

SOLAR MODULE RECYCLING



IMAGE: SMART ENERGY COUNCIL



TABLE OF CONTENTS

SOLAR MODULE RECYCLING	3
Main Processes	3
Silicon-based solar modules	4
Thin-film solar modules	5
Material Recovery Rates and Efficiencies	5
Legislation Around the World	5
Legislation in Australia	6
Recycling Around the World	7
Current Status in Australia	8
Main challenges and Further development	8
Economic Aspects of Recycling	9
Design for Recycling (DfR)	10

SOLAR MODULE RECYCLING

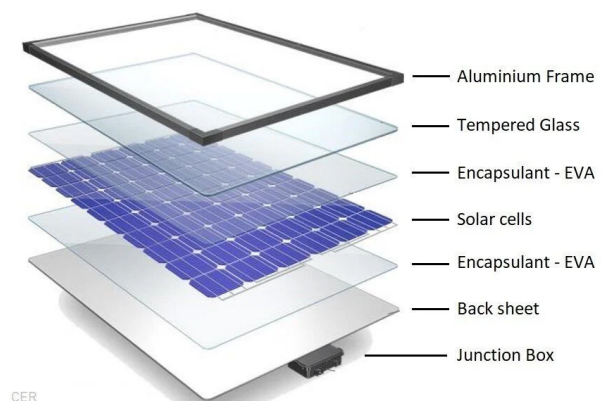
The global shift to renewable energy sources, led by solar photovoltaic (PV) technology, has ushered in an era of extraordinary growth. However, this rapid expansion presents a growing challenge: managing end-of-life solar modules. As the first wave of large-scale solar installations reach the end of their operational life, the need for effective and sustainable recycling solutions becomes increasingly important. This report analyses the complex landscape of solar module recycling, offering a comprehensive overview of the technologies, policies, and advancements shaping this vital sector.

This report offers a comprehensive analysis of solar module recycling processes, techniques, and global legislation, with a focus on Australia. It evaluates Australia's current recycling infrastructure and capabilities, identifying opportunities for development and outlining steps toward a sustainable solar module recycling ecosystem.

Main Processes

Currently, the two primary solar module technologies prevalent across the globe are silicon-based (Si) and thin-film.

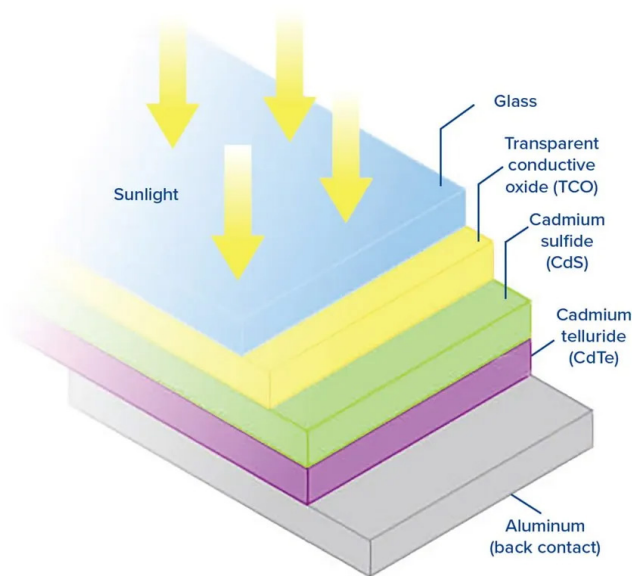
- **Si solar modules¹** are the most common type, constituting the majority of the market. They are known for their high efficiency and long lifespan. Si modules are further divided into monocrystalline and polycrystalline types, each with slight variations in efficiency and cost.



¹ Image from: Chen, P.-H.; Chen, W.-S.; Lee, C.-H.; Wu, J.-Y. Comprehensive Review of Crystalline Silicon Solar Panel Recycling: From Historical Context to Advanced Techniques. Sustainability 2024, 16, 60. <https://doi.org/10.3390/su16010060>



- **Thin-film solar modules²** are less common but offer certain advantages such as flexibility and potential for lower manufacturing costs. Cadmium Telluride (CdTe) is the most common thin-film technology, but other materials like Copper Indium Gallium Selenide (CIGS) and Amorphous Silicon (a-Si) are also used.



Recycling solar panels, regardless of their technology, entails a meticulous process of disassembling the various layers that have been securely adhered together. This separation is essential for the recovery and recycling of individual materials like glass, metals, and semiconductors. However, the layers are often bonded using strong adhesives and encapsulants designed to protect the panel from moisture and environmental damage, making the separation process challenging.

