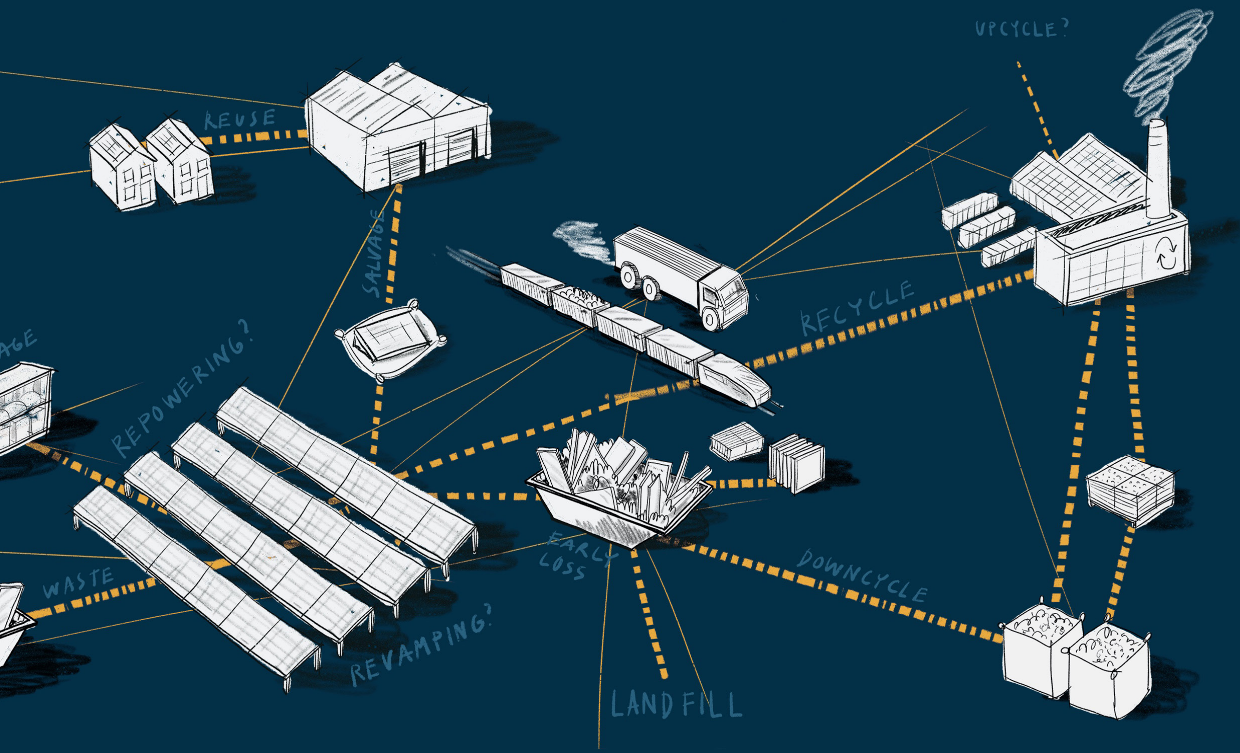
# For a Brighter and Sustainable Photovoltaic Industry

## Recommendations to help tackle end-of-life challenges

*Rabia Charef, Bethan Jones and Ana Rute Costa*




bluefield Solar Income Fund
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*Solar panels don't just deliver clean energy; they also have the potential to contribute to a more sustainable and circular use of materials. Striking the right balance between producing renewable electricity and managing resources wisely is one of the key challenges the sector must now tackle collectively to strive towards an all-encompassing vision of sustainability.*

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# Preface



The End of Renewable Asset Life Decisions (ERALD) research project was funded by EPSRC IAA at Lancaster University and Bluefield Solar Income Fund (BSIF), the first solar-focused investment company to be listed on the London Stock Exchange and a current member of the FTSE 250. This collaborative research partnership was formed in response to a growing need to identify responsible end-of-life solutions for renewable energy assets, with a primary focus on solar photovoltaic (PV) technologies.

Initially focusing on the latter stages of the asset lifecycle, our findings revealed that the levers for transformative change span the entire supply chain; no single stakeholder can achieve this shift alone. This underscores the necessity for a holistic research approach that fosters collaboration among industry, academia and policymakers. Consequently, the research underpinning this white paper pivots from an 'end-of-life' perspective to a comprehensive focus on circularity. Our aim is to map current practices, identify systemic barriers, drive efficiencies, create value and uncover synergies with other environmental and social agendas. We propose a strategic roadmap for future research, innovation and policy engagement, to accelerate the shift towards a more circular solar industry.

This white paper presents the outcomes of a literature review and industry consultation on current practices and challenges across the PV industry, highlighting potential solutions and providing recommendations for industry and policy makers. We delivered three focus group discussions and twelve semi-structured interviews, consulting a total of 33 UK stakeholders with wide-ranging expertise across the PV industry. We would like to thank all the stakeholders that anonymously contributed to this research and made this work timely, and essential to help move towards a more circular solar PV industry. **Our primary focus is on Crystalline Silicon (c-Si) PV Panels**, as they currently represent 95% of the PV market (Majewski and Dias, 2023). We will also present the opportunities for the transition towards a more circular PV industry and explain the lifecycle of solar PV panels from their production to reuse options before end-of-life. Indeed, c-Si PV panels dominate the market and have been associated with technical challenges with regards to recycling and other environmental impacts (Preet and Smith, 2024). These technologies can be complex and require effective recycling methods to recover valuable materials from them (Sulkan et al. 2025), which are currently under continuous research and development.

Due to rapid technology development and market growth, this work focuses on c-Si PV panels as a key waste of solar assets. The remaining infrastructure and equipment are considered to be reused and recycled; however, future research and guidance should provide a more holistic approach and consider all the materials present in a solar asset.

# Executive Summary



### *UK Policy Context*

The end-of-life of PV panels in the UK is currently regulated under the Waste Electrical and Electronic Equipment (WEEE) Regulations 2013, the UK's implementation of the EU WEEE Directive (2012/19/EU), which was designed to reduce the amount of electronic and electrical waste going to landfill and to promote reuse, recycling and recovery. These regulations place the responsibility for recycling PV panels on producers, meaning manufacturers and importers. They are required to be part of a Producer Compliance Scheme (PCS), which ensures proper collection and recycling of panels.

The UK is currently working to ensure that the increased volume of end-of-life solar panels is managed sustainably and doesn't become a significant waste problem. Aligned with the work developed by Department for Energy Security and Net Zero - DESNZ (Solar roadmap: United Kingdom powered by solar), the recommendations presented in this paper are intended to inform the government's policy ambition and help industry and researchers to define their priorities to tackle the challenges that affect the end-of-life of PV panels.

## *Recommendation 1 | Follow circular economy principles*

**Promote industry accountability and circular practices**: **(1)** Introduce clear regulations and targeted grants to mandate end-of-life planning and support circular practices across the PV sector, **(2)** Follow a revised waste hierarchy, adapted for PV panels, prioritising reuse, remanufacturing and refurbishment followed by recycling and energy recovery, **(3)** Consider decommissioning plans and circular strategies from the early stages of solar farm development, **(4)** Encourage multistakeholder participation in policy development, **(5)** Integrate the consideration of Environmental, Social and Governance (ESG) outcomes within end-of-life solutions, **(6)** Collaborate across the supply chain to drive efficiencies and enhanced transparency, accountability and value retention.

## *Recommendation 2 | Digitalise the Solar PV Industry and adopt materials passports to improve data standardisation and traceability*

The PV industry and governments should create and implement a digital PV Materials Passport (MP) to enable **data standardisation, transparency**, custody of materials and Lifecycle Assessment (LCA) accountability without compromising technical innovation.

## *Recommendation 3 | Prioritise design for disassembly, reuse, durability and recyclability*

The PV industry **should invest in design innovation, considering the Life Cycle Assessment (LCA) of a PV Panel,** and **(1)** Develop holistic technical solutions that consider end-of-life management and support material value retention (enabling reuse, reparability, durability and recyclability through design), **(2)** Adopt **eco-design principles and techniques** (e.g. avoid the use of materials that are difficult to recycle and rely on the use of fossil fuels to produce - such as EVA and POE, delamination solutions).

## *Recommendation 4 | Mitigate early loss scenarios and extend the lifecycle of materials*

Manufacturers and recyclers, supported by governments and research partnerships, should **(1) Explore synergies and opportunities for collaboration**, e.g. establish feedback loops between different members of the supply chain to facilitate the identification of challenges and the development of potential solutions, **(2)** Establishing shared recycling facilities, **(3) Develop technologies to support reuse and recycling, (4)** Suggest policy support for warranty tracking and predictive maintenance.

## *Recommendation 5 | Explore partial repowering and cannibalisation strategies*

Manufacturers and recyclers should create research partnerships and business models to **enhance material recovery rates and reduce waste**. Supported by materials passports, the PV Industry should **create a centralised digital spare part hub** to facilitate the exchange of second-hand PV panels and extend the life of solar farms.

## *Recommendation 6 | Explore reuse potential and second-hand market opportunities*

The PV Industry and governments should collaborate to facilitate **second-hand market opportunities**, **(1)** Develop **reuse and repair infrastructure**, **(2)** Expand upon reuse within the WEEE Regulations and create a **specific standard** for second-life PV panels, e.g. domestic use, **(3)** Create **third-party certifications** that can promote market transparency by confirming product quality, **(4)** Create financial incentives to stimulate the reuse market.



## *Recommendation 7 | Develop partnerships and second-hand market support*

Strengthen early, cross-sector collaboration and partnerships across the PV value chain, particularly between manufacturers, recyclers, policymakers and academics to: **(1)** Scale up reuse and repair infrastructure.

## *Recommendation 8 | Improve recycling processes and technologies*

Invest in the current PV recycling processes and technologies to: **(1) Minimise environmental impact and maximise material recovery** rates, **(2)** Inform disassembly, reuse and recyclability, **(3)** Inform and support Extended Producer Responsibility **(EPR) schemes.**

## *Recommendation 9 | Create specific regulations for PV panels*

**Enhance the specificity of the WEEE Directive with PV-panel specific regulations**: Policy makers should update/revise the WEEE Directive to make it more specific to PV panels and related regulations to: **(1)** Reclassify panels as business-to-business waste, **(2)** Require early end-of-life planning and support high-quality material recovery, **(3)** Enforce Extended Producer Responsibility (EPR), **(4)** Define **standards for reuse versus recycling**, **(5)** Create a **regulatory and financial** environment that encourages innovation in recycling and the growth of the second-hand market, without burdening compliance.

## *Recommendation 10 | Investment in research and knowledge exchange opportunities to tackle end-of-life of PV panels*

The **UK government** should provide targeted grant funding open to both academia and industry to research under three main categories:

### 1 - Materials

**(1a)** The LCA of PV panels from extraction to disposal to enable the most sustainable solution to be identified: environmentally friendly, financially viable, socially equitable,



**(1b) Further advance recycling technologies** to facilitate a circular economy and recover valuable materials;

### 2 - Systems and digitalisation

**(2a) Digitalisation of the PV sector** by implementing material passports, developing systems using AI and digital trackers,

**(2b)** Improved transportation, handling and storage of solar PV panels to avoid damage and early failure;

### 3 - Business models and design

**(3a) Alternative business models and markets**,

**(3b)** Alternative design of PV panels, considering **Design for Disassembly**. **The PV industry and governments should provide worldwide standards, regulations, and policies** that enable material custody throughout the supply chain and provide dedicated guidance for end-of-life solar assets.

# *Introduction*



Solar PV energy plays a vital role in the **global transition towards low-carbon energy production**, shifting away from fossil fuel intensive industries amidst climate change. The rapid growth of solar PV installations supports **enhanced national energy security, lower electricity costs** and contributes to the **reduction of greenhouse gas emissions**: an essential step towards achieving net zero energy goals (Lin et al., 2022). According to the International Renewable Energy Agency (IRENA), **the capacity of globally installed solar PV panels could reach more than 5,000 GW by 2050**, compared to 942 GW in 2021 (IRENA, 2023). As costs continue to fall and efficiencies improve, **PV technology is becoming an increasingly important contributor to a more sustainable energy landscape** (Markert et al., 2020).

**However, this rapid growth presents a crucial challenge: What happens to PV panels at the end of their life?**

Solar panels are typically designed to have a life span extending between 25 and 30 years. However, a growing trend in repowering and revamping to preserve asset value and utilise new technologies to generate more electricity per square metre, means panels may be removed before expected end-of-life and replaced with more efficient alternatives. Consequently, up to **78 million tonnes of PV waste could be produced by 2050, worldwide** (IRENA, 2016; Bošnjaković et al., 2023). Globally, there are significant concerns about the increasing number of end-of-life PV panels, an issue that needs to be addressed through the identification of responsible disposal solutions. Despite decommissioned panels containing valuable materials like silicon, silver and rare metals, the majority are recycled, sent to landfill or stored until advancements in recycling technologies are made (Suyanto et al., 2023; Yu et al., 2025). Rising supply chain pressures highlight the need to recover critical materials to mitigate future resource constraints (Deetman et al., 2021).

