Bringing retired PV modules back to life: From science-fiction to the reality of the circular economy in the PV sector

Module waste | The growing volume of PV waste presents an emerging environmental challenge, but also brings substantial value creation opportunities as the idea of bringing decommissioned PV modules back to life becomes more feasible. Researchers from imec, VITO and SoliTek chart the development of the second-life PV business as it transitions from theory to practice

Volume growth brings waste challenge

The solar photovoltaic (PV) energy industry is experiencing a radical growth, particularly evident over the last decade, evolving from a niche market into a large-scale, mainstream, cost-competitive renewable energy technology. The fact that nearly 80% of the worldwide PV installations (and, thus, PV modules) have been deployed only during the last five years speaks for itself. With the installed PV capacity today exceeding 600GWp, and in view of the current annual growth rate of 25-30% for new PV installations, we are entering the dawn of the terawatt (TW) era of global PV installations, a milestone that is foreseen to be reached by 2022 [1].

On the shadow side of this success, the number of PV modules that reach the end of their useful first life will also greatly increase after the time lag of lifecycle operation, accumulating proportionately as PV waste. Indeed, this massive growth of PV installations is translated into global PV waste projections of up to 8 million metric tonnes by the end of 2030; and up to 60-78 million metric tonnes cumulative, by 2050 [2]. As such, the ratio of PV waste to cumulative installed PV volume, being today lower than 0.6%, is expected to exceed 80% by 2050. Further to consider, these projections account neither for PV waste at production level nor waste from decommissioned PV for economic reasons, i.e. insurance claims and repowering. In other words, PV waste volume could even be much higher.

In this context, the exponentially growing PV waste presents an emerging technical and environmental challenge. Rather than considering such challenge a mountain too high to climb, one can envisage unprecedented, multifold value creation opportunities, such as new financing mechanisms and multiple revenue streams, across the whole PV value chain. Besides, PV recycling, recovery of raw materials, repair or refurbishment of decommissioned, failed or degraded PV modules and their recommissioning (second-life PV modules), are indispensable for a more sustainable, environmentally friendly and economically viable solar energy-based future.

From linear to circular business in the PV sector

Up to recently, PV end-of-life (EoL) management approaches have been mostly examined from the perspective of conventional product-based single-path business models (Figure 1):

1. A supplier sells new PV modules and batteries to the end-user;
2. The user then manages the PV energy generation;
3. Real-field (operational) life of a PV modules reaches the end;
4. PV modules enter the waste stream and are either recycled or disposed.

Indeed, in most cases, by default, once PV modules are decommissioned or fail, they enter the waste stream and are either disposed as waste (in their majority) or – in the best case – recycled, with the latter option representing today a clear minority of <10%, compared to disposal. Recent advances in PV recycling technology and processes, as well as pilot projects, led by PV recycling pioneers, such as PV CYCLE, First Solar, SolarWorld, Loser Chemie and

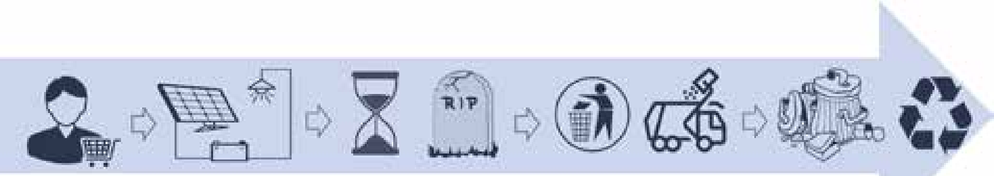


Figure 1: Simplified illustration of the conventional product-based single-path business model for PV modules, throughout their market and operational lifetime

