across technical, commercial, labour, regulatory and product-specific sources. Deconstruction and re-use are better represented in the broader circularity literature, although evidence specific to BIPV remains uneven and practical cost data are limited. Recycling is supported by a more developed body of technical and economic literature, particularly concerning treatment processes, material recovery and recovered-material value. The three pathways can therefore be assessed within a common circularity framework while allowing the level of detail and strength of conclusions to remain proportionate to the evidence available.

4 PV system repairability

This chapter assesses the repairability of IPV and BIPV systems using technical literature, PV repair and second-life studies, standards and regulatory sources, public commercial and warranty documentation, maintainer questionnaires and practitioner evidence.

The analysis starts by defining repairability at both system and component level, then presents a repair decision framework covering diagnostic triage, safety screening, compliance checks, economic assessment and intervention pathways. This framework is used to distinguish when repair, substitution, repowering, reuse or end-of-life routing is likely to be the most realistic outcome. It then examines the non-technical conditions that determine whether technically possible repair can actually be implemented. It reviews commercial strategies and warranty models, labour and competency barriers, regulatory barriers linked to certification, construction-product compliance, technical approvals, insurance, WEEE status and emerging EU circularity requirements. [1], [4], [5]

Because BIPV products can act simultaneously as PV modules and building elements, the assessment takes into account the functional lifetime from both an electrical-performance and building-envelope perspective.

The final sections compare repairability across product families, prioritise the main barriers by severity, recurrence and changeability, and translate the findings into recommendations for improving system repairability.

4.1 System-level repairability and dual functional lifetime

Repairability of IPV and BIPV products can be assessed at two levels: component level (module, inverter, cable, etc.) and system-level, considering the PV function, the building function, or both.

4.1.1 Component vs system repairability

At a component level, repairability depends on whether specific defects can be diagnosed and corrected without compromising electrical performance, insulation, mechanical integrity or long-term reliability. Technical evidence from PV repair literature shows that certain faults in modules, including ribbon or busbar interruptions, damaged backsheets, failed bypass diodes, junction-box defects, damaged cables and localised interconnection failures, can be repaired or managed in some cases. However, these examples do not imply that all PV modules, IPV products or BIPV systems are repairable at a component level. Repairability remains fault-specific, product-specific and dependent on post-repair safety and performance verification. [2], [3], [27]

At a system level, repairability refers to the capacity of a PV installation to be restored to safe and acceptable operation after a fault. A system may be highly repairable at system level even when its individual modules are not repairable at component level, provided that faulty modules can be safely and economically replaced. This distinction (module vs system repair) is central to BIPV and IPV because products may be integrated into roofs, façades, glazing, cladding, shading structures, waterproofing-adjacent layers or infrastructure systems. Repairability is therefore shaped not only by the physical intervention on the defective component, but also by access conditions, integration method, product-format stability, availability of compatible spare units, diagnostic evidence, warranty conditions, insurance acceptance,

certification constraints and the service chain through which intervention is authorised and executed. [1], [9], [10], [28], [12]

The focus of this chapter is system-level repairability. The objective is to assess the framework and barriers to repair of IPV or BIPV systems to maintain functional, safe and compliant operations, through targeted component repair, substitution or controlled replacement rather than through premature full replacement or end-of-life routing. This approach is consistent with second-life and repair guidance in the PV sector, which increasingly treats repair, refurbishment, requalification, re-use and recycling as linked circular-economy pathways rather than isolated technical actions.

In the EU, Directive (EU) 2024/1799 recognises repair as a lifecycle-extension mechanism and promotes conditions that can make repair more accessible, transparent and attractive to consumers. However, this directive does not extend to cover PV systems or BIPV systems; PV- and BIPV-specific repair obligations remain indirect until such time as product-specific repairability requirements are adopted. For IPV and BIPV systems, repairability is still governed mainly through the interaction of product standards, construction-product requirements, warranties, insurance rules, technical approvals, waste legislation and commercial service practices. [17], [18], [19], [29]

Repairability is not a purely technical property of a component - a product may be technically repairable but practically non-repairable if it cannot be safely accessed, if the intervention would damage the building envelope, if spare parts are unavailable, if repair would invalidate certification or warranty, or if labour and access costs exceed the value of the intervention. Conversely, a component that is not repairable may still belong to a repairable system if it can be safely diagnosed, removed and replaced with a compatible unit. [5], [15], [30]

4.1.2 Dual functional lifetime of integrated PV systems

IPV and BIPV products may perform both an electricity-generating (PV) function and a building or infrastructure function. PV functionality concerns electrical safety, power generation, degradation and system reliability. Building functionality may concern weather protection, structural integrity, fire performance, glazing safety, shading, acoustic performance or continued use of an infrastructure element. [9], [10], [12], [13], [31]

The two functions may deteriorate at different rates. An electrical fault may occur while the roof, façade or supporting assembly remains serviceable. The building function may deteriorate while the PV element continues to generate electricity. Where the two functions can be separated, local repair or selective replacement may preserve the unaffected function. Where they are physically or functionally inseparable, failure of one function may determine the practical service life of a larger assembly.

System-level repairability includes defective electrical component repair or replacement, as well as preserving or restoring associated building or infrastructure functions without unnecessary replacement of unaffected elements.

4.1.3 Scope of the assessment

Repairability is assessed across non-technical parameters: commercial, regulatory, operational, and labour dimensions, reflecting the multi-factor nature of intervention feasibility. Analysis focuses on intervention pathways occurring during the operational phase of IPV and BIPV installations. Full system replacement (repowering) is outside the scope of repairability and is a competing outcome in decision-making. End-of-life recycling processes are excluded from repairability but are considered where they influence repair versus replacement decisions. Manufacturing defects and factory-level rework are excluded, as the focus is on field-level intervention after deployment. Revamping and system upgrades are considered where they overlap with repair decision pathways and influence system lifetime extension.

Repairability is ultimately determined by the combined ability to identify faults, access components, perform compliant interventions, and restore system functionality (PV and building) at acceptable cost and risk.

4.2 Repair Decision Framework

This section introduces a repair decision framework because repairability is not only a property of the component or its condition but also the result of a decision process once a fault is detected.

It starts when a fault, underperformance issue or physical defect is detected, follows through to diagnosis, safety screening, warranty and compliance checks, economic assessment and selection of the most appropriate intervention pathway. The objective is to make explicit the decision logic that professionals usually follow, even when it is not formally documented. This can explain why a technically repairable fault may still lead to replacement (or other outcomes), and why targeted replacement of a faulty element can sometimes be the most realistic form of system-level repair. [32], [28]

This flow shows that possible decision outcomes are progressively narrowed as diagnostic certainty, safety, warranty, compliance, and economics are evaluated.