Despite these difficulties, innovative recycling technologies have emerged to address this challenge. These processes typically involve a combination of mechanical, thermal, and chemical techniques to separate the different components. The recovered materials can then be reused in the manufacturing of new solar panels or other products, reducing the need for virgin materials and minimising waste. Recycling solar panels not only conserves valuable resources but also helps to mitigate the environmental impact of solar energy production and prevent the disposal of valuable and (depending on the technology) potentially hazardous materials in landfills.

Silicon-based solar modules

Recycling solar modules involves a few key steps to recover valuable materials and minimise environmental impact. Currently, the main processes used consist in the following steps:

1. **Initial Dismantling:** The aluminium frame and the junction box (where the wires connect) are taken off. These parts are usually easy to recycle as they are made of materials that are very common and easy to recycle.
2. **Glass Separation:** The bulk of a solar panel is glass, so getting that separated is key. However, this step of the process is challenging. There are a few different processes that can be performed:

- **Mechanical:** This is the most common process used, mainly because it is the most financially viable of them all, at the moment. This process consists of shredding the panels using specific machines, then the glass is separated from the other materials (mainly metals) through mechanisms such as crushing and sorting.
- **Thermal:** This process involves heating the panel (usually in tailored furnaces) to break down the adhesive (known as ethylene vinyl acetate - EVA) that holds the glass to the solar cells and connections. This process has some variations, but it's usually more expensive than the mechanical process, which makes it more uncommon.
- **Chemical:** Similar to the thermal process, however this method uses chemical solutions to dissolve the adhesive (EVA) and separate it from the rest of the valuable materials. Again, this process uses different chemical solutions, but it's usually more expensive than the mechanical process, which also makes it more uncommon.

3. **Material Recovery:** Once the glass is separated, the focus shifts to getting the valuable materials out of the remaining parts. This includes metals such as: silicon, silver, copper, cadmium and tellurium, depending on the module technology.

While mechanical, thermal, and chemical processes currently exist for recycling solar modules, researchers are actively developing innovative methods to improve both the affordability and efficiency of material recovery. The primary goal of these advancements is to maximise the extraction of valuable materials, which can then be either upcycled into higher-value

2 Images from: <https://www.energy.gov/eere/solar/cadmium-telluride> and <https://www.intechopen.com/chapters/68684>

products or directly reused in the production of new solar modules. This focus on resource recovery and circularity not only reduces the environmental impact of solar panel waste but also supports a more sustainable and economically viable solar industry.

Thin-film solar modules

The most common recycling process for thin-film solar modules is the one developed by First Solar³, which aims to recover over 90% of the materials from the original modules. The process is a multi-step approach designed to recover valuable materials from end-of-life CdTe solar modules, and it consists in the following steps:

1. **Module Disassembly:** The process begins with the physical dismantling of the solar modules. Components like the glass substrate, metal frames, and encapsulant materials are separated.
2. **Material Separation:** Specialised techniques (shredding, milling, and chemical treatments) are employed to separate the remaining materials within the module.
3. **Material Recovery:** The key focus is on recovering the valuable semiconductor material, cadmium telluride (CdTe). Other materials like glass and metals are also recovered for reuse. Then the recovered CdTe component undergoes a purification process to ensure its suitability for use in new solar modules, completing the circular economy loop.

Material Recovery Rates and Efficiencies

Material recovery rates and efficiencies are crucial metrics for evaluating the sustainability and economic viability of solar panel recycling. There are, however, significant variations in the recovery of key materials like silicon, silver, aluminum, and glass, depending on the recycling process employed. Traditional mechanical crushing methods, while relatively straightforward, often result in lower recovery rates and material contamination, particularly for high-value components like silver and silicon. Conversely, more advanced techniques, such as chemical leaching and thermal processing, demonstrate higher recovery rates but may require more energy and specialized infrastructure. For instance, sophisticated chemical leaching processes can achieve silver recovery rates exceeding 95%, while mechanical methods might only yield around 80%.

Hybrid approaches, combining mechanical pre-treatment with chemical or thermal refinement, often present the most balanced solution, maximising recovery while minimising environmental impact. Thermal processes, which use high temperatures to separate materials, can effectively recover glass and aluminum, but may degrade the quality of silicon. Chemical processes, while capable of achieving high purity levels, can be environmentally intensive and require careful management of hazardous byproducts.

