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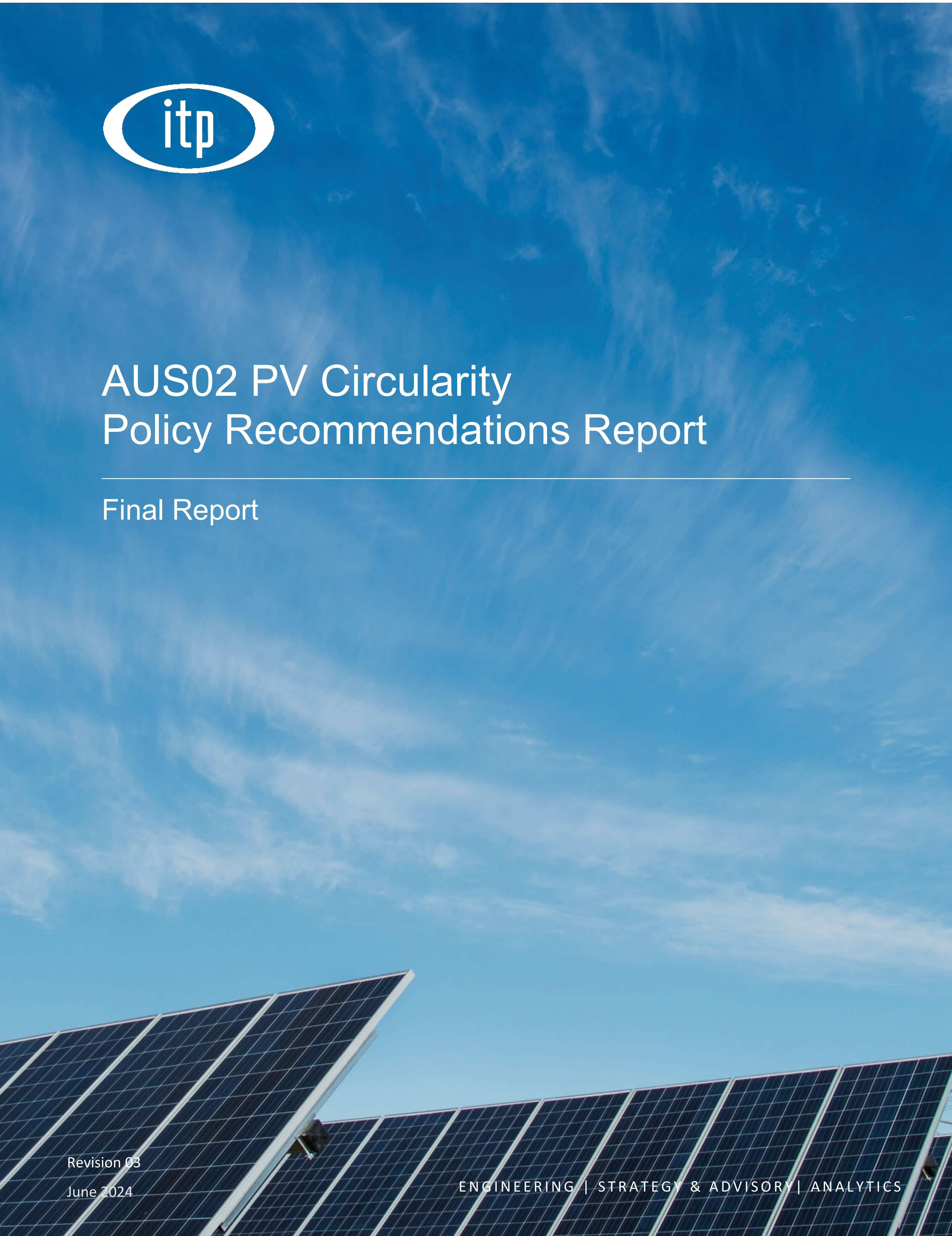

AUS02 PV Circularity Policy Recommendations Report

Final Report

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Client	GIZ	Client Contact	Thea Khitarishvili		

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ITP Renewables
Office: Level 1, 19-23 Moore St
Turner ACT 2612
Postal: PO Box 6127
O'Connor ACT 2602
Australia
Email: info@itpau.com.au
Phone: +61 (0) 2 6257 3511

itpau.com.au

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ABOUT THIS REPORT

This report was commissioned by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) as part of the EU Climate Dialogues (EUCDs) initiative. It provides policies and actions to facilitate photovoltaic (PV) circularity in Australia. The report draws on the findings from the five PV circularity policy dialogue workshops held between August 2023 and April 2024, and on the project team's engagement with key stakeholders to provide policy recommendations for facilitating PV circularity in Australia.

ABBREVIATIONS

ARENA	Australian Renewable Energy Agency
AUD	Australian Dollar
DCCEEW	Department of Climate Change, Energy, the Environment and Water
EEE	Electrical and Electronic Equipment
EoL	End-of-Life
EPR	Extended Producer Responsibility
EU	European Union
EUCDs	EU Climate Dialogues
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GW	Gigawatt (1 billion watts)
GWp	Gigawatt-peak, unit of power for PV panels tested at standard testing conditions
ITP	IT Power (Australia) Pty Ltd
kW	Kilowatt, unit of power
kWh	Kilowatt-hour, unit of energy (1 kW generated/used for 1 hour)
kWp	Kilowatt-peak, unit of power for PV panels tested at standard testing conditions
MW	Megawatt, unit of power
PV	Photovoltaic
STC	Small-scale Technology Certificate
TW	Terawatt (1 trillion watts)
TWp	Tewawatt-peak, unit of power for PV panels tested at standard testing conditions
UNSW	University of New South Wales
WEEE	Waste Electrical and Electronic Equipment

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EXECUTIVE SUMMARY

Australia has rapidly adopted solar photovoltaics (PV) in recent years, bolstered by feed-in-tariffs and government subsidies. At the end of 2023, Australia exceeded 34 gigawatts of installed PV capacity and is a world leader for installed solar capacity per capita, driven by high uptake of residential and commercial rooftop solar PV systems. This PV deployment will translate into an increase in PV waste generation, with Australia forecast to approach 1 million tonnes of cumulative PV waste by 2033, and over 3 million tonnes by 2050.

While Australia is leading in PV deployment, it is lagging in PV circularity. PV panels contain energy- and emissions- intensive materials such as aluminium and silicon, valuable materials such as silver and copper, and toxic materials such as lead, antimony, and cadmium (present in 5% of commercial panels). Without action, much of this PV waste will enter landfill, which results in resource loss and presents environmental and health hazards.

The circular economy framework presents strategies to reduce waste, mitigate environmental impacts, and maximise resource utilisation. Due to Australia's reliance on imported PV modules, there is limited potential for policy to influence module design and manufacturing. Therefore, circularity strategies should aim to extend PV operational life through actions such as reuse and repair, and minimise waste creation through recycling. This report presents policy options and supportive actions to improve PV circularity in Australia by addressing challenges for reuse, repair, and recycling. Eight key action areas to improve PV circularity in Australia are outlined below.

Action 1: National Coordination on PV Waste Management Policy

Efforts to manage PV waste should be co-ordinated nationally to ensure consistency across states and territories, which will support PV recyclers operating throughout Australia. National coordination could be achieved through a **National PV Waste Management Taskforce** established under the Federal Government in collaboration with state and territory governments, local councils, and industry bodies. A key goal of the Taskforce should be the development of a **National PV Waste Action Plan**, detailing the steps and actions that are needed to manage PV waste in Australia and improve PV circularity.

Landfill bans should be implemented consistently across Australian states and territories, to redirect PV waste towards circular management pathways and support recyclers to build inventory and establish economies of scale. This should include bans on landfilling PV laminate stacks (left over after removal of the aluminium frame, junction box and glass). However, landfill bans are a blunt instrument and may not be effective in achieving other outcomes such as high recycling rates and material recovery. As such, landfill bans must be complemented by supportive policies/actions to reduce other barriers to reuse and recycling.

Action 2: PV Product Stewardship

In October 2022, the Australian Government announced plans to develop a **national product stewardship scheme for solar PV systems** and household electronics, expected to commence in 2025. PV collection and recycling will be funded by liable parties (producers or importers) through fees paid to the scheme administrator once PV panels are placed on the market. The Project Team welcomes the establishment of product stewardship for PV in Australia, as it will support development of waste collection networks, improve the financial certainty for PV recyclers, and increase transparency for PV waste management.

Further, the proposed scheme should include options for liable parties to establish **voluntary partnerships with PV recyclers** to fulfill their regulatory obligations. This will support innovation by incentivising PV recyclers to pursue competitive advantages such as low pricing, high efficiency, or high rates of recovery of valuable materials. The proposed scheme should also incentivise high-value recovery of solar panels to achieve an outcome of over **80% material recovery** to align with the National Waste Policy. However, as this value can readily be achieved from a PV panel's aluminium frames and glass alone, additional financial incentives could be used to encourage the recovery of materials such as silver and silicon. Finally, stakeholder reporting obligations under the scheme should seek to align with the National Framework for Recycled Content Traceability, where possible. Target areas within the framework's scope include the quantity, composition, and quality of materials recovered.

Action 3: Development of PV Collection, Recycling, and Testing Infrastructure

Developing PV collection, recycling, and testing infrastructure across Australia will reduce logistic costs and ensure equitable access to collection services to support PV product stewardship. This should include collection points collocated with local council waste management facilities and PV retailers, allowing a 'reverse logistics' model, where installers can return PV waste when they acquire new stock. Additionally, testing infrastructure to ensure the functionality, safety, and performance of second-life panels can be collocated with recycling facilities to capitalise on existing collection networks. Target areas for developing recycling infrastructure include the greater Sydney, Melbourne, Brisbane, Adelaide and Perth regions, which will account for over 70% of expected waste by 2030. Establishing widespread PV recycling in Australia could see up to 350 local jobs at recycling facilities.

Action 4: Development of End Markets for Recovered Materials

Developing end markets for PV materials will be essential to support the business case for PV recycling by providing increased financial certainty. Further, end markets for PV materials will provide an incentive for recyclers to pursue high recovery rates. **Local PV manufacturing**, such as the establishment of local PV module assembly, solar glass and module frame manufacturing under the Australian Renewable Energy Agency's Solar Sunshot program, could provide a pathway to return recovered materials to the PV supply chain. Bonus production credits could be provided under the Solar Sunshot program for manufacturing PV modules or components with recovered materials. Prior to this, Australia could seek to connect PV recyclers with countries with existing PV manufacturing capacity such as Europe, the US, India, China, and South-East Asia for the export of recovered materials.

Action 5: Development of Standards and Guidelines for End-of-Life PV

Australia should seek to develop **nationally consistent standards and guidelines** on the management of PV during reuse, repair and recycling. For installers, guidelines for decommissioning, handling, and transport of used PV systems are important to minimise the number of broken and poorly packaged panels entering facilities for reuse and recycling. For recyclers, standards and/or guidelines regarding storing and processing of panels should be implemented to address risks such as leaching of toxic materials, toxic gases from thermal processes, the use of hazardous chemicals, and respiratory risks associated with crushing solar panels. Of particular concern are fine glass and silicon powders which may cause respiratory problems, including silicosis. For PV testing facilities, standards and guidelines should detail testing procedures for second-life PV panels to ensure the quality and safety of products entering the second-life market. At a minimum, testing procedures should include visual inspection, electroluminescence or photoluminescence tests, and power tests.

To prevent PV waste relocation overseas, Australia should develop standards governing the export of used PV in line with technical guidelines for transboundary movements of waste- and used electrical and electronic equipment under the Basel Convention.

Action 6: Removal of Technical Barriers to Streamline PV Recycling Activities

Policy actions could seek to streamline PV recycling processes such as panel characterisation and batch processing through increased product transparency. In particular, **panel standardisation** could reduce module variation in the market, reducing barriers to repair, reuse, and recycling. Given Australia's small market, this should involve partnering with larger markets such as the US and Europe, or global initiatives such as the International Energy Agency's Photovoltaic Power Systems program.

Additionally, Australia can mandate comprehensive and robust **PV panel labelling** detailing panel content, performance, and handling requirements, akin to the European Union's forthcoming Ecodesign labelling. This provides transparency, which can allow consumers to make sustainable purchase decisions. Further, it can communicate repair options to installers, streamline panel characterisation for re-use and recycling, and recovery rate tracking.

Action 7: Local Knowledge Building

Training programs should be developed for the future PV recycling workforce, potentially by leveraging expertise in countries with an established PV recycling industry, such as EU Member States. Education for consumers and installers can work to build awareness and reduce premature retirement of functioning PV systems.

Action 8: Research and Development

Funding research and development for end markets will be beneficial for unlocking offtake options and stimulating demand for materials recovered from PV waste, improving the business case for PV recycling. Research could also investigate the commercial viability of using recovered materials in manufacturing or other industrial processes, targeting the use of silicon and glass. Finally, research and development could investigate recycling processes targeting the recovery of high-quality materials for use in the PV supply chain.

1 INTRODUCTION

1.1 Project Background

The European Climate Dialogues (EUCDs) engaged ITP Renewables (ITP) and the University of New South Wales (UNSW) to conduct five policy dialogue workshops on solar photovoltaics (PV) circularity. A key goal of the workshops was to promote discussion and inform policy recommendations and actions for managing PV panels at end-of-life (EoL) in Australia. The recommendations for policy and supportive actions to improve PV circularity in Australia are presented in this report.

1.1.1 The European Union Climate Dialogues Initiative

The EUCDs project was launched in 2022 with the following objectives:

- **Facilitate exchanges on climate policy** options, expertise, success stories, and good practices between the European Union (EU) and non-EU economies to enable policy shifts in partner countries.
- **Advance bilateral trade, investment, and innovation** in line with the goals of the Paris Agreement.
- **Improve public awareness**, including in the business community, of the challenges and opportunities associated with the implementation of the Paris Agreement.

To achieve these objectives, the EUCDs support activities that facilitate cooperation among key stakeholders in the EU and 20 EUCDs partner countries, one of which is Australia.

The accelerated uptake of solar PV in recent years will result in future increases in PV waste. The EUCDs see solar PV circularity as an opportunity for knowledge sharing between the EU, Australia and other EUCDs countries, aiming to build understanding of technical and regulatory solutions for circularity and sustainable PV EoL management.

1.1.2 PV Circularity Policy Dialogue Workshops and Stakeholder Engagement

ITP and UNSW conducted five hybrid policy dialogue workshops on solar PV circularity, which are summarised in Appendix A. The policy dialogue workshops engaged over 140 individuals across Australia, Europe, China, India, and USA. Attendance was diverse and spanned academic organisations, consultancies, government agencies, industry bodies, PV manufacturers, quality testing laboratories, recycling and waste management companies, retailers, and solar developers.

1.2 Circular Economy Framework

The circular economy framework is a systemic approach to development that focuses on reducing externalities (such as waste and pollution) and maximising resource utilisation. The circular economy framework is aligned with the waste hierarchy but places greater emphasis on all stages of the product lifecycle. The framework is built on three core principles:[1]

- Eliminate waste and pollution.
- Circulate products and materials.
- Regenerate nature and natural systems.

Implementing a circular economy involves transitioning away from more traditional linear models for resource use, typically referred to as a take-make-waste model. In doing this, circular economy literature has classified a hierarchy of 10 strategies, numbered R0 to R9 in order of both priority and stage of life, as outlined in Table 1.[2]

[1] Ellen Macarthur Foundation, The Circular Economy in Detail
[2] Heath, G. et al. (2022) A critical review of the circular economy for lithium-ion batteries and photovoltaic panels – status, challenges, and opportunities, Journal of the Air & Waste Management Association, 72:6, 478-539, DOI: 10.1080/10962247.2022.2068878

Table 1: Circular economy hierarchy of strategies

Stage of life	Number	Strategy	Description
Beginning of life	R0	Refuse	Avoiding the consumption of materials. For manufacturers, this could involve the avoidance of toxic or critical materials through product design. For consumers, this could involve avoiding or reducing consumption of a product.
	R1	Rethink	Design of a product to increase usage and durability or management of a product to increase the number of uses.
	R2	Reduce	Decrease consumption of virgin materials.
Operational Life	R3	Reuse	Using a product again for the same functionality or purpose.
	R4	Repair	Restoration of defective, broken, or malfunctioning components with the overall goal of extending the lifetime of the product.
	R5	Refurbish	Improvement of the working condition, quality, or functionality of a product to either upgrade it or return it to its original state.
	R6	Remanufacture	Disassembly and processing of a product into components to be reused in a product with the same functionality.
	R7	Repurpose	Use of the product or its components again by a second customer for a different functionality or purpose.
End of Life	R8	Recycle	Recovery of product materials to be reused, where the materials do not retain their original structure.
	R9	Recover energy	Recovering energy from the end-of-life waste of a product.

