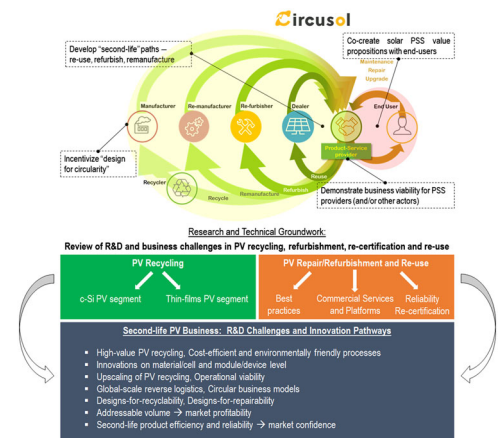




# Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification

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J.A. Tsanakas<sup>1</sup>  | A. van der Heide<sup>1</sup> | T. Radavičius<sup>2,5</sup>  | J. Denafas<sup>2,5</sup> | E. Lemaire<sup>3</sup> | K. Wang<sup>4</sup> | Jef Poortmans<sup>1,6,7</sup> | E. Voroshazi<sup>1</sup>

<sup>1</sup> PV Department, IMEC, EnergyVille II Campus, Thor Park 8320, 3600 Genk, Belgium

<sup>2</sup> Soli Tek R&D JSC, Mokslininkų str. 6A, Vilnius 08412, Lithuania

<sup>3</sup> Department of Solar Technologies, CEA-INES, 50 avenue du Lac Léman, F-73375 Le Bourget-du-Lac, France

<sup>4</sup> Unit Sustainable Materials Management, VITO NV, Boeretang 200, 2400 Mol, Belgium

<sup>5</sup> Kaunas University of Technology, K. Donelaičio g. 73, Kaunas 44249, Lithuania

<sup>6</sup> Katholieke Universiteit Leuven, Oude Markt 13, 3000 Leuven, Belgium

<sup>7</sup> Universiteit Hasselt, Martelarenlaan 42, 3500 Hasselt, Belgium

## Correspondence

Correspondence J.A. Tsanakas, PV Department, IMEC, EnergyVille II Campus, Thor Park 8320, 3600 Genk, Belgium. Email: ioannis.tsanakas@imec.be

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## Abstract

Photovoltaic (PV) waste, associated to the exponentially growing PV installations on global scale, presents today an emerging environmental challenge but also brings unprecedented and multifold value creation opportunities. In this context, significant PV business and research and development (R&D) efforts shift towards establishing a more sustainable, environmentally friendly and economically viable end-of-life (EoL) management for PV modules: including recycling, recovery of raw materials, repair/refurbishment and even re-use of decommissioned or failed PV modules. In the CIRCUSOL project, PV partners aspire to formalize the repair/refurbish and re-use value chains in the PV industry and propose a circular business model, based on a *product-service system* (PSS). Towards these goals, this review study introduces the relevant research groundwork, a status overview and today's R&D and business challenges in PV recycling, repair/refurbishment and re-certification aspects for second-life PV modules. The topics and the relevant reported literature are examined from both circular economy and technology perspective. The review indicates a considerable technological and operational know-how in PV EoL management that already exists and continuously evolves in mature PV markets. On the other hand, R&D in repair/refurbishment of decommissioned and/or failed PV modules remains scarce, and best practices and commercial services for reliability testing/re-certification and trading of second-life PV modules are neither standardized nor consolidated into any PSS or business model.

## KEYWORDS

PV recycling, PV re-use, PV refurbishment, circular business model, second-life PV modules

## 1 | INTRODUCTION

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, low-cost renewable energy technology. It is remarkable that nearly 80% of the worldwide PV installations (and, thus, PV modules) have been deployed only

during the last 5 years, with the installed PV capacity today exceeding 500 GWp and expected to overtake 1 TWp by 2022, in view of the current annual growth rate of 25-30% for new PV installations.<sup>1</sup>

Yet, inevitably, as PV deployment and penetration increase at such rates, 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. In quantitative terms,

this massive growth of PV installations is translated into an estimated global PV waste of 1.7-8 Mtons by the end of 2030 and up to 60-78 Mtons cumulative by 2050.<sup>2</sup> Further, these projections consider neither PV waste at production level nor waste from decommissioned PV for economic reasons, such as insurance claims and repowering. Thus, in reality, PV “waste” volume can even be much higher. Ultimately, such figures explain the gradual –though already significant–shift of research and development (R&D) efforts and business attention towards

- Streamlined PV operations and maintenance (O&M), to ensure maximum and cost-efficient operational first-life of PV components in the field; and
- Sustainable (profitable) end-of-life (EoL) management for PV installations and (when applicable) repair procedures, to establish long-term and competitive performance and reliability for second life PV components.