Research highlights that recycling can minimise environmental impacts, including CO2 emissions and the release of hazardous substances. Recovering valuable metals such as silver from the panels can also be financially beneficial. Sulkan et al., (2025) reported that the **growth of solar**

**energy** is expected to lead to significant **economic opportunities**, potentially generating **£11 billion** in economic value through recycling by 2050 ($15 billion) (Sulkan et al., 2025). Conjunctively, if we are to achieve net zero energy goals through increased PV deployment, we need to embed circular economy principles within the industry. Key materials used to produce solar PV panels are approaching critical scarcity levels and may be subject to commodity price fluctuations in the future (Bobba et al., 2020), creating an opportunity to salvage materials from old panels through recycling to recirculate in the manufacturing of new panels.

However, there are still **important challenges** within the recycling of solar PV panels that need to be addressed. The process can be costly and **energy-demanding**, largely due to the current design of panels that are not intended for easy disassembly. PV panel components are often **tightly bonded, making it difficult to separate and recover valuable materials efficiently**. By **advancing recycling strategies** and integrating **design-for-recyclability principles**, the solar industry can enhance material recovery, reduce resource depletion, and mitigate environmental risks, reinforcing its role as a long-term sustainable energy solution (Badran and Lazarov, 2025).

> *There is an urgent need to reevaluate the design of solar panels making them easier to disassemble to support better recycling and reuse. (Lunardi et al., 2018)*

By emphasising recyclability, promoting second-life use, and enhancing material recovery, the industry has the opportunity to reduce its **reliance on raw materials and its overall environmental impact.** Experts emphasise that efficient recycling solutions could reduce future raw material strain and improve the use of currently available resources (Badran and Lazarov,2025; Herceg et al., 2022). However, it is important that a holistic approach to this evaluation is adopted, with due consideration given to achieving a balance between asset performance, durability and other environmental and social factors.

Solar PV panels are one of the cleanest sources of electricity, presenting as a key step in the global energy transition towards achieving net zero energy goals. However, to strengthen the sectors' sustainability, it needs to transition from a linear to circular economy (Chowdhury et al., 2020).
The UK is in a strong position to lead the industry towards a circular economy. As of February 2024, there were **1,468,652 solar panel installations** across

**Table 1** | Challenges that affect end-of-life of PV panels and recommendations to address them (table on page 11) (Source: Drawn by Costa, 2025)

| Stage of the lifecycle of PV panels | | | R1 | R2 | R3 | R4 | R5 | R6 | R7 | R8 | R9 | R10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Transversal (T) | **T1** | Waste generated throughout the PV panels' lifecycle and end-of-life. | | | | | | | | | | |
| | **T2** | The PV panels with low quality have higher degradation rates. | | | | | | | | | | |
| | **T3** | There is a lack visibility/traceability across the PV supply chain: where/how materials are source and processed. | | | | | | | | | | |
| | **T4** | Lack of standardised Environmental Product Declarations. | | | | | | | | | | |
| | **T5** | The Solar Stewardship Initiative has still low adoption. | | | | | | | | | | |
| Raw materials (RM) | **RM1** | High social risks in material sourcing, e.g. Modern Slavery. | | | | | | | | | | |
| | **RM2** | The PV Industry is dependent on critical raw materials, e.g. silicon, silver, copper, aluminium. | | | | | | | | | | |
| Manufacturing (M) | **M1** | Use of EVA and POE to seal and protect the solar cells: panel materials are blended together = make disassembly and material separation difficult. | | | | | | | | | | |
| | **M2** | Polymer backsheets contribute to early failure. | | | | | | | | | | |
| | **M3** | Technology discontinuity: replacement not possible if the panels are not available anymore. | | | | | | | | | | |
| Distribution (Di) | **Di 1** | If PV panels are damaged during transportation, are malfunctioning/defective, they are replaced and don't go back to manufacturing. | | | | | | | | | | |
| Construction (C) | **C1** | Transport and installation damages: poor packing/stacking/forklift. | | | | | | | | | | |
| Use and maintenance (UM) | **UM1** | Absence of centralised spare parts hub. | | | | | | | | | | |
| | **UM2** | Early retirement of functional PV panels. | | | | | | | | | | |
| | **UM3** | Unbalanced supply/demand for available spare parts = over-replacement. | | | | | | | | | | |
| | **UM4** | Downtime risks due to poor spare parts management. | | | | | | | | | | |
| | **UM5** | Repowering with new, more efficient PV panels. | | | | | | | | | | |
| | **UM6** | Ownership changes hands quickly and is viewed as a future problem. | | | | | | | | | | |
| Decomissioning (D) | **D1** | Lack of proper storage and no information about PV panels content. | | | | | | | | | | |
| | **D2** | Lack of testing and recertification and reconditioning facilities. | | | | | | | | | | |
| | **D3** | Lack of spare parts due to rapid technology evolution. | | | | | | | | | | |
| | **D4** | High-cost reuse and recertification processes. | | | | | | | | | | |
| | **D5** | Lack of regulations and policies to support the development of second-hand market opportunities, e.g. reuse, recertification. | | | | | | | | | | |
| | **D6** | Stigma around second-hand PV panels: reuse avoided due to lack of guarantees and seen as lower quality. | | | | | | | | | | |
| | **D7** | WEEE directive is not specific to the PV industry and does not consider second-hand solutions. | | | | | | | | | | |
| | **D8** | Export risks: old PV panels becoming unmanaged waste. | | | | | | | | | | |
| Recycling (R) | **R1** | Recycling costs higher compared to landfill. | | | | | | | | | | |
| | **R2** | Lack of research into sustainable water treatment methods. | | | | | | | | | | |
| | **R3** | Use of chemicals during the recycling process: chemical methods are slow and costly. | | | | | | | | | | |
| | **R4** | Lack of more sustainable alternative substances to replace the use of chemicals during the recycling process. | | | | | | | | | | |
| | **R5** | Lower Global Warming Potential (GWP) for recycling compared to incineration and landfill. | | | | | | | | | | |
| | **R6** | Disparity between quantity of material, material recovery and material revenue: loss of material value through downcycling. | | | | | | | | | | |
| | **R7** | EVA is not recovered: the encapsulant layer is difficult to remove or use high temperature. | | | | | | | | | | |
| | **R8** | Thermal decomposition generates toxic gases. | | | | | | | | | | |
| | **R9** | Recycling facilities: the minimum annual waste volume required to be profitable: 20kt (Choi & Fthenakis, 2014). | | | | | | | | | | |
| | **R10** | PV panels are complex by design and difficult to disassemble. | | | | | | | | | | |
| | **R11** | Low purity of recovered materials. | | | | | | | | | | |
| | **R12** | Success measured by weight is misleading for solar PV panels: by focusing only on the weight parameter, we risk ignoring critical and valuable materials that exist in small proportions. | | | | | | | | | | |
| | **R13** | Around 90% of a panel's weight comes from glass, aluminium, and plastic, which are easy to recycle but not the most valuable. | | | | | | | | | | |
| | **R14** | Small amount (less than 5%) of materials like silicon, silver, and copper that make up over 50% of the panel's economic value. | | | | | | | | | | |

the UK (Milroy, 2025). With **strong government targets for net zero**, growing collaboration between research institutions and industry, and a policy focus on circular economy models, the UK can help drive innovation in sustainable PV panel design, reuse, and recycling.

This white paper is the outcome of a **collaborative project between academia and industry**. It aims to explore the challenges faced by the solar PV sector and propose practical strategies for creating a more sustainable and circular PV industry.



The background section of the white paper reviews the composition and production process of crystalline silicon (c-Si) panels, which continue to account for most PV installations worldwide. This provides the technical foundation for understanding the environmental impacts and opportunities for circularity. Next, we identified the main challenges that the PV industry face and provide 10 recommendations for government, industry and academia.

In **Table 1**, we present the identified challenges in relation to end-of-life of PV panels. In blue we map the challenges being presented and discussed to inform the recommendations. In yellow, we map the challenges that can be addressed by the recommendations made throughout the paper. However, some of these challenges are highly connected and intertwined. This mapping exercise was created to help us understand how to address the current challenges and identify the priorities to tackle end-of-life of PV panels.

# Background

## The composition of crystalline Silicon (c-Si) PV panels



### *The composition of the solar PV module*

Silicon PV panels represent approximately 95% of the global PV market (Majewski and Dias, 2023), and the first generation of PV technology. As illustrated in **Figure 1**, they are typically made of seven layers. The glass, aluminium frame and encapsulant typically represent 90% of the material weight of the panel (**Table 2**). A recent study shows that in Europe, the dynamic material composition of PV panels has changed over time. For instance, the use of bifacial panels has led to an increase in glass content. In parallel, the silver, silicon, aluminium and encapsulant contents have tended to decrease (**Figure 1**)(Kastanaki, 2025).

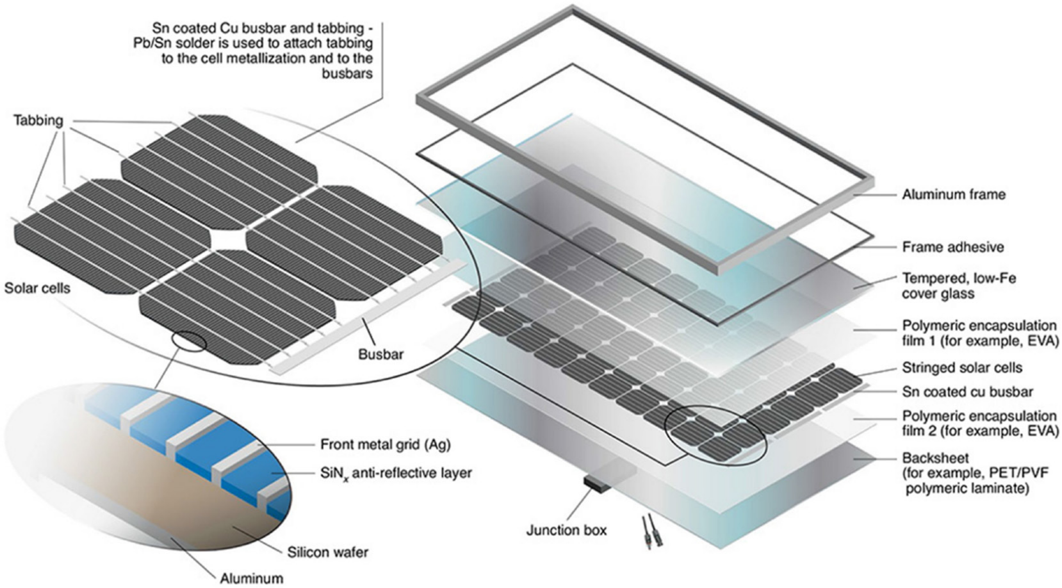



**Figure 1** | The conventional crystalline-silicon PV module design (Source: Heath et al., 2020)

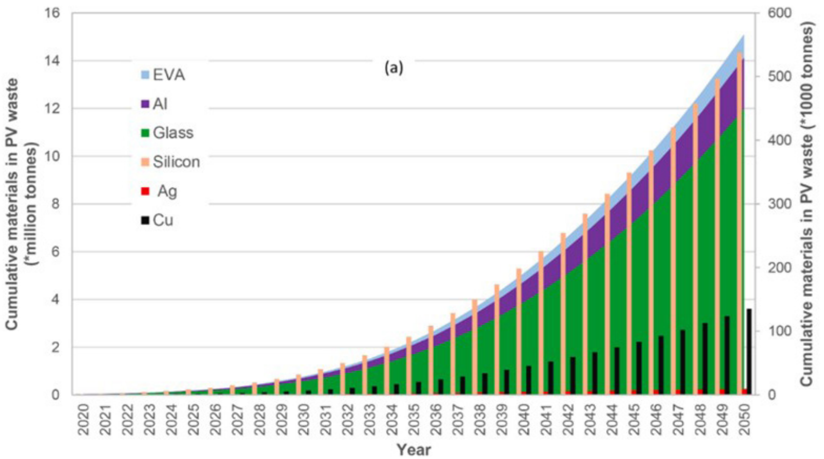



**Figure 2** | Accumulated amounts of silver, silicon, encapsulant, aluminium, glass (evolving material content) and Cu (fixed content) of c-Si PV panel waste under the Regular Loss scenario (Source: Kastanaki, 2025)

| Component | Material | Weight % |
|---|---|---|
| Solar cell (mono) | Si | 3 |
| Encapsulant | EVA | 10 |
| Ribbon | Copper | 1 |
| Backsheet | Tedlar | 4 |
| Aluminum frame | Al | 10 |
| Coated semi-tempered Glass | Glass | 70 |
| PV component connection & j-box | Cu & Ag | 2 |

**Table 2** | Weight distribution of materials of a silicon solar panel according to Majewski and Dias (2023)

## The solar PV panel lifecycle

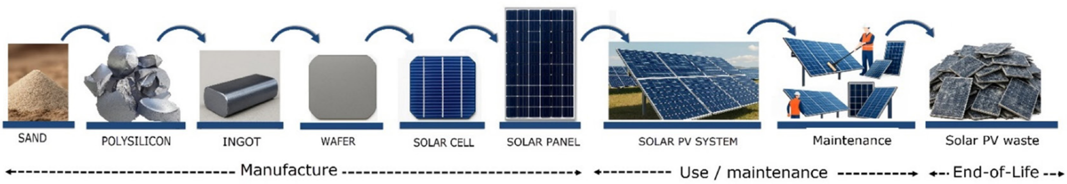



**Figure 3** | The solar PV panels lifecycle (Source: Drawn by Charef, 2025)

The process illustrated in **Figure 3** is the solar PV lifecycle, from raw material extraction to end-of-life. The production of c-Si solar PV panels is often characterised as energy-intensive, particularly during the **fabrication of silicon wafers,** which requires substantial energy input (Saad, 2024). The production of **polysilicon** itself can also be extremely energy intensive, leading to a high carbon footprint (Huang et al. 2017). Throughout the slicing stage of ingots to produce wafers, there is often a loss of valuable material, with energy and resources expended in its production (Madrigal et al. 2023).