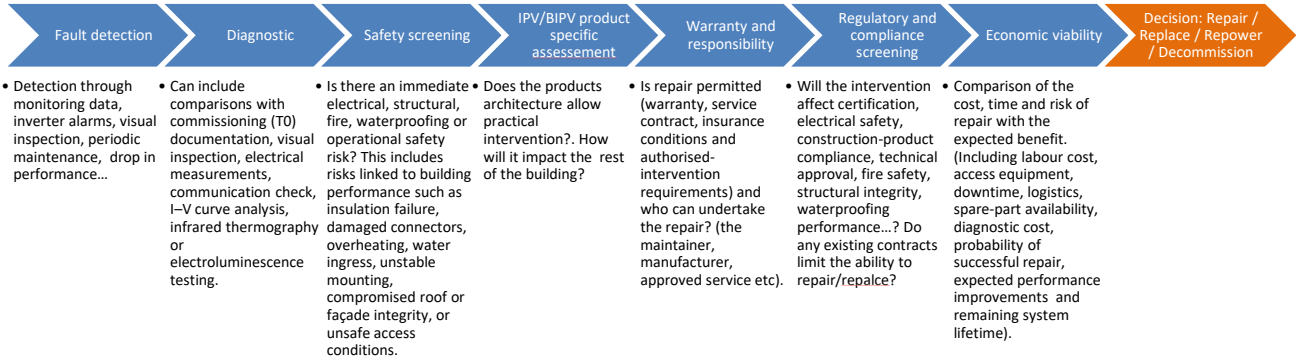


Figure 1 - Repair decision framework

4.2.1 Decision stages

A repair decision should move through linked checks: fault diagnosis and safety screening; assessment of product architecture and the affected PV/building functions; warranty and responsibility checks; regulatory and compliance checks; and comparison of total intervention cost, downtime, remaining life and expected post-intervention performance. [28], [33].

The preferred pathway may be on-site repair, component substitution, controlled replacement, repowering, preparation for re-use or end-of-life routing. For BIPV, the decision must also account for disturbance to roofing, facade, glazing, waterproofing or infrastructure functions. A technically repairable defect may therefore lead to replacement where access, compliance or responsibility cannot be demonstrated, while selective component replacement can still constitute successful system-level repair.

A functional-failure and remaining-life assessment specific to dual function elements (PV/building) should identify which function has failed, whether the other function remains serviceable, and whether the two can be treated independently. It should consider:

- whether the defect affects the PV function, the building or infrastructure function, or both;
- the remaining service life of the unaffected components;
- whether access to one function risks damaging the other;
- whether local intervention can restore the failed function;
- and whether replacement of a larger assembly would prematurely discard elements that remain functional.

Different criteria will favour a remedy that is repair, or replacement or repowering, as presented in

Table 1. Replacement decisions are likely to be prioritised where repair is not cost-effective, not technically feasible, or not compliant with certification and warranty constraints. Directive (EU) 2024/1799 if extended to cover PV systems could provide a transparency model through the European Repair Information Form, (specify the nature of the defect, suggested repair, price or maximum price, time to complete repair, temporary replacement availability, handover location and ancillary service costs.).

Throughout the decision process, a differentiation will be made between on-site repair, module or tile replacement, system repowering, or end-of-life routing. On-site repair is applicable where defects are localised, intervention remains reversible, and certified design parameters are not altered. Deconstruction constraints, particularly for bonded or integrated systems, may shift decision pathways towards replacement rather than repair or reuse.

Table 1 - Criteria favouring repair, replacement or repowering

Driver	When it favours repair	When it favours replacement
Labour and total intervention cost	Fault is accessible; repair is local; approved labour is available	Diagnosis is prolonged; specialised labour, multiple trades, scaffolding or long on-site time make repair uncertain or expensive; new component cost is low
Time and downtime	Repair can be completed on-site without extended testing	Exchange restores operation faster and supports uptime targets
Warranty status	Approved repair preserves coverage or is the prescribed remedy.	Unauthorised repair would void coverage, while replacement is the standard accepted remedy
Certification, approval and insurance	Like-for-like work does not alter certified or approved characteristics	Modification creates requalification, safety concerns, insurance or building-envelope liability
Logistics and parts	Approved parts, drawings, tools and expertise are readily available	Replacement stock and exchange logistics are standardised while repair parts are unavailable
Deinstallation disruption	Replacement would require major deconstruction, aesthetic rematching or recabling	The component is modular and exchangeable with limited disturbance
Expected remaining life	A targeted repair provides meaningful life and performance extension to both PV and building functions	Other components are near end of life, making repowering more rational, repair durability is uncertain or the replacement provides a more predictable warranty and performance outcome

4.3 Commercial strategies

This section analyses how commercial arrangements influence whether a failed photovoltaic or building-integrated photovoltaic component is repaired, replaced, substituted, or refunded, and whether a right to repair exists. Three different aspects are considered: product warranty conditions, O&M and service-provider terms, and other commercial conditions that sit outside both warranties and service contracts.

This analysis was based on a targeted review of manufacturer warranty documents, inverter warranty/ service documentation, BIPV product warranty terms, national BIPV requirements and practitioner evidence. The review focused on the clauses and practices that determine whether repair is practically supported or whether replacement becomes the default outcome. The main elements examined were:

- the remedy options available under warranty;
- whether manufacturers reserve discretion to repair, replace, substitute or compensate;
- whether labour, access, transport, deinstallation and reinstallation costs are covered or excluded;
- whether intervention must be performed by authorised actors; whether repaired, refurbished or substitute products are permitted; whether spare parts or equivalent products are available;
- how service models organise responsibility between manufacturers, installers, operators, owners and maintainers.

Table 2 - Three elements to commercial strategies examined: warranty, O&M and other commercial conditions

Aspect	What is examined	Main repairability questions	Limits
A. Product warranty conditions	27 products or items of equipment. including PV modules, BIPV products and inverter warranties.	Who chooses the remedy? Is repair permitted? Are labour, access and logistics covered? Must actors be authorised? Can equivalent, refurbished or substitute products be used?	A product warranty does not describe the full maintenance service available to the owner and may exclude field labour, access and logistics.
B. O&M and service-provider terms	10 installer, utility, installer-network and service-platforms., subscription and specialist O&M cases in the service-provider table.	Who diagnoses and acts? Are labour and access included? Are response times or uptime guaranteed? Are repairs capped? Who manages the manufacturer contact process?	O&M contracts, care plans, installer terms, utility maintenance offers, OEM service programmes have limited service descriptions.
C. Other commercial conditions	Commercial factors not created by either a product warranty or an O&M contract	Are spare parts and compatible products available? Is stock retained? Is the product standardised? Who carries liability? What are the access, deinstallation and coordination costs? Is there a secondary market?	Sources include Sphinx partner interviews, stock and supply strategies, product architecture, procurement and insurance practice, market structure. These sources explain context and practice but should not be presented as warranty or O&M contractual clauses.

4.3.1 Product warranty conditions

A targeted review of 27 public product and equipment warranty cases examined remedy authority, replacement and repair remedies, substitution rights, labour and field-cost allocation, and intervention controls. Where a contractual condition could not be established it was recorded as not determinable rather than inferred; the counts describe the reviewed documentary sample, not the European market.

Across the sample, remedy choice is commonly controlled by the manufacturer, warrantor or OEM. Replacement or exchange is more consistently documented than independent field repair, while labour, access, removal and reinstallation are frequently excluded or only conditionally covered. Equivalent or alternative substitution is documented in many cases and can preserve system continuity when the original product is unavailable, but substitution is distinct from repair of the failed product.

Table 3 -Summary of warranty conditions relevant to system repairability

Warranty dimension	Typical direction in the commercial documentary sources	Effect on repair
Remedy authority	13 manufacturer-unilateral; 3 OEM/service-provider; 2 prescribed replacement; 1 manufacturer via installer; 8 undetermined.	The claimant usually cannot choose repair over replacement.
Replacement remedy	11 warrantor chooses remedy; 3 other documented replacement-available cases; 2 prescribed replacement; 3 OEM exchange/replacement; 8 contractually undetermined	Replacement is widely organised, but often remains at the warrantor's discretion.
Repair remedy	12 repair/correction available; 4 limited circumstances; 2 no contractual repair remedy; 1 factory repair; 8 undetermined.	Repair frequently exists as a contractual option, but not necessarily as a claimant right or field service.
Substitution rights	18 cases explicitly document equivalent, alternative, refurbished, repaired or otherwise compatible substitution; 7 are undetermined; 2 provide continuity evidence without sufficiently specific substitution rights.	Substitution can maintain system continuity when an original product is unavailable but is distinct from repair of the failed product.
Labour and field costs	13 excluded; 6 partial/conditional; 8 undetermined.	The owner often pays decisive field costs even where a component remedy is covered; cost treatment can differ between product and installation/service warranties.
Authorised intervention	Mechanisms include prior approval, authorised or certified actors, approved service providers, OEM workflows and consequences for unauthorised intervention; these mechanisms are not aggregated into a single mutually exclusive quantitative category.	Independent intervention may be restricted in some cases, but prior approval, professional qualification and exclusive-network requirements are distinct mechanisms.