In the European Union (EU), today, Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU) addresses the waste management requirements of all electronics, including PV modules' waste, in the EU member states, indicating a 85/80 (%) recovery/recycling ratio of waste PV modules by mass to be recycled from 2019 onwards. In addition to such a regulatory scheme, it is obvious that EoL and recycling technologies must evolve and become available to meet the increasing requirements of WEEE for the case of PV waste. Yet limited research has been done on optimal EoL management considering recycling and/or re-use due to the long operational lifetime of PV modules (>20 years) and inverters (10 years or more) on one hand, and the limited predictability of defects or failures in fielded PV components on the other hand. For instance, it might be incorrect to extrapolate the current recycling data or systemize repair and re-use practices as it can be argued that they are rather minor issues today<sup>3</sup>; besides, relevant R&D efforts are still in progress, whereas PV technologies are rapidly evolving.

In this context, the exponentially growing PV waste particularly presents an emerging technical and environmental challenge; though, it also brings unprecedented, multifold value creation opportunities. One can envisage e.g. new financing mechanisms and multiple revenue streams across the whole PV value chain. 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 PV energy-based future. To unlock the benefits and maximize the impact of these opportunities, thorough knowledge and research foundation, along with real-field experience feedback, must be laid down at first. Likewise, streamlined decision-making and business models based on circular economy should be adopted.

Recently, Wade et al.<sup>4</sup> presented a comprehensive decision tree (Figure 1) depicting the different options for EoL management of decommissioned PV systems. A significant number of scientific studies<sup>5-10</sup> and public reports,<sup>3,11,12</sup> as well as research projects<sup>13,14</sup>

### Key outcomes of the study

- The current technology status, best practices and research/pilot efforts in PV recycling are reviewed and discussed, in both technical/technological terms as well as from a circular economy perspective.
- The technical/business landscape and best practices in PV repair/refurbishment, as well as in qualification testing for second-life PV, are reviewed and examined, in both technical and circular economy terms.
- Next and beyond this review, the technical challenges and innovation opportunities towards second-life PV business are also outlined. As such, the additional value creation opportunities stemming from PV re-use (second-life) or recycling are identified.

and collaborative platforms<sup>15</sup> have attempted over the last years to shed light on these different EoL paths and processes, with a major focus on PV recycling technologies, high-value material recovery, downstream EoL management models (collection-transportation-recycling) and life cycle analyses. So far, insights from the reported literature have been rather fragmented and somewhat one-sided, largely focusing on PV recycling processes and relevant innovation efforts. As such, the potential environmental and economic value of PV re-use remains relatively unexplored; also, knowledge or best practices in repair/refurbishment, reliability and certification/qualification of second-life PV modules have been scarce. Besides, even the most recent EoL management approaches have been mostly examined from the perspective of conventional product-based single-path business models; thus, missing out to address additional value creation opportunities stemming from PV re-use or recycling within circular business models.

## 2 | THE CIRCUSOL PROJECT: RATIONALE AND METHODOLOGY/VISION

Today, by default, once PV modules are decommissioned, they enter the waste stream and are either disposed or—in the best case—recycled. However, it is estimated that up to 80% of the PV waste stream can consist of product defects upon production, transportation or infant failures over the first 4 operational years,<sup>12</sup> instead of products that actually reach the end of their designed technical life. CIRCUSOL<sup>16</sup> partners and experts<sup>15</sup> estimate that about 45%-65% of these PV modules can be repaired or refurbished. Therefore, up to nearly 50% of the PV waste can be diverted from the recycling path. In practice, such ratio is likely to be even higher because decommissioned, though functional, PV modules currently also enter the “waste” stream.

On the other hand, re-use, repair and/or refurbishment remain rather informal and certainly neither systemized nor standardized in the PV industry and overall PV value chain today. In fact, these