# *Challenges and recommendations to help tackle end-of-life of PV panels*

# R1 | *Follow the circular economy principles*



***Challenges***

| | |
|---|---|
| **R1** | Recycling costs higher compared to landfill. |
| **R2** | Lack of research into sustainable water treatment methods. |
| **R3** | Use of chemicals during the recycling process: chemical methods are slow and costly. |
| **R4** | Lack of more sustainable alternative substances to replace the use of chemicals during the recycling process. |
| **R5** | Lower Global Warming Potential (GWP) for recycling compared to incineration and landfill. |
| **R6** | Disparity between quantity of material, material recovery and material revenue: loss of material value through downcycling. |

*"A balance between materials purity, process complexity, and throughput" (SSI_02)*[1]

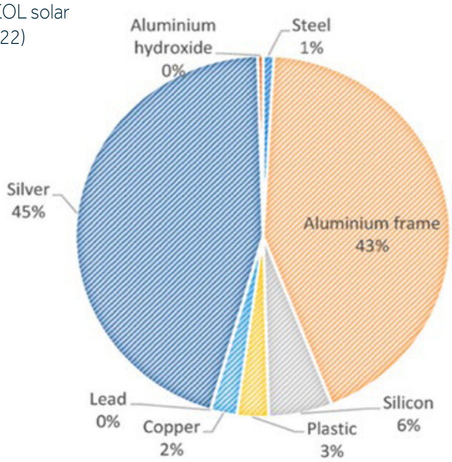
The recycling of solar PV panels has a lower **Global Warming Potential (GWP) of 48%** compared to landfilling and 49% compared to incineration and the Human Toxicity Potential (HTP) is reduced by 85% (Khankhoje et al. 2025). According to Lim et al. (2022), the recycling process of solar PV panels has a **lower GWP value at 25 kg CO2-eq** compared to that of landfilling at 121 kg CO2-eq. Due to wastewater generation and the use of certain chemicals, processes involving chemical recycling techniques (particularly acid etching and the subsequent recovery of metal) may have a higher HTP and freshwater ecotoxicity potential compared to landfilling (Lim et al., 2022).Moreover, the non-chemical recycling techniques, such as mechanical and thermal techniques have also some limitations. Indeed, the thermal treatment method shows lower impacts on climate change, fossil fuel potential, water consumption, ecotoxicity, human toxicity, and particulate matter production, but it has more pronounced effects on ozone depletion and land use (Sulkan et al., 2025).

Adopting more sustainable approaches for the management of end-of-life solar PV panels may be hindered by the recycling costs for some producers, **around £14-£22 ($20-$30) for one panel**, while landfill disposal is only **£0.7 - £1.5 ($1-$2)** (Okon Recycling, 2025). The collection cost of PV panels should also be considered, which may vary depending on the proximity of assets to recycling locations.

1 | SSI refers to Semi Structured Interview, the 02 means that this was second interview taking place during our data collection.

According to Lim et al. 2022, the **recovery of silver accounts** for the **highest proportion of generated revenue**, despite its small amount (**Figure 4**). Following silver, the recovery of aluminium frames generates the second highest revenue. The recovery of **plastic, silicon, and copper generates less than 11% of the revenue**, while the recovery of lead, steel and aluminium hydroxide are less than 1% each (Lim et al., 2022).

**Figure 4** | Breakdown of revenue for the EOL solar PV panel recycling plant (Wei Lim et al. 2022)






## *Recommendation 1 | Follow circular economy principles*

**Promote industry accountability and circular practices**:

**(1)** Introduce clear regulations and targeted grants to mandate end-of-life planning and support circular practices across the PV sector,

**(2)** Follow a revised waste hierarchy, adapted for PV panels, prioritising reuse, remanufacturing and refurbishment followed by recycling and energy recovery,

**(3)** Consider decommissioning plans and circular strategies from the early stages of solar farm development,

**(4)** Encourage multistakeholder participation in policy development,

**(5)** Integrate the consideration of Environmental, Social and Governance (ESG) outcomes within end-of-life solutions,

**(6)** Collaborate across the supply chain to drive efficiencies and enhanced transparency, accountability and value retention.

The treatment of PV panels should follow the circular economy approach and waste reduction principles, focusing on the **top of the "10 Rs waste hierarchy"** developed for the construction sector (Vermeulen et al. 2019). Weckend et al. 2016, recommended to reduce the number of materials in new modules and increase their efficiency. Materials that should be reduced are **silver, silicon, aluminium and encapsulants** (Weckend et al. 2016). In the waste hierarchy in **Figure 5**, reuse of PV panels will save energy, avoid the extraction of natural resources and prolong the useful life of materials contained within them (Pareek, 2021). Reuse is very limited, and its adoption is facing many challenges. To ensure a circular approach Kastanaki and Giannis (2022) suggest **locating the PV manufacturing facilities near recycling facilities** (Kastanaki and Giannis 2022). By ensuring efficient recycling, the elements extracted from old PV panels could provide a significant portion of materials needed in the manufacturing of new panels.



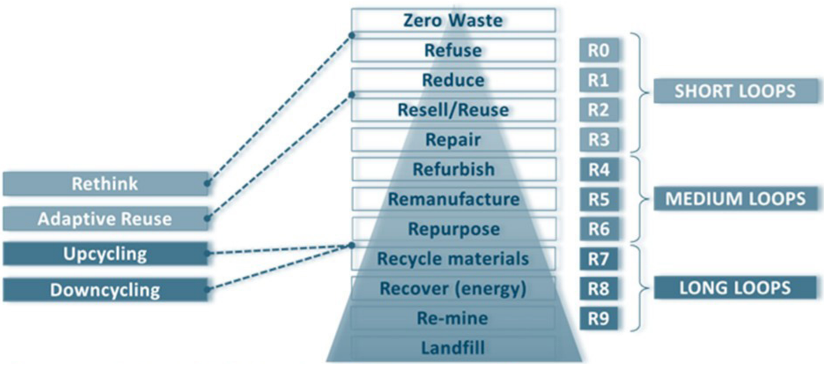



**Figure 5** | The waste hierarchy adapted from the Reike et al.'s model of the 10 Rs (Source: Drawn by Charef, 2025)

To move from a linear to a circular economy, the PV industry needs to follow the 10 Rs hierarchy to guide PV panel lifecycle strategies, in particular:

- Reduce material use in new modules, especially high impact materials (silver, silicon, aluminium, encapsulant);
- Reduce raw material use and keep material in a closed loop: use more recycled materials;
- Promote reuse of PV panels to reduce raw material extraction and prevent waste;
- Co-locate manufacturing and recycling facilities to enable efficient material recovery and reuse in new panels (close the loop);
- Invest in efficient recycling processes to ensure high-quality material recovery;
- Rethink the design of PV panels to make them easier to disassemble.

# R2 | *Adopt digital materials passports to improve data standardisation and traceability*

### *Challenges*

| | |
|---|---|
| **T3** | There is a lack visibility/traceability across the PV supply chain: where/how materials are source and processed. |
| **T4** | Lack of standardised Environmental Product Declarations. |
| **RM1** | High social risks in material sourcing, e.g. Modern Slavery. |
| **RM2** | The PV Industry is dependent on critical raw materials, e.g. silicon, silver, copper, aluminium. |

### *Environmental and social impacts in the PV supply chain*

In solving complex sustainability challenges, it is important to recognise and manage the broader positive and negative environmental and social impacts that may arise across the supply chain.

Increasingly, companies are using sustainability-related data to measure not only their **direct impacts** but also those occurring **within their supply chains** (Alves and Steinberg, 2022). Taking this **holistic perspective** is intended to enable **informed decision-making**, ensuring that positive changes in one area do not **inadvertently cause adverse effects** elsewhere.

For instance, like most mining activities, the extraction of silicon for solar PV panels is **an energy-intensive process** (Cristóbal et al. 2020). It can also be associated with social risks, such as **modern slavery**, as highlighted in by Cockayne et al. (2022). In addition, during the operational phase of solar PV farms, environmental factors must be managed, such as implementing effective land management practices to achieve an optimal balance between renewable energy production and biodiversity conservation (Copping et al. 2025).

### *The need for transparency and traceability*

One tool used to communicate environmental impacts is the Environmental Product Declaration (EPD). An EPD is a third-party verified document that provides data on a product's environmental performance throughout its lifecycle (from raw material extraction through manufacturing, use and disposal). While EPDs are critical for transparency and reporting, they are not always directly comparable due to lack of standardisation, inconsistencies in scope, data quality, and assumptions. The lack of harmonisation across EPDs, as highlighted by Konradsen et al. (2024), further complicates their use for product comparison. Moreover, EPD adoption in the EU and UK remains inconsistent, with only a few countries mandating their use in construction (Konradsen et al. (2024).

In response to concerns over supply chain transparency, the **Solar Stewardship Initiative (SSI)**[2] launched by SolarPower Europe – has released a Supply Chain Traceability Standard for solar manufacturers. This standard proposes a new bar for end-to-end supply chain accountability in the PV industry, by proposing a clear and verifiable chain of custody of materials towards a more sustainable and ethical solar industry. The SSI shows promise in being an enabling factor for a more circular industry, by advancing supply chain transparency and the availability of data relating input materials and processes in the production of PV panels, which may lead to opportunities to minimise any associated environmental impacts being identified.



***Leverage knowledge from other sectors***

According to our interview results, standardisation and traceability may only be provided within certain areas of the value chain when it becomes mandatory. This has been previously noted across other sectors, for example the **EU Digital Battery Passport** (Rizos and Urban, 2024) that enables product and supply chain tracking for batteries, their components and raw materials.

*“Use serial number tracking and digital twin platforms to enhance traceability, support decision-making, and potentially aid recyclers” (SSI_012)*

This need for comprehensive product and supply chain tracking, as exemplified by the EU Digital Battery Passport, extends to the construction sector, where material passports are increasingly recommended. These digital records provide crucial data on building materials and components, enabling the standardisation and traceability necessary for their effective reuse and recycling throughout the asset lifecycle, thereby fostering a circular economy (Charef and Emmitt, 2021).

Furthermore, the transition to a circular economy in the built environment is supported by dedicated digital frameworks. For example, a recent article, presents a structured digital approach to guide stakeholders in adopting circular practices. Such frameworks are essential to provide the tools and methodologies needed to effectively manage material information and facilitate circularity (Charef, 2024).

Ultimately, the transition to a circular economy is a collective process. The solar PV panel sector can significantly benefit from leveraging digital tools

2 | https://www.solarstewardshipinitiative.org/

and frameworks already being developed in the construction sector. Instead of starting from scratch, the solar PV industry can build on these advances to support its own transition to a more circular model, accelerating efforts to reuse, recycle, and improve resource efficiency.