1.3 PV Overview

PV panels are complex electronic products with global supply chains, as detailed below. This is key in framing expectations for PV waste and management options in Australia.

1.3.1 PV Panel Composition

PV panels convert light into electricity using a semiconductor material. While there are several PV semiconductor materials, crystalline silicon technologies have more than 95% of commercial market share. Thin-film[3] PV panels, primarily cadmium telluride, make up the remaining 5% of market share. While technology progression is inherently unpredictable, no significant market share changes are expected for these technologies in the next 10-20 years.

The construction of a conventional mono-facial crystalline silicon solar panel with a white backsheet is displayed in Figure 1. Although mono-facial panels have historically held the greatest global market share, the PV industry is transitioning to bifacial panels[4], particularly for utility-scale solar projects.[5] Bifacial panels can accept light on both sides of the panel, leading to higher energy yields, and are expected to dominate the market by 2027.[6] The weight distribution for different components of mono-facial and bifacial panels are shown in Figure 2. Glass contributes approximately 70-80% by weight while aluminium, used for the panel frame, contributes approximately 8-10%. Although the working solar cells represent only 3-4% of panel weight, they account for approximately 50% of the panel manufacturing cost.[7] This is largely due to the cost of high-purity silicon wafers and silver metal contacts.

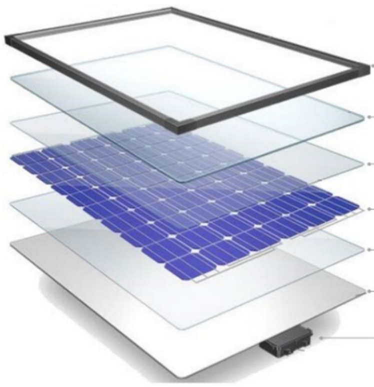

Figure 1: Traditional mono-facial crystalline silicon PV panel (Source: Adapted from Clean Energy Reviews)

[3] Other niche thin-film technologies include copper indium gallium selenide (CIGS), amorphous silicon (a-Si), and gallium arsenic (GaAs).
[4] Bifacial panels feature a clear backsheet or rear glass, allowing both sides of the panel to contribute to electricity generation.
[5] Special Report on Solar PV Global Supply Chains, International Energy Agency (IEA), 2022
[6] International Technology Roadmap for Photovoltaic (ITRPV), VDMA, 2022
[7] Based on values reported by PVinsights for July 2023 and ITRPV for December 2022 (www.pvinsights.com)

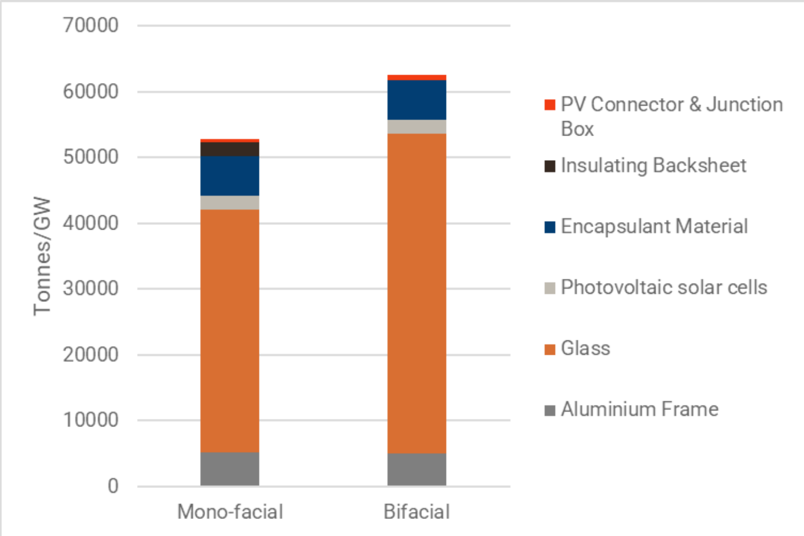

Figure 2: Panel compositions by mass for Trina Solar[8]

Toxic Materials

PV panels can contain toxic materials, as outlined below:

- Lead is contained in some PV solders and some metallisation pastes.
- Cadmium is used for the cadmium-telluride thin-film PV technology, which makes up approximately 5% of PV panels globally.
- Antimony is added to solar glass to reduce photodegradation.

When PV panels are deposited in landfill or the environment, toxic materials can potentially leach into groundwater, which presents environmental and health hazards.

Precious Metals and Rare Earth Elements

PV panels also commonly contain critical materials such as precious metals and rare earth elements. Silver is one such precious metal, and a key component of PV panels. Increases in PV production under business as usual is expected to put significant pressure on silver supplies. PV production accounted for approximately 13% of silver production in 2020. [9]

[8] Environmental Product Declaration: TSM-DEG15M.20(II), TSM-DEG15MC.20, TSM-DEG17M.20(II), TSM-DEG17MC.20, EPD Italy, 2020, viewed 12th Sept 2023.
[9] Hallam, B. et al. (2023). The silver learning curve for photovoltaics and projected silver demand for net-zero emissions by 2050. Prog Photovolt Res Appl. 2023; 31(6): 598-606. doi:10.1002/pip.3661

Further, some PV technologies with smaller market share, such as silicon heterojunction or thin-film cells, use rare earth elements indium and/or gallium.[3] Cadmium telluride thin-film panels require tellurium, and use approximately 40% of the global tellurium supply.[10]

Disposal of panels in landfill will result in the loss of critical materials from the PV supply chain, resulting in the requirement for additional mining, with negative environmental impacts.

Evolving PV Panel Designs

Substantial changes to panel components and panel design have occurred over several decades, including substantial changes to the physical size (see Figure 3). A summary of key changes is detailed in Table 2.

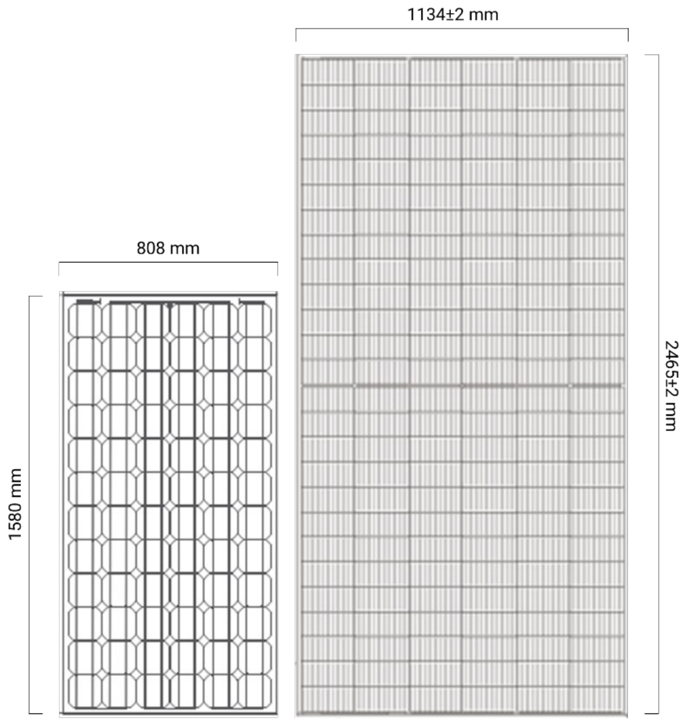

Figure 3: JinkoSolar panel comparison: 200W panel released circa 2011 (left), 615-635W panel released in 2023 (right)

[10] Tellurium Summary 2024, US Geological Survey, 2024

Table 2: Changes in panel characteristics over time

Component or characteristic	Description
Wafer/cell and panel sizes.	Newer cells are larger, dwarfing earlier models. The shift to larger wafer/cell sizes has also increased the panel size over time, as displayed in Figure 3.
Cell technology	The market has been historically dominated by aluminium back surface field solar cells. Since 2017, passivated emitter and rear contact (PERC) cells have dominated the market. However, the industry is now shifting to the use of tunnel oxide passivated contact (TOPCon) cells.
Panel efficiency	Solar cell and panel efficiency has increased in newer panels. This, alongside larger panel sizes, has led to panels with higher nameplate power ratings. Technology development has also increased durability with lower long-term efficiency degradation.
Solar cell technology	Solar cell technologies have changed over time, as detailed above, from Al-BSF to PERC (both using p-type doped silicon), and now towards TOPCon and silicon heterojunction (n-type doped silicon). This will increase the amount of silver used per cell, and the dependence on materials such as indium and bismuth (required for silicon heterojunction).
Silver content	The silver consumption for PV panels (in milligrams per Watt) has decreased continuously over time. Noting silver consumption may increase with the uptake of TOPCon technology.
Junction boxes	Junction boxes, initially located on the short edge of the panel, are now typically located in the centre of the panel. Further, half-cell panels have three separate junction box components across the panel.
Backsheet materials	Backsheet materials have typically been polyvinyl fluoride (PVF) films, however many other materials are now also used including polyethylene terephthalate (PET), fluoroethylene vinyl ether (FEVE), polyvinylidene fluoride (PVDF) and polyamide (PA). Bifacial panels have no backsheet and instead require a rear glass layer.
Aluminium frames	The industry is reducing the thickness of aluminium frames. There are also new solar panels available with steel or fiberglass reinforced plastic (FRP) frames.
Glass thickness	The shift to bifacial panels has increased the overall glass thickness from approximately 3.2mm to approximately 4.4mm (2.2mm + 2.2mm). However new bifacial panels are heading to thinner glass layers of 1.6-1.8mm (total thickness of 3.2 – 3.6mm).

1.3.2 PV Manufacturing

The global PV supply chain is dominated by China, which accounts for 75 - 97% of global panel manufacturing capacity from polysilicon production through to PV panel assembly (see Figure 4).[11] Panel assembly has the lowest level of supply concentration at 75%, while ingot/wafering has the highest at 97%. Across the value chain, Australia and other markets, including Europe, are heavily reliant on imported PV materials.

Australia currently has limited PV manufacturing capacity, despite having manufactured PV cells, panel components, and panels in the past. The only active PV panel producer is Tindo Solar in Adelaide, annual manufacturing approximately 30 megawatts (MW), less than 1% of the annual PV deployment in Australia, detailed in Section 1.3.3 below.[12]

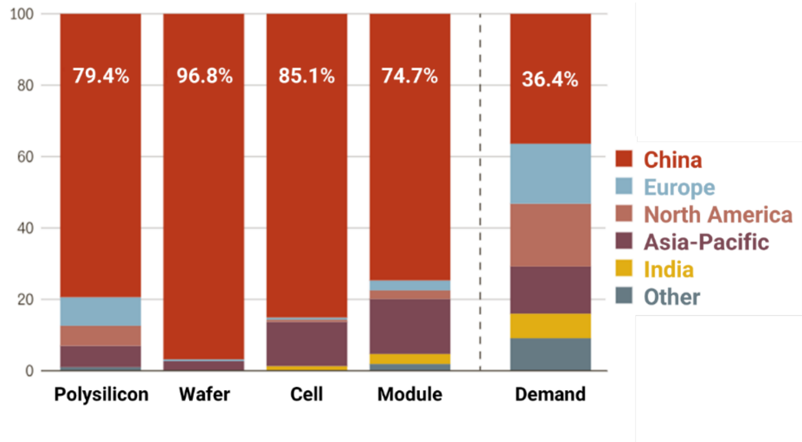

Figure 4: 2021 PV Supply Chain Production Capacity[13]

1.3.3 PV Deployment

Historic and future solar PV deployment will determine the scale and distribution of future PV waste streams. Future deployment also depends on material consumption and supply chain pressures that may arise, particularly for rare earth minerals.

[11] Sun H., China to hold over 80% of global solar manufacturing capacity from 2023-26, Wood Mackenzie, 2023
[12] Watt M. et al., Silicon to Solar Study, Australian Photovoltaic Institute, 2024
[13] Witsch K., The shares of Chinese solar companies are in free fall, Handelsblatt, 2024

Global PV Deployment

Globally, PV production has been increasing exponentially for several decades (see Figure 5). In 2023, the global PV industry deployed 440 GW of solar panels, exceeding 1.6 terawatt peak (TWp) of cumulative installed capacity. In 2023, China installed 277 GWp, more than 50% of the total PV deployed that year. Europe, the second largest global PV market, installed 56 GWp of PV in the same year to reach almost 270 GWp of total capacity.[14]

By 2050, the IEA predicts that a global capacity of almost 15 TWp of solar PV will be required to fulfil the Paris Climate Agreements, equating to 630 GWp of additional capacity per year from 2030.[15] Another analysis, used in the International Technology Roadmap for Photovoltaics (ITRPV) 'broad electrification' scenario, suggests that more than 60 TWp may be needed by 2050 with annual PV deployment increasing to 4.5 TWp.[6] This represents a x40 fold increase in the installed PV capacity, and x10 fold increase in current deployment levels.

Countries and regions around the world continue to increase their targets and expectations for renewables such as solar. As part of the REPowerEU plan, the European Union has recently increased its target to 42.5% of final energy consumption from renewables by 2030, with an aspiration to reach 45%. As part of this, the EU's Solar Energy Strategy aims to reach 600 GW_{AC} – upwards of 750 MWp – of installed PV by 2030,[16] and could see 69% of electricity coming from renewables. The importance of solar for decarbonisation is embedded throughout EU legislation, including in the Energy Performance Buildings Directive, which ensures new buildings are solar ready and includes future rooftop solar mandates for certain building types. These measures could drive the installation of an additional 200 GW of rooftop PV by 2030.[17]

[14] Masson G., et al., Snapshot of Global PV Markets 2024, International Energy Agency Photovoltaic Power Systems Programme, 2024
[15] Bouckaert S. et al., Net Zero by 2050: A Roadmap for the Global Energy Sector, International Energy Agency, 2021
[16] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions: EU Solar Energy Strategy, European Commission, 2022
[17] Energy Performance of Buildings Directive, European Commission, 2024

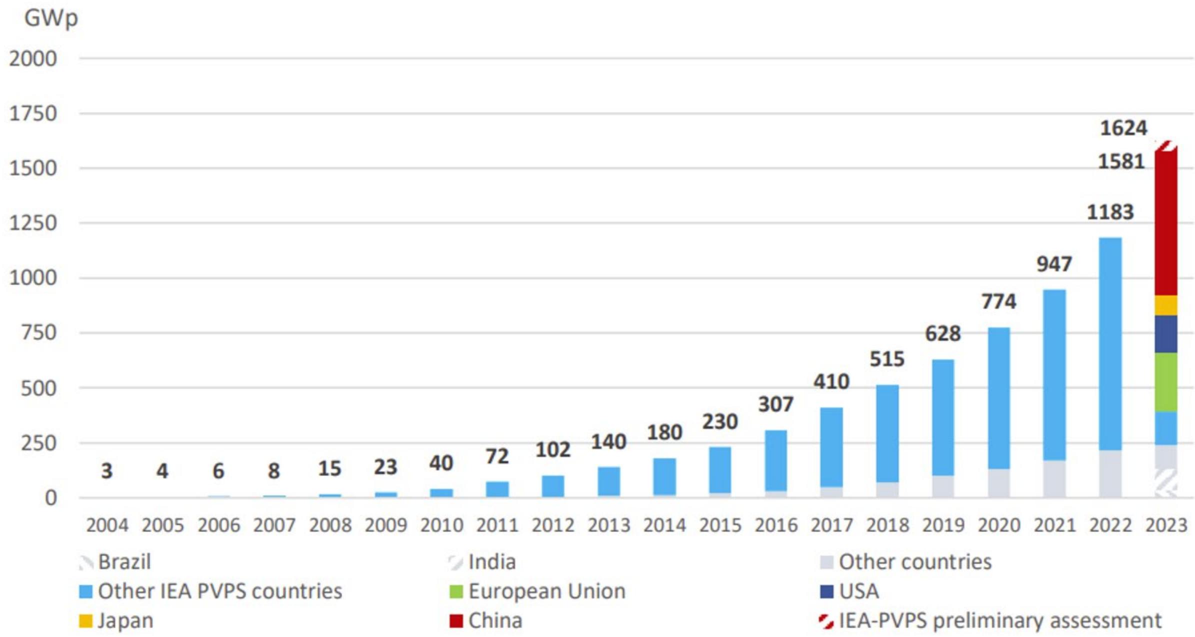

Figure 5: Global cumulative installed PV from 2004 to 2023.[14]

Australian PV Deployment

Australia has rapidly adopted solar PV over the last 14 years (see Figure 6), supported by generous feed-in-tariffs (FiTs) and government subsidies. Figure 7 shows the annual PV installations in Australia by sector. Early deployment of PV systems in Australia was largely driven by residential roof-top and, since 2017, commercial PV installations. Approximately 30% of Australian households now have a PV system,[18] with 90% of all installations having a capacity of less than 10 kWp.[19] From 2018, there has been a significant increase in the deployment of large, centralised PV systems in Australia.