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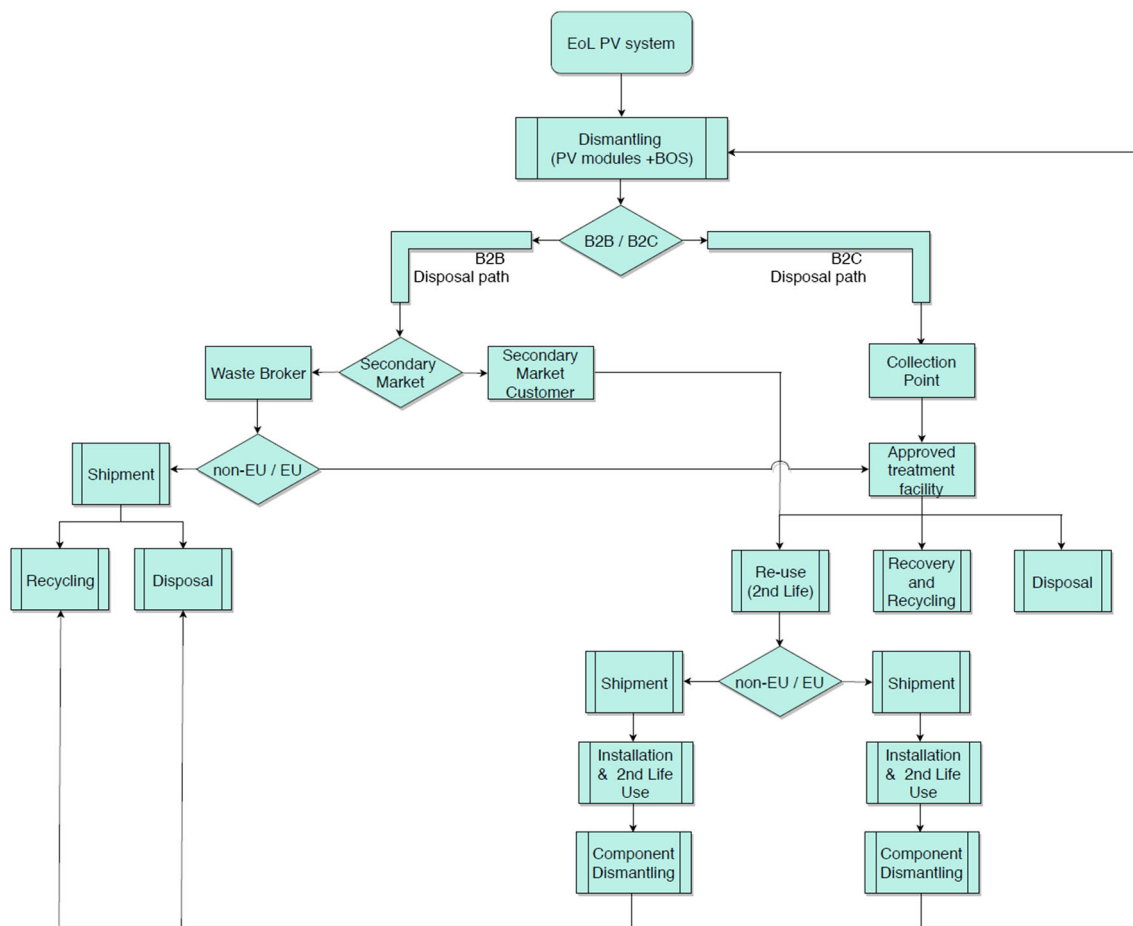
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**FIGURE 1** Decision tree for EoL management of a decommissioned PV system as proposed by Wade et al.<sup>4</sup>; figure adapted from the original version in<sup>4</sup> [Colour figure can be viewed at wileyonlinelibrary.com]

activities are currently performed by independent private companies, without any support from the original manufacturers. On this basis, today, there are only limited insights and hardly any standards on the characterization, 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 (2014/35/EU), relevant conformity assessment and safety requirements are still applicable, equally for both first- and second-life PV modules.

CIRCUSOL aspires to formalize the recycling, repair/refurbish and re-use segment in the PV value chains and to propose adapted technical standards/regularity framework for these emerging EoL business pathways for PV. This will be the foundation to develop and validate a *product-service system* (PSS) in the PV sector (next to the batteries sector, which is also addressed in CIRCUSOL), to enable the implementation of circular business models. The proposed PSS-based circular business model and its underlying value-creation goals throughout PV EoL are depicted in Figure 2. As such, PV modules can be designed for both recyclability and circularity towards second-life paths, i.e. for re-use, re-manufacturing and/or refurbishment. Moreover, in this way, decision making for the optimal life path for each PV module can be consolidated and carried out by *product service providers*, who are also responsible for co-creating value propositions to the PV end-users.

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. PV researchers and stakeholders in CIRCUSOL aim to bring insights into rather unexplored topics: (i) reliability testing and certification aspects for repaired/refurbished (second-life) PV modules; (ii) cost, application and market segment analysis, for a circular supply chain for PV modules; and (iii) market acceptance and policy recommendations.

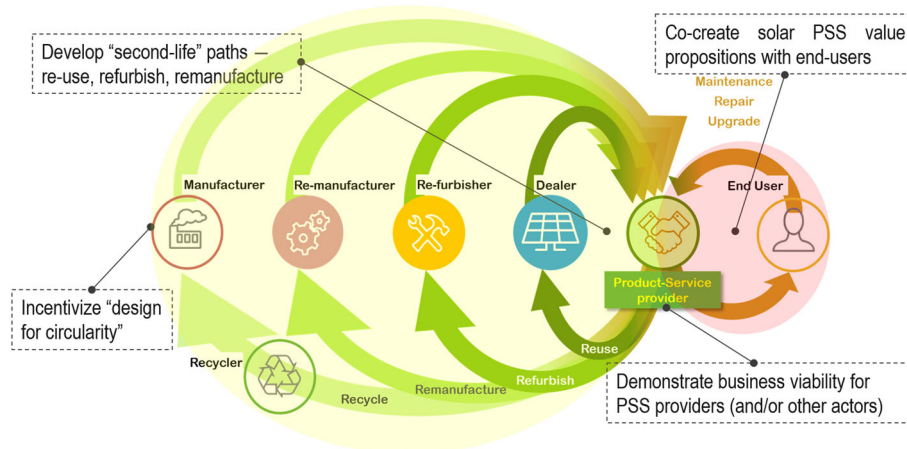
As a first step, towards these goals, this review introduces the relevant research and technical groundwork, a status overview and today's R&D and business challenges in (i) PV recycling (Section 3) and (ii) repair/refurbishment and re-certification aspects for second-life PV modules (Section 4). The topics—and the relevant reported literature—are examined from both circular economy and technology perspective.