***The potential of using Materials Passports***

Most participants agreed that the PV industry would benefit from the

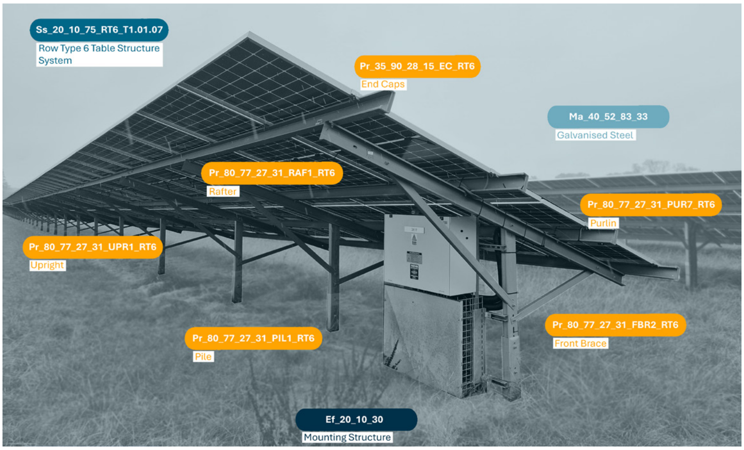



**Figure 6** | Example of Materials Passports application based on Materials Passports policy paper (Costa and Hoolahan, 2024) (Source: Drawn by Jones, 2025)



*"Develop material passports to record manufacturing data, energy use, and performance metrics, which can inform repair, reuse, or recycling" (SSI_011)*

adoption of materials passports to facilitate data standardisation, traceability and help to make informed decisions, previously developed for the construction sector (Costa et al. 2024). Furthermore, we carried out a pilot research project to develop a full materials passports database (Charef et al. 2024) for a c.50MW solar farm. This database included information such as product specifications, material composition, origin, age, and recycling or reuse potential (Figure 6). It was based on the Materials Passports policy paper (Costa and Hoolahan, 2024) and confirms that **data accountability is critical for making informed decisions** at the end-of-life of PV panels, whether they should be reused, repaired or recycled.

## *Recommendation 2 | Digitalise the Solar PV Industry and adopt materials passports to improve data standardisation and traceability*

The PV industry and governments should create and implement a digital PV Materials Passport (MP) to enable data standardisation, transparency, custody of materials and Lifecycle Assessment (LCA) accountability without compromising technical innovation.

# R3 | *Prioritise design for disassembly, reuse, durability and recyclability*



***Challenges***

| | |
|---|---|
| **R6** | Disparity between quantity of material, material recovery and material revenue: loss of material value through downcycling. |
| **R7** | EVA is not recovered: the encapsulant layer is difficult to remove or use high temperature. |
| **R10** | PV panels are complex by design and difficult to disassemble. |
| **R11** | Low purity of recovered materials. |

*"Advocate for longer-lasting modules to reduce lifecycle waste" (SSI_012)*

***Material separability***

PV panels can be very durable and built to last for decades, but their design can also make them **difficult to disassemble or repair.** Indeed, they are composed of various materials and **multiple bonded layers** (glass, encapsulants, silicon cells, metals, etc.), which are fused to ensure long-term performance. However, this same durability becomes a barrier when we try to repair, reuse, or recycle them. Careful consideration must be given to this complex trade-off to achieve an **optimal balance between the longevity and performance** of PV panels and their **ease of disassembly**; this challenge is explored in more detail within recommendation 8.

***Recycling techniques***

Once a PV panel is decommissioned, recycling becomes a viable option, though the processes involved can be complex. Currently, three main techniques predominate: **mechanical, thermal, and chemical**. The recycling process involves several steps, starting with removal of **aluminium frames and the extraction of as much glass as possible using a glass mill**. The remaining materials are then processed to recover silicon, silver, copper, and other elements. However, current methods often face challenges with purity and material loss, hindering effective recovery (Chen et al. 2024).

Additionally, some recycling processes lead to **downcycling**[3] , where materials may lose some of their original value. The efficient separation of PV panel materials is key to enhancing the environmental benefits of recycling (Rout et al. 2025).

***Challenges in recycling PV panels***

One of the primary challenges is the **complex multi-layer design** of PV panels. Efficiently isolating valuable components such as glass, silicon, and various metals can be difficult due to their tight integration within the panel structure.



The **encapsulant layer** a key component in the c-Si PV panels, protects the cells from damage and degradation, but poses a significant challenge during recycling. Removing or debonding the EVA is crucial yet difficult. Several techniques have been explored, each with specific challenges, such as high energy consumption for thermal methods or the use of hazardous chemicals and by-product generation in chemical methods (Chen et al. 2024). Some recyclers use organic solvents to dissolve the EVA, but this process is time consuming and generates hazardous liquid waste.

*"Encourage design for disassembly and lead-free and alcohol-free components, which support better recyclability and environmental compliance" (SSI_010)*

**Achieving high purity** in recovered materials, especially silicon and precious metals like silver, is critical for their reuse in secondary high-value applications, but this is complicated by the difficulty in separating the tightly bonded layers (Chen et al. 2024). A French company, use a **high-value recycling process** focusing on recovering ultra-pure materials **like silicon, silver and copper.** **Silver** represents only **0.08% of a PV panel's weight** but represents around **50% of its economic value**. Current, **80-90%** of the silver can be recovered and the company aims to improve the recovery rate to 100% through the investment in additional purification processes.

The IEA Report provides some guidelines for Designing for Recycling (DfR) of PV panels that should support industry innovation (IEA-PVPS, 2021):

- Clear identification of module construction and composition could enable **safer and more efficient** recycling processes.
- **Backsheet** materials have a direct **impact on recyclability** and should be selected with that in mind.
- **Choice of metal** affects recyclability (recycling processes) and costs.
- **Considering alternatives to encapsulants** or using reversible encapsulants, can facilitate disassembly of PV modules.

3 | Downcycling is the process of recycling materials into products of lower quality and less functionality than the original.

- Simplifying the variety of materials will decrease the **number and complexity** of module materials: but this strategy will come with some trade-offs that will need to be carefully assessed.
- Using different sealants in the aluminum frame could enable **module separation without component damage**. This will support reuse.



### *Recommendation 3 | Prioritise design for disassembly, reuse, durability and recyclability*

The PV industry should invest in design innovation, considering the Life Cycle Assessment (LCA) of a PV Panel, and **(1)** Develop holistic technical solutions that consider end-of-life management and support material value retention (enabling reuse, reparability, durability and recyclability through design), **(2)** Adopt eco-design principles and techniques (e.g. avoid the use of materials that are difficult to recycle and rely on the use of fossil fuels to produce - such as EVA and POE, delamination solutions).

# R4 | *Mitigate early loss scenarios and extend lifecycle of materials*

### *Challenges*

| | |
|---|---|
| **T1** | Waste generated throughout the PV panels' lifecycle and end-of-life. |
| **T2** | The PV panels with low quality have higher degradation rates. |
| **M3** | Technology discontinuity: replacement not possible if the panels are not available anymore. |
| **C1** | Transport and installation damages: poor packing/stacking/forklift. |
| **UM5** | Repowering with new, more efficient PV panels. |
| **D1** | Lack of proper storage and no information about PV panels content. |
| **D2** | Lack of testing and recertification and reconditioning facilities. |
| **D3** | Lack of spare parts due to rapid technology evolution. |
| **R9** | Recycling facilities: the minimum annual waste volume required to be profitable: 20kt (Choi & Fthenakis, 2014). |

### *Performance warranty vs. Product warranty*

Solar PV panels are usually sold under **two different warranties: a performance warranty**, typically spanning 25 years, **ensuring a minimum power output** (often 80–94% of the original capacity), and a shorter product warranty, covering physical defects or failure, lasting anywhere from **5 to 25 years**. The issue with these two benchmarks, is that they do not accurately reflect the reality in terms of panel longevity or the economic value of PV systems. According to the industry and academic literature, **the best time to undertake maintenance to increase performance** is around **year eleven** (Peters et al, 2021). It is important to note that the maintenance applies to the entire PV system, not just the panels. For example, inverters are often repowered or replaced around year 15. While PV panels are generally expected to last longer, there are still cases where they fail earlier than expected due to manufacturing issues, environmental conditions, or improper handling.

### *Challenges leading to Early loss scenarios of PV panels*

PV panels are usually designed to last 25 to 30 years. However, a study suggests that panels installed today should ideally be operated for 50 years, Peters et al. (2021). The authors modelled two scenarios, integrating module failure rates to more accurately predict when waste might be produced, to help inform end-of-life planning and recycling market development. These are known as Regular Losses and Early Losses. In the **Regular Loss Scenario**, it is assumed that PV panels reach their expected and manufacturer guaranteed 30-year lifespan with no premature retirement or failures. In the **Early Loss Scenario**, we consider premature failures, accidents, or early replacements, including all likely **"infant", "mid-life", and "wear-out" failure possibilities**, before the panel's 30-year lifetime is up (IRENA-IEA 2016; Buehler, 2018). This reduced panel longevity has several potential causes, classified under 6 categories in Figure 7, and may lead to earlier volumes in PV waste being generated.

Many of these early losses are preventable. Poor manufacturing quality

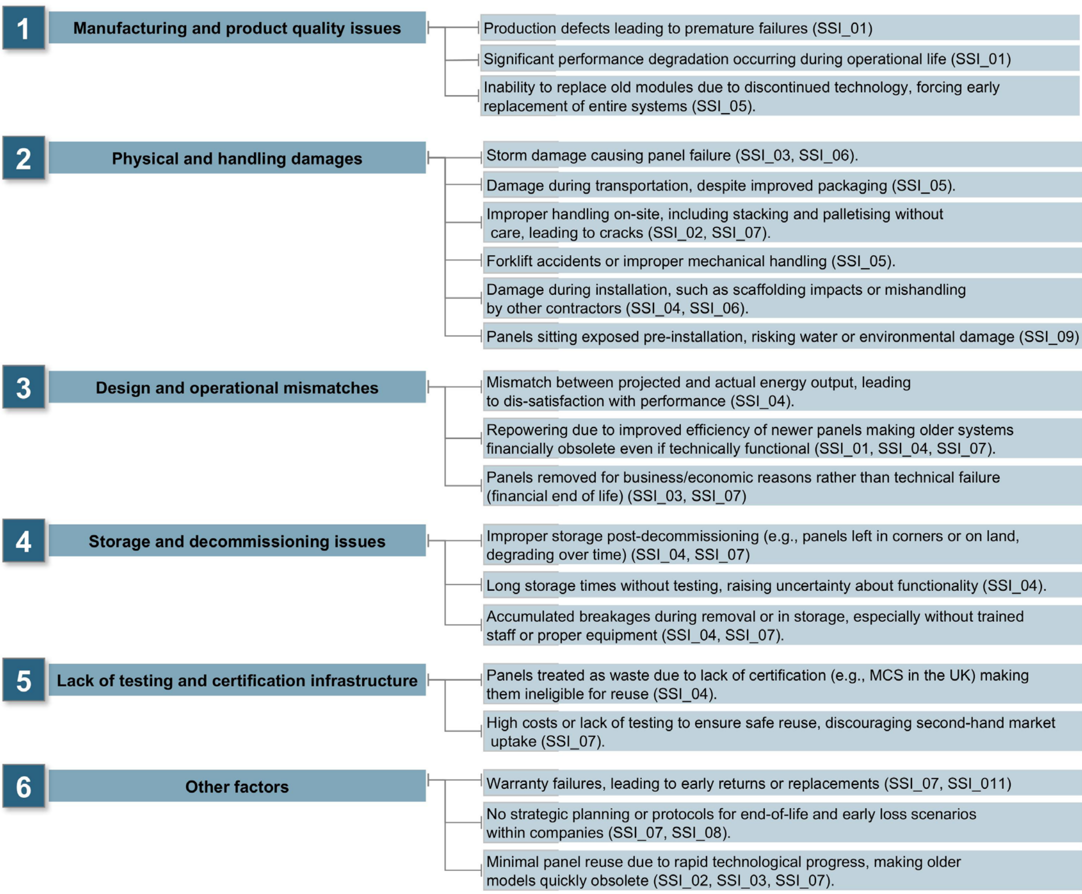



**Figure 7** | Early Loss Scenario Causes (Source: Drawn by Charef, 2025)

or unexpected rapid performance decline can result in early failure. Physical damage during transport, handling, or installation also contributes significantly. This may be due to rough handling or environmental exposure. In some cases, panels are not technically defective but are removed early because newer, more efficient models make older ones appear economically obsolete and may make more efficient use of available land area. Some sites could also be decommissioned because the model of PV panels installed is no longer available on the market. A lack of proper storage conditions and testing infrastructure further complicates efforts to assess whether panels can be safely reused.



***Invest in recycling facilities – second-hand market organisation***

Although many studies and reports have forecasted a large amount of PV waste, Nyffenegger et al., (2024) reported that the unpredictable volumes of materials available for reuse and recycling hinder substantial investments in the PV recycling sector. This uncertainty makes it difficult for both public and private stakeholders to commit to the long-term infrastructure needed for efficient recycling.

In Europe, Germany and Italy will be the f**irst countries to generate 20kt** of PV waste annually (Choi and Fthenakis, 2014). Countries need to prepare themselves by **investing in recycling facilities** to be able to manage the amount of waste forecasted. Without such preparation, valuable resources may be lost, and waste management systems overwhelmed.

*Manufacturers are already working on their own recycling solutions, focusing on **lead-free panel designs** and promoting the recovery and reuse of materiails like silicon, silver, aluminium and glass. The aim of eliminating the use of lead is due to potential environmental and health risks at the end-of-life of the PV panels (Heath et al., 2020).*

Recycling old panels enables the recovery of valuable materials like silicon, silver or rare metals (rather scarce or difficult to extract), enabling a closed loop and a more resilient economy. While some of these materials may not currently have a high market value, they are finite and expected to gain strategic importance as demand for clean energy technologies increases. According to the IEA (2025), **global demand for critical minerals** used in solar technologies is projected to grow significantly, making early recovery efforts essential for future supply security.