4.3.2 Service and other commercial conditions

Warranty terms do not capture the full intervention pathway. O&M contracts and service models can bundle diagnosis, labour, access and logistics, but may also prioritise rapid exchange where uptime and predictable cost are dominant objectives. Beyond contracts, long-term spare-part availability, format continuity, stock strategy, liability allocation and responsibility across manufacturers, installers, owners and maintainers can determine whether an otherwise permitted repair can be executed. [34], [15].

Table 4 – Non warranty linked elements of commercial strategies affecting repair vs replacement decisions

Commercial condition	Why it is separate from warranty/O&M	Influence on repair decision
Spare-parts and compatible-product availability	A warranty may promise a remedy without guaranteeing long-term stock of identical parts	No compatible part can make repair or like-for-like replacement impossible
Product standardisation and format continuity	Determined by product and portfolio strategy	Standard dimensions and electrical characteristics reduce lock-in and support partial replacement
Buffer stock and surplus production	A supply-chain and inventory decision	Retained tiles, modules or class-B units can extend the practical service life of bespoke systems
Liability and insurance allocation	A risk-management condition across contracts and actors	Actors may choose replacement because it is easier to document and insure than non-standard repair.
Fragmented responsibility	A value-chain organisation problem	Manufacturers, installers, roofers, electricians and owners may each control only part of the pathway

These cross-cutting conditions explain why the same warranty wording can produce different outcomes in different projects. Repairability depends on the complete commercial architecture: product design, stock, supply continuity, service organisation, cost allocation, liability and decision authority.

4.3.3 BIPV-specific commercial constraints

Integration into the building envelope introduces additional liability related to waterproofing, structural integrity, and aesthetics, significantly constraining repair interventions. Warranty validity is frequently tied to original installation conditions, certified installers, and location-specific configurations, limiting reuse and relocation. Removal and reinstallation costs can represent a substantial share and may exceed component cost in access-intensive cases. Compatibility constraints, including visual and electrical matching, reduce feasibility of partial repair and favour larger-scale replacement.

BIPV warranty logic for some products reinforces replacement-first strategies more strongly than standard PV systems. These constraints are intensified where products are bonded, highly customised, or dependent on specific supply chains, because even technically feasible replacement may be difficult without continued access to compatible formats and integration methods.

This does not mean that BIPV always favours replacement. In some installations, replacement is more disruptive than a local repair because it requires roof deconstruction, façade access or aesthetic rematching. The repair/replace outcome depends on whether a documented repair procedure, authorised skills and evidence of restored performance are available. Where they are absent, controlled replacement remains the more predictable liability and compliance pathway.

4.3.4 Conclusions on commercial strategies

Across the PV and BIPV products evaluated, replacement, exchange and substitution are more consistently formalised than independent field repair. Warranty and service structures favour controlled and standardised interventions; repair becomes more practicable where labour, logistics, documentation and liability are explicitly addressed. [9], [10], [15], [34].

4.4 Labour competency

Labour competency influences IPV repairability through the availability and interaction of several occupational categories capable of diagnosing faults and intervening on existing systems. Installation generally follows a predefined product configuration, documented procedures and known component specifications. Repair instead requires technicians to identify the origin of a fault, understand how an installed and potentially ageing system was assembled, determine whether defective components can be accessed or replaced, and restore both the electrical and building-envelope functions of the system. [11], [35].

Labour barriers are not limited to workforce shortages. They may also result from repair-specific experience gaps, fragmented competencies between occupations, insufficient product information, or the absence of an actor able and willing to coordinate and accept responsibility for the complete intervention.

4.4.1 Occupational competency interfaces

BIPV repair commonly spans several occupational domains rather than a single recognised trade. PV maintainers and electricians cover diagnosis, isolation, testing and reconnection; roofers, waterproofing specialists, facade contractors and glaziers address access and reinstatement of the building envelope; manufacturers or system integrators may retain product-specific information on dismantling, compatibility and permissible substitutions. [11], [13] [12], [28], [28]

The principal labour difficulty is therefore often the interface between competencies. A repair may require one actor to diagnose the fault, another to make the electrical system safe, another to access the integrated product and another to restore the building function. This increases coordination needs, responsibility uncertainty and cost, particularly where no actor is clearly responsible for validating the complete repaired system.

4.4.2 Survey of maintainers

Empirical evidence collected through a survey of maintenance professionals in France supports the distinction between shortages of skilled labour, gaps in repair-specific competence and difficulties coordinating several occupational categories. The results also indicate that labour barriers are seen to be closely connected to safety, professional responsibility, documentation and the economic viability of intervention. The findings should nevertheless be interpreted as indicative rather than statistically representative, given the limited questionnaire sample (40 respondents).

Within the sampled questionnaires, respondents identified safety risks and the possibility of non-compliance among the principal reasons why repair may be avoided. Responses indicate that concerns about professional liability, the absence of guarantees for repaired components and uncertainty regarding the

condition of ageing systems further reduce willingness to intervene. These observations are consistent with the regulatory, warranty and practitioner evidence reviewed and suggest that the labour barrier is not limited to whether technicians possess the practical ability to undertake a repair but also whether an appropriately qualified actor is willing to accept responsibility for the intervention and whether sufficient evidence is available to demonstrate that the repaired system can safely return to service.

BIPV-specific repair training was limited among respondents and whilst this observation is indicative of the survey sample rather than a measurement of European training provision, industry experts have also expressed this sentiment.

Taken together, the empirical evidence suggests that labour competency is product-dependent. The same market may contain the individual capabilities required for diagnosis, electrical safety, physical access, building-envelope reinstatement and verification, while lacking a viable mechanism for combining them for a particular product. It would seem that repair becomes less likely where these competencies are fragmented, where product-specific knowledge remains inaccessible or where no actor is willing to assume responsibility for the repaired assembly. Product architecture therefore affects labour requirements, while service organisation determines whether the required competencies can actually be mobilised. [11]

These findings are consistent with the functions addressed in established PV standards. IEC 62446-1 emphasises system documentation, inspection, testing and maintenance, while IEC 61724-1 establishes monitoring principles that support the identification of performance anomalies. IEC 62446-3 demonstrates that infrared diagnosis itself requires defined procedures and competent interpretation. For integrated systems, IEC 63092-1 and IEC 63092-2 further reflect the need to consider both PV and building-related requirements. The standards provide a technical basis for several relevant competencies, but do not by themselves resolve the occupational coordination, contractual responsibility or product-specific knowledge gaps identified here. [32], [28], [33], [12] [13]

The highest constraints occur where intervention affects both electrical and building-envelope functions, particularly in bonded, roof-integrated and façade-integrated systems. Electrical isolation is supported by an established occupational category, whereas component substitution, reinstatement and final acceptance often require knowledge and responsibility distributed across several actors.