### 3 | PV RECYCLING: CURRENT STATUS AND CHALLENGES

PV recycling approaches are typically classified into *bulk recycling* (recovery of high mass fraction materials, i.e. glass, aluminium and copper) or *high-value recycling* (semi-conductor and precious metals

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**FIGURE 2** The PSS-based circular business model, envisaged in CIRCUSOL project; coupling circular product management and value-added product service [Colour figure can be viewed at wileyonlinelibrary.com]

recovery). As such, recycling practices include (i) extraction of the encapsulant from the laminated module structure, by applying standard thermal, mechanical or chemical methods and (ii) recovery of the metals from the crystalline-silicon (c-Si) cells matrix (for c-Si PV modules) or recovery of the metals and the glass substrate (for thin film PV modules).<sup>11,17</sup>

### 3.1 | PV recycling in the c-Si PV segment

In the c-Si PV segment, which represents by far the largest share of PV installations, PV CYCLE comprises a Joint Producer Responsibility system and a recycling pioneer, which has contracted a number of PV recycling companies and technology developers, over the last years. As such, PV CYCLE was the first to establish a downstream PV module recycling and waste logistics process throughout the EU. In 2016, their contractors' recycling processes achieved a record recycling ratio of 96% for c-Si PV modules (fraction of solid recycled),<sup>18</sup> meaning that not only glass and aluminium is recycled but also silicon. In particular, after the removal of the cables, junction box and frame from the PV modules, PV CYCLE's process includes shredding, sorting and separation of the module's materials, allowing the latter to be sent to specific recycling processes associated with each material.<sup>8</sup>

Following First Solar's (since 2005) and SolarWorld's (2007-2012) PV recycling facilities, in 2017, Veolia has opened their European PV module recycling plant in Southern France (in contract with PV CYCLE France). With a 95% recovery ratio, their recycling process isolates all PV component materials, from the soda-lime glass to the aluminium frame, junction box and connection cables.<sup>19</sup> Recovered materials are then directed to various industries. The aluminium frame material is directed towards aluminium -based refinery; polymeric materials are recycled to fuel used in cement industry; silicon cells to precious metal sectors; cables and connectors are crushed and sold in the form of copper shots; whereas glass, recovered as clean cullet, is used in the glass manufacturing industry. As a side note on the latter, the glass recovered from such PV recycling process gets eventually

contaminated with iron (Fe)—due to the involved shredding process—and therefore cannot be considered as a low-Fe (i.e. high value) glass product. Veolia aims to build more similar installations, as PV waste ramps up in the coming years.<sup>19</sup>

SolarWorld is another pioneer and key actor in PV recycling that has a well-established c-Si recycling programme and process, based on a thermal processing method, with which EVA is eliminated through burning, followed by manual separation of metals, silicon and glass. Then, Si cells are re-etched, and at the end of such process clean wafers can be re-used. SolarWorld's recovery ratios typically exceeded 84% of the module weight, namely, 90% of the glass and 95% of the semiconductor materials.<sup>8</sup> Yet it should be clarified that SolarWorld and its recycling subsidiary are no longer in operation. On the other hand, Loser Chemie's recycling process for c-Si PV starts with crushing and mechanical separation.<sup>20</sup> Afterwards, chemical treatment is performed, followed by solid-liquid separation. As a last step of the recycling process, glass is chemically treated, whereas aluminium -based metallization is recovered.

At early R&D/pilot stage, a novel PV recycling process line has been investigated by Sasil, in Italy, in the framework of EU LIFE's project FRELP.<sup>14</sup> Experimental research outcomes,<sup>6</sup> supported by experts' insights, resulted in a recycling process-prototype, where c-Si PV modules are mechanically disassembled, followed by multiple processing steps, i.e. glass separation, cutting, sieving, acid leaching, filtration, electrolysis, neutralization and filter press. After the latter step, any remaining waste is in liquid and sludge form, containing unrecovered metals and residual calcium hydroxide (hazardous). Yet, in 2016, Sasil announced that due to the low amount of PV waste that time and economic limitations, a PV recycling plant based on the aforementioned process will not be built.

In Japan, NPC Group has developed a recycling process for c-Si PV modules which can recover glass without any destructive process.<sup>21</sup> Recycling starts with automatic separation of aluminium frames after processing PV modules by means of a hot-knife/cutter blades. The glass, the solar cells matrix and the EVA sheets can be directed for further recycling. Key (relative) advantages of such process are (i) its fully

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automated features, (ii) the fact that it enables the recovery of intact high-value glass and (iii) the fact that both the recycling/separation equipment and the PV module inspection (quality control) tools are directly supplied by NPC Group.