In 2021, annual PV deployment in Australia reached 5 GWp, although this has declined somewhat since then. At the end of 2023, Australia exceeded 34.2 GWp of installed PV capacity.[20] In the same year, Australia had the highest solar PV capacity per capita in the

[18] Solar PV and Batteries, Department of Climate Change, Energy, the Environment, and Water, 2022.
[19] Systems of less than 10 kWp are most commonly installed on residential rooftops as they are best suited to residential loads.
[20] Australian PV Market since April 2001, Australian PV Institute, 2023

world.[21] Approximately 64% of Australian capacity is made up of small-scale PV systems with a capacity below 100 kWp.[21]

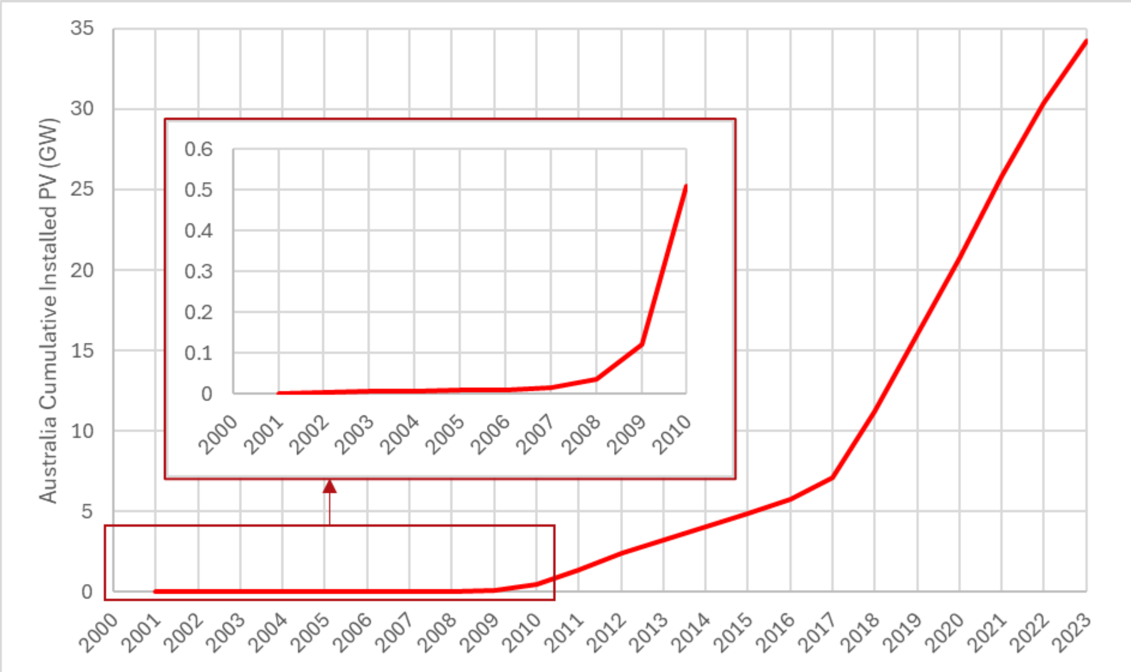

Figure 6: Cumulative installed PV in Australia from 2001 to September 2023[20]

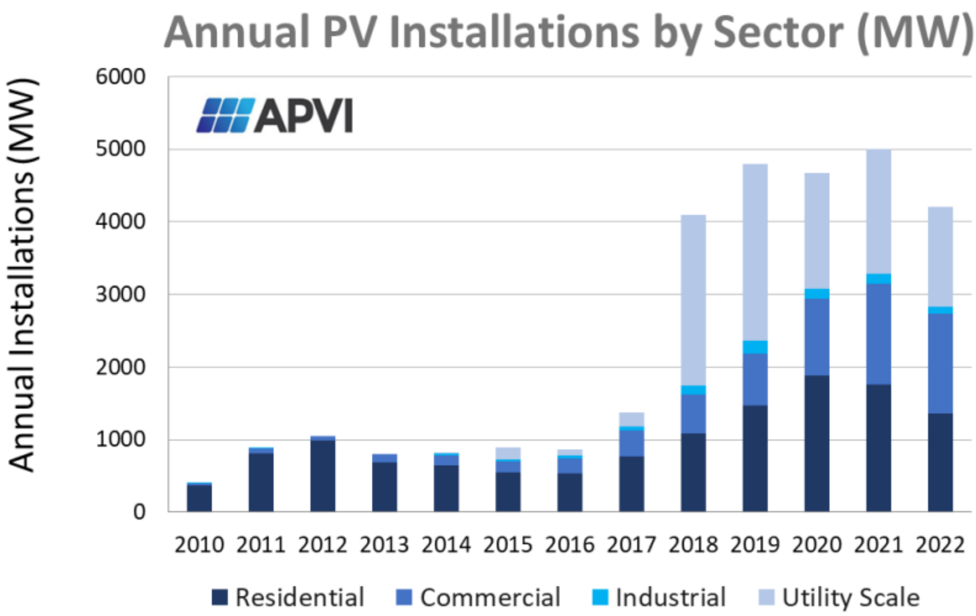

Figure 7: Annual PV installations by sector (Source: APVI)[21]

[21] Carroll D., Australia's cumulative installed PV capacity tops 29.7 GW., 2023

Australia has a renewable energy target of 82% of electricity by 2030 (representing around 15% of final energy consumption).[22] This, and Australia's emissions reduction targets fall well short of targets elsewhere such as in Europe. A recent analysis by Net-Zero suggests Australia may require approximately 300 GW of PV for domestic use by 2050, a 10-fold increase in the current cumulative installed capacity. This will require an annual uptake of 8-16 GWp from now to 2050. For more ambitious scenarios where Australia seeks to become a renewable energy superpower and major exporter of clean energy and 'green hydrogen', PV capacity may need to be as high as 2 TWp by 2050,[23] a 60-fold increase in the installed capacity.

1.4 PV Waste

This section details drivers of PV waste in Australia and provides projections for the volume of PV waste globally and in Australia.

1.4.1 Drivers of PV Waste

The primary drivers of PV waste are:

1. Panels reaching the end of their design life
2. Premature retirement
3. Premature failure

These are outlined below.

End of Design Life

PV panels generally feature performance warranties of 25 to 30 years. Ideally, the volume of PV panels reaching EoL lags installation by this length of time. Such is the case for utility-scale solar farms, which typically plan for an operational life in line with the performance warranty.

Premature Retirement

Panels commonly enter the waste stream prior to reaching the end of their design life, with a recent analysis identifying that the average PV panel lifetime in Australia may be 15-20 years, substantially shorter than the expected 25 years. Residential systems are more susceptible to

[22] Powering Australia, Department of Climate Change, Energy, Environment and Water, accessed 24th May 2024.
[23] Davis D., et al., Modelling Report Summary, Net Zero Australia, 2023

early retirement at around 15 years.[24] In many instances, removed solar panels are still functional. Another recent study by Reclaim PV Recycling observed that approximately one third of solar panels decommissioned from a site in Queensland were suitable for reuse.[25]

THE OVERWHELMING CONSENSUS FROM WORKSHOP PARTICIPANTS WAS THAT PANELS ARE DECOMMISSIONED VERY EARLY INTO THEIR LIFESPAN AND WHILE THEY ARE STILL FULLY FUNCTIONAL

There are several – primarily economic – factors that may cause premature PV retirement:

- **Small-scale Technology Certificate (STC)[26] rebates** are paid upfront, which incentivises PV uptake, but does not incentivise system retention. Further, the STC rebate, although reduced, can still be received for replacement systems, providing an incentive to remove an older system to install a newer one.
- **Recent improvements in panel performance** can prompt early replacement of rooftop systems, as the higher power output of newer panels may be attractive to PV owners, particularly those with increased electrical load and limited roof capacity.
- **Whole-of-system replacement can be easier** than individual panel/inverter replacement or system expansion in many cases. This can be due to limited roof space, compliance standards, and the relative ease of replacing small rooftop systems. In the case of expansions, the installer will be required to make the existing system compliant with current standards, which can be challenging given the relatively long lifespan of PV systems components. Therefore, in many cases it is easier to replace the existing system with a higher capacity system.
- **Consumer knowledge** regarding the expected performance and lifetime of PV panels is poor, and can lead to early system retirement, as consumers are not aware of the design life, warranties, and expected performance of their systems.

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[24] Tan V. et al. (2022). Estimating the Lifetime of Solar Photovoltaic Panels in Australia. Sustainability 14, 5336. https://doi.org/10.3390/su14095336

[25] Peacock B., One third of disused solar panels found fit for reuse as recycling partnership strengthens circular push, PV Magazine Australia, 2022

[26] The STC rebate is a government subsidy for systems under 100 kWp. The rebate's value is based on the system's expected generation to 2030.

Premature Failure

PV waste can occur prior to the end of design life due to faults or damage. This is the primary cause of PV waste generation from utility-scale solar farms prior to decommissioning. Faults and damage can arise due to mishandling during transport and installation, inclement weather, or poor manufacturing. Common PV panel faults and their causes are listed in Table 3 below. Example electroluminescence images of a panel with and without microcracks in the cell, which can impact performance but are typically invisible to the naked eye, are shown in Figure 8.

Table 3: Common PV panel faults[27]

Fault	Cause(s)
Backsheet degradation	• Weather • Burning from hotspots • Physical damage (e.g. backsheet cracking)
Potential-induced degradation (PID)	• Potential difference between cells and other components such as the glass or frame • Humidity and temperature
Junction box failure	• Moisture penetration • Poor fixture to panel • Poor wiring
Glass breakage	• Hail • Snow • Physical damage or stresses
Laminate discolouration	• Photodegradation of encapsulant
Interconnection faults	• Physical damage or stresses • Manufacturing issues
Cell cracking (displayed in Figure 8)	• Physical damage or stresses • Elevated temperatures • Manufacturing issues

[27] Aghaei, M. et al (2022). Review of degradation and failure phenomena in photovoltaic panels, Renewable and Sustainable Energy Reviews, Volume 159, https://doi.org/10.1016/j.rser.2022.112160

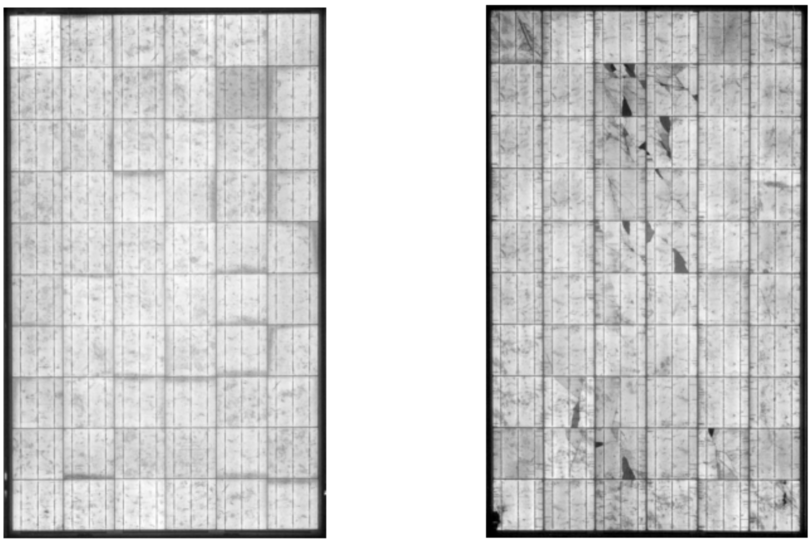

Figure 8: Electroluminescence imaging showing no major degradation or cell cracking (left) and severe cell cracking (right)[28]

1.4.2 Forecast Global PV Waste

A 2016 study by the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) projected cumulative global PV panel waste to reach between 1.7 and 8 million tonnes by 2030, escalating dramatically to between 60 and 78 million tonnes by 2050. Annually, the study projected PV waste of 2.5 to 3.5 million tonnes starting from 2040, expanding to 5.5 to 6 million tonnes from 2050 onward.[29] The study was based on an average panel lifetime of 30 years, where any situations leading to an early retirement of PV panels will increase waste volumes.

However, PV deployment has been accelerating at a higher rate than expected at the time of the IEA study and further acceleration is anticipated given global net zero emissions targets. Consequently, PV waste is projected to increase more quickly in the coming decades. In response, regions such as Australia have updated their PV waste volume projections to reflect the current situation more accurately.

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[28] McCann, M., Test report for Circular PV Alliance, 2022

[29] Heath G., Wade A., Weckend S., End-of-Life Management: Solar Photovoltaic Panels, International Renewable Energy Agency (IRENA) and International Energy Agency (IEA), 2016

1.4.3 Forecast Australian PV Waste

The high uptake of commercial and residential PV in early years, coupled with the shorter expected lifetime of these systems, indicates that the bulk of Australia's PV waste in the short-term will be from rooftop systems. As no utility-scale solar farms were commissioned in Australia prior to 2010,[30] it is unlikely many solar farms will have decommissioning plans prior to 2035.

A recent study from the UNSW School of Photovoltaics and Renewable Energy Engineering provided projections for PV waste in Australia to 2050.[31] The study estimated Australia will exceed 50,000 tonnes of annual PV waste in 2025, increasing to over 90,000 tonnes by 2035. Figure 1 displays the projected PV waste in Australia.

To put the volume of PV waste in context, it is estimated Australia will produce 92,000 tonnes of annual PV waste in 2035, which is less than 0.2% of Australia's total waste in the 2021-2022 financial year of 76 million tonnes. In contrast, the waste of ash from coal-fired generation represents 16% of national waste, while organics represent 19%, and building and demolition materials represent 33%. Despite this, efforts to improve PV circularity present an opportunity to minimise the environmental impacts of PV waste and alleviate material supply pressures.