Table 5 - BIPV repair vs architectural and competency interfaces as evaluated by the authors

Repair operation	Architectural interface	Competency interface	Main constraint	Indicative constraint
Electrical isolation and reconnection	PV circuit, connectors and concealed cabling	PV maintainer–electrician	Requires appropriately qualified electrical personnel and knowledge of the installed configuration	Medium
Access to roof-integrated components	PV module or tile–roof covering	Electrician/PV specialist–roofer	Electrical isolation and roof access are performed by different occupations	Medium–high
Intervention on bonded systems	PV module–adhesive–waterproofing membrane	PV specialist–membrane specialist–manufacturer	Removal may damage the membrane and depends on product-specific procedures	High
Façade or glazing intervention	PV module–fixing system–façade or glazing assembly	PV specialist–façade contractor/glazier	Electrical and building-envelope competencies are institutionally separate	High
Fault diagnosis	Electrical system–PV component–building envelope	Diagnostician–electrician–building specialist	Fault symptoms may have electrical, module or construction-related causes	Medium–high
Component substitution	Existing component–replacement component–complete system	PV specialist–manufacturer–construction trade	Electrical, dimensional and building-performance compatibility must be assessed together	High for proprietary systems
Post-repair verification	Repaired PV system–restored building element	Electrician–roofer/façade specialist–lead contractor	Individual trades may validate their own work without accepting the complete assembly	High
Coordination of the complete repair	All affected system interfaces	Lead contractor–specialist trades–manufacturer	No single actor may coordinate the intervention or assume overall responsibility	High

Note: Constraint levels are qualitative and derived from the SPHINX maintainer survey, partner interviews and the technical analysis presented above. “High” indicates that repair depends on several occupational domains, product-specific knowledge or unclear responsibility. The ratings are exploratory and are not statistically representative of European labour availability.

4.5 Regulatory barriers to repair

Regulatory frameworks shape repairability indirectly through overlapping regimes covering product certification, electrical safety, construction law, technical approvals, liability allocation, and waste management. [12] [13] [18], [19] [20], [29] [36] [37], [38]

This section examines the conditions under which an IPV repair triggers compliance checks, who may request these checks, and how the resulting requirements affect practical repair feasibility. These requirements are not necessarily barriers in themselves; they become barriers when they delay, restrict or prevent an otherwise technically feasible repair because the required evidence, authorised actor, procedure or responsible party is unavailable or disproportionate to the intervention. The analysis does not seek to provide an exhaustive legal review, but identifies the mechanisms through which regulation, technical assessment, insurance and contractual control may block repair.

The regulatory consequences of an intervention depend on whether it changes the product design, installation configuration or assessed performances of the original system. Product architecture determines what must be disturbed; labour organisation determines who can perform the work; and the compliance framework determines what (if any) evidence is required before the system can return to service.

This analysis distinguishes between barriers resulting from:

- obligations arising from EU or national legislation;
- standards defining tests, documentation or performance requirements;
- technical assessments used to demonstrate fitness for use or application;
- insurance, warranty and authorised-service conditions;
- empirical findings from the maintainer questionnaire and practitioner evidence;

The analysis looks at EU and national legal texts, technical standards, and official technical-assessment guidance. Legal texts are used to identify binding obligations; standards to identify technical evidence and verification requirements; approval-body documents to characterise national assessment routes; additionally, the maintainer survey results, practitioner evidence and a review of commercial warranty documents provided complementary information. The analysis is qualitative and does not constitute a complete legal opinion or a quantitative ranking of national repairability

The collected documentation demonstrates that PV repair governance is indirect and fragmented, combining EU repair policy, WEEE reuse/waste rules, BIPV standardisation, construction-product compliance and warranty conditions. IEA PVPS Task 15 reports have been used as secondary synthesis of the interaction between electrical and construction requirements for BIPV and to contextualise the country-specific examples below.

4.5.1 Regulatory decision framework

Repair decisions depend on technical feasibility and on whether the intervention remains within applicable electrical, product, building and waste-law requirements. Where several regulatory checks apply simultaneously, the additional proofs of compliance and approval steps may delay or deter repair.

The regulatory and compliance/certification context will frame interventions differently depending on the type of intervention:

- Diagnosis and routine maintenance, without alteration of the product or system configuration.
- Like-for-like replacement, using an identical component and preserving the original installation conditions.
- Equivalent substitution, using a non-identical component claimed to remain compatible with the existing system.
- Design-modifying repair, changing materials, dimensions, components, fixings, bonding, wiring or another assessed characteristic.
- Removal for reuse or end-of-life treatment, where the legal status of the removed product must also be considered.

Existing national and technical frameworks already distinguish between forms of intervention. Germany's VDI 2883 Parts 1 and 2 separate maintenance, inspection, repair, testing, documentation and spare-parts management for grid-connected PV systems. Italian GSE procedures for Conto Energia installations distinguish significant and non-significant maintenance or technological-modernisation interventions. These examples show that regulatory treatment can be linked to the extent of the intervention rather than treating every change as a new product or system design. [39], [25]

Like-for-like replacement generally remains closer to the original system configuration than equivalent substitution or design-modifying repair. Additional evidence may be required where the intervention changes a characteristic defining the original qualification, technical assessment or installation approval. Depending on the context, this evidence may be requested by a competent regulatory or building-control authority, an electrical inspector, a technical-assessment or conformity-assessment body, an insurer, a warranty provider, or the project owner under contractual or procurement requirements. Such requests are most likely where the intervention affects electrical safety, module design, waterproofing, structural behaviour, fire performance, glazing safety or another building-related function covered by the original compliance evidence.

Table 6 -Regulatory layers that can impact repair. The effects depend on the intervention, original documentation, national implementation, product architecture and contractual arrangements

Regulatory layer	Trigger	Effect on repair	Potential practical result
Module qualification and retesting requirements, including IEC TS 62915	Change to module design	The manufacturer, assessment body, purchaser or insurer may request proof that the altered design remains within the parameters of the qualification	Additional assessment or testing; replacement may be selected where evidence is unavailable
Electrical-safety requirements	Disconnection, reconnection or modification of the electrical installation.	Intervention and post-repair checks may be restricted to qualified actors	Limits who can perform and approve the repair

Building codes and construction requirements	Change affecting a roof, façade, glazing system, fixing or another building element	A building authority, technical controller, project owner or insurer may request proof that the building functions are preserved	Repair may require additional documentation, inspection or technical assessment
Technical-assessment, warranty and insurance conditions	Intervention outside documented or approved procedures	The assessment holder, manufacturer, warranty provider or insurer may restrict acceptable components, procedures or actors	Repair may be redirected through an approved installer, product or service network
WEEE and waste legislation	Removal followed by entry into the waste stream	The status of the module as a used product or waste must be established	Direct reuse, preparation for reuse or regulated waste-treatment route

It can be inferred that a technically successful intervention may be unacceptable where the evidence needed to demonstrate continued electrical, construction or insurance compliance is unavailable. Conversely, repair or replacement does not automatically require requalification simply because an intervention has occurred. The consequence depends on which characteristics have changed and which compliance route applies.

4.5.2 Regulatory and compliance mechanisms

Repair can intersect several compliance layers: module qualification and electrical safety; construction-product or building-performance requirements; national technical assessments or accepted installation rules; warranty and insurance conditions; and waste status where products are removed. A like-for-like intervention may remain within the original evidence base, whereas changes to materials, geometry, fixings, electrical characteristics or building function may require additional assessment, testing or approval. [18], [20], [27], [40], [41]

The practical issue is not that regulation generally prohibits repair, but that responsibility for demonstrating continued compliance can become unclear after non-identical modification. This can favour a documented replacement route where equivalent parts exist. The effect is strongest for BIPV elements that also provide weather protection, facade, glazing, structural, fire or other construction functions.