In China, on the other hand, ordinary (pilot) PV recycling plants are recycling c-Si PV waste employing abrasive machining under cryogenic conditions and electrostatic separation.<sup>22</sup> The frame and junction box of PV modules are separated mechanically; then, the rest of the module is smashed and grated in cryogenic temperatures, and the mixture gets electrostatically separated into EVA particles, a powder mixture of Si, Ag, Al and Tedlar particles. It is however reckoned that, due to its consequent low purity, the Si recovered through such pilot plants and recycling process is not suited for reprocessing new Si wafers.

Details on the actual capacity (rate) and the intrinsic cost of the described PV recycling processes are rather limited. The claimed recycling capacity for Sasil's prototype accounts for 8000 t/a (i.e. tons per year), whereas Veolia and NPC are capable to recycle PV modules at a rate of 4000 t/a and 2400 t/a, respectively.<sup>23</sup> Moreover, NPC's reported cost of PV recycling is determined to be 780 €/t.

Figure 3 provides an overview of the different c-Si PV recycling process flows and steps, for the aforementioned key actors in this segment. On such basis, Table 1 presents a (non-exhaustive) breakdown list of recovered component materials throughout the c-Si PV recycling processes of Sasil and NPC, towards further recycling, re-use, re-manufacturing or disposal, in a circularity context.

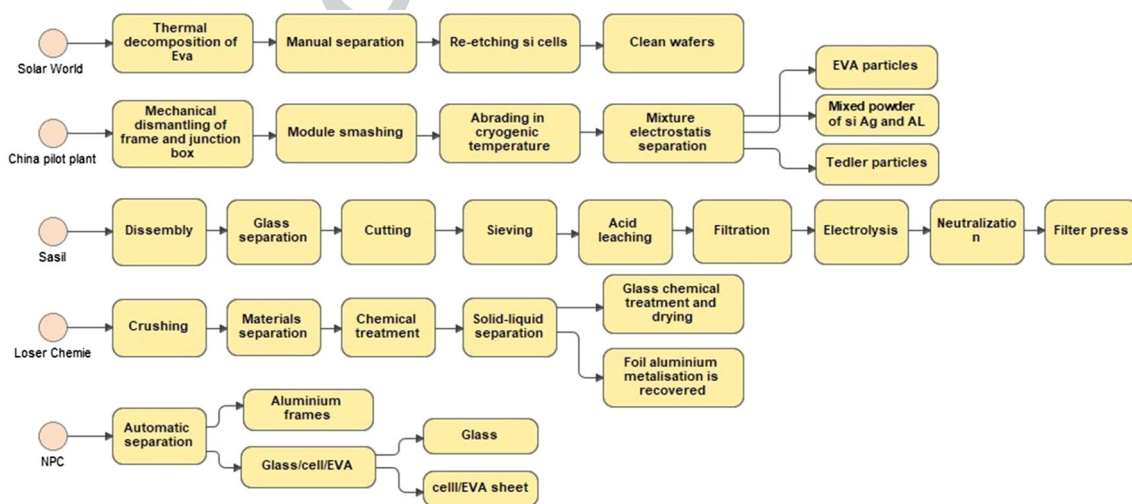
### 3.2 | PV Recycling in the thin films (compound) PV segment

In the thin film PV segment, First Solar is at the recycling technology forefront, running today a downstream scheme of collection, transportation and recycling for its CdTe modules.<sup>24</sup> In overall, First Solar's commercial recycling process recovers 90% of the glass from CdTe modules, for re-use in new glass products, and 95% of the semiconductor

**TABLE 1** Breakdown list of c-Si PV components/materials recovered throughout the recycling schemes of Sasil and NPC, and directed towards second-life, further recycling or disposal streams.

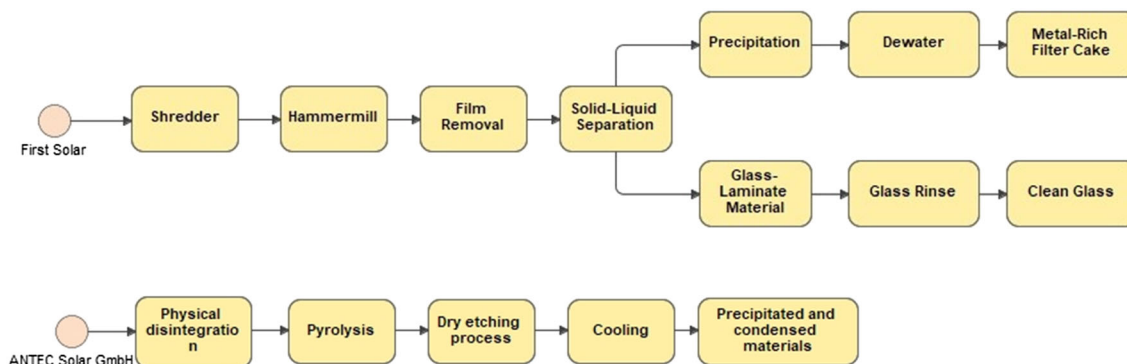
Material	Sasil	NPC
Aluminium	Towards secondary aluminium production	Traded to aluminium recycler
Copper	Traded to copper recycler	Cell sheet is traded to refinery industry
Glass	Glass culets can be used as a substitute or raw material for packaging	Traded to glass recycler for glass wool
Semiconductor (Silicon)	Used as metallurgical-grade silicon, metal subsidy	Cell sheet is traded to refinery industry
Silver	Towards secondary silver production	Cell sheet is traded to refinery industry where silver is extracted
Cables	Traded to copper recycler	Traded to copper recycler
EVA	Incinerated	Cell sheet is traded to refinery industry
Contaminated glass	Disposal in landfill	No contaminated glass during NPC process
Fly ash (hazardous waste)	Disposal in special landfill	Traded to refinery industry that takes care of hazardous waste
Liquid waste	Contains metallic residue; disposal in special landfill	No liquid waste during NPC process
Sludge (hazardous waste)	Contains metallic residue; disposal in special landfill	No sludge during NPC process