The purity of recovered materials directly influences their suitability for reuse and, consequently, their market value. High-purity silicon, for example, can be reintegrated into the production of new solar cells, closing the loop and reducing the demand for virgin materials. However, if the recovered silicon is contaminated with impurities, it may only be suitable for lower-grade applications, such as metallurgical silicon production. Similarly, high-purity silver can be used in electronic components, while contaminated silver may only find applications in less demanding industries. Achieving high material purity requires sophisticated separation and refining processes, which often come with increased costs. Therefore, optimising material recovery rates and efficiencies while ensuring high purity is a key challenge in the development of sustainable and economically viable solar panel recycling solutions.

Legislation Around the World

The lack of global standardisation in solar module recycling legislation needs urgent attention. With growing environmental concerns, governments are recognising the importance of responsible solar module disposal. Extended Producer Responsibility (EPR) models, where manufacturers are responsible for product end-of-life management, are being adopted by many jurisdictions. However, EPR implementation remains inconsistent, with some regions having comprehensive frameworks and others lacking specific legislation. This regulatory patchwork creates challenges for manufacturers and hinders recycling efforts. Harmonisation of solar module recycling legislation is crucial to establish a level playing field, promote a strong recycling industry, and ensure solar energy's environmental benefits are not compromised.

³ <https://www.firstsolar.com/en/Solutions/Recycling>

Examples of Recycling Regulations for Solar Modules

- **European Union (EU):** The Waste from Electrical and Electronic Equipment (WEEE) Directive⁴ mandates collection and recycling targets for solar modules. This directive ensures that producers are responsible for the end-of-life management of their products, promoting the development of a circular economy for solar panels. Specific targets are set for collection and recycling rates, and member states are required to implement measures to achieve these targets.
- **United States:** While there is no federal-level mandate for solar panel recycling, several states have taken the initiative to implement take-back programmes and recycling requirements for solar manufacturers⁵. These programmes aim to ensure that solar panels are properly recycled at the end of their lifespan, preventing valuable materials from ending up in landfills and reducing environmental pollution. Some states also offer incentives for solar panel recycling, such as tax breaks or grants.
- **China:** China has implemented policies to encourage domestic recycling capacity and reduce reliance on waste imports. The country has introduced regulations and standards for solar panel recycling⁶, and has provided financial support for the development of recycling facilities. These policies aim to create a sustainable and self-sufficient solar panel recycling industry in China, while also addressing the environmental challenges associated with solar panel waste.
- **India:** India has recently included solar panels under its Extended Producer Responsibility (EPR) regulations for e-waste⁷. This means that solar panel manufacturers are now responsible for the collection and recycling of their products at the end of their lifespan. The EPR regulations aim to promote environmentally sound management of solar panel waste and encourage the development of a circular economy for solar energy.

- **Japan:** Japan's legal framework for solar panel recycling, while not mandatory, sets specific targets for material recovery and recycling rates. This framework is supported by the Waste Management and Public Cleansing Law (1970)⁸ and the Japan Photovoltaic Energy Association (JPEA) Recycling Guidelines (2014)⁹, which together provide a structured approach to PV waste management and aim to minimise environmental impact. Additionally, Japan has implemented a deposit system that ensures solar panel owners contribute to recycling costs.
- **South Korea:** South Korea has implemented a producer responsibility scheme for solar panel recycling¹⁰, with manufacturers being responsible for the collection and recycling of their products. The country has also established a fund to support research and development in solar panel recycling technologies.

The worldwide regulatory landscape for solar panel recycling is rapidly changing as more countries realise the need for sustainable end-of-life practices for solar energy systems. It is critical to develop strong recycling infrastructure and policies to maintain the environmental benefits of solar energy and mitigate waste management challenges, especially with the industry's continuous growth. As the solar industry expands, it is anticipated that more countries will implement specific legislation to manage the environmental and economic challenges of end-of-life solar modules.

Legislation in Australia

While a comprehensive federal legislative framework for solar panel recycling has yet to be established in Australia, several states and territories have taken proactive steps by initiating programmes and policies aimed at addressing this emerging challenge. These initiatives encompass a multi-faceted approach, with a strong emphasis on developing the necessary infrastructure for collection and recycling, raising

4 https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en

5 <https://www.epa.gov/hw/end-life-solar-panels-regulations-and-management>

6 <https://www.sciencedirect.com/science/article/abs/pii/S0045653523021094>

7 <https://www.lexology.com/library/detail.aspx?g=e85300c9-e1fb-4745-b007-b94eeef97005#:~:text=A%20cornerstone%20of%20India's%20e,sound%20disposal%20of%20e%2Dwaste>

8 https://www.env.go.jp/en/recycle/basel_conv/files/Waste_Management_and_Public_Cleansing.pdf

9 In Japanese: <https://www.jpea.gr.jp/wp-content/themes/jpea/pdf/t171211.pdf>

10 https://unosd.un.org/sites/unosd.un.org/files/session_7._je_dong-sik_k-eco.pdf

public awareness about the importance of responsible disposal, and encouraging industry stakeholders to adopt sustainable practices throughout the solar panel lifecycle.