Therefore, if recycling techniques become more efficient, **metals recovered from old panels** could form a large portion of resources needed to **make new**

**panels**. Moreover, as suggested by Kastanaki and Giannis, (2022) and some interviewees, to ease the process, **manufacturing plants** could be **located close to recycling plants** to maximise efficiency. This co-location would reduce transportation costs and emissions while encouraging continuous feedback between manufacturers and recyclers.

Figure 8 below, illustrates the key stages in the solar PV panel manufacturing process, based on interview analysis. It highlights **four production phases**: ingot pulling, cell production, module assembly, and final testing. While the process is highly efficient—with less than 1% waste during cell and module production—defective modules that fail testing are diverted from customer delivery. These modules, along with waste silicon generated earlier, represent **key opportunities for material recovery** through **in-house or external recycling**, or even the **second-hand market** where reuse is viable.



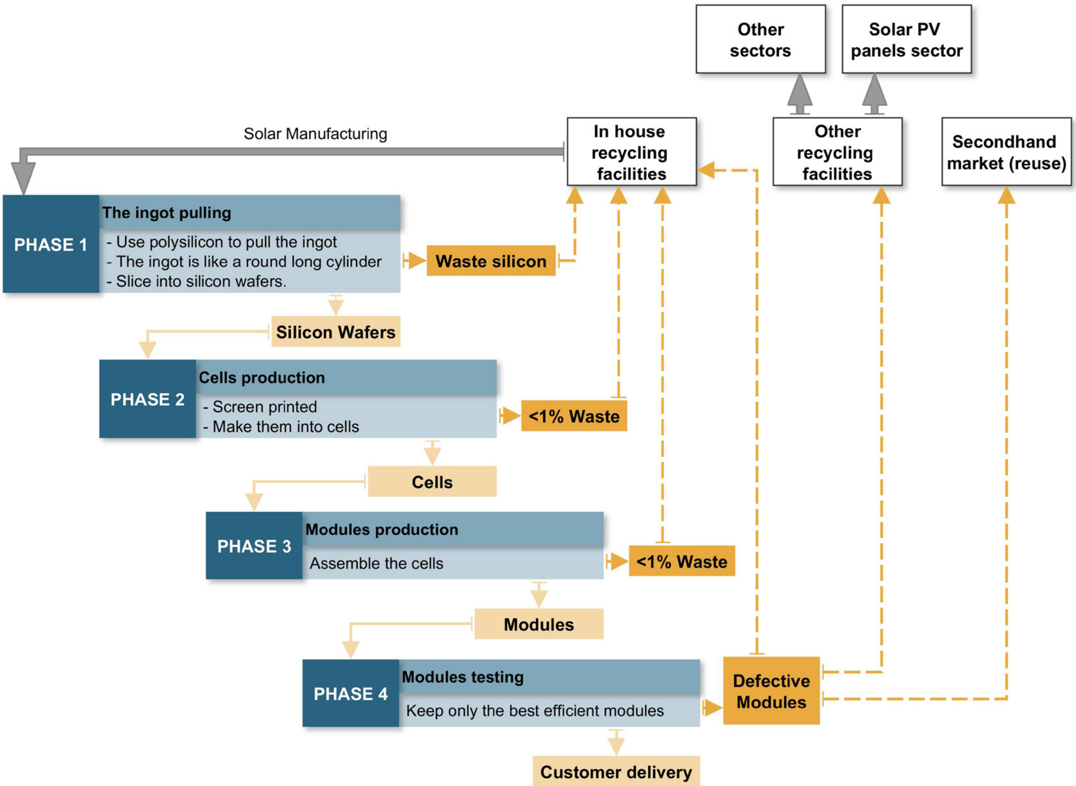



**Figure 8** | Waste generated throughout the solar PV panels manufacturing: from the ingot to the module testing (Source: Drawn by Charef, 2025, based on the semi structured interviews)

## *Recommendation 4 | Mitigate early loss scenarios and extend the lifecycle of materials*

Manufacturers and recyclers, supported by governments and research partnerships, should:

**(1) Explore synergies and opportunities for collaboration**, e.g. establish feedback loops between different members of the supply chain to facilitate the identification of challenges and the development of potential solutions,

**(2)** Establish shared recycling facilities,

**(3) Develop technologies to support reuse and recycling,**

**(4)** Suggest policy support for warranty tracking and predictive maintenance.

# R5 | *Explore partial repowering and cannibalisation strategies*



### *Challenges*

| | |
|---|---|
| **UM1** | Absence of centralised spare parts hub. |
| **UM2** | Early retirement of functional PV panels. |
| **UM3** | Unbalanced supply/demand for available spare parts = over-replacement. |
| **UM4** | Downtime risks due to poor spare parts management. |
| **D3** | Lack of spare parts due to rapid technology evolution. |

*"Instead of full asset repowering, companies can adopt partial repowering, using data to identify and replace only failed modules" (SSI_012)*

### *Avoid full repowering*

According to SolarPower Europe, some decommissioned PV panels are **still functioning** and can generate up to **80% of their initial capacity** (SolarPower Europe, 2024). While repowering or revamping[4] can improve the performance of solar farms, it may lead to the retirement of PV panels that are still functioning. However, there are arguments to suggest that this strategy makes the most efficient use of limited land area available to site utility scale solar farms. Some interviewees suggested to also consider partial repowering. Where possible, reuse options for decommissioned but functional panels should be prioritised, either within the same site or elsewhere.

One practical approach is to **create centralised spare parts centres**, where panels can be stored **and later used** to replace defective modules, an approach often referred to as **cannibalisation**. This involves **removing functioning components from** one solar farm to use them as **spare parts** or replacements in another solar installation. PV panel technologies are rapidly evolving with some models discontinued, making it difficult to find replacement parts. The creation of a centralised digital spare parts hub would facilitate the maintenance and extend the life of solar assets by locating compatible spare parts.

4 | **Repowering** involves replacing outdated components of a solar PV farm, like panels or inverters to boost performance and efficiency. **Revamping** refers to repairing or optimizing existing equipment without full replacement, such as fixing wiring or updating monitoring systems.

Strategic repowering should aim to reconcile the need to improve energy efficiency with the objective of extending the lifetime of existing modules, reducing waste and supporting a more circular solar economy.

***Create a centralised spare part hub***

As solar PV technologies evolve, replacing defective modules can become challenging. Identical PV panels with the same physical and electrical characteristics may no longer be available on the market. This unbalanced supply/demand creates technical challenges that may lead to more equipment being replaced than is technically required. These challenges are a key reason why the creation of centralised spare parts hub could be a fundamental strategy.



Spare parts are intended to replace similar items and play a key role in ensuring solar PV farms run smoothly. Their proper management is critical to **avoid downtime**. The **location of the spare parts hub** is also important, as it helps minimise transportation distances and associated emissions. According to SolarPower Europe (2021), commercial contracts often recommend stocking at least 0.2% of specific spare parts to support long-term operation.

*"Cannibalising still-functional modules to extend asset life is a cost-effective and environmentally beneficial practice" (SSI_012)*

As shown in **Figure 9**, a centralised spare parts centre is a facility where solar panels that have been removed from service, but are still functioning, can be stored, tested, and reused. These hubs can act like **"second-hand parts banks"** for the solar PV industry, offering a reliable source of replacements for aging and damaged systems (Secondsol, n.d.).

*When combined with materials passports, these hubs can be managed more efficiently. Materials passports provide essential information about each panel's specifications, condition, history and material composition. This enhances transparency and helps identify, track, and match decommissioned panels with reuse opportunities across solar projects.*

Technicians can quickly assess whether a panel is compatible with a given system, helping extend the life of solar components, reduce waste, and support a more circular solar economy.

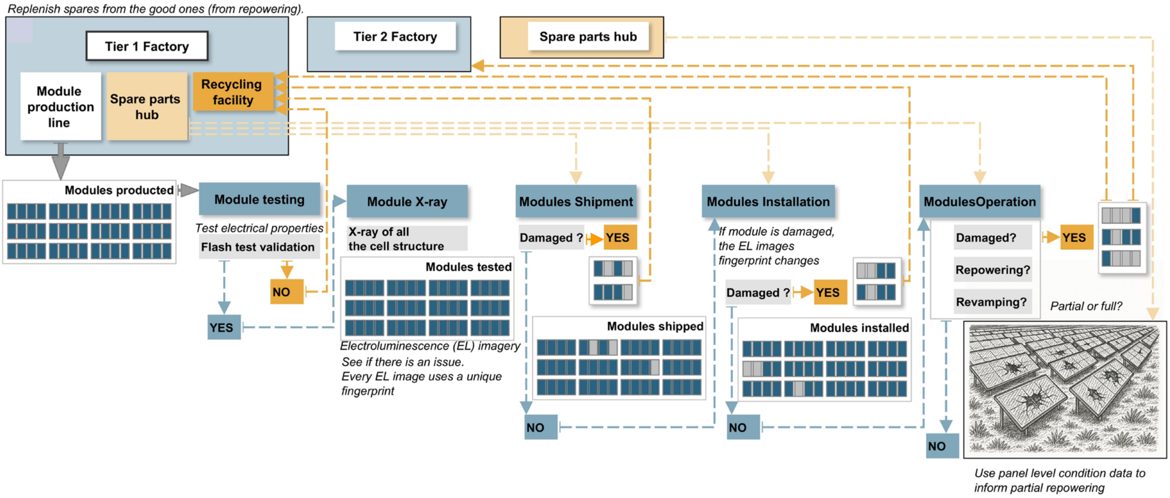



**Figure 9** | Waste generated from the module production to the end-of-Life (Source: Drawn by Charef, 2025, based on the semi structured interviews)

## *Recommendation 5 | Explore partial repowering and cannibalisation strategies*

Manufacturers and recyclers should create research partnerships and business models to **enhance material recovery rates and reduce waste**. Supported by materials passports, the PV Industry should **create a centralised digital spare part hub** to facilitate the exchange of second-hand PV panels and extend the life of solar farms.

# R6 | *Explore Reuse potential and second-hand market opportunities*



### *Challenges*

| | |
|---|---|
| **T2** | The PV panels with low quality have higher degradation rates. |
| **D4** | High-cost reuse and recertification processes. |
| **D5** | Lack of regulations and policies to support the development of second-hand market opportunities, e.g. reuse, recertification. |
| **D6** | Stigma around second-hand PV panels: reuse avoided due to lack of guarantees and seen as lower quality. |

***High cost of the reuse process and gap in regulations***

According to several authors and interviewees, the current reuse of PV panels is very limited (Radavicius et al., 2021; Van Opstal and Smeets, 2023). Due to the **high cost of the reuse process**, the eligible panels are typically those prematurely retired and in need of minimal repair before 11 years Peters et al. (2021) or 12 years for Kastanaki, (2025). Indeed, they need to be in good condition to be eligible for reuse (Freeman, n.d.) and handled by a specialised logistics company to ensure no damage occurs during transport. Both professionals in the field and researchers agree that there is a clear **gap in regulations** when it comes to certification standards, safety protocols, and warranty requirements for enabling a robust reuse pathway (Pareek, 2021).

***Poor quality of Solar PV panels***

Peters et al. (2021) suggest that panels with **degradation rates exceeding 1.5%** per year have **limited remaining value** and are **unlikely to be viable for reuse**, even at no cost. According to some authors, the standard efficiency degradation rate for PV panels is around **0.8% per year**, under normal conditions (Hocine and Samira, 2019) while others reported a **0.7%** efficiency degradation rate (Van Opstal and Smeets, 2023b). The authors highly recommend buying PV panels with **better quality and durability**, even if they are more expensive, as they will be able to produce more electricity and therefore revenue across their lifetime.

### ***Cost of reuse: recertification process***

There are also **legal issues** preventing the refurbishment or reuse of operational second-hand PV panels, due to **certification requirements, safety measures and warranty**. Moreover, the **recertification process is very expensive**, which may impact the business case for reuse (for those buying and selling). The buyers of second-hand panels may want a warranty which would be difficult to provide.

### ***Recovered PV panels could generate extra income through reuse***

Regarding additional revenue streams, the sale of recovered PV panels for reuse could generate extra income for asset owners. Indeed, according to Pareek (2021) the profits gained by the seller of second life modules could become higher than the cost for recycling or landfilling. According to Kastanaki (2025), "If all waste is diverted to recycling, the gross value of recovered materials will reach £27 - £40 (€32-47) billion by 2050." Under current conditions, a used panel sells for about 36% of the price of a new panel, while repair costs average £48 ($65) per module. After overcoming certification barriers, one-quarter of all PV panels reaching end-of-life by 2050 could be reused instead of being recycled or sent to landfill (NREL, 2021). Therefore, there are considerable opportunities in the investment of facilities aiming to extend the PV panels lifetime, whether for repair, reuse or recycling.