[30] Carroll, D., Australia's first utility-scale solar farm marks 10th anniversary, 2022
[31] Deng R., Tan V., Niu C., Egan R., Scoping Study: Solar Panel End-of-Life Management in Australia, University of New South Wales, The Australian Centre for Advanced Photovoltaics, and Neoen, 2024

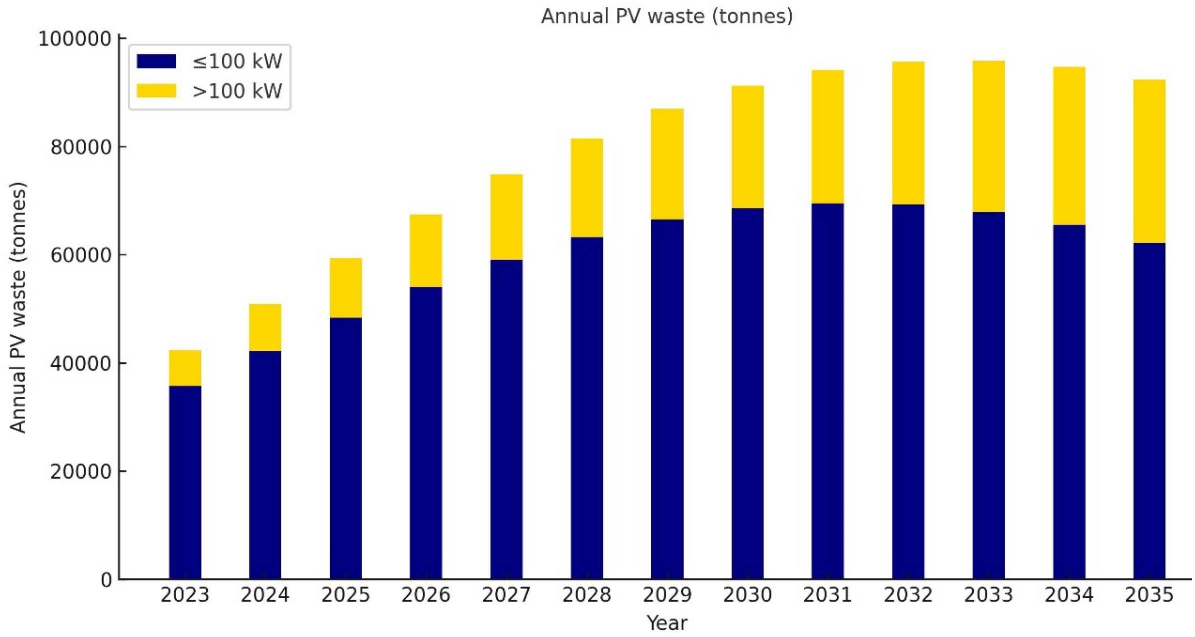

Figure 9: Future PV Waste projections in Australia.[31]

2 PV WASTE MITIGATION OPTIONS

Due to Australia's reliance on imported PV panels, circularity strategies should aim to extend PV operational life and minimise waste creation at EoL (R3-R9 in Table 1), as these are the stages of the PV life that occur within Australia. From the workshops and literature, reuse (R3) and repair (R4) are the most viable strategies to extend PV operational life, while recycling (R8) is the most viable pathway to manage waste at EoL.

Figure 10 shows a pathway for improved PV circularity accounting for PV reuse and recycling. The context surrounding PV reuse, repair, and recycling in Australia are detailed thereafter.

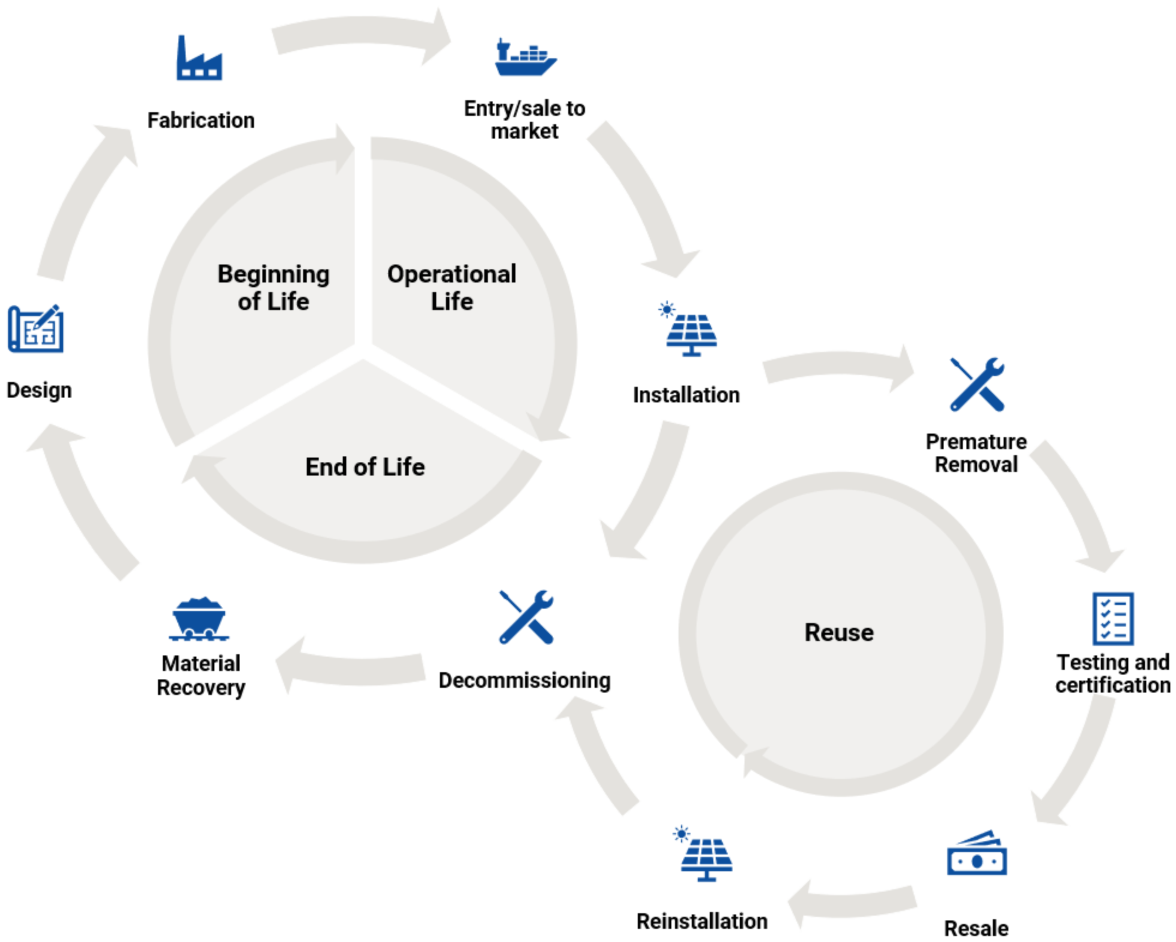

Figure 10: Path for PV circularity

2.1 PV Reuse

Reuse can prevent premature entry of PV into the waste stream when functioning panels are decommissioned.

2.1.1 PV Reuse in Australia

Workshops and literature identified niche applications for PV reuse in Australia. Many of these options were off-grid applications such as community solar farms, bore pumps, hobby farms, and caravans.[32,33,34]

PV recycler Elecsome stated that they often receive operational panels at their processing plant. They visually inspect panels for physical damage before sending them for testing. Suitable panels are sent for reuse in an off-grid solar farm adjacent to their processing plant. Several other organisations have sought to develop community solar projects with second-hand panels, while some PV recyclers use functional panels in on-site PV systems to power their operations.

Australia's first large-scale solar farm (10 MW), used to power a now un-used copper mine, is currently entering decommissioning after eight years of operation. "Neoen's preference is for the solar panels to be reused as they remain in good condition", however no pathways or partners have been identified yet.[35]

2.1.2 Challenges Facing PV Reuse in Australia

Compliance Challenges

Uncertainty regarding the compliance of used PV panels inhibits reuse markets in Australia. In particular, installers and consumers can have concerns around the safety and performance of second-life PV, given the product's history may be unknown. While performance and safety testing may alleviate these concerns, stakeholders have noted this can be costly and logistically challenging. As such, this testing does not always occur during resale.

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[32] Mathur D., Gregory R., Hogan E., Do solar energy systems have a mid-life crisis? Valorising renewables and ignoring waste in regional towns in Australia's Northern Territory, Energy Research & Social Science Vol. 76, 2021, https://doi.org/10.1016/j.erss.2021.101934

[33] Barfoot C., McCubbin D., Recycling and Reuse of Used Solar Panels: An investigation into current opportunities for Gippsland, Gippsland Climate Change Network, 2021

[34] Reclaimed PV Panels Market Assessment Industry Report, Circular PV Alliance, 2023

[35] Neoen calls time on pioneering off grid solar and battery project, decommissions Degrussa, Renew Economy, 2024.

Limited Competitiveness

New panels are the prime competition for PV reuse markets. New panels are relatively cheap, around US$0.15-0.25/Wp, and are often eligible for an upfront rebate through Small-scale Technology Certificates (STCs), which can reduce the Capex of a new system by approximately 50%. These products will often come with a manufacturer's performance warranty of 25 years, which builds consumer confidence.

In contrast, the logistics of transport and testing can increase the cost of second-hand panels, impeding their price competitiveness. Further, these products receive no subsidies and are viewed as inferior products compared to new panels, given they have a shorter expected lifetime and may not be eligible for manufacturer warranties. These factors limit the competitiveness of second-life PV panels, therefore inhibiting reuse applications.

Export Markets

Conversations with stakeholders and literature have revealed that decommissioned PV modules from Australia, Europe, and North America are commonly exported to markets such as Africa, Timor-Leste, the Middle East, and Southeast Asia.[36,37] While the export of waste electrical and electronic equipment (EEE) such as PV is constrained by the Basel Convention, the regulations around export of EEE for reuse are less clear. Through the dialogue sessions, it was highlighted that exports under the guise of PV reuse can potentially be used as a vehicle for the relocation of PV waste and avoidance of EoL management responsibilities. This is of particular concern if there are limited regulations or other controls to ensure the quality of PV panels exported for reuse. Further to this, countries importing used PV panels may lack regulations governing proper disposal or treatment of PV waste, which can lead to either dumping or landfill of reused PV once it reaches end of life.

[36] Carroll D., Sunday read: Out of landfill, back in the stream, PV Magazine Australia, 2021
[37] Strupeit L., Tojo N., Clyncke C., Franco M., Ben-Al-Lal I., Circular Business Models for the Solar Power Industry - Guide for Policy Makers, Circusol, 2023

2.2 PV Repair

Prioritising repair over replacement could decrease the rate at which PV panels and inverters enter the waste stream.

2.2.1 PV Repair Options in Australia

PV Panel Repair Options

Common PV faults are outlined in Section 1.4.1. While many of these faults cannot feasibly be repaired, the following options are available for some faults:

- **Backsheet degradation** can be addressed by specialised repair tapes or silicone coatings
- **Potential-induced degradation (PID)** can, in some cases, be addressed by the operation of anti-PID devices overnight
- **Junction box failure** can be addressed by replacing the junction box

PV System Repair Options

Underperformance or failure of a PV system may occur due to a single faulty component such as a panel or inverter. Failure of an inverter is more likely given its design life is around 10-12 years, much shorter than that of a PV panel. In such cases, system owners and installers may seek to replace an entire system, as outlined in Section 1.4.1. However, inverters can often be replaced, given the availability of an appropriate substitute.

To enable component replacement, the CEC has outlined repair options that do not require the system to be updated to meet current installation standards, as outlined in Table 4.[38]

2.2.2 Challenges Facing PV Repair in Australia

Limitations for Repair Options

Although there are some options for PV panel repair (detailed in Section 0), these options are limited, with damaged (Figure 11 displays hail damaged PV), degraded, or faulty panels often

[38] Installation requirements for alterations, additions, repairs and upgrades to existing grid-connected PV arrays, Clean Energy Council, 2016.

requiring removal or replacement. Further, like-for-like panel replacement can be challenging due to the conflict of space constraints and the tendency for newer panels to be larger and have different electrical properties (detailed in Section 1.3.1), which may incentivise replacement of the system as a whole.

Additionally, repair can be prohibitively expensive. Despite low material costs, it requires diagnosis and repair for each faulty panel, involving significant manual labour.

Table 4: System repair options

System repair works	Notes
Panel replacement with equal or higher power output (wattage).	This allows installers to replace a single faulty panel.
Panel removal and reinstallation in the same location	This allows installers to remove panels for the purpose of repair or fault diagnosis. Victoria is an exception, where this work is classed as an alteration, which requires updating and reinstalling the system per current standards.
Inverter replacement with a model of the same topology[39]	This allows installers to replace an inverter without needing to replace the system itself. Victoria is an exception, where a repair is only applicable when the replacement inverter has the same manufacturer, model number, and specifications as the original, or it is the manufacturer's recommended replacement.

Figure 11: Hail damaged solar panels in Canberra[40]

[39] Inverter topologies are transformer/isolated and transformerless/non isolated inverters

[40] Cranney K., Wilson G., How does smoke, dust, and hail affect solar panel performance?, CSIROscope, 2020

2.3 PV Recycling

Recycling is focused on recovering materials from PV panels at EoL. Given the finite operational lifetime of PV panels, recycling will be required to enable PV circularity regardless of any other circularity strategies undertaken. As such, the establishment of PV recycling capability is a critical path for facilitating PV circularity in Australia.

Feedback at the workshops indicated that stakeholders were strongly supportive of PV recycling and product stewardship initiatives, with several stakeholders already engaging in such activities. Stakeholders voiced support for policy to provide clear guidance on proper waste management pathways for EoL PV.

2.3.1 Benefits of PV Recycling

There are various environmental, social, and economic benefits of PV recycling. PV recycling can reduce the environmental impact and health risks from toxic materials and avoid the potential leaching of these materials into groundwater. In addition, recovering valuable and critical materials will reduce supply chain constraints as the PV industry continues to grow, reducing the need for additional mining. With the energy required to recover materials from PV panels being a fraction of that to manufacture panels, recycling PV panels will greatly reduce the emissions of making future PV panels from recycled materials.[41]

A recent report by the Australian Centre for Advanced Photovoltaics (ACAP) identified that an average 20 kg solar panel contains $20 worth of materials, presenting the opportunity for Australian PV recycling to unlock up to AU$1 billion in materials and up to 350 jobs by 2035.[31]

2.3.2 PV Recycling Technology Overview

While there are various approaches to PV recycling, the process broadly consists of the following steps:[42]

[41] Büşra Artaş S., Kocaman E., Hüseyin Bilgiç H., Tutumlu H., Yağlı H., Yumrutaş R., Why PV Panels must be recycled at the end of their economic life span? A case study on recycling together with the global situation, Process Safety and Environmental Protection, Volume 174, pg. 63-78, 2023, https://doi.org/10.1016/j.psep.2023.03.053
[42] Deng R., et al., A techno-economic review of silicon photovoltaic panel recycling, 2019, https://doi.org/10.1016/j.rser.2019.04.020

4. Disassembly: removal of the aluminium frame, junction box, cable, and backsheet (if applicable).
5. Delamination: detaching the glass from the solar cells.
6. Solar cell recycling: separating the silicon and metal (e.g. silver, aluminium, copper).
7. Metal extraction: extraction and purification of metals.

Various approaches to each step in the process are detailed in Appendix A.

2.3.3 International PV Recycling Technology in Practice

PV recycling, with various rates of recovery, has been demonstrated in several commercial applications. Three overseas pilot projects demonstrating the technical viability of high recovery PV recycling are detailed below.

Full Recovery End of Life Photovoltaic (FRELP) Project

The EU has a long history of managing new types of waste streams and recycling e-Waste. In 2013, the FRELP Project was commissioned by the EU and developed by Italian glass recycler SASIL Srl in partnership with PV CYCLE Italy.[43] The project's aim was to test and develop technologies for 100% recycling of end-of-life PV panels in an economically viable way.[44] The project reported high material recovery rates and culminated in the establishment of a pilot plant capable of processing 1,300 panels per day.[45] The FRELP process consists of four stages, summarised in Table 5.43[-46]

Despite high material recovery rates, the FRELP project was unable to achieve its stated objectives of 100% recovery and economic viability, with the pilot plant ceasing operations due to insufficient panel feedstock and inability to reach economic viability.[47] In 2021, the Italian startup Tialpi established an experimental PV recycling plant based on the FRELP process.

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[43] Latunussa C, Mancini L, Blengini G, Ardente F, Pennington D. Analysis of material recovery from photovoltaic panels. EUR 27797. Luxembourg (Luxembourg): Publications Office of the European Union; 2016. doi:10.2788/786252
[44] European Commission, Full Recovery End-of-Life Photovoltaic, 2016
[45] Tan J., et al., End-of-Life Photovoltaic Panels, 2022, https://doi.org/10.3390/en15145113
[46] Frelp by Sun, https://www.frelp.info/
[47] Heath G., et al., Research and development priorities for silicon photovoltaic panel recycling to support a circular economy, 2020, https://doi.org/10.1038/s41560-020-0645-2

Table 5: FRELP Process Description

Phase	Processes	Recovered Product(s)
1	1. Cutting cables and panel edges. 2. Detachment of aluminium frames. 3. Disconnection of the junction box. 4. Cleaning the backsheet. 5. Removal of the glass by heating and cutting with a vibrating knife. 6. Optical separation using a camera system to obtain high quality glass free from adhesive residues.	• Insulated cable (100%$_{weight}$ recovery rate) • Aluminium (99.4%$_{weight}$ recovery rate) • Glass (98%$_{weight}$ recovery rate)
2	7. Cutting the solar cells and backsheet into smaller pieces (approximately 2 cm by 3 cm). 8. Incineration at an authorised plant to remove the backsheet and encapsulant[48] residue.	• Solar cell
3	9. Pyrolysis of the solar cell to produce metallic silicon ash. 10. Hot acid leaching of ash to dissolve metals. 11. Filtration, washing and drying of the silicon.	• Metallurgical grade silicon (98% purity, 97%$_{weight}$ recovery rate) • Acidic solution containing metal salts
4	12. Electrolysis treatment of acid solution.	• Silver and copper • Calcium nitrate solution (can be reused in agriculture) • Metal hydroxides (to be sent to landfill)

JinkoSolar PV Recycling Pilot

JinkoSolar is the top panel supplier in Australia. In 2017, Jinko began market research into PV recycling, with an equipment prototype established in 2018 followed by the construction of a 12 MW recycling pilot line in 2019. In 2022, the pilot line passed final acceptance check.