4.6 BIPV type sensitivity to repairability

Repairability is strongly influenced by installed architecture. The relevant characteristics are accessibility, reversibility of fixings, separability, intervention granularity, ability to separate electrically, component compatibility and the degree of coupling between the PV function and the building or infrastructure function. [9], [10]

Bonded and highly integrated systems can require wider intervention where removal disturbs membranes, glazing or surrounding construction. Roof-integrated tiles provide finer replacement granularity but may require sequential access and long-term format continuity. Mechanically fixed or framed configurations generally preserve a wider substitution space, while facade, glazing and infrastructure systems remain dependent on their specific structural, weather, safety or acoustic functions. These are architecture sensitivities rather than universal rankings: the actual pathway remains defect- and project-specific.

4.7 Consolidated assessment of barriers and recommendations for improving system repairability

Barriers were prioritised through a structured qualitative assessment undertaken by the report authors.

Ratings were informed by convergence across the literature review, warranty and service-document analysis, the maintainer questionnaire, regulatory evidence and public technical documentation. Because these sources differ in scope and representativeness, the ratings indicate the relative importance of barriers within the evidence reviewed.

4.7.1 Assessment method

Each barrier is assigned a primary category and assessed on severity, recurrence and changeability, with a separate confidence rating. Severity reflects consequence when the barrier occurs; recurrence reflects breadth across the reviewed evidence, not European market prevalence; changeability reflects whether realistic short- to medium-term action can materially reduce the barrier.

- **Severity** assesses the consequences of the barrier when it occurs
- **Recurrence** assesses the extent to which the barrier recurs across the elements and product-system configurations reviewed
- **Changeability** assesses the extent to which the barrier can realistically be mitigated or changed

Because the empirical evidence is qualitative and not statistically representative of the European market, recurrence should be interpreted as recurrence in the reviewed evidence, rather than as a measured European market frequency.

Severity

Severity reflects how strongly a barrier influences the repair-versus-replacement decision when it is present.

- **High**: the barrier can directly prevent local repair, strongly favour broader replacement or make intervention technically, legally or economically impracticable.
- **Medium**: the barrier materially increases cost, delay, uncertainty or coordination, but does not usually determine the outcome alone.
- **Low**: the barrier is secondary, context-specific or generally manageable through existing intervention arrangements.

Severity is assigned according to the demonstrated consequence of a barrier when present, rather than the number of sources in which it appears.

Recurrence in the reviewed sources

The term **recurrence** is used instead of market prevalence because the evaluation base is qualitative and not statistically representative of Europe; it is the recurrence in the reviewed evidence.

- **High:** the barrier appears across several independent evidence streams and multiple product or actor contexts.

- **Medium:** identified repeatedly, but concentrated in particular configurations, countries, actors or contractual settings.
- **Low:** the barrier appears in isolated cases or is supported mainly by analytical inference.

Independent evidence streams are distinct source types, not document counts; duplicate evidence of the same condition is treated as one stream. High recurrence requires ≥3 independent streams across >1 product/actor context; Medium requires ≥2 streams but concentrated in one context; Low indicates isolated evidence or mainly analytical inference.

Changeability

Changeability reflects whether the barrier could be materially reduced through realistic intervention over a short- to medium-term horizon.

- **High:** the barrier can be addressed through improved practice, documentation, monitoring, tools or training without major structural change.
- **Medium:** mitigation requires coordinated action, product development, service reorganisation or contractual change.
- **Low:** the barrier is embedded in legacy product architecture, established warranty structures, regulatory systems, technical approvals or multi-actor risk arrangements.

A low-changeability rating does not mean that the barrier should be ignored. It means that mitigation is likely to require longer-term collective action rather than an isolated project-level measure.

Confidence

- **Strong:** supported by at least three independent evidence types, including direct documentary or empirical evidence, with no major unresolved contradiction**.**
- **Moderate:** supported by more than one evidence type, but with limited geographical, case or empirical coverage.
- **Indicative:** supported mainly by individual cases, stakeholder observations or analytical inference.

The assessment was performed through expert synthesis by the report authors. The ratings express relative positioning within the evidence reviewed and should not be interpreted as precise measurements.

4.7.2 Consolidated barrier assessment

Table 2 – Barriers by type

Barrier	Category	Severity	Recurrence	Changeability	Key actors	Confidence
Uncertainty over continued applicability of product qualification or technical-assessment evidence after repair or modification	Regulatory	High	Low	Low	Standards bodies, technical-assessment bodies, manufacturers, regulators	Moderate — supported by standards and national assessment evidence; evidence from completed field repairs remains limited.
Warranty restrictions on repair	Commercial	High	High	Low	Manufacturers, insurers	Strong — supported by the structured warranty review and public manufacturer documentation across multiple product contexts.
Labour cost vs replacement cost	Commercial / Other (economic)	High	High	Medium	Installers, O&M providers	Moderate — supported by warranty and service documentation, maintainer responses and practitioner evidence.
Irreversible integration or destructive removal (bonded systems, for example)	Technical	High	Medium	Low	Manufacturers	Moderate — supported by public product documentation and technical literature; field-repair evidence remains limited.
Extent of dismantling, access and reinstatement required (BIPV)	Operational	High	Medium	Low	Installers	Moderate — recurrent in technical literature and practitioner evidence, but not supported by representative intervention-time or cost data.
Lack of spare parts / standardisation / format obsolescence	Operational / Technical	High	Medium	Medium	Manufacturers	Moderate — reported across commercial documentation and technical literature, but long-term market-wide availability has not been quantified.
Liability and insurance constraints	Regulatory / Commercial	High	Medium	Low	Insurers, asset owners	Moderate — supported by regulatory studies, survey evidence and commercial documentation; direct insurer evidence is uneven.
Lack of system commissioning (T0) baselines	Operational / Other (contractual)	Medium	Medium	High	Installers, operators, certificators, owners	Moderate — supported by standards and practitioner evidence, but recurrence has not been measured systematically.
Lack of product specific repair procedures	Technical/Operational	Medium	Medium	Medium	Manufacturers, service actors	Moderate — identified across public product-document reviews and practitioner evidence, but procedure availability has not been surveyed systematically.
Lack of product identification, component information and diagnostic documentation	Commercial	Medium	Medium	High	Manufacturers, O&M providers, repairers	Moderate — supported by standards, maintainer evidence and practitioner findings across several actor contexts.

Barrier	Category	Severity	Recurrence	Changeability	Key actors	Confidence
Lack of repair price and conditions transparency	Commercial	Medium	Medium	High	Repairers, manufacturers, O&M providers	Indicative — principally supported by stakeholder and practitioner evidence rather than a structured market review.
Limited diagnostic capability or access to diagnostic data	Technical	Medium	High	High	O&M providers	Moderate — supported by diagnostic literature, standards and maintainer evidence across several actor and product contexts.
Skills gap (multi-disciplinary)	Labour	High	High	Medium	Training bodies, manufacturers	Moderate — supported by training literature and the maintainer questionnaire across several occupational contexts; survey coverage remains geographically and statistically limited.
Fragmented responsibility (actors)	Operational	Medium	High	Medium	All actors	Strong — convergent evidence from warranties, service arrangements and the maintainer questionnaire.
Aesthetic constraints (BIPV)	Social	Low	Low	Medium	Architects, clients, manufacturers	Indicative — identified in published product and architecture cases; evidence is limited and does not show aesthetics to be a primary repair barrier.
Waste classification (WEEE)	Regulatory	Medium	Medium	Low	Policymakers	Moderate — the legal mechanism is well documented, but its practical effect on repair and re-use decisions is less systematically evidenced.
Lack of refurbished components and second-life replacement	Commercial	Medium	Medium	Medium	Market actors	Indicative — supported mainly by circularity literature and practitioner observations; BIPV-specific market evidence remains limited.
Rating method: Severity reflects the consequence of a barrier when it occurs. Recurrence reflects the breadth and repetition of the barrier across the evidence reviewed, not statistical prevalence in the European market. High recurrence requires at least three independent evidence streams across more than one product or actor context; Medium requires at least two streams with contextual concentration; Low indicates isolated evidence or mainly analytical inference. Changeability reflects the extent to which a barrier could be reduced through identifiable technical, organisational, commercial or regulatory action over a short- to medium-term horizon. Confidence describes the strength and diversity of supporting evidence and does not modify the severity, recurrence or changeability rating.						