Specific measures undertaken by these state and territory governments include providing financial incentives or subsidies for recycling facilities, establishing collection points or take-back schemes for end-of-life solar panels, and mandating producer responsibility for managing solar panel waste. Additionally, these initiatives may also involve conducting research and development to improve recycling technologies and processes, as well as collaborating with industry and research institutions to foster innovation in solar panel recycling.

The recycling of solar modules in Australia is primarily driven by market forces and industry initiatives, rather than specific legislation mandating recycling. However, there are some state-level programs and policies that indirectly support recycling efforts:

- **New South Wales:** Offers interest-free loans for solar-battery systems, promoting the use of longer-lasting and potentially more recyclable technologies. Also, by implementing the Solar & Energy Efficiency Grant for Apartments, encourages the adoption of solar power in multi-unit dwellings, which can potentially lead to increased recycling rates as these systems may be replaced more frequently.
- **Queensland:** Although there is no legislation yet, the SEC pilot programme in Queensland is a crucial step towards sustainable solar panel end-of-life management in Australia. It prioritises collection and recycling of solar panels from various sources and will collect data to inform future policies. Installers may receive incentives, and the programme's success will influence national policies for solar panel recycling, job creation and economic growth.
- **Victoria:** Provides rebates and interest-free loans for solar panel and battery installations, indirectly supporting the growth of the solar market and potentially increasing the future volume of end-of-life modules. Also, implemented the Solar for Rentals Program that encourages landlords to install solar systems, which may contribute to a larger pool of solar panels for potential recycling in the future.
- **Australian Capital Territory:** The Sustainable Household Scheme offers zero-interest loans for solar and battery storage systems, promoting the adoption of renewable energy technologies.

- **Other States and Territories:** While specific recycling-focused legislation is limited, most states and territories have policies related to waste management and e-waste disposal, which may indirectly cover solar modules as a component of electronic waste.

Recycling Around the World

The global landscape of solar panel recycling is varied, reflecting differing levels of regulatory foresight and technological advancement. While the need for sustainable end-of-life management for solar modules is broadly acknowledged, practical implementation varies considerably between countries. The WEEE Directive in Europe sets a precedent with mandated collection and recycling targets, but maintaining high recovery rates and economic viability remains challenging. China, a major producer and consumer of solar panels, is actively developing its domestic recycling infrastructure to manage its own waste stream. In contrast, the United States lacks a unified federal approach, resulting in a patchwork of state-level initiatives and a gap in comprehensive national recycling. India has recently included solar panels under EPR regulations, representing a proactive step, but faces the challenge of establishing robust collection and processing networks.

Barriers to solar module recycling include economic, technological, and infrastructural aspects. High costs associated with collection, transportation, and the recycling process itself often outweigh the market value of recovered materials, creating a disincentive for investment. Also, current technological methods are not sufficiently advanced to efficiently and cost-effectively extract all valuable materials from the diverse composition of solar modules. A lack of adequate infrastructure, including specialised recycling facilities and standardised collection systems, further impedes efficient and widespread recycling. These combined barriers pose a significant challenge to the sustainability of the solar energy industry, necessitating a concerted effort from stakeholders to develop innovative and economically viable solutions.

On the other hand, recycling solar modules provides numerous benefits, including job creation in collection, transportation, processing, and materials recovery. Additionally, recycling reduces the need for virgin materials, thereby lowering production costs and environmental impact. It also recovers valuable materials like silicon, silver, and copper, reducing the

need for mining and extraction. Recovered materials can be used to manufacture new products, creating new economic opportunities and promoting a circular economy where materials are reused and recycled, minimising waste and environmental impact.

The drive towards a more sustainable world has led to increased efforts in solar module recycling. Research is ongoing to develop more efficient and cost-effective recycling technologies. Voluntary take-back programmes and recycling initiatives are being developed by manufacturers and industry associations, while governments are implementing policies such as Extended Producer Responsibility (EPR) to incentivise recycling and promote sustainable end-of-life management. Increased public awareness is crucial to promote greater participation in solar module recycling programmes.