Jinko's recycling process uses specialised equipment to physically remove the aluminium frame, junction box, and backsheet. The glass is removed via pyrolysis. The silver from the solar cells is dissolved in acid, leaving the silicon. The silver can then be extracted from the

[48] Most literature refers to EVA as the encapsulant. The efficacy of this technique with other encapsulant materials, such as polyolefin, is not evident.

resulting solution. This process culminates in a total recovery rate of over 92%, with 95% recovery rate for silver, silicon, and copper. The recycling process also uses thermal recirculation to reduce overall energy consumption. The Jinko process consumes approximately 13 kWh per kW of PV processed. This represents a very small fraction of the embedded energy to manufacture a PV module and module components and from raw materials.

The silicon recovered from Jinko's recycling process can have a purity of up to 99.9999% (6-nines purity). This is representative of high-quality metallurgical grade silicon and could be suitable for use in polysilicon production in the PV supply chain or in other industries that use silicon of this grade. Further, recovered aluminium and glass can be used by manufacturers in the PV supply chain. For example, SilFab Solar recently announced a partnership with SolarCycle in the USA for manufacturing solar panels using recycled solar glass.[49]

The electricity required for Jinko's recycling process is approximately the same energy as required for the panel assembly process. However, this represents less than 5% of the embodied electricity in a panel including materials. Key electricity savings from using recovered materials to fabricate new PV panels will be the avoidance of metallurgical silicon and alumina refining, and aluminium smelting.

Veolia France

In March 2017, with PV CYCLE France, Veolia launched the world's first dedicated PV panel recycling facility in the Bouches-du-Rhône region of France. It recovered 1,800 tonnes of materials in 2018. Firstly, the aluminium frame and junction box are taken apart, then the panels are cut into small squares suitable for processing (Figure 12). The machine consists of a grinder, sifter, eddy current separator and optical sorter. These components work together to separate and sort materials, achieving more than 95% material recovery yield by weight at a large scale. Secondary raw materials are re-injected into various sectors in line with circular economy principles. Glass (65-75% rate of recovery) is reused in the glass sector. The aluminium and copper can be resold in commodities markets.

[49] Silfab Solar chooses SOLARCYCLE for recycled glass, Renewable Energy World, 2024

Figure 12: Solar panel recycling by Veolia France

2.3.4 PV Recycling in Australia

The commercial practices of photovoltaic (PV) panel recycling in Australia, which began in 2021, are gradually developing. Currently, eight companies in the country claim to have businesses in solar panel recycling, as displayed in Figure 13. However, most of these are still in the preparation or development phase, with only a few capable of large-scale operations.

- PVIndustries (NSW, VIC)
- Solar Professional (NSW)
- Elecsome (VIC)
- Solar Recovery Corporation (VIC, QLD)
- Scipher Technologies (VIC)
- Lotus Energy Recycling (VIC)
- WA Recycling (WA)
- Reclaim PV (SA)

* By the end of 2022

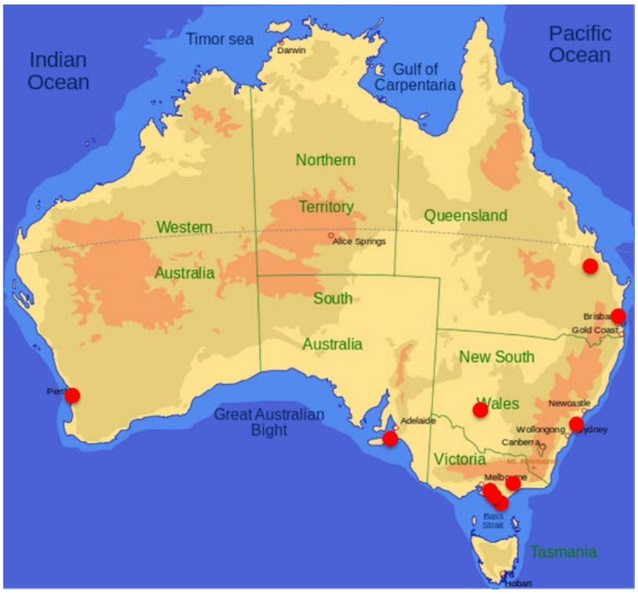

Figure 13: Australian PV recycling companies

These companies, summarised in Table 6 below, predominantly use mechanical delamination technologies for recycling solar panels. This method effectively separates components such as the aluminium frame, junction box, glass, and plastics, leaving behind a mix of valuable materials including silver and silicon. The extracted aluminium and copper cables can be sold to local scrap metal recyclers. The high-value materials can be sold to metal refiners.

Stakeholder engagement revealed challenges in identifying domestic markets for recycled solar panel glass, primarily due to the absence of a local PV manufacturing industry in Australia. This limitation prevents the circular reuse of glass in new PV production. Consequently, the glass is currently repurposed as a sand substitute in construction applications, such as in concrete, fillers, or road bases.

Table 6: Summary of PV recycling service providers in Australia

Company	Summary of operations
Lotus Energy Recycling	Lotus Energy Recycling launched Australia's first solar recycling plant in 2020 in Melbourne, Victoria. The plant uses no chemicals, using mechanical processes to shred the panels and sort the recovered materials. Lotus Energy have used recovered materials for products such as a timber-look concrete sleepers and their own boardroom table.
Elecsome	With their first plant started operation in 2023 in Victoria, Elecsome has been able to recover glass fines from solar panels for use in nano-engineered concrete aggregate branded as SolarCrete. This allows cement mix manufacturers to save between 50-80% of the sand typically used in these products. Elecsome's facility can achieve a recycling rate of over 97%.
PVIndustries	PVIndustries has developed its own modular machinery that is manufactured in Australia at low cost, with short lead times, allowing PVIndustries to quickly increase recycling capacity. As volumes have increased and PVIndustries has received increasing panel volumes from solar farms, the need for a high-capacity plant has become evident. PVIndustries is currently designing a 'bulk' solar panel processing plant capable of achieving five times greater throughput than the Australian industry currently achieves. It will initially be located in their Melbourne facility.
Solar Recovery Corporation	Solar Recovery Corporation (SRC) recovery centres use patented world-leading technology to fully recover raw materials from all type of solar PV panels. SRC has a strong focus on maximum material recovery from end-of-life Solar PV Panels for recycling back into the manufacturing stream. The processing technology recovers 99+% of materials from Solar PV Panels into clean streams of silicon, aluminium, copper, glass, and plastic.

2.3.5 Challenges for PV Recycling

While PV recycling can present significant environmental benefits, the industry faces challenges that can inhibit the business case for recycling solar panels. Such challenges are detailed below.

Convenience of Landfill

Landfill remains the simplest option for PV panel disposal at EoL for much of Australia. As such, PV recyclers must compete with landfill to accumulate inventory for material recovery.

Landfill also provides little oversight for PV waste, where there is typically no tracking of barcodes on disposed solar panels, providing uncertainty as to the location and volume of EoL PV panels at waste management centres. Details related to current government policies on the landfill of PV waste are presented in 4.2.

Import and Export of PV Waste and EoL Panels

The Basel Convention[50] strongly inhibits the export of waste PV. Therefore, PV waste management and initial processing must occur in Australia to achieve material circularity, particularly if PV panels contain hazardous materials such as lead, antimony and cadmium. In Australia, the Basel Convention is governed under the Hazardous Waste Act 1989. However, the Waigani Convention will allow Australia to import PV waste from signatory countries in the South Pacific region to assist with waste management.[51]

Material Recovery and Safety Challenges

Silicon for use in PV panels requires a high level of purity, which is difficult to obtain with current recycling approaches. The recovery process for silicon typically involves chemical and thermal processes, which adds costs. The need for high-throughput recycling processes for financial viability will also inevitably result in cell/wafer breakages, and fully recovered wafers/cells are likely to be unsuitable for new panels due to technology evolution. Fully recovered silicon is metallurgical grade at best, requiring further processing to be suitable for use for wafer and solar cell manufacturing. Further, Australia has no polysilicon purification expertise, limiting domestic offtake options.[12] A safety risk for crushed crystalline silicon is silicosis, a serious respiratory disease.

Silver is a high value material and can provide significant revenues for recyclers. However, the recovery of silver is onerous, typically requiring chemical and thermal processes, which adds costs. Further, trends in solar cell manufacturing are putting downward pressure on silver content in panels, which will impact recycler revenue streams in the long-term.

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[50] Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, 2019
[51] Waigani Convention, 2010

Glass used for bifacial panels can present challenges for the purity of recovered products. Workshop stakeholders identified recycling challenges related to the difference in front and rear glass used for bifacial panels. While both use ultra clear glass with low iron content, the rear glass includes a printed grid with impurities such as titanium dioxide and silicon dioxide. This increases the reflection of the rear glass to prevent losses due to sunlight passing through the panel. However, this grid is difficult to remove during the recycling process and the recovered glass is difficult to use. Thus, mixing of recovered front and rear glass might impede the recycling process, so these two material streams should be kept separate. Crushed glass, particularly when present as fine powders, may present risks for respiratory illnesses. Additionally, if metals are not appropriately removed from glass after shredding processes, the recovered glass may be conductive or contain hazardous materials, presenting safety concerns when used for construction materials.

Fluorine-containing backsheets can create toxicity challenges at the end of life due to the emission of toxic gases during combustion. This presents health and safety concerns requiring mitigation during recycling processes.

Encapsulants are an effective adhesive, however this makes them challenging to remove during recycling. Contamination of recovered materials with encapsulant may decrease their value.

Logistics Challenges for Distributed Rooftop Solar

The highly distributed nature of rooftop PV systems in Australia presents a unique challenge. The small quantities of solar panels from residential and commercial rooftop systems can reduce economies of scale for collection and transport. This can increase the costs incurred by recyclers to accumulate inventory, which may inhibit their business case. Given that the bulk of PV waste in Australia will arise from small-scale systems in the short-term, catering for such systems will be key in designing a PV waste management network in Australia.

Logistics Challenges for Regional, Remote, and Very Remote Communities

Much of Australia consists of remote areas which are home to small communities, as displayed in Figure 14. Regional, remote, and very remote communities face substantial logistical challenges due to extended travel distances, poor road infrastructure, and small PV waste volumes resulting in high collection costs for PV installers and recyclers. A study of PV waste in the Northern Territory (NT), which largely consists of remote or very remote areas, identified that local governments lack direction or funding to manage PV waste, leaving the onus on the installers. In the same study, installers stated they either stockpile panels or resell them. Anecdotally, some installers may dump waste panels in the environment.[32] Many of these challenges in the NT are also faced by other remote areas of Australia such as Northern Queensland and Northern Western Australia.

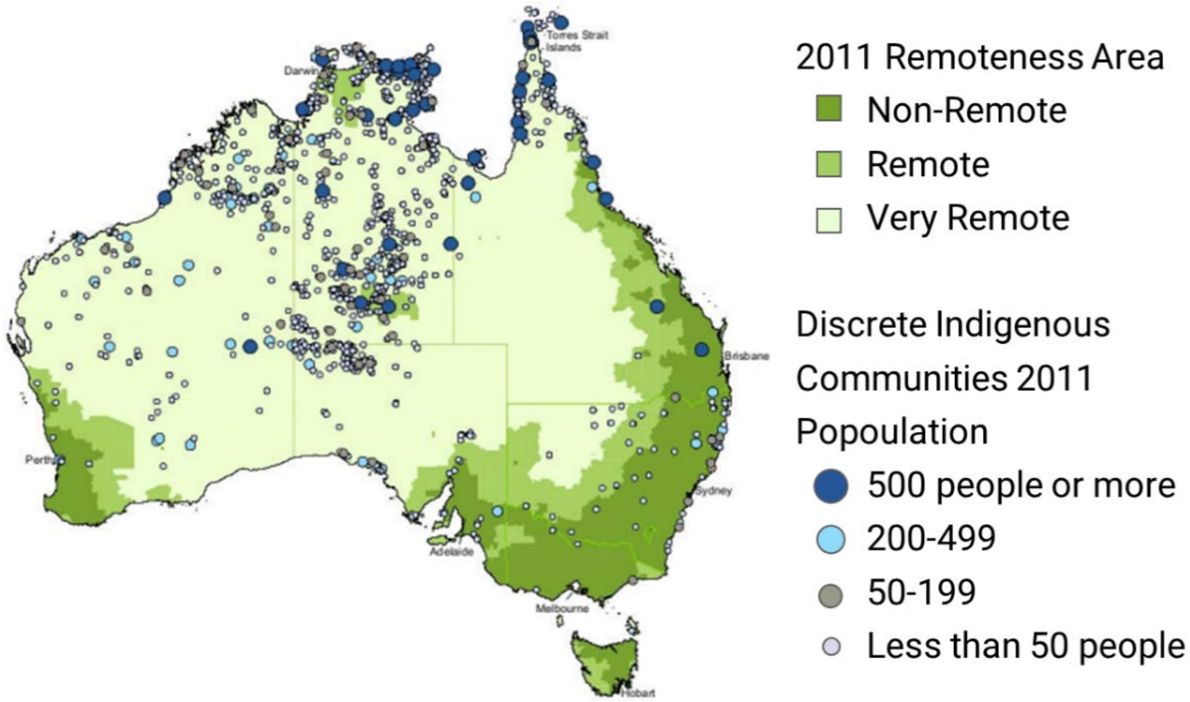

Figure 14: Remoteness structure of Australia including discrete Indigenous communities[52]

Variability in Panels

Panel dimensions and characteristics have changed significantly over time, as identified in Section 1.3.1. This requires recyclers to accommodate an immense number of panels in their automated processes. These variations in panel characteristics may also affect the purity of recovered material streams, or require multiple toolsets to minimise material contamination between different panel types.

[52] Reforms to Human Services Chapter 9: Human Services in Remote Indigenous Communities, Productivity Commission, 2017

Economies of Scale

The long lifetimes of PV panels and inverters result in relatively low levels of waste in the short term compared to the volume being installed, which may inhibit the potential for economies of scale in the shorter term. This is a key factor in the economic sustainability of PV recycling, [53] and may affect the ability of recyclers to scale in the future to meet higher levels of PV waste as detailed in Section 1.3.3. Such was the case for the EU's Full Recovery End of Life Photovoltaic (FRELP) project, where the pilot plant was forced to shut down due to insufficient feedstock.

Lack of End Markets

Workshop stakeholders, particularly PV recyclers, highlighted that identifying end markets in Australia was especially challenging. This largely stems from a lack of local PV manufacturing capability, as identified in Section 0. This presents challenges for highly specialised PV materials like recovered silicon and glass.

Silicon end markets in Australia are limited by a lack of polysilicon purification, ingot, wafer, and cell manufacturing capability, which are required if silicon is to re-enter the PV supply chain. Until this capability is realised, recovered silicon will need to be exported if it is to be used in the PV supply chain. Otherwise, other end-use cases need to be established for the recovered silicon, such as use in the aluminium industry.

Glass from PV panels can present challenges for material circularity due to its composition. Solar glass is highly specialised. Most solar glass is produced using the rolled glass manufacturing method with trace amounts of antimony to reduce photodegradation in operation.[54] In contrast, Australian glass manufacturers use the float glass method, which cannot tolerate the presence of antimony. This prevents Australian glass manufacturers using glass cullet (broken or waste glass) recovered from PV panels, due to the inability of the float-glass method to tolerate antimony. The presence of antimony in recovered glass may also

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[53] Cui H. et al., Technoeconomic analysis of high-value crystalline silicon photovoltaic panel recycling processes, 2022, https://doi.org/10.1016/j.solmat.2022.111592
[54] Addressing uncertain antimony content in solar glass for recycling, European Solar PV Industry Alliance, Recommendations Paper Series II, 2023

inhibit exports of processed solar glass cullet, as per the Basel Convention regarding the movement of hazardous waste between nations.