*"Reuse is currently limited due to handling damage, lack of certification, and low economic viability. However, emerging demand for reused panels exists, particularly in non-domestic applications" (SSI_011)*

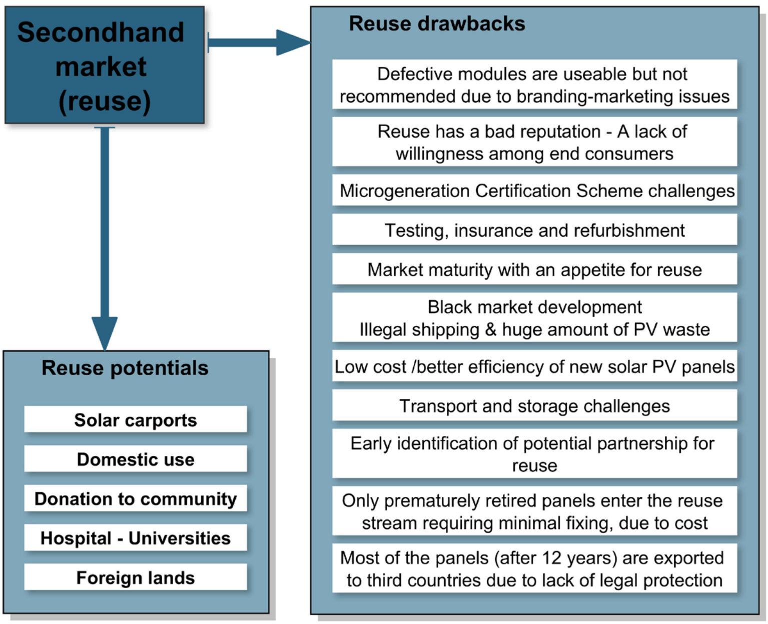



**Figure 10** | The reuse market challenges and opportunities according to the interviewees (Source: Drawn by Charef, 2025)

### *Reuse potentials*

Figure 10 gives an overview of the **challenges and opportunities** of reusing **PV panels**, extracted from the interviews conducted. Some of the items shown in Figure 9 are confirmed through existing literature. In Europe, instances of PV panels being transferred to LIC/NEEs (Low Income Countries / Newly Emerging Economies) have been noted in research (Pareek, 2021). Although this may be well-meaning (i.e., as part of social impact initiatives for communities without access to renewable energy), questions have been raised by the industry around whether donated PV panels will work and whether the countries they are being donated to have been supported with the necessary skills and infrastructure to operate, maintain, and dispose of them correctly (Kinally et al., 2022). Moreover, interview participants believe that there are several reuse potentials that could be considered, such as solar carports, domestic use, donation to communities, hospitals and universities. In terms of cost, the price of a second-hand PV panel has been assessed as approximately 70 % of the price of new panels (Weckend et al., 2016).



### *Building trust in recovered solar PV panels through certification*

Despite the **long lifespan and slow degradation** of solar panels (less than 1% efficiency loss per year), their reuse faces challenges. Many older panels remain functional and could be reused (Deline et al., 2021), however the market for second-hand panels remains small. This is mainly **due to concerns over quality, safety, and a lack of trust**. Buyers often perceive reused panels as unreliable, even when their environmental value is high. To address these concerns, **third-party certifications** could play a crucial role by verifying **product performance and safety**. Re-certification, including checks for installation, maintenance, and efficiency, are essential for building trust. However, there are still no widely available standard processes for certifying reused panels (Tsanakas et al., 2020).

*"Companies should develop testing protocols and establish quality standards to expand second-life markets" (SSI_011)*

## *Recommendation 6 | Explore reuse potential and second-hand market opportunities*

The PV Industry and governments should collaborate to facilitate **second-hand market opportunities**, **(1)** Develop **reuse and repair infrastructure**, **(2)** Expand upon reuse within the WEEE Regulations and create a **specific standard** for second-life PV panels, e.g. domestic use, **(3)** Create **third-party certifications** that can promote market transparency by confirming product quality, **(4)** Create financial incentives to stimulate the reuse market.

# R7 | *Develop partnerships and second-hand market support*



*"Rather than being downstream and being told, there's 8 megawatts of solar panels to get rid of, it's actually having that ability to talk in advance to say, well actually have you thought about repair and recovery". (SSI_03)*

***Challenges***

| | |
|---|---|
| **Di 1** | If PV panels are damaged during transportation, are malfunctioning/defective, they are replaced and don't go back to manufacturing. |
| **D2** | Lack of testing and recertification and reconditioning facilities. |
| **D5** | Lack of regulations and policies to support the development of second-hand market opportunities, e.g. reuse, recertification. |
| **D6** | Stigma around second-hand PV panels: reuse avoided due to lack of guarantees and seen as lower quality. |
| **D7** | WEEE directive is not specific to the PV industry and does not consider second-hand solutions. |
| **D8** | Export risks: old PV panels becoming unmanaged waste. |

***Collaboration and partnership***

Strong and coordinated collaboration is fundamental in enabling circular economy practices across the solar PV sector. While many stakeholders express a willingness to collaborate, efforts remain fragmented. In many cases, actors operate in isolation, due to a lack of a standardised framework or upstream or downstream visibility in the supply chain. Below in Figure 10. the current gaps, analysis and strategic recommendations are structured around two key pillars: **strategic partnerships and innovation-driven collaboration.**

In the solar PV sector, **effective collaboration is needed** and could be split in two pillars, as illustrated in **Figure 11**. To transition towards circular economy, the stakeholders across the value chain need to **build strong partnerships and test new ideas**. Both need the right conditions in place to succeed. It is crucial to bring different people and organisations together, from manufacturers and recyclers to local authorities, academics and Government bodies.

Focusing on innovation and testing new ideas through pilot studies is also important. These might include trying different ways to reuse panels, using

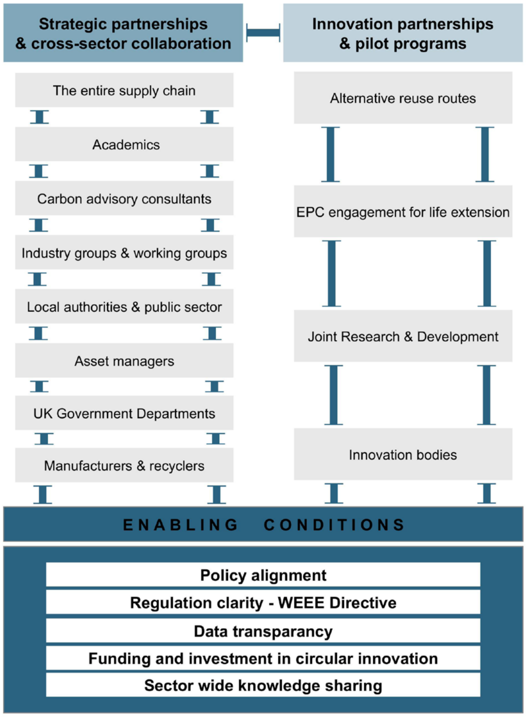



**Figure 11** | Two pillars for an effective collaboration (Source: Drawn by Charef, 2025)

*"There's still this stigma that a reused panel is a broken panel—so without proper standards and reassurance, people just won't take the risk (...) Policy could recognise reuse as a compliance route in WEEE targets—that would change the game". (FG3 participant)*

novel technologies to extend their life, or working with research organisations to find better recycling methods.
However, there are a set of upstream considerations that must be in place to enable circularity across these areas, acting as a common denominator between them. Clear policies, better regulation (like how the WEEE Directive is applied), open data and funding for circular research and innovation projects.

***Unlocking the potential of the second-hand PV panel market: Connect donors with recipients***
In addition to collaboration and partnership efforts, the sector must create a more structured secondary market for solar panels. Organising and strengthening this market is essential to reduce waste and extend the lifespan of PV panels. The following recommendations point out the key elements to unlock their second-hand market potential.

The market for used photovoltaic solar panels holds considerable potential to reduce waste and extend the lifespan of valuable materials. However, as highlighted by industry stakeholders in our interviews, the second-hand

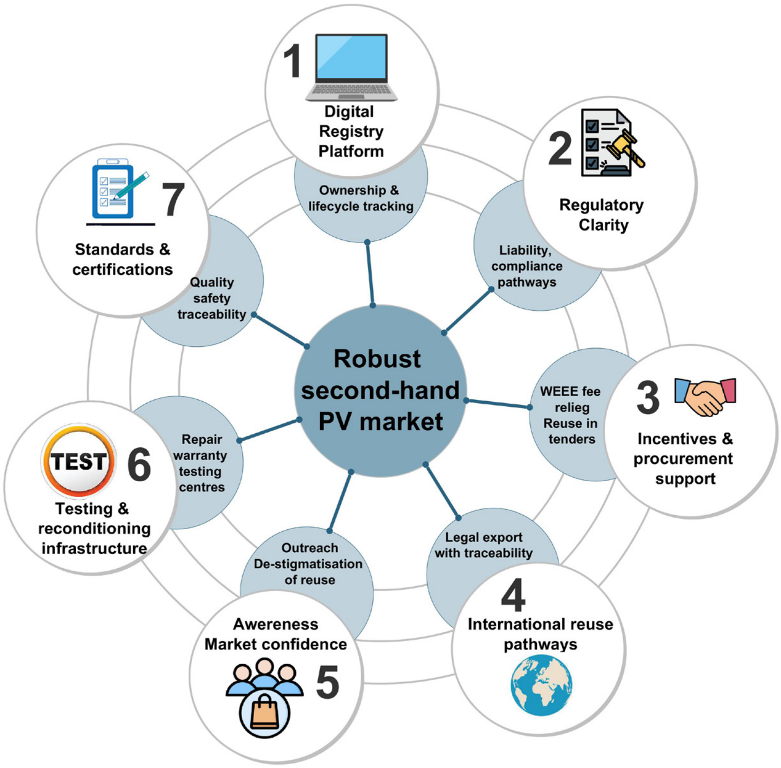



**Figure 12** | Robust Second-hand PV Market (Source: Drawn by Charef, 2025)

market remains **underdeveloped, insufficiently regulated**, and often **mistrusted** (Figure 12). One major barrier is the **lack of regulatory clarity.**

Currently, recovered PV panels are often **automatically classified as waste,** even if they remain functional. This **legal ambiguity discourages reuse** and **limits opportunities for second-life applications**. Stakeholders also highlighted **confusion regarding compliance and liability**, with a lack of clarity about who is responsible if a reused panel fails.

Another challenge is a **lack of facilities**. While there are promising examples of reuse applications already in operation, such as the SecondSol[5] second-hand solar PV trading platform in Europe there is less available information or research to indicate that this solution has **not yet reached commercial scale** across the UK. As one interviewee pointed out, reused panels are often handled in ways that **risk damage during transport or storage**. Without

5 | https://www.secondsol.com/en/index.htm

proper testing and **reconditioning centres**, it is difficult to ensure the safety and reliability of reused PV panels.

A significant barrier to the adoption of second-hand products, is the **prevailing stigma**, as they can be perceived as **low quality and high risk**. This challenge is further compounded by the **low cost of new PV panels** and **the absence of recertification facilities**. Digitalisation presents a promising solution by enabling the **tracking of PV panels** and ensuring transparency, which is essential for **building trust**. Government intervention is essential in this context, particularly through the provision of **incentives for reuse**. There is a strong demand from stakeholders for the **development of technical standards and certification schemes**, specifically tailored to second-hand PV panels. Finally, the international trade of PV panels also requires careful consideration to prevent the disposal of old PV panels in countries lacking appropriate regulations.



### *Recommendation 7 | Develop partnerships and second-hand market support*

Strengthen early, cross-sector collaboration and partnerships across the PV value chain, particularly between manufacturers, recyclers, policymakers and academics to scale up reuse and repair infrastructure.

# R8 | *Improve recycling processes and technologies*



### *Challenges*

| | |
|---|---|
| **M1** | Use of EVA and POE to seal and protect the solar cells: panel materials are blended together = make disassembly and material separation difficult. |
| **M2** | Polymer backsheets contribute to early failure. |
| **R7** | EVA is not recovered: the encapsulant layer is difficult to remove or use high temperature. |
| **R8** | Thermal decomposition generates toxic gases. |

### *Current recycling technologies*

The **most common approach** for managing the end-of-life of solar PV panels is **recycling**. The main recycling techniques used for c-Si solar PV panels include: (1) **Mechanical**, (2) **Thermal treatment**, (3) **Chemical treatment** and (4) **Hybrid techniques**. However, none of the current methods achieve 100% recycling.