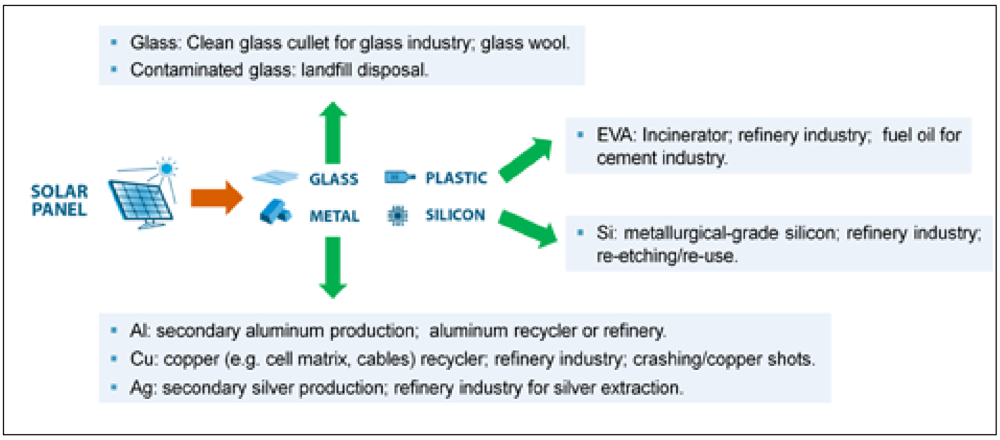


Figure 2. Recovery and secondary use streams for the different PV components and materials

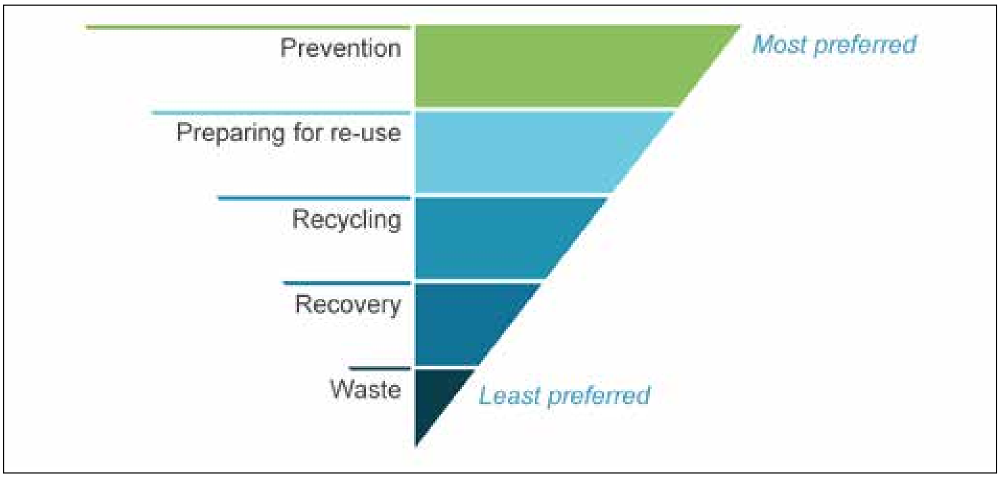


Figure 3. Waste hierarchy, also applicable to PV EoL management, according to the EU waste legislation

NPC Group, allow the recovery and re-use of most materials in a PV module (Figure 2).

The first complete system-scale PV decommissioning and high-value recycling, which was undertaken by a commercial service provider and resulted in the remanufacturing and recommissioning of second-life PV modules, has been reported by K. Wambach et al. [3]. The case study was led by SolarMaterial AG who, in one year, completed the recycling of Germany's oldest PV system, installed in 1983 on the Pellworm island. In total, 17,568 PV modules have been dismantled and recycled, the recovered solar-grade silicon wafers were reprocessed by Sunways AG and the new-made cells were used for manufacturing of new PV modules by Solarwatt. All PV modules, that were installed in this "second-life" PV system, were certified by SolarWorld AG as original equipment manufacturer (OEM) products, with full warranty (25 years).

Beyond recycling and recovery of raw materials, repairing/refurbishing PV modules for re-use (i.e. second life) or even preventing PV failures are even more preferred EoL practices, in view of the relevant legislation on waste hierarchy (Figure 3). Indeed, PV modules with extended lifetime (or second life), through their re-use or repair, will increase their overall (lifetime) energy yield, for the same bill of materials and embedded energy used for their manufacturing, eventually lowering their lifecycle environmental impact.