materials (i.e. Te and Cd, after the metal composites being processed and purified by a third party) for use in First Solar's new thin film PV modules.<sup>24</sup> An overview of the thin film PV recycling process steps and workflow, adopted by First Solar, is depicted in Figure 4.



**FIGURE 3** Overview of the different c-Si PV recycling process steps and workflows applied by key actors [Colour figure can be viewed at wileyonlinelibrary.com]

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**FIGURE 4** Overview of the different process steps and workflows applied for thin film PV recycling by First Solar and ANTEC Solar [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

described recycling process is operated by First Solar at industrial scale since 2005, with operations in Germany, the United States, Malaysia and Vietnam resulting to a cumulative 40 000 tons of recycled PV waste. Whereas specific recycling costs for this EoL PV segment are varying and strongly depend on the logistics costs, including collection and shipping, the German national register for waste electronic equipment (Stiftung EAR) has established average treatment costs of 230€/t as a basis for calculating the producer guarantees, which could be used as a fair proxy. Moreover, laminate- and glass-based materials recovered through such process are typically re-used towards industries of rubber and glass products respectively.

Recently, Loser Chemie GmbH has also developed a collection-and-recycling scheme—similar to the one of First Solar—for several types of thin film PV modules, i.e. CdTe, CIGS and GaAs, employing a patented process based on proprietary technology.<sup>20</sup>

At research/pilot stage, a project funded by the Japanese Government, via the New Energy and Industrial Technology Development Organization (NEDO), focuses on improving PV recycling processes for both c-Si and thin film (CIS) modules, deploying furnace-base pyrolysis of polymer sheets.<sup>8,25</sup> In addition, similarly to First Solar's recycling technology, ANTEC Solar designed a pilot plant for recycling of CdTe/CdS thin film PV modules.<sup>5,26</sup> As shown in Figure 4, Antec Solar's recycling process starts with the physical disintegration of the module into fragments, which are then are processed through oxygen-containing atmosphere, at a temperature of at least 300°C, resulting in pyrolysis of EVA. In the dry etching process step that follows, the fragments are exposed to a chlorine-containing gas atmosphere, at a temperature of more than 400°C. During this process, CdCl<sub>2</sub> and TeCl<sub>4</sub> are generated which are then condensed and precipitated during cooling.

#### 4 | PV REPAIR/REFURBISHMENT AND RE-CERTIFICATION: CURRENT STATUS AND CHALLENGES

In the course of PV modules' operational lifetime, it is not uncommon that physical degradation, defects or failures occur in only a single PV component (e.g. cell cracks or bypass diode failures); whereas the rest

of the module structure itself might still remain intact. Different reliability issues on PV module level can be classified into infant mortalities (< 4 years of field exposure), mid-life failures (beyond 4 years and less 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).<sup>27</sup> 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.<sup>27</sup> Although targeted on/off-site repairs on individual PV components are technically and practically feasible or, at least, can be explored, these PV modules (or even worse, a whole PV string, in some cases) are still decommissioned and directed towards disposal or recycling, at best case.

From a circular PV business perspective, next to PV recycling, on- or off- site repair of failed PV module components by specific service providers (and the need for their re-certification), gain increasing interest and can enable the operation of entire second-life PV systems. Repair/refurbishment of PV modules may be applied to any of the following cases: (i) defective frames and mounting clamps; (ii) faulty bypass diodes and defective wire connectors in junction boxes; (iii) certain PV backsheet defects; and (iv) potential-induced degradation (PID).

Apart from individual cases of failed modules, repair/refurbishment can also be performed to entire strings of a defective installation. Specialized 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 labor 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.

Before any repair, each PV module is cleaned and undergoes electrical (I-V) characterization at standard test conditions (STC) by means of a solar simulator, and any kind of defect or failure is thoroughly documented through additional thermal/optical characterization 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 characterization at STC 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. Finally, upon its qualification, each refurbished module is commissioned and being accordingly packaged for shipment.

Recently, Glatthaar et al.<sup>28</sup> 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<sup>29</sup> and I-V characterization, 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 module's operational status.