Through the workshops, and ITP's discussions with solar recyclers, we are aware that the primary use for recovered glass is as an aggregate substitute for concrete in the construction industry, which can use the material in large volumes. This can provide recyclers with greater revenue certainty as they scale in the short-term. However, this solution does not realise full circularity of glass, as is possible with other glass products in Australia. In addition, the use of recovered glass for construction materials likely reduces the earning potential of recyclers, compared to selling it for use in the production of specialised solar glass.

3 REVIEW OF GLOBAL PV CIRCULARITY POLICIES

Various countries have implemented policies to improve the circularity of PV. In particular, the EU has a long history of managing new types of waste and recycling e-waste, as detailed in Section 3.1 below. A summary of key PV circularity policies in selected regions and countries is detailed below in Table 7. Further information on policies implemented by China, Japan, USA, and India is provided in Appendix C.

Table 7: Summary of global PV circularity policies in selected regions

Country/ Region	Initiatives
Europe	• 2012 Waste Electrical and Electronic Equipment (WEEE) Directive mandating PV product stewardship. The extended producer responsibility (EPR) obliged industries to establish compliance schemes and producer responsibility organisations (PRO). o France/Germany: Minimum recovery rate for PV panels at 85% with 80% material recovery rate o Germany: Free collection points for residential customers at municipal waste collection points with a financial guarantee from the manufacturer o Italy: Distinction based on system size. Small systems can be taken to a national collection centre or returned to a PV retailer. Larger systems can be taken to a collection centre or given/transported to an appropriate waste management facility/authorised entity. • Ecodesign and energy labels for PV panels and inverters regarding materials, emissions, performance, repairability and recyclability. These aim to empower customers to inform purchase decisions
China	• National Development and Reform Commission (NDRC) has announced plans to establish recycling systems for retired PV panels by 2025 including standards and rules for decommissioning, transport and handling PV assets at end of life. • Landfill ban for PV • National standard for recycling/reuse of thin-film PV panels for building materials.
Japan	• PV panels treated under the Waste management and Public Cleaning Act. • Levy introduced in 2022 to ensure proper decommissioning and disposal for PV systems over 10 kW implemented through an adjustment to Feed-in-Tariffs (now a Feed-in-Premium scheme)
USA	• No federal regulations governing PV waste management • Washington has implemented a take-back requirement at no cost to the consumer • California has classified PV as universal waste to reduce handling requirements. Waste must be taken to a designated handler/recycler.
India	• PV waste added to the E-Waste Management Rules in 2022, including extended producer responsibility. PV waste must be registered in the E-waste portal to ensure waste is properly processed. Downstream waste is also tracked.

3.1 Europe

3.1.1 Waste Electrical and Electronic Equipment (WEEE) Directive

In 2012, as a world-first, the EU mandated PV recycling for all EU members through the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU, which has been a key piece of legislation driving the global push for PV recycling. As such, all EU members operate a PV product stewardship scheme in some respect. These schemes require liable entities to either operate a take-back and recycling scheme or to join a collective scheme through a Producer Responsibility Organisation (PRO), which provides third-party end-of-life management services compliant with the WEEE Directive. Detail on the product stewardship schemes operated by France, Germany, and Italy are provided below.

France

In 2014, France published the Waste Electrical and Electronic Equipment (WEEE) Decree 2014-928. This presented a legal obligation for French producers[55] to organise and finance the collection and recycling of their discarded PV panels returned by consumers and businesses. The minimum recovery rate for PV panels was set at 85%, with an 80% material recovery rate. Producers may do this themselves or join a collective scheme that provides the collection and recycling services. Under the collective scheme, participants pay a fee (eco-participation) to develop and finance future collection, sorting and recycling operations for each new PV panel.[56]. This eco-participation is transferred to an entity (known as the eco-organisation) responsible for delivering the required waste management services.

The eco-organisation Soren (formerly PV-Cycle France) is responsible for both collection and recycling of PV panels. Through a tendering process run by Soren, private entities are contracted to deliver these services. It operates as a monopoly, which allows for the centralisation of PV waste management in France.

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[55] A producer is any natural or legal person established in France and engaged in manufacturing, reselling, or selling PV panels under their own name, or placing PV panels on the French market from a third country (including another EU country). This also includes any natural or legal person established outside France who sells PV panels directly to private households or other end users.

[56] The fee ranges from €0.36-1.22 per panel

Germany

Since 2018, PV panel end-of-life management has been regulated by the Electrical and Electronic Equipment Act “Elektrogesetz”. Manufacturers and retailers are required to register PV panels placed on the market, with manufacturers subject to extended producer responsibility (EPR) fees. This makes them responsible for the collection and recycling of PV panels, at a target rate of 85% and 80%, respectively. Under the scheme, all PV panels require registration and a specific EoL treatment, however the collection process is different for panels sold business-to-customer compared to those sold business-to-business. Business-to-consumer panels are collected free of charge from municipal waste collection points, with the manufacturer required to pay a financial guarantee fee to mitigate the risk of insolvency. Business-to-business panels also require take-back/collection, however there is no financial guarantee required from the manufacturer. Consequently, businesses may have to pay collection fee.

Italy

In 2014, Italy implemented Legislative Decree No. 49/2014, making producers responsible for financing the recovery of WEEE at end-of-life, including PV panels. The legislation makes a clear distinction between ‘domestic’ WEEE (systems less than 10 kWp) and ‘professional’ WEEE (systems greater than 10 kWp).

Italy’s energy services manager [57] sets requirements for panel disposal, which applies to PV systems benefiting from a FiT.

For domestic systems, end-of-life PV systems must be:

- Sent to one of more than 4,000 national collection centres; or
- Managed through the distributor/installer (e.g. old panels can be returned upon purchasing new ones)

For professional systems, end-of-life PV systems must be:

- Given to an entity authorised to manage PV panel waste;

[57] Gestore dei Servizi Energetici SpA

- Transported to an authorised treatment plant; or
- Sent to a national collection centre.

3.1.2 Ecodesign and Energy Labelling

In addition to the WEEE Directive, EU has proposed Ecodesign and Energy labels for PV, which will mandate robust labelling on PV panels and inverters detailing the following:

PV panels:

- Energy yield
- Durability and quality assurance
- Performance with long-term degradation
- Repairability
- Recyclability
- Carbon footprint

PV Inverters:

- Efficiency
- Durability and quality assurance
- Smart readiness
- Repairability
- Recyclability

With respect to recyclability, manufacturers will be required to report on the potential to separate and recover the semi-conductor, frame, glass, encapsulant, and backsheets. Further, they will be required to detail the content, in grams, of critical and environmentally relevant materials including:

- Lead
- Cadmium
- Silicon metal
- Silver
- Indium
- Backsheet fluorinated additives
- Gallium
- Tellurium
- Metal solder and contacts
- Glass fining agents (e.g. antimony)
- Phthalates in power cables

The forthcoming Ecodesign and energy labelling aims to incentivise PV products with increased performance, durability, circularity, and environmental sustainability. It also aims to empower consumers to make informed purchase decisions.

4 REVIEW OF AUSTRALIAN CIRCULARITY POLICIES

Australia's waste programs fall under the jurisdiction of the Commonwealth Department of Climate Change, Energy, the Environment and Water (DCCEEW). Key current legislation includes the following:

- Hazardous Waste (Regulation of Exports and Imports) Act 1989
- Hazardous Waste (Regulation of Exports and Imports) Levy Act 2017
- Recycling and Waste Reduction Act 2020
- Recycling and Waste Reduction (Consequential and Transitional Provisions) Act 2020
- Recycling and Waste Reduction Charges (Customs) Act 2020 Recycling and Waste Reduction Charges (Excise) Act 2020
- Recycling and Waste Reduction Charges (General) Act 2020

In 2009, a National Waste Policy was developed to provide a national framework for waste and resource recovery in Australia. This policy was updated in 2018. The 2019 National Waste Policy Action Plan provide targets and actions to implement the 2018 National Waste Policy, with an update to the action plan provided in an Annexure in 2022.[58]

Of particular importance to PV, as part of the action plan, glass was banned from export as of the 1st of January 2021 unless a licence is obtained. This requires that all glass waste be processed before export. In addition, the Product Stewardship Investment Fund was established, along with a Product Stewardship Centre of Excellence, who presented at the third workshop in the PV circularity policy dialogue series.[59]

4.1 Existing Product Stewardship in Australia

Australia has one existing regulatory product stewardship scheme[60] for electrical waste, the National Television and Computer Recycling Scheme (NTCRS). While this does not include PV waste, it is a precedent for regulated e-waste management via product stewardship in

[58] National Waste Policy Action Plan 2019, Department of Climate Change, Energy, the Environment, and Water, 2019
[59] National Waste Policy Progress Summary Report 2021, Department of Climate Change, Energy, the Environment, and Water, 2021
[60] Product stewardship schemes typically assign responsibility for EoL management to stakeholders (e.g. manufacturers, distributors, installers, or consumers) throughout the product lifecycle.

Australia. Further to the NTCRS, the Federal Government recently announced the e-stewardship scheme, which will cover PV and small electronic devices. In addition to this, the Smart Energy Council and Activ Group are developing their own voluntary PV product stewardship scheme through a pilot project in partnership with the Queensland State Government.

4.1.1 National Television and Computer Recycling Scheme

The NTCRS came into effect in 2011, making it the first product stewardship scheme in Australia. It aimed to reduce e-waste going to landfill, increase recovery of useable materials, and connect households and small businesses to an industry-funded recycling service. The scheme uses a co-regulatory approach, which combines government regulation with industry action. Under this approach, government sets the outcomes to be met by the scheme, and industry takes responsibility for funding and implementing product stewardship. The regulation specifies three key outcomes:[61]

- The provision of reasonable access to collection services in metropolitan, regional and remote areas;
- Recycling targets increasing annually to 50% in FY2015-16, and 80% in FY2026-27; and
- A material recovery target of at least 90%.

The first target year of the scheme, FY2012-13, saw 40,813 tonnes of e-waste recycled, which was 98.8% of the scheme's target, and double the recycling rate prior to the scheme's implementation. In FY2013-14, the target was exceeded with a total of 52,700 tonnes,[62] while 50,500 tonnes were collected in 2020-21, 43% of the estimated waste eligible for the scheme in that period.[63]

4.1.2 Voluntary Smart Energy Council PV Product Stewardship Pilot

The Smart Energy Council presented at the first workshop on their pilot Solar Stewardship Scheme, conducted in partnership with the Queensland Government and the Activ Group.

[61] National Television and Computer Recycling Scheme - Operation of the Scheme, Department of Climate Change, Energy, the Environment and Water, 2015
[62] Evaluation of the National Television and Computer Recycling Scheme, Australian Continuous Improvement Group, 2017
[63] Pickin J., Wardle C., et al., National Waste Report 2022 prepared for DCCEEW, Blue Environment, 2022

The second stage of the program, which commenced in 2024, involves implementing a pilot program for on-ground collection, recovery, and processing of PV panels. The pilot is focused on rooftop installations and will aim to address economic and logistical obstacles for PV panels at EoL.

4.2 Landfill Bans on PV and E-Waste

Landfill bans are administered by the relevant state or territory government. Victoria is the only state to have implemented a ban on PV waste going to landfill. Several other jurisdictions including Western Australia, South Australia, and the Australian Capital Territory have implemented landfill bans on E-waste, although it is not clear whether these bans cover PV waste. In 2023, the Queensland Government released a draft e-products action plan, which included a proposal to ban the dumping of solar panels within 5-10 years.[64]

4.3 Proposed Australian E-Stewardship Scheme for PV and Small Electronic Devices

In October 2022, the Australian Government declared its intention to develop a national regulatory product stewardship scheme targeting solar PV systems and household electronics. The discussion paper detailing proposed legislation was released for feedback on 20 June 2023, with consultations closed 23 July 2023.[65]

The purpose of the proposed legislation is to ensure Australia manages decommissioned solar PV systems in an environmentally sustainable manner, with proposed objectives listed below.[66]

- Reduce waste to landfill, especially hazardous materials in electronic waste
- Increase the recovery of reusable materials in a safe, scientific, and environmentally sound manner
- Provide convenient access to e-stewardship services across Australia

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[64] Draft Queensland E-Products Action Plan 2023-2033, Department of Environment and Science Office of Circular Economy, 2023

[65] Regulation for small electrical products and solar photovoltaic systems, Department of Climate Change, Energy, the Environment and Water, 2023

[66] Wired for change: Regulation for waste small electrical products and solar photovoltaic systems, Department of Climate Change, Energy, the Environment and Water, 2023

- Support Australia's transition to a more circular economy
- Foster shared responsibility across the life cycle of a product.

The legislation proposed in the discussion paper drew on the implementation and learnings from the EU's WEEE directive, as detailed in Section 4.3.1 below.

4.3.1 Learnings Applied from the European Union's WEEE Directive

As highlighted in Section 3.1 above, Europe was the first region to legislate product stewardship for PV and other electronic products. This provides Australia with the opportunity to apply learnings from the implementation of product stewardship in Europe. The E-Stewardship discussion paper applies several learnings based on the implementation of the WEEE Directive in the EU. Key learnings for Australia to implement in product stewardship policy are outlined below:

- Product stewardship can provide an effective model for the management of EoL PV. This involves the application of EPR fees and PROs, which have been similarly applied in several other countries following the EU's implementation of the WEEE directive, as highlighted in Table 7. The discussion paper highlights that Australia will apply a similar approach for the E-Stewardship Scheme.
- Small-scale PV waste should be treated differently to large-scale PV waste once it reaches EoL. This is evident in several EU Member States, which will collect panels from the site rather than requiring the owner to deposit them at a collection point. Further, in some Member States the last owner of a large-scale PV system will pay some, or all, of the costs for EoL management.
- Central coordination can achieve better outcomes, as this allows a single entity to provide oversight for data collection, consumer awareness, collection, recycling, and audits. Central coordination should also seek to foster competition between compliance organisations to drive innovation and reduce costs for the delivery of collection and recycling services.
- Recovery targets based solely on weight can result in the loss of valuable materials, which often make up a small proportion of the PV panel by weight. Reviews of the WEEE directive suggested reporting and management requirements for recovering valuable materials and removing harmful chemicals.

- EU Member States have commonly failed to achieve collection targets, due in part to challenges associated with accurately estimating the volume of decommissioned PV in a year. The collection targets can also create a disincentive for PV reuse and repair due to the onus placed on volumes of panels reaching end-of-life. Reviews of the WEEE directive suggest an obligation to recycle all available e-waste.
- Reviews of the WEEE directive have called for uniform standards applied to all organisations as weak enforcement has often led to low collection rates. This may see producers take alternative actions such as disposing of PV in landfill or exporting PV waste.
- Reviews of the WEEE directive have also suggested fees are published and applied consistently across producers and importers. They have also recommended fees are visible at the point of sale to increase consumer awareness of recycling.

4.3.2 Structure of the Scheme

The proposed structure is illustrated in Figure 15, with stakeholders and responsibilities summarised in Table 8. It is proposed that network operators will provide bids to the scheme administrator in a tendering process.