The recycling process typically involves **four steps**: (1) separation of the junction box and frame from the module, (2) separation of the encapsulant, (3) separation of the glass panel and c-Si cells via thermal, mechanical or chemical processes and lastly (4) extraction and purification of c-Si cells and valuable metals (such as silver, copper, aluminium and lead) through mechanical, electrical and/or chemical processes. The efficiency of recycling is illustrated in the % recycling rate in Table 3.

| Components | c-Si Weight % | Recovery % |
|---|---|---|
| Glass | 71 | 90 |
| Silica | 4 | 90 |
| Aluminium | 13 | 90 |
| EVA | 9 | 0 |
| Copper | 0.1 | 95 |
| Silver | 0.1 | 95 |

**Table 3** | The efficiency of recycling (Smith and Bogust, 2018)

To recycle solar panels, scientists employ careful heating or chemical treatments to separate and recover valuable components like the silicon wafers, glass, and aluminium frames.

***Use of EVA – POE to protect the solar cells and polymer backsheets***

According to Isherwood (2022), the recycling of PV panels is complicated by the use of backsheets and encapsulants.

For c-Si PV panels, Ethylene Vinyl Acetate (EVA) and Polyolefin Elastomer (POE) materials are commonly used by manufacturers to **seal and protect** the solar cells inside the panels, from heat, water and UV radiation, which are all factors that can lead to accelerated PV degradation. These materials are used with the intention of helping to extend the lifespan of panels, enabling them to last 25-30 years or more. However, EVA and POE **effectively bond the panel materials together** making the different layers such as, glass, silicon and metals, difficult to separate during the recycling process. As you can see in **Figure 1**, the **EVA-containing** encapsulant layers sandwiching the semiconducting monocrystalline silicon cell usually contain **silver and copper** which can be **difficult to recover**.

Therefore, the challenge lies in using materials like EVA/POE to create **stronger, longer-lasting panels** and the increased complexity of recycling these materials, as their inclusion inhibits disassembly. Alternatively, if we don't use them, recycling becomes easier, but **the panels may not last as long** (SSI_010).

Another challenge is the recycling of the **polymer backsheet**. Proper recycling through thermal or chemical decomposition can recover intact wafers for reuse or reprocessing. However, these processes may create environmental impacts in other areas. For instance, **thermal decomposition** can generate **toxic gases**, whilst **chemical methods can be slow**, generate additional pollution, and sometimes require additional energy expenditure through heat to eliminate residues (Wang et al. 2022).

***Backsheet location***

According to our research, while **backsheets constitute a small portion** of the PV panel, they can pose a significant challenge in advancing towards more circular solar PV panel design. The backsheet, located at the rear of the panel, is not easily visible during routine inspections. This can result in early signs of damage going unnoticed, allowing degradation to progress and potentially compromising the overall integrity and performance of the panel over time (SSI_10). This issue highlights the durability dilemma (section 3.6) that should be addressed by the PV industry.

### *Summary*

The trade-off between durability and recyclability is a critical consideration in the lifecycle management of solar PV panels. On one hand, prioritising durability involves using materials like EVA/POE that enhance longevity and performance, enabling the panels to withstand harsh environmental conditions, thereby extending their operational life and reducing the frequency of replacements. However, panels designed for maximum durability often incorporate materials and construction techniques that are difficult to disassemble and recycle. This complexity can lead to higher costs and technical challenges in the recycling process, potentially resulting in improper disposal and the loss of valuable materials. Conversely, prioritising recyclability involves designing panels that are easier to disassemble and process at which could act to simplify the recycling process, reduce costs and improve the materials recovery rates. However, prioritising recyclability over durability may inadvertently increase the total amount of waste generated over the asset's lifetime.



To address this issue, a balanced approach is necessary. Policymakers and industry stakeholders should promote the development of innovative designs that optimise durability and recyclability, as well as recycling processes that seek to minimise adverse environmental impacts.

## *Recommendation 8 | Improve recycling processes and technologies*

Invest in the current PV recycling processes and technologies to:

**(1) Minimise environmental impact and maximise material recovery** rates,

**(2)** Inform disassembly, reuse and recyclability,

**(3)** Inform and support Extended Producer Responsibility **(EPR) schemes.**

# R9 | *Create specific regulations for PV panels*

### *Challenges*



| | |
|---|---|
| **UM6** | Ownership changes hands quickly and is viewed as a future problem. |
| **D5** | Lack of regulations and policies to support the development of second-hand market opportunities, e.g. reuse, recertification. |
| **D7** | WEEE directive is not specific to the PV industry and does not consider second-hand solutions. |
| **R12** | Success measured by weight is misleading for solar PV panels: by focusing only on the weight parameter, we risk ignoring critical and valuable materials that exist in small proportions. |
| **R13** | Around 90% of a panel's weight comes from glass, aluminium, and plastic, which are easy to recycle but not the most valuable. |
| **R14** | Small amount (less than 5%) of materials like silicon, silver, and copper that make up over 50% of the panel's economic value. |

*WEEE Directive recycling target:*

*At least 85% must be recovered*

*At least 80% must be recycled by weight*

***Regulatory Framework: Classification and inconsistencies***

The Waste Electrical and Electronic Equipment (WEEE) Regulations 2013 are the UK's implementation of the EU WEEE Directive (2012/19/EU), which were designed to reduce the amount of electronic and electrical waste going to landfill and to promote reuse, recycling and recovery. Solar PV panels were officially brought under scope of these regulations in 2014. Post-Brexit, the **UK has retained the WEEE framework** and adapted it to fit domestic regulatory structures. Solar PV panels continue to fall under its scope.

> One interviewee explained *"Under the WEEE regulations we have a treatment provider supporting the treatment and collection and the producer compliance schemes that report data to the Environment Agency and manage collections and treatment activities."*

However, there is ongoing confusion around classification, particularly the distinction between **Business-to-Consumer (B2C)** and **Business-to-Business (B2B)** waste. In the UK, most PV panels, although used in commercial solar farms, are currently **treated as B2C waste**. This classification subjects them to **stricter and more costly recycling obligations**. If these panels were correctly classified as B2B, they could be collected in bulk, tested, and reused more efficiently.

When classified as **B2C waste**, PV panels must undergo a stricter and more expensive recycling process, complicating their reuse or resale. Given that these panels usually come in bulk from solar farms being upgraded or repowered, reusing them is more practical, easier and cheaper.

Incorrect classification can lead to improper recycling or unfairly shift recycling costs to other parts of the supply chain. Correct B2B classification would hold producers and large users more accountable and support better waste management planning.



*"Advocate for Reclassification of solar panels under WEEE to reflect that most are B2B, not B2C, which affects funding and responsibility." (SSI_011)*

***Policy and regulatory needs***

Stakeholders are calling for clearer and more supportive policies. Many interviewees highlighted the importance of **broad stakeholder engagement with UK Government bodies** (such as DESNZ and DEFRA - Department for Environment, Food and Rural Affairs). According to them, **government policies** play a **crucial role** in accelerating circular economy practices within the solar PV sector, not only by setting rules, but also by creating the conditions for long-term change.

There is a **real appetite for more structured and binding frameworks**; many have indicated that in the absence of regulatory drivers, commercial incentives alone will not be sufficient in transforming industry behaviour. Although awareness across the sector is increasing, many stakeholders do not have robust plans in place for end-of-life of PV panels which may be in part, due to the **short ownership cycles** of solar assets. Stakeholders urged stronger legislation, mandatory circularity planning and targeted government grants.

Several interviewees emphasised the importance of not only meeting recycling quotas but also ensuring that recycled materials are recovered to a quality suitable for reintegration into new manufacturing cycles. They also stressed the **importance of policies that clarify the distinction between reuse and recycling processes**, enabling businesses to make **informed, low-risk decisions**. While these measures are not yet mandated in the UK, they are seen by many stakeholders as essential to drive circular practices in the solar PV sector.

***The WEEE Directive: weight-based targeting***

The **WEEE Directive, while valuable, is not "tailored" to PV panels.** Interviewees pointed out that it **lacks clarity on second-hand market development, reuse standards and recycling quality**. Indeed, the directive currently uses **weight-based targets** to measure recycling success, which is problematic for solar PV panels. About 90% of a panel's weight is made of glass, aluminium and plastic, having all low value compared to silver, copper and silicon that represent 5% of the weight but over **50% of the economic value** (Figure 13). Therefore, if we seek purely weight-based recycling rates, we will continue to lose critical materials (Majewski and Dias, 2023).



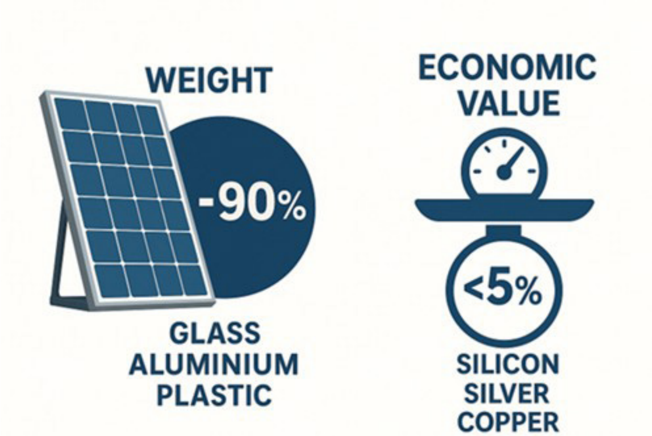



**Figure 13** | The PV Panels Weight Dilemma (Source: Drawn by Charef, 2025)

*"Advocate for Support for extended producer responsibility (EPR) models and leasing schemes (e.g., "pay-per-watt" models) to promote sustainable design and recovery." (SSI_011)*

## *Recommendation 9 | Create specific regulations for PV panels*

**Enhance the specificity of the WEEE Directive with PV-panel specific regulations**: Policy makers should update/revise the WEEE Directive to make it more specific to PV panels and related regulations to:

**(1)** Reclassify panels as business-to-business waste,

**(2)** Require early end-of-life planning and support high-quality material recovery,

**(3)** Enforce Extended Producer Responsibility (EPR),

**(4)** Define **standards for reuse versus recycling**,

**(5)** Create a **regulatory and financial** environment that encourages innovation in recycling and the growth of the second-hand market, without burdening compliance.

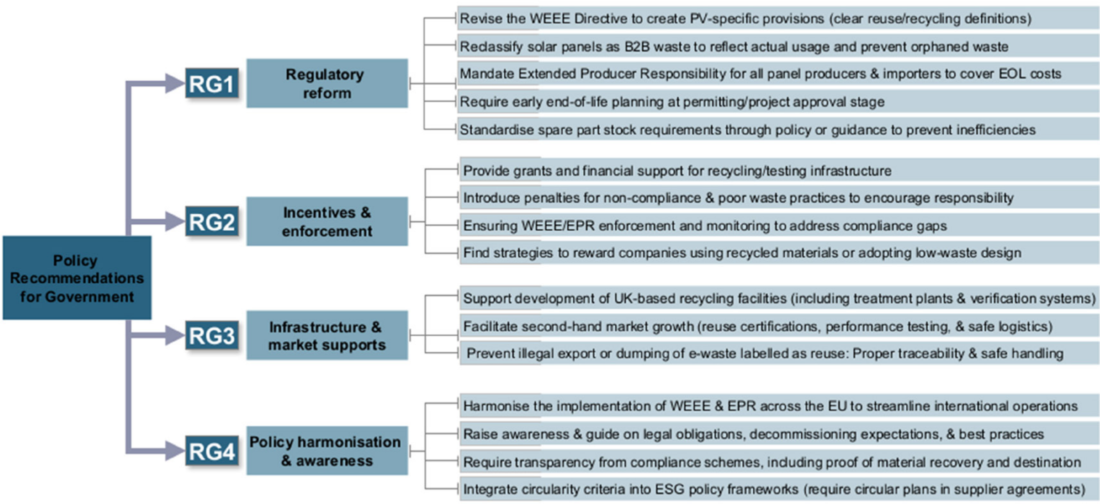



**Figure 14** | Policy-related recommendations for Government, insights from interviews (Source: Drawn by Charef, 2025)

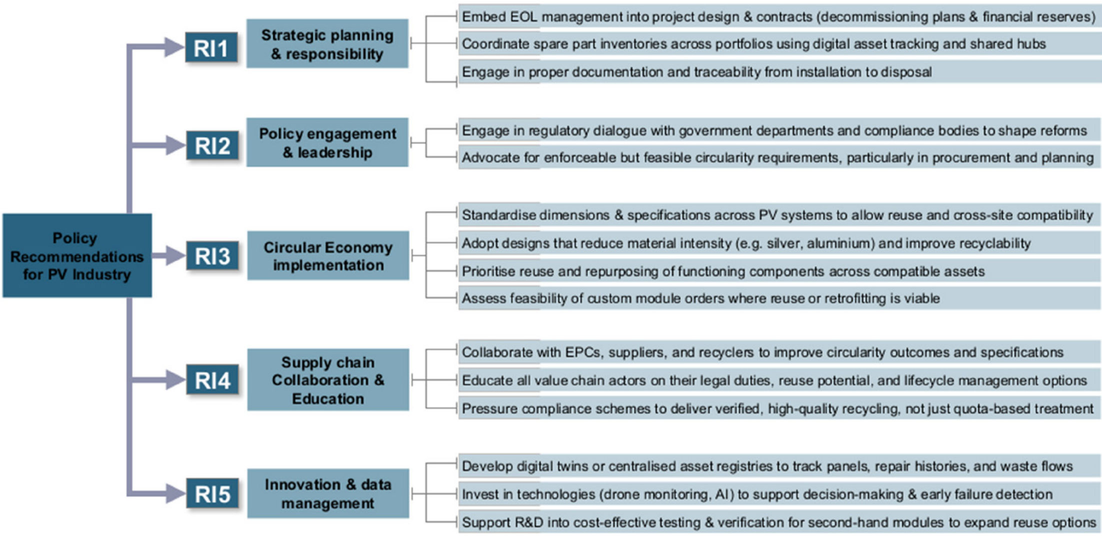



**Figure 15** | Policy-related recommendations for PV Industry, insights from interviews (Source: Drawn by Charef, 2025)

# **R10** | *Investment in research and knowledge exchange*



Solar panels don't just deliver clean energy; they also have the potential to contribute to a more sustainable and circular use of materials (Lin et al., 2022). Striking the right balance between producing renewable electricity and managing resources wisely is one of the key challenges the sector must now tackle.