In quantitative terms, CIRCUSOL [4] and field PV reliability experts [5] reckon that 45-65% of failed and/or decommissioned PV modules today can be diverted from the disposal/recycling path, towards second-life PV (re-use), upon repair/refurbishment. In practice, this ratio is likely to be even higher since decommissioned though functional PV modules currently also enter the aforementioned waste stream.

It becomes clear that the aforementioned "take-make-dispose" linear models (Fig. 1) are neither sustainable nor sufficient to bring out the environmental, technical and economic benefits of PV recycling, repair/refurbishment and re-use. On the other hand, circular business models and cradle-to-cradle designs can be the key towards streamlining EoL decision-making which, in turn, can help to slow, close and narrow resource loops in the PV sector. On this basis, a *Product-Service System* (PSS) has been proposed by CIRCUSOL, to enable the implementation of circular business models in the PV sector (Fig. 4). Such a PSS-based circular business model:

- introduces *product service providers*, to consolidate and carry out decision making for the optimal life path for each PV module, as well as to co-create value propositions to the PV end-users;
- incentivises innovation towards PV designs-for-circularity (see section 'Designs-for-circularity'), that facilitate second-life paths, i.e. recycling, re-manufacturing or refurbishment and re-use.

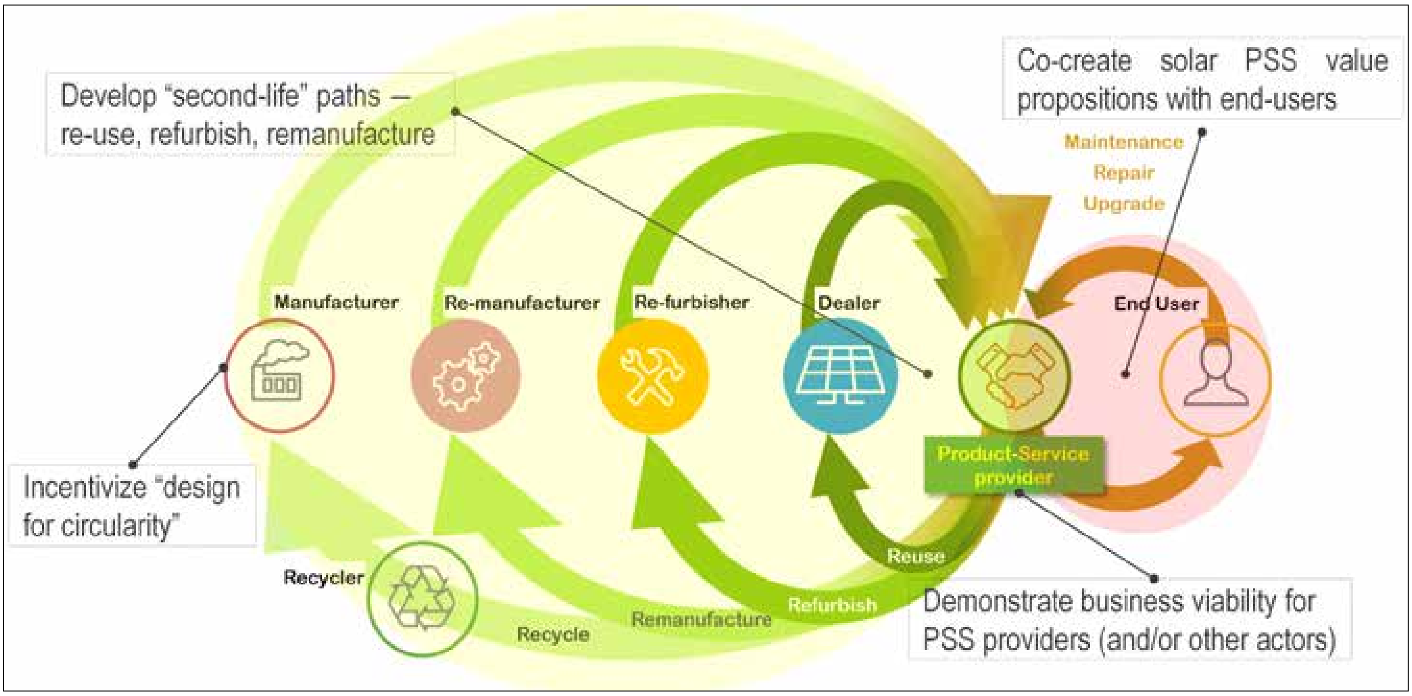
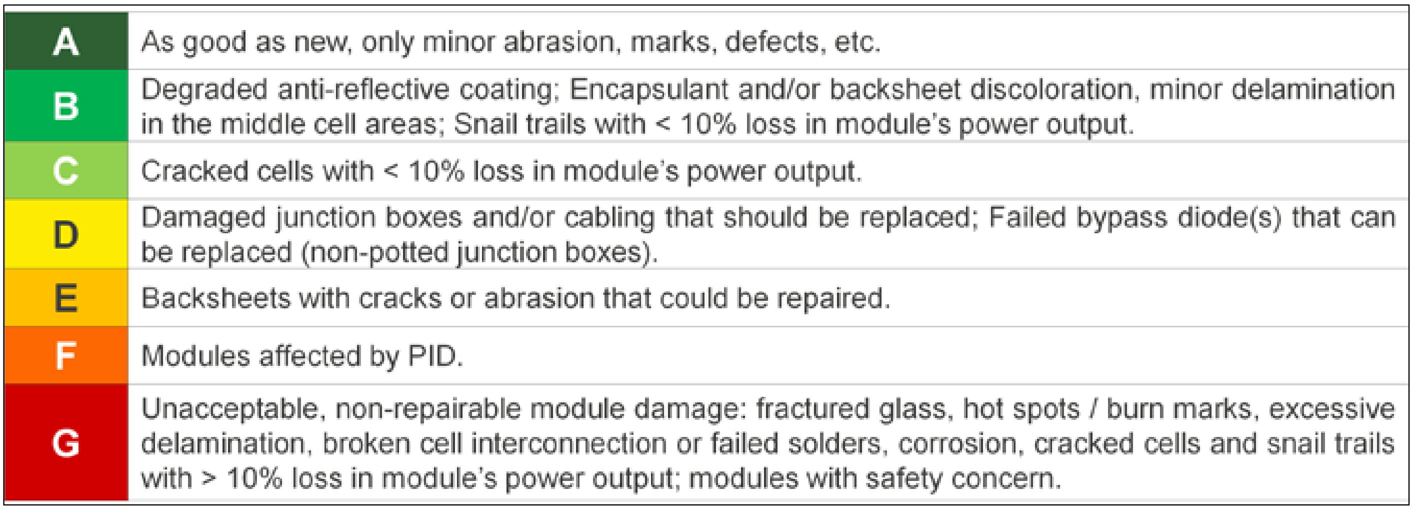


Figure 4. The PSS-based circular business model, envisaged in CIRCUSOL project; coupling circular product management and value-added product service



A	As good as new, only minor abrasion, marks, defects, etc.
B	Degraded anti-reflective coating; Encapsulant and/or backsheet discoloration, minor delamination in the middle cell areas; Snail trails with < 10% loss in module's power output.
C	Cracked cells with < 10% loss in module's power output.
D	Damaged junction boxes and/or cabling that should be replaced; Failed bypass diode(s) that can be replaced (non-potted junction boxes).
E	Backsheets with cracks or abrasion that could be repaired.
F	Modules affected by PID.
G	Unacceptable, non-repairable module damage: fractured glass, hot spots / burn marks, excessive delamination, broken cell interconnection or failed solders, corrosion, cracked cells and snail trails with > 10% loss in module's power output; modules with safety concern.