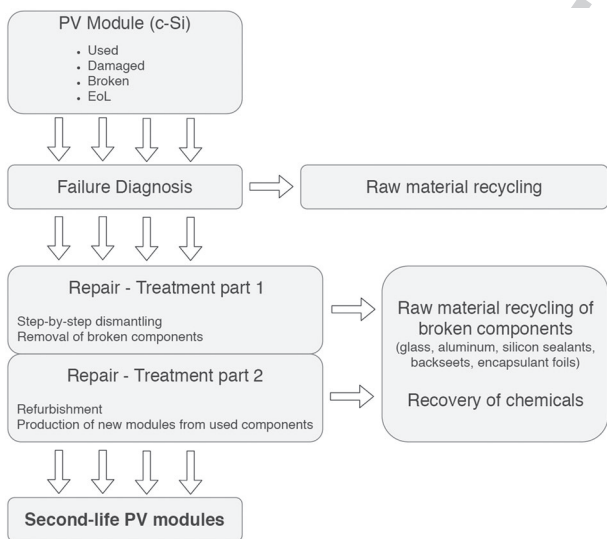
Eventually, some cases of PV module failures, such as damaged (fractured) glass, cracked cells and snail trails, turn out to be beyond refurbishment. Whether refurbishing a PV module is worth it or not, often depends on the kind of failure and the layout of the PV system where the module was installed and operated during its first-life. For instance, roof-integrated PV systems need to be completely dismantled, even if only one or two modules are

under-performing, because such installations are only waterproof in their entirety.<sup>30</sup>

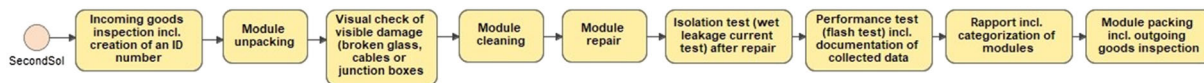
More recently, upon maturation of the PV industry over the last five years, several companies and platforms emerged and are offering refurbished second-life PV modules. Notably pvXchange, SecondSol and Solar-Pur GmbH offer mostly for business-to-business (B2B) and exchange platforms, trading in decommissioned and refurbished PV modules and components.<sup>31-33</sup> Such platforms may also provide 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.<sup>30</sup> 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.<sup>33,34</sup> Figure 6 presents an overview of SecondSol's procedure for repair/refurbishment of decommissioned PV modules, towards re-use/trading of second-life PV modules. Indicative repair/refurbishment costs for PV modules range from approximately 20€ 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 characterization/testing, prior to and after repair.<sup>33</sup> In terms of reparability, Rinovasol Group specifically 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 IECCEB Scheme certification.<sup>34</sup>

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 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, i.e. under controlled laboratory conditions, as per International Electro-technical Commission (IEC) standards. Such quality testing procedures only determine the basic reliability of PV modules and enable the comparison of different PV module types, on the basis of quality or test certificates. Hence, in fact, the existing framework of PV qualification testing provides neither actual lifetime expectancy of a PV module nor any correlation to certain repairable failure modes for in-depth assessment and re-certification of second-life PV modules.

In this context, details regarding 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



**FIGURE 5** Overview of the "PV-Rec" refurbishment/recycling concept proposed by J. Glatthaar et al.<sup>28</sup>; figure adapted from the original version in<sup>28</sup>



**FIGURE 6** Overview of repair/refurbishment process flow adopted by SecondSol for decommissioned PV modules [Colour figure can be viewed at wileyonlinelibrary.com]

Colour online. B&W in print



or misinterpreted. Most importantly, re-certification and quality standardization for such modules practically neither exist nor are under any development, as TÜV Rheinland and IEC experts reckon.<sup>35,36</sup> This, in turn, highlights the importance, ambition and novelty of the relevant research activity planned in the framework of CIRCUSOL Project, on setting up the technical groundwork for the development of (optimal) reliability testing and “re-certification” protocols, for second-life PV modules traders and/or refurbishment service-providers.

## 5 | FURTHER DISCUSSION—OUTLOOK

### 5.1 | Technical innovation and opportunities in PV recycling

For 2016, the Urban Mine Platform—developed in the context of ProSUM project—reported a PV waste release of 2.5 ktons Si solar cells in the EU.<sup>37</sup> This number is much lower than the projection for the global cumulative PV waste for 2016 (43.5 ktons), which eventually highlights the economical obstacles for the development and optimization of PV recycling or refurbishment processes; which are also reflected, i.e. in the implementation difficulties faced by the FRELP project. In addition, with a closer look at the technical/business landscape of PV recycling today, we identify a clear lack of innovation and implemented schemes for high-value PV recycling.

However, with a significantly higher number of PV installations and modules expected to reach end-of-life, further R&D challenges will emerge towards the need for

- even higher recovery/recycling ratios;
- cost-efficient and environmentally friendly processes; and
- recovery of higher grade, quality/value materials and/or materials for PV re-manufacturing or re-use (second-life PV).