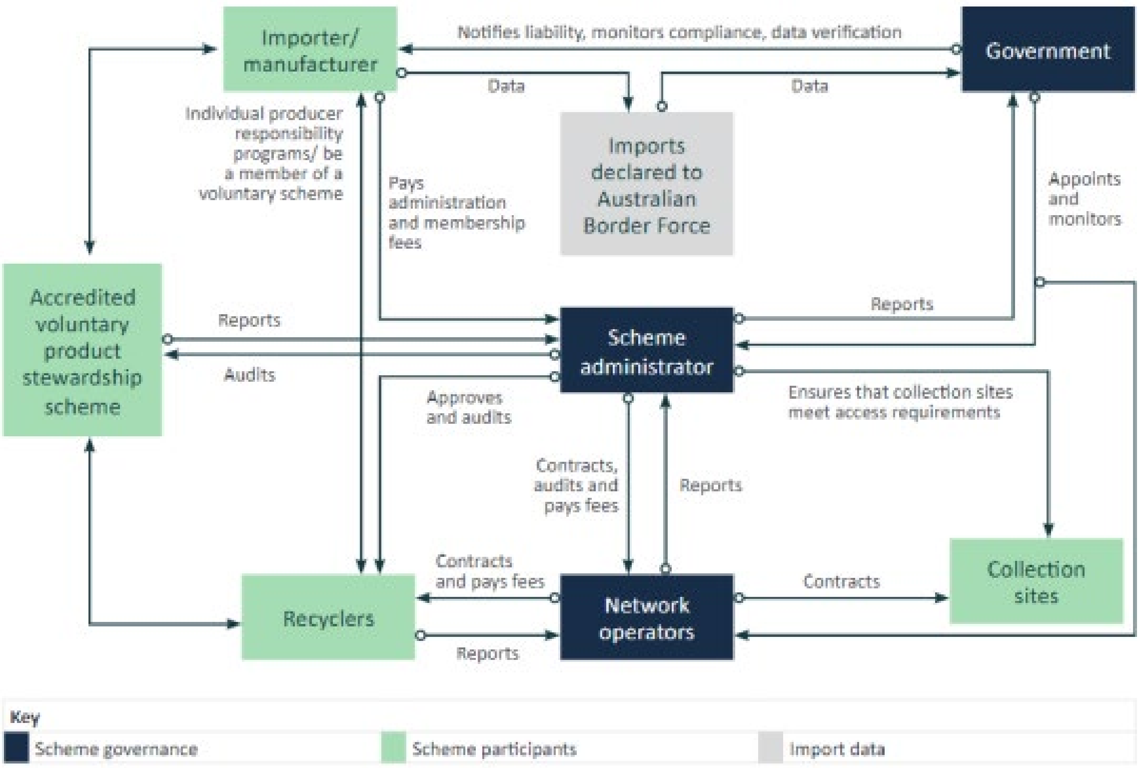

Figure 15: Proposed Structure of the Australian e-Stewardship Scheme for PV and Small Electronic Devices[66]

Table 8: Proposed stakeholders and responsibilities for the Australian e-Stewardship Scheme for PV and Small Electronic Devices

Stakeholder	Responsibilities
Scheme Administrator	• Ensure the scheme meets its outcomes. • Risk management, audits of recyclers and recycling network operators, and ensuring appropriate and equitable public access to the scheme. • Report to the government on the scheme's performance. • Contract network operators to undertake collection and recycling.
Network Operators	• Establish and manage collection, transportation, and recycling services for a designated geographic area. • Manage contracts with approved recyclers to ensure recycling occurs (recycling network operators can also be recyclers if they are able to meet the obligations for both roles under the scheme). • Pay recycling fees. • Report recycling outcomes to the scheme administrator.
Liable Parties	• Register with the scheme administrator. • Manage their obligations under the scheme by paying scheme administrator fees or implement their own program to manage collection and recycling of their products. Programs will need to be registered with the scheme administrator and meet auditing and reporting obligations.
Recyclers	• Register with the scheme administrator as an approved recycler. • Contract to network operators to conduct recycling in line with the standards required by the scheme.
Australian Government	• Managing the compliance of liable parties. • Appoint scheme administrator and network operators. • Provide oversight and undertake regular compliance activities to ensure scheme obligations are upheld.

4.3.3 Scheme Funding

The scheme will be funded by liable parties through fees paid to the scheme administrator once PV panels are placed on the market. A liable party is an entity that imports or produces a quantity of products covered under the scheme above a threshold.[67] Fees will be held until those PV panels enter the waste stream.

The scheme may include eco-modulated fees, whereby a lower liability is placed on panels meeting certain design criteria such as recyclability or avoidance of components using toxic

[67] Thresholds are yet to be determined but they are expected to cover 95% of PV panels.

materials. In practice however, the paper notes that this can often increase administrative burdens while incentives remain insufficient to change design behaviours.

Small-scale PV systems (less than 100 kWp) and large-scale PV systems are treated differently under the scheme. However, it is not yet entirely clear how large-scale PV will be addressed.

4.3.4 Small-Scale PV Waste

For small-scale PV waste, 3 targets are expected for the scheme, as detailed in Table 9 below.

Table 9: Proposed targets and obligations for the Australian e-Stewardship Scheme for PV and Small Electronic Devices

Target/Obligation	Considerations
Recovery Target and Obligations	The recovery target would be the proportion of material recovered from the recycling process as a new product or commodity. The discussion paper notes the target will need to consider the technical and economic feasibility of recovering valuable materials. In some cases, energy recovery via a process such as incineration will be preferred over disposal in landfill. An example of this are panel backsheets. Recovery targets would accompany reporting and traceability obligations imposed on network operators and the scheme administrator. They will be required to provide data on the recovered materials, management pathways for recycling, and management of contaminants and residual waste.
Access Obligations	The scheme will use authorised collection points volunteered by entities such as PV installers and distributors, local governments, state and territory governments, and recyclers. Authorised collection points will need to meet eligibility requirements, which are still under discussion. They will be required to accept free drop-off for PV waste, with limitations based on capacity, health and safety.
Education and Awareness	It is proposed the scheme administrator will provide the federal government with an annual public awareness and education plan on PV system sustainability. The plan would aim to create public awareness on maximising the operational life of PV systems, alternative options to decommissioning functional systems, and sustainability of PV systems sold by liable parties under the scheme.

5 PV CIRCULARITY PATHWAYS FOR AUSTRALIA

This section presents policy options and actions to support PV circularity in Australia, based on insights from stakeholders during the PV circularity workshop series. Additional policy options that were taken into consideration are presented in Appendix D.

Action 1: National Coordination in PV Waste Management Policy

A consistent opinion from policy workshop stakeholders is that efforts for managing PV EoL waste must be co-ordinated nationally to ensure consistency across states and territories.

Action 1.1 National Taskforce on PV Waste Management

A pathway to national co-ordination of PV waste management in Australia is through the creation of a National PV Waste Management Taskforce under DCCEEW. The taskforce should include members from state government departments managing waste, local councils (eg. Australian Local Government Association), and industry bodies and work with the taskforce on Consumer Energy Resources.

The taskforce should oversee efforts to remove barriers to PV waste management in Australia and promote circularity through policy, education, and the establishment of appropriate PV waste management capacity and capability. Given recovered materials are ideally used as resources for Australian PV manufacturing, it may also be appropriate to coordinate efforts with initiatives such as ARENA's Solar Sunshot[68] program under DCCEEW and the Australian Government's recent announcement of the National Reconstruction Fund.[69]

Anticipated efforts for co-ordination under the National PV Waste Management Taskforce are provided below.

[68] Australian Solar Sunshot program, 2024. https://arena.gov.au/funding/solar-sunshot/
[69] Renewables and low emission technologies, National Reconstruction Fund Corporation, 2023

Action 1.2 Developing a National PV Waste Action Plan

A key path to addressing PV waste in Australia is the development of a National PV Waste Action Plan, detailing the steps and actions that are needed to manage PV waste in Australia and improve PV circularity.

The National PV Waste Action Plan should be developed in consultation with key stakeholders from the broader 2018 National Waste Policy and 2019 National Waste Policy Action Plan, including DCCEEW, state and territory governments, local council representatives, as well as representatives from the Taskforce on Consumer Energy Resources. Given the growing volume of PV waste expected over the coming decades, once developed, the strategy and action plan should form part of future revisions of Australia's overarching National Waste Policy and National Waste Policy Action Plan. The National PV Waste Action Plan must consider requirements and detail actions to address challenges related to PV waste, as identified in Sections 2.1.2, 2.2.2, and 2.3.5 above.

The National PV Waste Action Plan may also seek to include consideration of the actions outlined in this report.

Action 1.3 Harmonised State Landfill Bans on PV Waste

There was strong consensus among workshop stakeholders that Australia must ban PV from entering landfill to address challenges identified in Section 2.3.5. This should be applied consistently throughout Australia in all states and territories, to avoid the potential movement of PV waste between states or council jurisdictions for the purpose of cheap disposal in landfill. This should include bans on landfill for both the entire PV modules, as well as the PV laminate stacks (what remains after removal of the aluminium frame, junction box and glass). This will avoid the landfill of the laminate stack as 'residual waste' and ensure appropriate recovery of the valuable and potentially hazardous materials contained within. For states with existing and planned e-waste bans that do not explicitly include PV, the position on PV waste must be clarified.

Participants also noted that landfill bans – while effective in diverting waste from landfill – are a blunt instrument and may not be effective in achieving other outcomes such as high rates of recycling and material recovery. In the absence of supportive infrastructure and policy, a landfill ban on PV waste could force key stakeholders to simply stockpile PV waste. This can increase operational costs due to increased storage requirements, as was the case for defunct Australian recycler Reclaim PV.[70] As such, landfill bans must be complemented by supportive policies and actions to reduce other barriers to reuse, recycling and material recovery.

Action 2: PV Product Stewardship

The Project Team welcomes the establishment of product stewardship for PV in Australia, as it will support development of waste collection networks, improve the financial certainty for PV recyclers, and increase transparency for PV waste management. The following sections detail further considerations for the implementation of the scheme.

Action 2.1 Material Recovery Targets and Outcomes

The e-stewardship discussion paper notes that the product stewardship scheme will feature a recovery target, although it does not detail how this will be evaluated, only that it will aim to consider technical feasibility and the cost of extracting different materials. Recovery targets under the e-stewardship scheme should seek to incentivise high-value and high-quality material recovery in line with current technology (Section 2.3.3).

Several options for targets and incentives to promote improved PV circularity outcomes are presented below and discussed further thereafter:

- Weight-based recovery targets
- Ramping recovery targets
- Material-specific recovery targets
- Emphasising recovery rates during the tender process
- Material-specific recovery incentives
- Application-based recovery incentives
- Incentivise commodity recovery

[70] Peacock B. Weekend Read: Solar recycling's glass ceiling and other problems, PV Magazine, 2023

Weight-based recovery targets have been implemented in several international product stewardship schemes, as detailed in Section 3.1.1. These often stipulate recovery of 85% of the total panel by weight. While relatively easy to measure, weight-based recovery targets may lower the importance recyclers place on critical or toxic materials, as they require additional complex processes and make up only a small percentage of the panel's weight when compared to glass and aluminium.

The Australian National Waste Policy has a 2030 material recovery target of 80% by weight.[71] To align with the National Waste Policy, an initial weight-based recovery target of 80% should be used. However, this target can be achieved for PV by the glass and aluminium frame alone, which risks recovery processes neglecting high-value or toxic materials within the solar cell. Appropriate supportive measures must also be in place to ensure the recovery of key materials such as silicon, copper and silver as discussed below. This will eliminate the possibility of disposal of the entire laminate stack as 'residual waste' (also discussed in Action 1.3).

Given processes implemented overseas, and the capability of some existing PV recyclers in Australia, a weight-based recovery target of 90% may be viable for mainstream PV products. However, values should consider the encapsulant and backsheet, which account for 7-13% of the weight of a module, and depending on the recycling process used, may not be recovered.

Ramping recovery targets would involve increasing recovery targets for recyclers as the scheme matures. This may allow the scheme to achieve high recovery rates without inhibiting participation in the short term, allowing recyclers to develop technology to meet the targets as they scale their operations. The pathway for ramping recovery targets should be technically feasible, therefore it could be worthwhile to set future targets in line with high-recovery or good-practice recycling processes demonstrated in Australia or globally, such as those discussed in Section 2.3.2.

Material-specific recovery targets can mandate the recovery of toxic materials or rare earth minerals to reduce supply chain pressures and environmental impacts. However, it will be difficult to mandate specific material targets due to uncertainties in quantities in each panel.

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[71] National Waste Policy, Department of Climate Change, Energy, the Environment, and Water, 2023

It is noted that some guidance on the material types and quantities can be obtained from documents such as Environmental Product Disclosure (EPD) statements. However, given EPDs typically have material cut-offs of 1% or 2%, additional information may be required for materials such as silver, lead, indium, bismuth, which may be present in PV, but not disclosed. Material-specific recovery targets may also incur additional administrative load. The e-stewardship discussion paper states that the scheme administrator and network operators will be required to trace the types of materials recovered and the various waste management pathways regardless. This should include valuable and critical materials in the panel. At a minimum, the mass of recovered valuable materials should be recorded to support good-practice recycling and material recovery.

Emphasising recovery rates during the e-stewardship tender process will allow recyclers to bid on a platform that is not solely based on price. This will allow the scheme administrator to evaluate tender offers on their technical capacity, which can incentivise recyclers to pursue higher recovery rates. In contrast, a price-only tender process is likely to incentivise cheaper service offerings but may adversely affect recovery rates or service quality.

Material-specific recovery incentives could be used to compensate recyclers delivering higher recovery rates for high value or critical materials. Recovery of these materials requires additional processing and costs, which may deter recyclers. However, they improve the circularity outcomes for PV as they can reduce consumption of virgin materials once they are reused. Providing financial incentives through the e-stewardship scheme could prompt recyclers to seek these higher levels of recovery and improve circularity outcomes. Another potential financial mechanism is providing production credits based on material recovery.

Application-based recovery incentives could be used to prioritise materials returned to the PV industry and high-value applications, such as recovered glass cullet for manufacturing new solar glass or other glass applications, rather than for use in construction materials. This will avoid ‘downcycling’ of recovered materials. In addition, targets should incentivise appropriate extraction of valuable materials from glass cullet to ensure scarce materials like silver are recovered and used for to appropriate applications. As above, production credits could be used as a financial instrument. This likely needs be material-specific, with silicon, silver and glass the most pressing materials to consider for such incentives to promote PV circularity.

Action 2.2 Voluntary Partnerships for PV Recyclers

The e-stewardship scheme engages network operators as an intermediary to arrange logistics and contract recyclers, who will all likely receive a fixed subsidy for meeting the required performance standards. During consultation, stakeholders identified the need for any Australian e-stewardship scheme to include provisions for liable entities to partner directly with PV recyclers for end-to-end management of PV waste at EoL. This can incentivise recyclers to develop premium service offerings, such as high-value material recovery. A similar approach is employed in Europe, where liable entities can opt to meet their responsibilities under the stewardship scheme themselves or through a third-party provider such as a PRO.

Given the lengthy time between installation and decommissioning, appropriate fail-safe mechanisms may need to be established if one or more parties face financial difficulties prior to the end-of-life of the PV assets.

Action 2.3 Traceability and Reporting Obligations

The scheme should adopt the National Framework on Recycled Content Traceability. Recyclers should be obligated to regularly (monthly or annually) report on recycling inflow and outflow regarding the quantity and quality of materials, using standardised methods for calculating recycling rates. Recyclers should also be obligated to track materials downstream. The scheme should implement an audit system to ensure traceability obligations are met.

Action 3: Development of Infrastructure

The development of PV collection, testing, and recycling infrastructure will be critical to ensure PV waste is captured and properly managed for both reuse and recycling. This is particularly important to address logistics challenges faced by regional, remote, and very remote communities in Australia, as identified in Section 2.3.5.

Action 3.1 Development of PV Collection Infrastructure

Workshop participants consistently noted that appropriate collection models could include drop-off centres at local councils, as with the NTCRS, as well as 'reverse logistics' models for installers, detailed below. Without PV waste management policies in place, local councils can still be proactive in establishing collection facilities for EoL panels along with implementing procedures to record serial numbers of panels. This information can improve the understanding of PV panel life and PV waste volumes in Australia, noting access to data will require coordination with the STC scheme. To avoid stockpiling of PV waste, Councils can also develop partnerships with solar panel recyclers and entities that are developing voluntary product stewardship schemes, such as the Smart Energy Council.

Action 3.2 Reverse Logistics Options

Development of collection infrastructure should seek to employ reverse logistics, where possible. A reverse logistics model seeks to streamline EoL logistics using existing infrastructure, behaviours, or knowledge. This can reduce logistics costs, increase transparency and assist in tracking PV waste management against policy targets, such as collection and material recovery rates.