Current Status in Australia

Currently Australia's solar panel recycling is facing the challenges of establishing a robust and economically viable system. While the nation has embraced solar energy installation and use with enthusiasm, the corresponding infrastructure for managing end-of-life modules is still lacking. Currently, there's no federal legislation mandating solar panel recycling, leaving the onus on state-level initiatives and industry-led programs. This has resulted in a fragmented approach, with limited standardised collection and processing facilities.

Queensland's SEC pilot program represents a significant step forward, aiming to establish a framework for collection and recycling, and providing valuable data for future national strategies. However, the lack of widespread, accessible collection points and the absence of clear, consistent regulations across all states and territories remain significant hurdles. The economic viability of solar panel recycling is also a key concern, as the costs associated with collection, transportation, and processing often outweigh the value of recovered materials. This necessitates exploring innovative recycling technologies and potentially implementing financial incentives to encourage participation.

Looking ahead, Australia needs a cohesive national strategy to address the growing volume of end-of-life solar panels. This would involve developing comprehensive legislation, investing in recycling infrastructure, and fostering collaboration between government, industry, and research institutions. Without such coordinated efforts, the environmental

benefits of solar energy risk being undermined by the challenges of managing its waste stream.

Main challenges and Further development

As discussed in this report, the recycling of solar modules is a critical aspect of ensuring the long-term sustainability of solar energy. While solar power offers numerous environmental benefits, the increasing volume of end-of-life solar panels poses significant challenges, including:

- Solar panels are made from different materials such as glass, silicon, metals (aluminum, copper, silver, etc.), and polymers. They also have different sizes of cells, and consequent sizes of modules, which makes it difficult to develop one unique and standardised recycling process and requires tailored machines to accommodate different sizes and technologies.
- The cost of recycling solar panels can sometimes outweigh the value of the recovered materials, since the most valuable materials are in small amounts in solar modules. There is also the cost for transportation and labour, which in Australia can be very significant.
- Establishing efficient collection and transportation systems for end-of-life solar panels is crucial. This is particularly challenging in remote areas, where several solar farms are located in Australia. The build up of sufficient recycling infrastructure is crucial.
- Consistent, comprehensive and mandatory regulations are needed to promote responsible solar panel recycling. Many regions are still developing their regulatory frameworks, leading to inconsistencies and uncertainties and a lack of incentives from government and other stakeholders for the development of more modern and efficient re.
- Some solar panels contain potentially hazardous materials, such as lead (from the solder of older modules) and cadmium (only in thin-film technologies, such as CdTe). Proper handling and disposal are essential to prevent environmental contamination.
- Educating the public, policymakers, and the solar industry about responsible solar panel disposal is essential. This includes not just information on potential environmental hazards, economic benefits of recycling, but also the roles and responsibilities of individuals, businesses, and governments in promoting and being accountable for responsible disposal of solar panels.

All these challenges need to be addressed, which shows that there is significant room for improvement in this sector. The future developments will be crucial to ensure the industry's success both in Australia and around the world. By overcoming these challenges and embracing innovation, the solar panel recycling industry can become more efficient, sustainable and economically viable, contributing to a circular economy and reducing the environmental impact of solar energy.

- Research and development of current technologies are needed to create more efficient and cost-effective recycling technologies. This includes developing methods to recover valuable materials with high purity, faster and using as much automation as possible to reduce labour costs.
- Efforts from the manufacturing industry to standardise solar panel design, size and materials to facilitate recycling processes, and reduce costs of transportation and the recycling process itself.
- Extended Producer Responsibility (EPR) programs serve to shift the onus of end-of-life management onto manufacturers. This strategic allocation of responsibility aims to incentivise the development of panel designs that are amenable to recycling, and at the same time reducing costs associated with end-of-life processing.
- To minimise environmental impact and promote sustainability, the solar industry should prioritise circular economy principles. This includes reusing and refurbishing solar panels, in addition to recovering and recycling components and materials from decommissioned panels.
- Efficient collection networks and logistics solutions are essential for proper end-of-life solar panel management. Key components include convenient collection points, cost and impact minimisation strategies, clear handling guidelines, and adequate recycling capacity. Success depends on effective collaboration between all stakeholders.
- Finally, governments play a crucial role in promoting solar panel recycling by implementing supportive policies, providing financial incentives, and establishing clear regulatory frameworks.