Table 1. Proposed classification of observed defects and failures of PV modules, to determine their repairability

Field experience and second-life PV business: State of play

In the course of PV modules' operational lifetime, physical degradation, defects or failures may occur in only a single component (e.g. cell cracks or bypass diode failures); whereas the rest of the module structure itself may remain intact. Different reliability issues at a PV module level can be classified into infant mortalities (<4 years of field exposure), mid-life failures (beyond four years and fewer than 15 years of field exposure) and end-life or wear-out mechanisms (>15 years of field exposure, until and beyond the module's performance warranty) [6]. Field experience indicates typical PV module failure rates ~0.15-0.25% per year, meaning that approximately 2% of the entire fleet of a PV plant is predicted to fail after 11-12 years [6].

The most commonly experienced reliability issues and failures of PV modules in the field are encapsulant delamination and browning; fractured glass, frame or backsheet; bypass diode and junction box failures; cell cracks (often with consequent snail trails); broken cell interconnections; corrosion and potential-induced degradation (PID) [5, 6]. The necessity and time (urgency) of decommissioning PV modules with such problems, and the decision for repair (if technically feasible) is largely based on on-site visual inspection and field characterisation, combined with empirical evidence. Table 1 proposes a classification of such failures observed in fielded PV modules, to determine their repairability. Field experience and current technology indicate that, in principle, repair/refurbishment of PV modules and/or recovery of their electrical performance may be typically applied to: i) defective frames and mounting clamps; ii) faulty bypass diodes and defective wire connectors in junction boxes; iii) certain PV backsheet defects; iv) early PID.

Eventually, as indicated in Table 1, some cases of PV module failures, such as damaged (fractured) glass, cracked cells and snail trails, turn out to be beyond refurbishment. Whether refurbishing a PV module is worth it or not often depends on the kind of failure and the layout of the PV system where the module was installed and operated during its first life. For instance, building-integrated PV (BIPV) systems may need to be completely dismounted, even if only few individual (repairable) modules fail, to ensure the integrity of their multifunctionality (e.g. waterproofness) [7].

Therefore, before any repair, each PV module is cleaned and undergoes electrical (I-V) characterisation, by means of a solar simulator, while any kind of defect or failure is thoroughly documented, through additional thermal/optical characterisation methods and visual inspection. Then, repairing certain defective parts of a module is, at most times, a straightforward task. For instance, defective junction boxes or bypass diodes are completely removed and replaced by new ones. Upon completion of all repair tasks, the refurbished (second-life) PV modules undergo a new I-V characterisation to determine their new power, current and voltage outputs. In terms of reliability/qualification testing, an IEC 61730-based high-voltage test is a common practice among repair service providers, to ensure safety. Finally, upon its qualification, each refurbished module is commissioned and accordingly packaged for shipment.

Recently, Glatthaar et al. [8] introduced "PV-Rec", a practical tailor-made repair/recycling process for individual PV modules based on a reliable failure analysis and selection procedure (Figure 5). In that approach, visual inspections of EoL or failed PV modules are complemented by electroluminescence (EL) and/or infrared (IR) imaging measurements [9] and I-V characterisation, similarly to the task flow described above. In this way, module defects/failures are accordingly quantified and classified, so that the most appropriate recycling or repair procedure can be assigned to each module. In the same study, refurbishment could ideally be achieved by eliminating module defects in single repairs, which fully restore PV modules' operational status.

Apart from individual cases of failed modules, repair/refurbishment can also be performed to entire strings of a defective installation. Specialised companies can produce small runs of refurbishable modules; however, repairs may only be viable starting at a certain number of modules, as this is done by small manufacturers and requires manual labour and experience. In general, the greater the number of faulty PV modules that can be repaired at once the better, because the responsible technician needs to remove each module and place it on a transport pallet.