The prioritisation confirms that practical repairability is not determined by technical feasibility alone. Across the elements reviewed, the most recurrent high-severity barriers (high recurrence high severity) are warranty restrictions, the labour cost of repair relative to replacement, lack of compatible spare parts/format obsolescence, and skills gaps. These barriers explain why a technically feasible intervention may not be implemented.

A second group of barriers is potentially severe but more dependent on the product and intervention context. These include uncertainty over whether existing qualification or technical-assessment evidence remains applicable after modification, irreversible integration, deinstallation complexity and liability or insurer constraints. Their effect is greatest where repair would affect both the PV function and a building or infrastructure function, such as waterproofing, structural resistance, glazing, fire or acoustic performance.

The assessment also identifies barriers with comparatively high changeability ie that could be mitigated with relative ease. Missing commissioning baselines, insufficient product information, lack of repair procedures, limited access to diagnostic data and underuse of monitoring can be reduced through improved documentation, organisation and information management. These barriers therefore represent the most direct opportunities for improving repairability in the short term.

The barriers are interdependent. A BIPV product's architecture determines the physical scope of repair, number of occupations required, the cost of access and re-commissioning, and the proofs needed to demonstrate continued compliance (if required). Component obsolescence can transform a simple replacement into a non-identical substitution, creating additional electrical, geometric and regulatory checks. Missing or inadequate documentation can increase diagnostic uncertainty (or cost) and reduce the willingness of actors to accept responsibility for the repaired system.

The results show that different configurations are exposed to different combinations of barriers. Bonded systems are particularly sensitive to destructive removal and waterproofing restoration. Roof-integrated tiles are sensitive to sequential access, labour requirements and long-term format compatibility. Mechanically fixed systems generally preserve a wider possibility of substitution but remain dependent on electrical, dimensional and building-performance compatibility. Infrastructure-integrated systems may offer comparatively favourable access while remaining subject to structural, geometric and safety requirements.

Note: The prioritisation is based on qualitative evidence with uneven coverage. The maintainer questionnaire is geographically concentrated and data from completed BIPV repairs remain limited. The confidence assessment is intended to make these limitations explicit.

4.7.3 Recommendations for repairability

The assessment supports six cross-cutting priorities for system repairability:

1. Maintain a transferable commissioning (T0) record with installed configuration, baseline measurements and intervention history.
2. Provide product identification, compatibility information, dismantling guidance and post-intervention verification requirements for the expected service life.
3. Plan spare-part and substitution strategies, including equivalent-product criteria where identical components are unavailable.
4. Design access, fixings and interfaces to support reversible intervention without unnecessary disturbance to the building or infrastructure function.
5. Clarify responsibility among PV, electrical and building-envelope actors, including who validates return to service.
6. Make labour, logistics, authorisation and remedy choice transparent enough to compare repair and replacement on total intervention cost.

5 Deconstruction and re-use

5.1 Deconstruction conditions and economics

Deconstruction is the interface between system repair, re-use and recycling. For BIPV, removal may affect roofing, facade, glazing, waterproofing or other building functions, so the practical cost extends beyond detaching the PV product. The deconstruction questionnaire identified labour, access, logistics, sorting and building reinstatement as recurring considerations; because direct practitioner responses were limited, these observations are treated as qualitative rather than representative cost evidence.

The report therefore uses a cost-accounting framework rather than a predictive model. For an individual project: net deconstruction cost = direct dismantling labour + access/lifting + packing + transport + treatment/disposal + building reinstatement - payments actually received for reusable components or scrap. Installation labour may be used only as an indicative starting assumption where dismantling-time data are unavailable; actual removal conditions can differ substantially.

5.2 Re-use conditions

Re-use is viable only where the removed product retains safe functional value and sufficient evidence exists to support a second application. Controlled removal, traceability, product identification, handling history, electrical testing and condition assessment are therefore essential. Where the PV element also performs a building function, second-life assessment may additionally need to consider dimensions, glazing or roofing performance, fixing compatibility and the requirements of the new application. [1], [4], [5], [9], [10], [42].

Waste status and responsibility can also determine whether a technically serviceable product reaches a second-life route. A product intended for re-use should therefore have its ownership, classification, testing responsibility, logistics and acceptance criteria defined before deinstallation. Where those conditions cannot be demonstrated, recycling may remain the safer downstream route.

5.3 Recommendations

1. Plan for reversible deconstruction at design and installation stage, with accessible interfaces and documented removal sequences.
2. Maintain product identifiers, electrical characteristics, installation records and intervention history so recovered products can be assessed.
3. Separate PV removal, logistics, testing and building reinstatement when planning and costing deconstruction.
4. Define condition-assessment, testing, ownership and routing criteria before removal where re-use is intended.

6 Recycling and contribution to the circular economy

Recycling is the material-recovery pathway when continued functional use is no longer appropriate. BIPV can introduce additional pre-treatment requirements because PV laminates may be combined with non-standard glass, coatings, adhesives, frames, roof or facade attachments and other construction materials. These elements should be separated where practicable before conventional PV treatment. [14], [43], [44], [45], [46].

6.1 Mass recovery and value recovery

PV recycling performance should not be assessed by mass recovery alone. Glass represents most module mass, but contaminated or finely crushed cullet may have low-value outlets. Clean aluminium and copper have more direct secondary-material markets, while silicon and silver represent smaller mass fractions but can carry significant embedded economic and environmental value. Advanced delamination and selective separation can improve purity and value retention, although the economics depend on scale, yield and market conditions. [43], [42], [45], [46], [47]

6.2 Implications for higher-value recycling

Recycling strategies should preserve material quality rather than focus only on recovered mass. Where technically and economically justified, accessible frames, cables, junction boxes and other separable components should be removed before destructive processing. Product composition and BIPV-specific attachments should be documented so recyclers can select appropriate pre-treatment, and reporting should distinguish collection, mass recovery, purity and the actual destination of recovered materials.

7 Conclusions and recommendations

The assessment shows that repairability of IPV and BIPV systems is a **multi-factor issue**. A necessary distinction is made between **component repair**, where a defective product or component is physically repaired, and **system repair**, where the objective is to restore the complete installation to safe, functional and compliant operation. System repair may be achieved through local repair, substitution or selective replacement. A component that cannot itself be repaired may therefore still belong to a repairable system if it can be identified, accessed, removed and replaced without unnecessary wider intervention.

This distinction also connects repair directly to **deconstruction, re-use and recycling**. Replacing a defective module, tile or other integrated element may require partial deconstruction of the surrounding roof, façade or infrastructure assembly. The removed component may then be repaired for re-use, transferred to a second-life application or routed to recycling. Component replacement can therefore constitute a successful system repair even where the removed component itself reaches a different circularity pathway. Repair, re-use and recycling should consequently be understood as interconnected value-retention routes rather than as entirely separate or strictly sequential end-of-life options.