Exemplary innovations and material/design-for-recyclability practices that (potentially) enable addressing the above challenges are found on both material/component and module/device level. Apollon Solar is developing the New Industrial Cell Encapsulation (NICE) technology, which can render PV modules encapsulant-free, by replacing the encapsulant layers with neutral gas filling. As such, apart from material costs-saving, the NICE module technology simplifies the fabrication process (no soldering, no lamination needed) while yielding more environmentally friendly and simple recycling process for such modules, enabling 100% recyclability as per Apollon Solar's claim.<sup>23,38,39</sup>

Technical innovations on the solar cells' electrical circuit level, such as the introduction of glued ribbons or the application of electrically conductive adhesives, eliminate the need for lead-based ribbons, thus allowing recycling/recovery processes free of hazardous lead waste residues. Further, glued ribbons require lower

process temperature, at cell/module fabrication stage, which particularly suits the fabrication of PV modules based on high-efficiency cell technologies. Yet, the relatively higher cost of such solutions, i.e. due to the use of silver in glued ribbons compounds, still comprises a significant constraint.<sup>40–42</sup> On the other hand, at encapsulation level, the incorporation of silicone sheets can be considered as an interesting alternative to polymer-based encapsulations, such as EVA or POE, which generally bring considerable technical complications in PV recycling.<sup>43</sup>

From a more procedural and workflow perspective, the integration of radio-frequency identification (RFID) technology in PV modules can streamline collection-transportation-processing schemes for EoL PV, by tracking and identifying waste, on the basis of reverse logistics.<sup>44</sup> In turn, the latter comprises an excellent facilitating tool towards PSS-based circular business models for the PV industry. RFID-based information on raw PV materials and components allow service-providers in the whole value chain—from manufacturers to recyclers—to monitor and access information relevant for them. As such, RFID-integrated PV modules can reduce warehouse costs for PV manufacturers while allowing them to monitor the manufacturing process. Additional information on certain PV modules, i.e. on possible component changes, repairs or inspection outcomes, can be updated through the RFID, by repair/refurbishment and O&M service providers; whereas, RFID can assist PV recyclers to identify details on the exact PV materials composition, properties and value, in view of their recovery/re-use.

Finally, from a business/market point of view, challenges (thus, opportunities) on PV recycling are mostly associated with:

- upscaling of PV recycling operations and their optimization (i.e. mass-treatment, on-site processing);
- streamlining collection-transportation networks and global-scale reverse logistics;
- ensuring operational viability (need for sufficient PV waste, i.e. bankability); and
- implementation of sustainable and circular business models, namely towards re-use or second-life PV.

### 5.2 | R&D gaps towards second-life PV business

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, compared with PV recycling service providers. Based on our review analysis, there are two main “pillars” of R&D gaps and market factors-constraints that need to be timely addressed, to enable the bankability and success of second-life PV business:

- *Addressable volume towards market profitability.* As it was discussed earlier, the reparability 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

- The target volume, i.e. the failed PV modules the repair of which is technically feasible, and the occurrence of repairable failures.
- 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 year 3 and year 4 of operation, during which they may consist 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.
- 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 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, systemizing appropriate labelling as well as time- and cost- efficient characterization 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, because PV modules in failed state degrade much faster,<sup>45</sup> 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 standardized reliability testing, as it has been also discussed in Section 4. 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 re-gain the trust of the end-user.

## 6 | CONCLUSION—SUMMARY

In this review study, we presented a status snapshot on PV recycling, refurbishment and recertification as key aspects and second-life paths throughout a PSS-based circular economy model for PV. Publicly available literature, best practices, commercialized solutions and R&D gaps or emerging challenges, associated to each of these topics, were examined from both a circular economy and technology point of view.

It is well understood that the growing PV waste represents a new environmental challenge, which, however, also comes with new opportunities to create new services and pursue new economic avenues. As we presented in Section 3, although the clear lack of high-value PV recycling, there is substantial technological and operational know-how in bulk PV recycling, in mature PV markets, in several countries. This can guide the development of effective PV EoL and waste management, as well as PV design-for-recyclability and/or PV design-for-circularity solutions, as well as streamlined PSS-based circular economy business models. On the other hand, as it has been discussed in Section 4, technology and research in repair/refurbishment of failed, decommissioned PV modules remains very limited. Besides, best practices and commercialized services especially for reliability testing/recertification and trading of second-life PV modules are far from being standardized and optimal.

Through this review, we also identified and listed, in Section 5, certain knowledge gaps, potential innovations and opportunities in both PV recycling and second-life PV business sectors, focusing on a circular business model perspective. On the basis of this groundwork, CIRCUSOL aims to formalize the recycling and repair/re-use segments in the PV value chain, through the following main R&D pathways:

- assessment and validation of PV design-for-recyclability and design-for-reliability concepts;
- development of tailored, cost-efficient reliability testing and characterization protocols for both failed/repared and “healthy”/decommissioned, second-life PV modules; and
- cost-profit and life cycle analysis for the PV re-use (i.e. second-life) business case.

Ultimate goal of PV partners in CIRCUSOL is to develop and validate market mechanisms, such as service-based business models, to enhance circularity in the solar PV power sector.

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## ORCID

J.A. Tsanakas  <https://orcid.org/0000-0002-8230-4635>

T. Radavičius  <https://orcid.org/0000-0002-5222-7499>

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