Recently, upon maturation of the PV industry in several countries, pioneer companies and platforms emerged and are offering refurbished second-life PV modules. Notably pvXchange, SecondSol and Solar-Pur GmbH offer mostly for business-to-business (B2B) and exchange platforms, trading in decommissioned and refurbished PV modules and components [10-12]. Such platforms may also provide

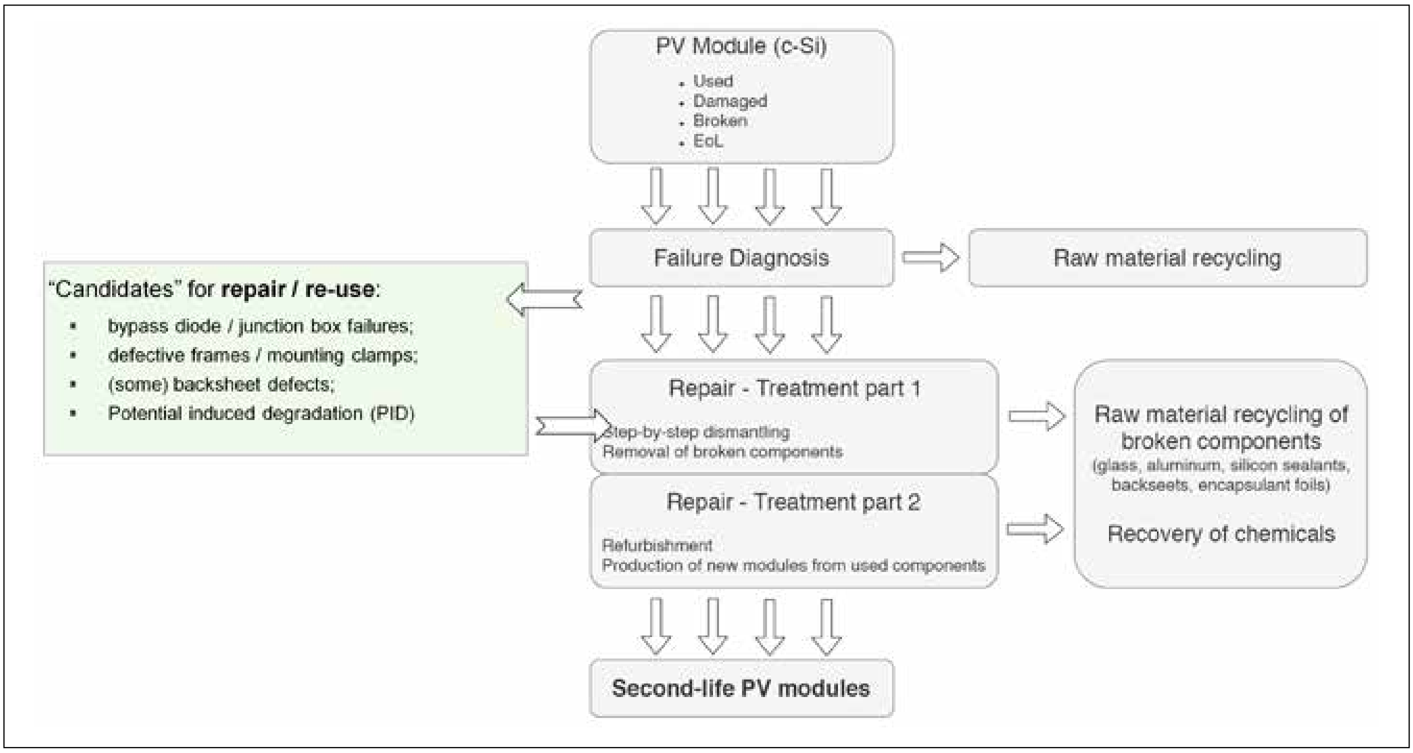


Figure 5. An adapted procedure towards second-life PV, based on the "PV-Rec" concept of J. Glatthaar et al. [8]

quality control, repair and installation services. PV modules' repair/refurbishment is commissioned by PV installation or insurance companies with positive experience in relevant repair projects, and the repaired PV modules are typically given a two-year warranty [7].