Economic Aspects of Recycling

The economic viability of solar module recycling is a complex interplay of costs, market demands, and policy support. Given the increasing demand for resources like high-purity silicon, silver, and

aluminum in various industries, these recovered materials have significant potential value. Therefore, a comprehensive cost-benefit analysis is crucial when evaluating recycling processes. This analysis must weigh the expense of advanced techniques, such as chemical leaching or thermal treatments, against the potential revenue from the recovered materials. Despite challenges due to fluctuating commodity prices and the need for consistent, high-quality output, subsidies and incentives like tax breaks or feed-in tariffs for recycled materials can make the recycling industry more financially viable by offsetting costs and improving market returns.

The solar panel recycling market is set to grow due to a combination of factors. As discussed in this report, the rapid increase in solar panel installations will result in more end-of-life PV modules that will need to be recycled. Additionally, governments are continuously implementing regulations to mandate proper disposal and recycling, and there is a growing demand for a circular economy to address environmental concerns. Although some regions still lack recycling infrastructure, and technological and economic challenges remain, this growing market continues to encourage investment in advanced recycling technologies and logistics solutions. It is expected that standardised recycling processes and quality control could potentially further enhance market stability and investment.

The solar panel recycling sector also presents a significant opportunity for job creation. This potential extends across various stages of the recycling process, including the collection and transportation of end-of-life solar panels, the dismantling and separation of components, the processing and recovery of valuable materials, and the refinement of these materials for reuse in new products. As the solar industry continues to grow and the volume of decommissioned solar panels increases, the demand for skilled workers in the recycling sector is also expected to rise, contributing to economic development and environmental sustainability.

The strategic placement of recycling facilities can maximise local job opportunities. Locating facilities near solar farm clusters or in regions with existing manufacturing infrastructure can reduce transportation costs and create synergies with related industries. Moreover, investing in research and development, as well as worker training programs, will foster a skilled workforce and ensure the industry's long-term sustainability. The transition to a circular

economy, where materials are recovered and reused, is essential for minimising environmental impact and promoting resource efficiency. Solar module recycling plays a crucial role in this transition, reducing the need for virgin materials and minimising waste. This closed-loop approach aligns with global sustainability goals and offers a compelling economic and environmental proposition.

Design for Recycling (DfR)

To enhance the recyclability of solar panels and minimise waste, manufacturers should include end-of-life recycling and material recovery aspects in their initial design. This involves considering the entire lifecycle of the product. Starting with a careful selection of raw materials, prioritising using recyclable, widely available and/or non-toxic materials that have established recycling processes, avoiding the use of hazardous materials and substances that are difficult to recycle.

The recyclability of a solar panel module is significantly impacted by its design, as all the layers are firmly bonded together to prevent moisture from penetrating the solar cells, which can cause damage and reduce efficiency. Manufacturers should prioritise designs that enable easy disassembly and component separation for recycling, without compromising solar cell efficiency or causing damage. The use of adhesive materials, such as EVA (Ethylene-vinyl acetate), is a common design element in solar modules that poses a significant challenge for recyclers due to the difficulty in separating and obtaining high-purity recycled materials. To address this, some manufacturers are exploring and testing efficiency and durability for alternative solutions, including different types of adhesives and even vacuum solutions.

Other solutions may involve using fasteners and connections that can be readily removed, clear labelling and identification of different components and materials, the use of standardised components and sizes across different solar panel models and manufacturers. These upgrades allow for easier identification, sorting, and processing of materials during recycling, leading to increased efficiency and material recovery.

Establishing partnerships with recycling companies and industry stakeholders is crucial to build a robust and comprehensive recycling infrastructure for solar panels. This collaborative effort requires investment in research and development to create efficient, safe, and cost-effective recycling processes that maximise the recovery of all materials. It also necessitates ensuring that recycled materials are high-quality and can be reintroduced into the supply chain at competitive prices, creating a circular economy for the solar and other industries.

Finally, developing a network of collection points, transportation systems, and recycling facilities is essential to handle the growing volume of end-of-life solar panels safely and responsibly. Collaboration with governments and regulatory bodies is also needed to establish clear guidelines, standards, and incentives that promote solar panel recycling and create a level playing field for all stakeholders. Besides, educating consumers, installers, and manufacturers about the importance of solar panel recycling and their role in supporting a sustainable energy future is vital. By fostering collaboration and innovation across the solar value chain, we can ensure that the rapid growth of solar energy is accompanied by responsible end-of-life management practices, minimising environmental impact and maximising resource recovery.