Across the reviewed evidence, practical repairability depends on the interaction of product architecture, accessibility, reversibility, component compatibility, labour and occupational coordination, commercial and warranty conditions, regulatory and compliance requirements, documentation, economics and allocation of responsibility. These factors are particularly important for BIPV because the PV element may simultaneously perform roofing, waterproofing, façade, glazing, acoustic, structural or other building and infrastructure functions. Repair is successful only where the relevant electrical and non-electrical functions can be restored with sufficient confidence.

The strength of these conclusions varies across the evidence base. The distinction between component and system repair, the importance of product architecture, and the influence of warranty conditions, compatibility, documentation and fragmented responsibility are supported by several independent sources. By contrast, quantitative evidence remains limited for completed BIPV repair interventions, dismantling time and cost, post-repair verification, second-life qualification outcomes and long-term spare-part availability. Findings should be interpreted as a qualitative synthesis of recurring mechanisms and conditions within the sources and material reviewed, not a statistically representative estimate of European market practice.

The main practical implication is that circularity should be considered throughout the system lifecycle. IPV and BIPV products should be designed and managed so that access, reversible intervention, compatible replacement, documentation, responsibility allocation, deconstruction, re-use and recycling remain viable options when needed. The objective is not to maximise repair or re-use in every case, but to avoid situations in which technically viable higher-value pathways are excluded simply because information, compatible components, recognised procedures or responsible actors are unavailable.

The report supports a common set of cross-cutting priorities: improve accessibility and separability at design stage; maintain transferable technical and commissioning documentation; establish realistic spare-part and substitution strategies; define repair, dismantling and post-intervention verification procedures; clarify responsibility between PV, electrical and building-envelope actors; and integrate lifecycle considerations more consistently into procurement, service arrangements, technical assessments and future product requirements.

References

[1] G. Oreski, I. Tsanakas, L. Bruckman and U. Jahn, “Performance and Reliability Aspects of 2nd Life Photovoltaic Modules,” IEA PVPS Task 13, 2026.

[2] F. G. Rosillo, M. B. Nieto-Morone, J. B. Esteva, F. Soriano, S. Temprano, C. Gonzalez and M. C. Alonso-Garcia, “Repairing ribbon bus bar interruptions in photovoltaic modules using non-intrusive interruption location,” *Renewable Energy,* vol. 223, 2024.

[3] M. B. Nieto-Morone, F. G. Rosillo, M. A. Munoz-Garcia and M. C. Alonso-Garcia, “Enhancing photovoltaic module sustainability: Defect analysis on partially repaired modules from Spanish PV plants,” *Journal of Cleaner Production,* vol. 461, 2024.

[4] I. A. Tsanakas, G. Oreski, G. Eder, A. Gassner, A. van der Heide, D. M. Godinho Ariolli, G. Oviedo Hernandez, D. Moser and K. Wambach, “Toward Reuse-Ready PV: A Perspective on Recent Advances, Practices, and Future Challenges,” *Advanced Energy and Sustainability Research,* vol. 6, 2025.

[5] D. Ariolli, G. Oviedo Hernandez and A. van der Heide, “Repair/re-use and in-source recycling of PV modules and BOS components,” Trust-PV, 2023.

[6] J. A. Tsanakas, A. van der Heide, T. Radavicius, J. Denafas, E. Lemaire, K. Wang, J. Poortmans and E. Voroshazi, “Towards a circular supply chain for PV modules: Review of today’s challenges in PV recycling, refurbishment and re-certification,” 2019.

[7] K. Wambach, K. Baumann, M. Seitz, B. Mertvoy and B. Reinelt, “Photovoltaic (PV) Recycling, Reusing and Decommissioning: Current Landscape and Opportunities for Standardization,” 2020.

[8] M. McCann, R. Basinet and L. Jones, “PV panel re-use around the world: State-of-the-art. Overview Report,” PVLab, The Australian National University, Circular PV Alliance, 2023.

[9] F. Parolini, P. Bonomo, F. Frontini, G. Bellenda, M. Caccivio, A. Federova, S. Boddaert, N. Martin Chivelet and H. R. Wilson, “Advancing BIPV Standardization: Addressing Regulatory Gaps and Performance Challenges,” 2024.

[10] N. Martin Chivelet, C. Kapsis and F. Frontini, Building-Integrated Photovoltaics - A Technical Guidebook, IEA PVPS Task 15, 2025.

[11] P. Bonomo, G. Battaglia, F. Frontini, S. Thorsteinsson, N. Martin Chivelet, R. Yang, M. Tabakovic, A. Schneider, B. Rau, G. Lobaccaro, T. Akbarinejad, K. Matai, K. Jun-Tae, C. Klinga and L. F. Mulcue Nieto, “BIPV: Education and Training Activities for Solar Architecture,” 2026.

[12] International Electrotechnical Commission, “Photovoltaics in buildings - Requirements for building-integrated photovoltaic modules and systems”.

[13] European Committee for Electrotechnical Standardization, “Photovoltaics in buildings”.

[14] International Renewable Energy Agency; International Energy Agency Photovoltaic Power Systems Programme, “End-of-Life Management: Solar Photovoltaic Panels,” 2016.

[15] Voltec Solar; Megasol; SoliTek; Dyaqua; EDILIANS; Heliup; Meyer Burger; Solarstone; SunStyle; Tejas Borja; Wienerberger Wevolt; Avancis; Onyx Solar; Ingeteam; Heliatek/HeliaSol, “Manufacturer warranty and technical documentation”.

[16] DualSun, “Contrat de garantie commerciale de durabilité,” 2023.

[17] European Parliament and Council of the European Union, “Directive (EU) 2024/1799 of the European Parliament and of the Council of 13 June 2024 on common rules promoting the repair of goods and amending Regulation (EU) 2017/2394 and Directives (EU) 2019/771 and (EU) 2020/1828,” Official Journal of the European Union, 2024.

[18] European Parliament and Council of the European Union, “Regulation (EU) 2024/1781 establishing a framework for setting ecodesign requirements for sustainable products,” Official Journal of the European Union, 2024.

[19] European Parliament and Council of the European Union, “Regulation (EU) 2024/3110 laying down harmonised rules for the marketing of construction products,” Official Journal of the European Union, 2024.

[20] European Parliament and Council of the European Union, “Directive (EU) 2024/1275 on the energy performance of buildings,” Official Journal of the European Union, 2024.

[21] Belgium government, “Royal Decree of 8 September 2019 establishing the RGIE/AREI; Royal Decree of 7 July 1994 on fire and explosion prevention; and applicable regional building and planning frameworks”.

[22] European Commission, “Product-specific ecodesign regulations establishing repairability, spare-part and disassembly requirements for selected product groups, including Commission Regulation (EU) 2019/2023 for household washing machines and washer-dryers and Commission Regulation (EU) 2023/1670 for smartphones and slate tablets,” 2019; 2023.

[23] Deutsches Institut für Bautechnik; related German technical-rule bodies, “General building authority approvals (abZ), general construction technique permits (aBG), MVV TB, DIN 18516-1, FVHF BIPV façade guidance and product-specific approvals including Z-70.3-293 and Z-70.3-300”.

[24] Germany Government, “ElektroG: assessment of preparation for reuse before initial treatment where technically possible and economically reasonable”.

[25] Italy government, “Legislative Decrees No. 49/2014 and No. 152/2006; GSE procedures under the Ministerial Decree of 23 June 2016; and GSE Operating Instructions for End-of-Life Management of Incentivised PV Modules,” 2025.

[26] Republique Francaise, “Code de la construction et de l’habitation; Code des assurances; applicable NF DTU and NF C 15-100 requirements; and Decree No. 2010-301 of 22 March 2010 concerning electrical installation conformity verification in specified contexts”.