At the core of second-life PV module business, SecondSol's and Rinovasol Group's GmbH activities range from collection and repair of decommissioned or failed PV modules to the quality control/testing and trading of second-life (refurbished) ones [12, 13]. Rinovasol Group reckons that up to 90% of defective PV modules are potentially repairable, while claiming three international patents in relevant technology and design aspects, as well as IECEE CB Scheme certification [13]. Indicative repair/refurbishment costs for PV modules range from approximately €20 (US$22.16) to up to €90 per module, considerably depending on the handled volume, the quantity or severity and type of failure/defect, as well as on the required characterisation/testing, prior to and after repair [12]. It does become evident that second-life PV modules close to the upper margin of such repair-for-reuse costs, cannot even be competitive, cost-wise, with brand new (thus, of higher efficiency) PV modules that have the same (or even lower) price tag. One would then wonder if and how second-life PV and re-use business can survive today such fierce competition, in a market of consistently decreasing PV module prices. The recurring though plain explanation is that, in many cases, PV system owners and operators need to replace failed/decommissioned PV modules with identical or similar ones, in terms of type/model or (at least) power rating, to retain existing subsidies and feed-in tariffs. Therefore, apart from being a "greener" option, second-life PV module types provide a straightforward solution and prompt replacement for "retired" PV modules that are neither produced anymore nor traded as new today.

Looking at today's technical landscape on post-repair PV reliability testing and (re-)certification, second-life PV traders and relevant service providers face substantial challenges. Although the PV industry gained, through the years, significant experience in PV reliability issues, this experience is largely based on rigorous and extensive "design qualification" and "type approval" testing sequences for newly produced PV modules, i.e. under controlled laboratory conditions, as per IEC standards.

On the other hand, those familiar with the PV industry recognise that repair and/or refurbishment of second-life PV modules remain rather informal and certainly neither systemised nor standardised. In fact, these activities are independently performed by the aforementioned companies, with limited (or even without) support from the original PV module and component manufacturers. On this basis, today, there are only limited insights and hardly any standards on the characterisation, reliability testing, certification or labelling for second-life PV modules. Yet, it should be clarified that, from a functional perspective and in view of the Low Voltage Directive (LVD) (2014/35/EU), relevant conformity assessment and safety requirements are still applicable, equally for both first- and second-life PV modules.

In this rather vague context, details on the reliability/qualification testing of second-life PV modules that are adopted and applied by the aforementioned actors are not publicly disclosed. As a result, claimed duration of warranty periods for refurbished PV modules may be judgement-based, somewhat subjective and often misleading or misinterpreted. Besides, the extent and nature of the applied PV repair/refurbishment actions should be carefully drawn, to ensure the integrity and validity of CE (i.e. *Conformité Européenne*) marking in second-life PV modules to be traded within the European Union. However, most importantly, efforts towards re-certification and quality standardisation for such modules neither exist nor are practically under any development at this moment, as TÜV Rheinland and IEC experts reckon [14, 15].

How can second-life PV become reality in circular business?

Designs-for-circularity: Innovation and opportunities

Exemplary innovations and material/design-for-recyclability practices that (potentially) facilitate circularity are found on both material/component and module/device level. Apollon Solar's NICE technology, which can render PV modules encapsulant-free by replacing the encapsulant layers with neutral gas filling, simplifies the fabrication process (no soldering, no lamination needed), while enabling more environmentally friendly and simple PV recycling process, claiming 100% recyclability [16-18]. Also, the use of glued ribbons or electrically conductive adhesives, can eliminate the need for lead-based ribbons, thus allowing recycling/recovery processes free of hazardous lead waste residues [19-21]. Besides, considerable technical complications in PV recycling, associated with the challenging elimination of EVA or POE, can be overcome with the incorporation of alternative materials, such as silicone sheets [22].

From a more procedural and workflow perspective, the integration of radio-frequency identification (RFID) technology in PV modules can streamline collection-transportation-processing schemes, by tracking and identifying decommissioned PV materials and waste, on the basis of reverse logistics [23]. In turn, the latter comprises an excellent facilitating tool towards PSS-based circular business models for the PV industry.

In all cases, these innovative design solutions do not grasp yet any significant market share, due to their relatively high cost and/or their unproven field reliability and applicability.