### *Recommendation 10 | Investment in research and knowledge exchange opportunities to tackle end-of-life of PV panels*

The **UK government** should provide targeted grant funding open to both academia and industry to research under three main categories:

**1 - Materials (1a)** The LCA of PV panels from extraction to disposal to enable the most sustainable solution to be identified: environmentally friendly, financially viable, socially equitable, **(1b) Further advance recycling technologies** to facilitate a circular economy and recover valuable materials;

**2 - Systems and digitalisation (2a) Digitalisation of the PV sector** by implementing material passports, developing systems using AI and digital trackers, **(2b)** Improved transportation, handling and storage of solar PV panels to avoid damage and early failure;

**3 - Business models and design (3a) Alternative business models and markets**, **(3b)** Alternative design of PV panels, considering **Design for Disassembly**. **The PV industry and governments should provide worldwide standards, regulations, and policies** that enable material custody throughout the supply chain and provide dedicated guidance for end-of-life solar assets.

# Closing Remarks



The **Figure 16** presents a summary of the recommendations presented above and highlights in blue the circular economy cycle of the materials, **prioritising design for disassembly, remanufacturing with recycled materials and reducing waste and downcycling where possible**.

The yellow lines show the importance of data transparency and accountability to inform the decisions throughout the lifecycle of materials. In white we explore potential reuse cycles of PV panels, and the light blue dashed lines highlight the need to recycle all the PV panels lost throughout the supply chain.

Solar panels don't just deliver clean energy; they also have the potential to contribute to a more sustainable and circular use of materials. **Striking the right balance between producing renewable electricity and managing resources wisely is one of the key challenges the sector must now tackle collectively to strive towards an all-encompassing vision of sustainability.**

Collaboration between the PV industry, policymakers, and researchers is essential to implement these recommendations and unlock the full potential of solar as a resilient, sustainable energy solution for a brighter future.

**Figure 16** | Roadmap for the Photovoltaic Industry, recommendations to help tackle end-of-life challenges (Figure on page 53) (Source: Drawn by Costa, 2025)

# Roadmap for the Photovoltaic Industry

Recommendations to help tackle end-of-life challenges

**1** *Recommendation 1 | Follow circular economy principles*

**2** *Recommendation 2 | Adopt digital materials passports to improve data standardisation and traceability*

**3** *Recommendation 3 | Prioritise design for disassembly, reuse, durability and recyclability*

**4** *Recommendation 4 | Mitigate early loss scenarios and extend lifecycle of materials*

**5** *Recommendation 5 | Explore partial repowering and cannibalisation strategies*

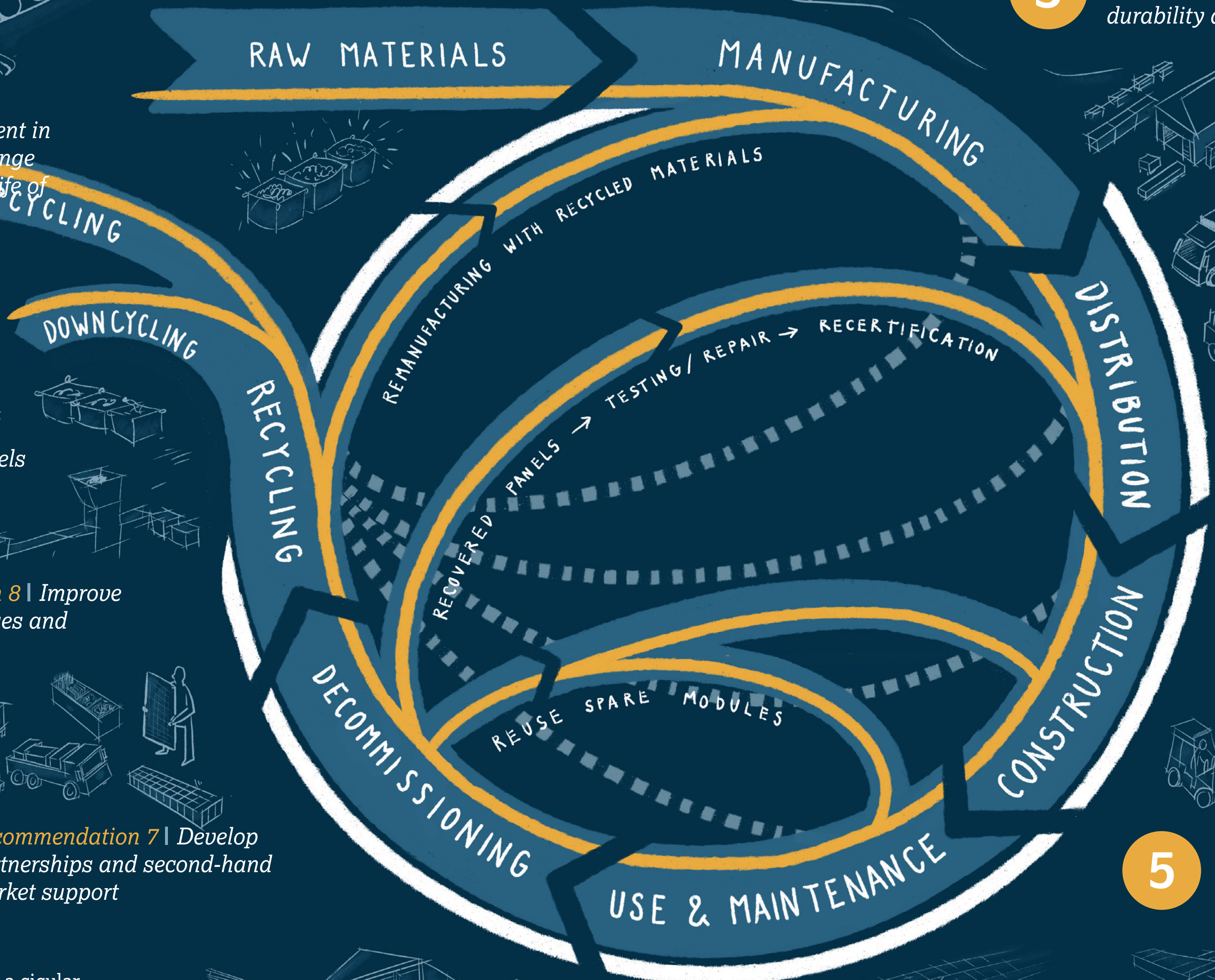
**6** *Recommendation 6 | Explore reuse potential and second-hand market opportunities*

**7** *Recommendation 7 | Develop partnerships and second-hand market support*

**8** *Recommendation 8 | Improve recycling processes and technologies*

**9** *Recommendation 9 | Create specific regulations for PV panels*

**10** *Recommendation 10 | Investment in research and knowledge exchange opportunities to tackle end-of-life of PV panels*




- PV Panels lifecycle to create a cicular economy
- Early loss recycling loops
- Digital Materials Passports
- Second-hand markets, e.g. domestic use, universities, hospitals, community hub

The PV industry, government and researchers need to work together to achieve these recommendations. If we tackle the challenges that affect the end-of-life of PV panels now, we will be able to build a truly sustainable and brighter future.

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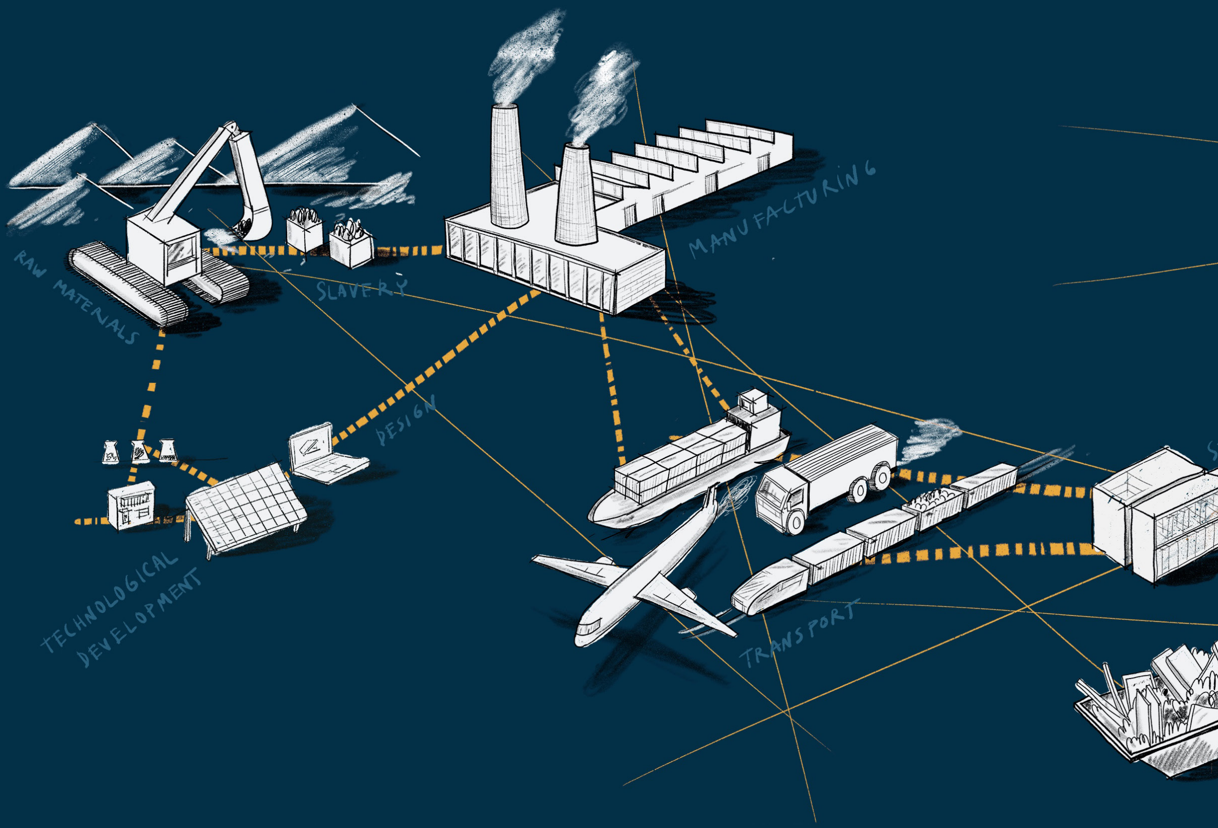
The solar photovoltaic (PV) industry plays a vital role in the global transition to low-carbon energy. With the rapid growth of installations, PV technology supports enhanced energy security, lower electricity costs, and contributes significantly to reducing greenhouse gas emissions: an essential step towards achieving net-zero energy goals.

However, to fully capitalise on its benefits, there must be a focus on addressing the end-of-life of PV panels. Solar panels are generally designed to have a lifespan between 25 and 30 years. Nevertheless, PV panels can be removed after only 10 to 15 years due to early life failures, and replaced with more efficient ones. Consequently, up to 78 million tonnes of PV waste may be produced globally by 2050.

Improved recycling practices, better panel designs for disassembly, and the transition to a circular economy model are essential for enhancing the sustainability of the solar PV industry. The UK has a significant opportunity to lead in these efforts, both in terms of innovation and policy development.




The End of Renewable Asset Life Decisions (ERALD) research project was funded by EPSRC IAA at Lancaster University and Bluefield Solar Income Fund (BSIF), a FTSE 250 solar-focused investment fund. The main output of this project is this white paper that summarises the main challenges to achieve a circular solar PV sector and highlights potential solutions, providing recommendations for industry and policy makers. Our primary focus is on Crystalline Silicon (c-Si) PV Panels, representing 95% of the PV industry market worldwide.