[27] G. Eder, Y. Voronko, A. Gassner, R. Schifferegger, G. Oreski and S. Feldbacher, “Development of a repair methodology for PV modules with damaged backsheets,” in *IEA PVPS Task 13 Webinar*, 2024.

[28] H. Gholami, H. N. Røstvik, M. N. Manoj Kumar and . S. S. Chopra, “Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway,” *Solar Energy,* pp. 488-502, 2020.

[29] C. Zhou and L. Shilong, “Reverse Logistics Network Optimization for Retired BIPV Panels in Smart City Energy Systems,” *Buildings,* vol. 15(14), p. 2549, 2025.

[30] International Electrotechnical Commission, “Photovoltaic system performance - Part 1: Monitoring”.

[31] International Electrotechnical Commission, “Photovoltaic systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems”.

[32] International Electrotechnical Commission, “Photovoltaic systems - Requirements for testing, documentation and maintenance - Part 3: Photovoltaic modules and plants - Outdoor infrared thermography”.

[33] Becquerel Institute for SPHINX, “Enquête sur les barrières non-techniques à la réparabilité des systèmes PV sur bâti,” 2025.

[34] European Parliament and Council of the European Union, “Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE),” Official Journal of the European Union, 2012.

[35] M. Libra, D. Mrazek, I. Tyukhov, L. Severova, V. Poulek, J. Mach, T. Subrt, V. Beranek, R. Svoboda and J. Sedlacek, “Reduced real lifetime of PV panels - Economic consequences,” *Solar Energy,* vol. 259, 2023.

[36] European Committee for Standardization, “Glass in building - Laminated glass and laminated safety glass”.

[37] Verein Deutscher Ingenieure, “Maintenance of photovoltaic installations - Fundamentals and methods of testing and measurement”.

[38] J. Leloux, L. Narvarte, A. Luna and A. Desportes, “Automatic fault detection on BIPV systems without solar irradiation data,” in *29th European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam*, 2014.

[39] International Electrotechnical Commission, “Photovoltaic module safety qualification”.

[40] SMA Solar Technology; Fronius; Enpal; Helion; Otovo; Iberdrola; SolarCare; Stern Energy; EDF ENR; Luminus Solutions; 3S Swiss Solar Solutions; Svea Solar; Endesa, “Service, maintenance and inverter warranty documentation”.

[41] CIRCUSOL, “Labelling and certification protocols for second-life PV modules,” 2022.

[42] International Electrotechnical Commission, “Photovoltaic modules - Type approval, design and safety qualification - Retesting,” 2023.

[43] International Electrotechnical Commission, “Terrestrial photovoltaic (PV) modules - Design qualification and type approval”.

[44] Centre Scientifique et Technique du Bâtiment; Commission chargée de formuler les Avis Techniques, “Avis Technique, Document Technique d’Application and Appréciation Technique d’Expérimentation procedures for building-integrated photovoltaic systems”.

[45] Spain government, “Ley 38/1999 de Ordenación de la Edificación; Real Decreto 314/2006 approving the Código Técnico de la Edificación; and Real Decreto 842/2002 approving the Reglamento Electrotécnico para Baja Tensión”.

[46] Switzerland, “Ordinance on Low-Voltage Electrical Installations (OIBT), including Article 14; ESTI Directive No. 220; relevant SIA standards; and AICAA/VKF fire-protection rules”.

[47] H. e. a. Gholami, “Lifecycle cost analysis of tailor-made BIPV façade: Solsmaragden case study in Norway.,” *Solar Energy,* vol. 211, p. 488–502, 2020.

[48] European Parliament and the Council of the European Union, “Commission Delegated Regulation supplementing Directive (EU) 2024/1275 as regards the establishment of a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements.,” 2025. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=intcom%3AC%282025%294133.

[49] E. Commission, “COMMISSION DELEGATED REGULATION (EU) supplementing Directive (EU) 2024/1275 as regards the establishment of a comparative methodology framework for calculating cost-optimal levels of minimum energy perfo,” 2025.

[50] R. Deng, N. L. Chang, Z. Ouyang and C. M. Chong, “A techno-economic review of silicon photovoltaic module recycling,” *Renewable and Sustainable Energy Reviews,* vol. 109, pp. 532-550, 2019.

[51] M. Bošnjaković, M. Galović, J. Kuprešak and T. Bošnjaković, “The End of Life of PV Systems: Is Europe Ready for It?,” *Sustainability,* vol. 15, p. 16466, 2023.

[52] J. Cristobal Garcia, D. Caro, G. Foster, G. Pristera, F. Gallo and D. Tonini, “Techno-economic and environmental assessment of construction and demolition waste management in the European Union,” Joint Research Centre (JRC), Luxembourg, 2024.

[53] B. Bayram, K. Greiff, L. Gerlich, A. Luthin, L. Hildebrand and M. Traverso, “Environmental and economic implications of selective demolition and advanced recycling of construction waste,” *Sustainable Production and Consumption,* vol. 57, pp. 61-79, 2025.

[54] T. Curtis, G. Heath, A. Walker, J. Desai, E. Settle and C. Barbosa, “Best Practices at the End of the Photovoltaic System Performance Period,” National Renewable Energy Laboratory (NREL), Golden, CO, 2021.

[55] L. J. M. A. A. M. J. M. M. M. E. Rabin Basnet, “Advancing circular economy of silicon Photovoltaics: Current status and challenges of PV module reuse,” *Solar Energy Materials and Solar Cells,* vol. 292, 2025.

[56] European Parliament and Council of the European Union, “DIRECTIVE 2008/98/EC on waste and repealing certain Directives,” Official Journal of the European Union, 2008.

[57] European Commission, “Commission Recommendation (EU) 2026/510 of 6 March 2026 on revising the European assessment framework for safe and sustainable by design chemicals and materials,” 2026.

[58] International Energy Agency PVPS Task 12, “Status of PV Module Recycling in Selected IEA PVPS Task12 Countries,” IEA, 2022.

[59] G. A. Heath, T. J. Silverman, M. Kempe, M. Deceglie, D. Ravikumar, T. Remo, H. Cui, P. Sinha, C. Libby, S. Shaw, K. Komoto, K. Wambach, E. Butler, T. Barnes and A. Wade, “Research and development priorities for silicon photovoltaic module recycling to support a circular economy,” *Nature Energy,* vol. 5, pp. 502-510, 2020.

[60] P. Dias, L. Schmidt, M. L. Marina, N. L. Chang, G. Spier, R. Corkish and H. Veit, “Comprehensive recycling of silicon photovoltaic modules incorporating organic solvent delamination – technical, environmental and economic analyses,” *Resources, Conservation and Recycling,* vol. 165, p. 105241, 2021.

[61] Sustainability Victoria, “PV Panel Reprocessing: Research into Silicon-Based Photovoltaic Cell Solar Panel Processing Methods, Viable Materials Recovery and Potential End Market Applications.,” HRL Technology Group Pty Ltd, Australia, 2019.

[62] V. Thompson and V. Shaw, “Chinese PV Industry Brief: Solar glass prices on the rise,” 4 March 2025. [Online]. Available: https://www.pv-magazine.com/2025/03/04/chinese-pv-industry-brief-solar-glass-prices-on-the-rise/.

[63] World Bank, “Commodity Markets,” 4 August 2026. [Online]. Available: https://www.worldbank.org/en/research/commodity-markets.

[64] European Parliament and Council of the European Union, “Régulation (EU) 2024/1781 establishing a framework for the setting of ecodesign requirements for sustainable products,” 2024.