4.2 Second-life PV: R&D gaps and key market factors

As of today, there are substantial gaps in knowledge/R&D and technology, in relation to the segments of PV refurbishment/repair and second-life PV reliability testing. This, in turn, explains the much smaller and relatively fragmented market being addressed, in contrast to the thriving standard PV business and the immense growth of PV installations. There are two main "pillars" of R&D gaps, being market factors-constraints that need to be timely addressed, to enable the bankability and success of second-life PV business [24]:

- *Addressable volume towards market profitability*. As it was discussed earlier, the repairability of decommissioned PV modules is directly dependent on the type of failure/defect occurred during their (first) operational life. Service providers in this segment have to access and properly assess statistics and diagnostic data from PV O&M actors (e.g. failures' occurrence and severity, degradation rates, impact on system performance, correlation with plant characteristics and age), to be able to determine:
    - o The target volume, i.e. the failed PV modules the repair of which is technically feasible, and the occurrence of repairable failures.
    - o The age and share of these "repairable" PV modules, out of the overall volume of failed ones. For instance, PID issues are mainly reported through years three and four of operation, during which they may comprise up to 30-40% of reported failures. Bypass diodes and junction boxes failures are spread over the first 10 years of operation, with a share typically ranging between 15% and 25% of all reported failures.
    - o The cost of the needed repair actions, i.e. whether the repair/refurbishment of certain PV modules makes sense cost-wise, considering current prices of new PV modules.

Next to the above, one should note that there is a considerable volume of fielded PV modules that, although being non-failed ("healthy"), are still decommissioned in view of economic and/or technical reasons, e.g. insurance claims, repowering or lack of spares. In principle, such modules (especially the "younger" ones) are considered as very promising candidates towards PV re-use (second-life) business. In this direction, systemising appropriate labelling as well as time- and cost-efficient characterisation and reliability/qualification testing comprise the central R&D gaps to be addressed.

- *Product efficiency and reliability towards market confidence*. In practice, the (remaining) efficiency of repaired/refurbished PV modules will depend on the years of their field exposure (thus power degradation rate), at the moment of the repair. In other words, efficiency-wise, repairing relatively "young" PV modules, i.e. with infant failures, has higher added-value potential. Besides, since PV modules in failed state degrade much faster [5], timely and efficient detection of failed (yet repairable) modules in a PV system is another critical aspect. Next to product efficiency, another major challenge towards the bankability of second-life PV business is the lack of market confidence or "trust" in the reliability (and safety) of refurbished PV modules. Evidently, the latter stems from the lack of relevant regulatory framework and standardised reliability testing, as it has been also discussed above. In fact, considering that a PV module's warranty is intrinsically lost once a refurbishment/repair action is conducted, there is a need to somehow "certify" that the repaired, second-life module is safe and can regain the trust of the end-user.

Finally, next to the above, the societal impact of second-life PV business and its market development shall be studied and quantified in view of its job creation potential. When looking into the value chain, PV re-use (and preparation for re-use, i.e. field inspections, repair/refurbishment, characterisation and reliability testing, as well as the R&D pathways towards PV designs-for-circularity, the second-life PV business case can be definitely associated with creations of jobs in a broad educational/technical range, e.g. technicians, field engineers, researchers in PV industry and research/academia.

Looking ahead

It is well understood that PV waste is becoming a pressing environmental matter and a new technical challenge for the PV industry; which, however, also actuates with new R&D opportunities, to prepare today towards sustainable EoL practices and circular economy-based services for the PV sector.

In this article, we have provided the research and technical groundwork towards the second-life PV business, outlining current best practices, market landscape and constraints. We have identified certain knowledge and regulatory gaps, which largely explain the scarcity and struggles of second-life PV market players on one hand, and the limited public awareness and confidence of (potential) end-users, on the other hand. In this regard, credible understanding and practical validation of performance, reliability and safety of second-life PV modules are instrumental for trust-building and opening up second-life PV markets.

With these in mind, our future work will focus on formalising the recycle, repair and re-use segments in the PV value chain, through the following main R&D pathways:

- assessment and validation of PV design-for-circularity concepts;
- development of tailored, cost-efficient reliability testing and characterisation protocols for both failed/repaired and "healthy"/decommissioned, second-life PV modules;
- cost-profit and lifecycle analysis for the PV re-use (second-life) business case. ■

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