Reverse Logistics for Collection Points

Reverse logistics schemes operated by Australian PV recyclers have collocated collection points with waste management facilities and PV equipment retailers. This allows the collection infrastructure to leverage existing behaviours of PV installers, such as depositing panels at waste management facilities. Further, collocating collection points with PV equipment retailers allows installers to economise on transport of PV waste, as they will need to attend these locations to collect stock regardless.

Reverse Logistics for PV Waste Tracking

The proposed e-stewardship scheme states that both the scheme administrator and the network operators will be required to track recovered materials and management pathways. This will be key to providing transparency and tracking PV waste management against policy targets such as collection and material recovery rates.

To address the need for tracking throughout the panel lifecycle, researchers from the Australian Centre for Advanced Photovoltaics have proposed a reverse logistics model, which uses the existing system of barcodes, serial numbers, and geotagged pictures currently used by installers to claim rebates from STCs.[72] Under the reverse logistics model, installers or network operators would be responsible for scanning panels prior to depositing them at a collection centre. This provides data on EoL PV to be used by recyclers, governments, and the scheme administrator. However, it is worth noting this process will increase administrative load for installers and network operators. Given network operators have reporting obligations under the e-stewardship scheme, they should be responsible for scanning panels.

Action 3.3 Development of PV Recycling Infrastructure

Current PV recycling capability in Australia is detailed in Section 2.3.4. Over time, efforts in Australia should focus on expanding PV recycling capability to provide higher value-add propositions for the recovered materials and improving PV circularity, ideally feeding recovered materials back into the PV supply chain. This will reduce the environmental impact of manufacturing new PV panels and avoid potentially hazardous and valuable materials from entering landfill, while creating up to 355 direct jobs at PV recycling facilities by 2035.[31] Further to this, it is anticipated these activities will create additional employment opportunities such as logistics management and administration.

Australian studies have identified priority locations for PV recycling facilities to minimise transport distances for collection. This includes the greater Sydney, Melbourne, Brisbane, Adelaide and Perth regions, as illustrated in Figure 16. These locations can capture over 70% of expected waste by 2030.[31]

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[72] Leyton D, Chang N, Corkish R, 2021, 'A Reverse Logistics Model for End-of-Life Solar Panels Using Existing Transport Processes.', in Passey R (ed.), Proceedings of the Asia Pacific Solar Research Conference 2021, Australian Photovoltaics Institute, Sydney, presented at Asia Pacific Solar Research Conference 2021, Sydney, 16 December 2021 - 17 December 2021, https://apvi.org.au/solar-research-conference/wp-content/uploads/2022/02/Leyton-David-A-Reverse-Logistics-Model-for-End-of-Life-Solar-Panels-Using-Existing-Transport.pdf

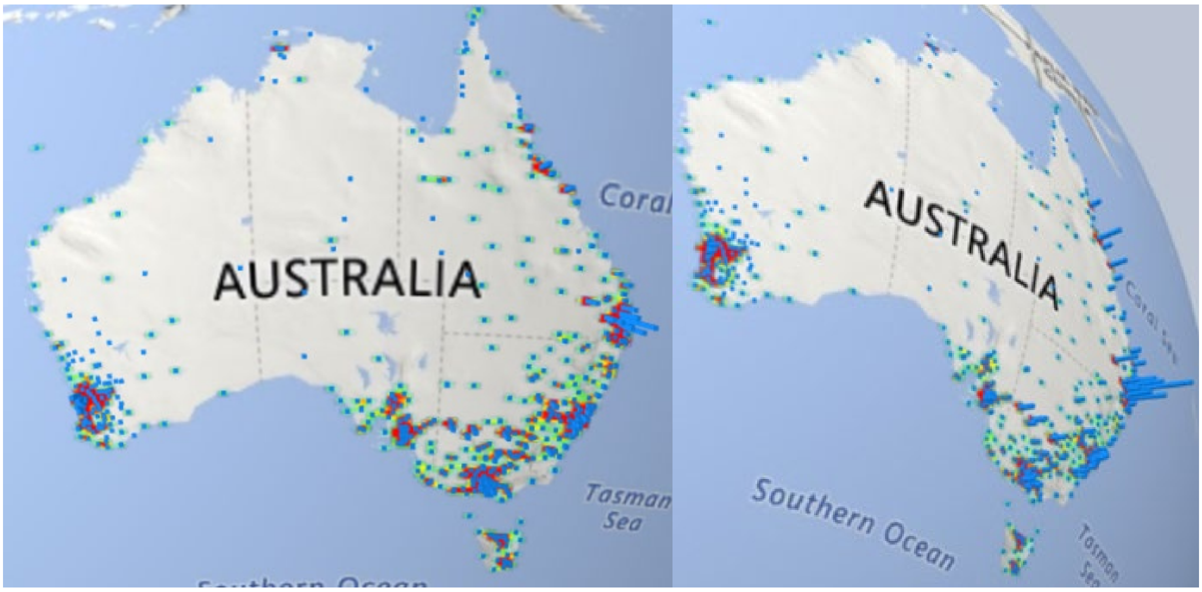

Figure 16: Australia PV waste forecast by location.[31]

Given the requirement of chemical processing for high-value recovery of materials from PV panels during recycling, streamlined permitting and approval processes could support the timely establishment of these solar recycling facilities.

Both federal and state governments can provide financial assistance for building PV recycling capacity and infrastructure. This could support research and development for commercial recycling processes targeting recovery of high-value materials from PV panels. At a national level, this could include the provision of concessional finance through the Clean Energy Finance Corporation. The Recycling Modernisation Fund (RMF) and ARENA could also support establishing and operating recycling facilities.

Action 3.4 Development of PV Testing and Certification Infrastructure

Testing and certification facilities will be required for assessing the suitability of panels for reuse and provide any certification required. In addition, these facilities can also serve to assist with assessing insurance and warranty claims. The establishment of PV testing/certification infrastructure should be coordinated nationally, targeting a small number of facilities across Australia at locations close to large load centres for residential-scale and utility-scale PV. Testing facilities would likely be located in the vicinity of PV recycling infrastructure, and it is noted that some PV recyclers have testing facilities in-house.

Action 4: Development of End Markets for Recovered Materials

Several workshop stakeholders, including recyclers, highlighted end markets for recovered materials (particularly glass and silicon, as detailed in Section 2.3.5) as a challenge for PV recycling in Australia. Developing end markets for PV materials will be essential to support the business case for PV recycling by providing increased financial certainty and lowering costs required to reach international end markets. Further, end markets for PV materials will provide an incentive for recyclers to pursue high recovery rates. Where possible, development of end markets should seek to prioritise circularity as outlined below:

1. **PV circularity**, with recovered materials used to facilitate a circular economy for the PV industry.
2. **Material circularity**, with recovered materials used to facilitate a circular economy within other industries.
3. **Avoidance of waste**, with recovered materials used in another industry, albeit without long-term material circularity.

However, the path Australia and other countries will take towards PV circularity is likely to be driven by avoiding waste, moving towards an end goal of PV circularity. The most immediate opportunities to avoid landfill of PV materials are the use of recovered glass cullet for construction materials, and the use of recovered aluminium frames for Australia's PV manufacturing or for general applications requiring aluminium.

The following sections identify opportunities for Australia to realise additional end markets for PV recovered materials.

International Collaboration on PV Circularity

Without significant Australian PV manufacturing capacity, one option to improve PV circularity is the processing of PV waste in Australia, with recovered materials exported to countries with existing manufacturing capacity for PV materials and panels. This will ensure that recovered materials remain in the PV supply chain. Potential regions for collaboration will be Europe, the US, India, China, and South-East Asia.

Establishment of Local PV Manufacturing

Local PV manufacturing could present a domestic end market for all materials recovered from EoL panels, which supports a circular economy for PV in Australia. This would increase demand for recovered materials and could provide an incentive for PV recyclers to pursue high rates of recovery for all PV materials. 50,000 tonnes of PV waste – the amount Australia is expected to produce in 2025 – will provide sufficient glass and aluminium for approximately 1 GW of local PV module manufacturing.

Of course, the establishment of a PV supply chain in Australia, while viable, will take significant time and investment.[12] Once Australia has a suitable level of PV module manufacturing capability, Australia may also start to manufacture panel components such as aluminium frames and solar glass, providing offtake opportunities for recovered PV materials with increased PV circularity. We note that, for off-take of recovered glass cullet, Australia will require the establishment of 'rolled glass' production capability that can tolerate the presence of antimony.

Research and development will be required to explore options for recovery and reuse of materials such as silicon and glass in a domestic PV supply chain, given the challenges identified in Section 2.3.5.

To support offtake opportunities of recovered PV materials in Australia, the DCCEEW could co-ordinate efforts to establish PV recycling with efforts to establish local solar manufacturing, as recently announced with A$1 billion of support for ARENA's Solar Sunshot program.[73] This could include production credits for manufacturing panel components, as recommended in a recent study on local PV manufacturing opportunities in Australia,[12] and government supported offtake agreements. Consideration will need to be given to the higher production costs in Australia compared to countries like China. Additionally, premiums for production credits could be provided when using recycled materials recovered from retired PV panels.

Action 5: Standards and Guidelines

Australia should seek to develop nationally consistent standards and guidelines on the management of PV during reuse, repair and recycling. This should be paired with education and training, so that stakeholders are aware of any obligations they may have. Industry bodies

[73] Solar Sunshot for our regions media release, Prime Minister of Australia the Hon Anthony Albanese, 2024

could be engaged in the development and dissemination of any standards and guidelines, given they have strong networks and relationships within the industry.

Action 5.1 Guidelines on PV Decommissioning, Handling, and Transport

Standards and guidelines for decommissioning, handling, and transport of used PV systems are important to minimise the number of broken and poorly packaged panels entering facilities for reuse and recycling. Such standards and guidelines could provide guidance on data collection and tracking of panels delivered to collection points. This data could assist with the characterisation of PV waste, which can inform both recyclers and government. These guidelines could be included as part of the PV installer accreditation process, given accredited installers will likely be responsible for system removals.

Action 5.2 Standards and Guidelines for PV Storage and Processing

Standards and guidelines regarding storing and processing of EoL panels should be implemented to address risks such as leaching of toxic materials, toxic gases from thermal processes, the use of hazardous chemicals, and respiratory risks associated with crushing solar panels. Of particular concern are fine glass and silicon powders which may cause respiratory problems, including silicosis. Any policies around product stewardship and government assistance should ensure that recyclers and other relevant stakeholders meet minimum safety requirements to be eligible under the scheme, including mandating the completion of silica awareness training. Safety standards should outline engineering controls, administrative controls, and personal protective equipment (PPE).

Action 5.3 Standards for PV Reuse Testing

Standards and guidelines should also be developed for testing procedures for second-life PV panels. Testing procedures include:

- Visual inspection to identify obvious failures and damage to the panel's structural integrity.
- Electroluminescence or photoluminescence tests to identify cell cracking and degradation. This can also provide an indication of hotspots, which can present both performance and safety concerns.
- Power tests to determine performance relative to nameplate capacity.

- Wet leakage test to ascertain current leakage, which presents a safety risk. However, some stakeholders opposed the need for a wet leakage test given the cost of the test presents a financial barrier to reuse.

Action 5.4 Standards for PV Reuse Exports

To increase transparency and minimise the relocation of PV waste through exports, as detailed in Section 2.1.2, Australia should develop standards and guidelines regarding the export of used PV.

In 2023, technical guidelines were developed for government agencies wishing to implement, control, and enforce legislation regarding the transboundary movements of waste EEE and used EEE under the Basel Convention. These technical guidelines specify the following provisions for used EEE to be exported:[74]

- An invoice or contract stating the EEE is for direct reuse and is fully functional.
- Evidence of evaluation or testing by a qualified and trained technician, with records provided for all items.
- A declaration by the holder that none of the EEE is waste according to the Basel Convention.
- Appropriate protection for each item against damage during transport, loading, and unloading.

These guidelines provide a framework for Australia to regulate the export of used PV, ensuring product quality and offtake for reuse. Further controls could include the guaranteed EoL management to prevent landfill or dumping in the importing country. In implementing regulation for the export of used PV, one key stakeholder highlighted that port authorities should be trained in the proper inspection of PV panels, as product quality can extend beyond visual or cosmetic defects and can differ from other used EEE.

[74] Technical guidelines on transboundary movements of electrical and electronic waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention, UNEP, 2023

Considerations must be given to what should happen with product-stewardship fees assigned for recycling in Australia at the end-of-life, as well as the testing and reporting requirements for accountability.

Action 6: Streamlining PV Recycling Processes

Given the volume of panel variations on the market, as detailed in Section 2.3.5, policy actions can reduce variation and increase product transparency. This can help streamline PV recycling processes such as panel characterisation and batch processing.

Action 6.1 Panel Standardisation

Standardisation of panel designs for PV could mitigate challenges for PV repair, reuse and recycling due to the large number of panel variations. Given Australia's market size, this may be best implemented through international collaboration, such as the IEA PVPS program. However, it is noted that any efforts to standardise panels may stifle future innovation. Further, due to the design life of PV, the benefits of standardisation for PV waste management may not be fully realised until 25-30 years after implementation.

Panel manufacturers and recyclers should also be involved in the development of standards. In July 2023, nine leading PV manufacturers[75] unanimously voted to adopt a standard module size using rectangular silicon wafers. They have also established a Photovoltaic Size Standardisation Research Group to promote standardisation of cells and module sizes.[76]

Action 6.2 Environmental Labelling

As with the EU's forthcoming Ecodesign and energy labelling (detailed in Appendix 3.1.2), Australia can mandate comprehensive and robust labelling on PV panels detailing panel content, performance, and handling. Labelling provides transparency, which allows consumers to make sustainable purchase decisions, communicates repair options to installers, and streamlines panel characterisation during the recycling process. Further, comprehensive labelling could lower the administrative burden of reporting on material

[75] Astronergy, Canadian Solar, DAS Solar, JA Solar, JinkoSolar, LONGI, Risen Energy, Tongwei Solar, and Trina Solar
[76] Bhambani A., 9 Leading Integrated Solar Module Manufacturing Companies Reach Consensus Over Rectangular Silicon Wafer Modules, 2023

recovery targets. Labels should be easily visible, and able to last at least 30 years or longer than the warranted life of the panel, to remain useful once the panel reaches end of life. One potential option is to include the label as a QR code to direct consumers/installers/recyclers to a landing page with all the required details. Details for what labelling should include are shown in Table 10.

Table 10: Panel labelling scope

Detail	Inclusions
Durability and quality assurance	Expected panel lifetime, performance and product warranties, and degradation, with the consumer as the intended audience.
Repairability	Potential to replace cables, junction box, bypass diodes, and backsheet, with the installer as the intended audience.
Recyclability	Any guidance on panel dismantling and details of critical and environmentally relevant raw material content.

ITP's suggestions for critical and environmentally relevant materials to be included in the scope are summarised in Table 11, noting the inclusion of bismuth as a future material of interest for the EU's Ecodesign labelling.

Table 11: Critical and raw materials in PV panels

Material	Presence in PV panels	Considerations
Lead	Lead is present in solders and some metallisation pastes.	Lead and lead alloys are listed as hazardous waste under Annex VIII of the Basel Convention, which can impede or prohibit the transboundary movements of such waste.
Cadmium	Cadmium is a key component of some thin-film panels (<5% of solar panels)	Cadmium and cadmium alloys are listed as hazardous waste under Annex VIII of the Basel Convention, which can impede or prohibit the transboundary movements of such waste.
Silicon	Key semiconductor material for crystalline silicon panels (>95% of solar panels)	High purity material in solar panels. Material recovery provides an alternative to quartz mining and refining for metallurgical grade silicon. Recovered silicon will need to undergo further processing to achieve purity levels required for PV.
Silver	Silver is used for the contacts for most silicon solar panels including industry-dominant PERC cells.	Silver is a precious metal, where increases in PV production under business as usual is expected to put significant pressure on silver supplies.[9]
Indium	Indium is a key component of some (CIGS) thin-film panels.	Indium is a rare earth element, with its abundance comparable to silver.
Backsheet fluorinated additives	Many monofacial panels use fluorinated backsheets due to their durability and price point.	Fluorinated additives can release toxic fumes upon incineration. A registered incinerator is required to properly burn off the backsheet during recycling.
Gallium	Gallium is a key component of some (CIGS) thin-film panels.	Gallium is a rare earth element. While more abundant than indium or silver, its abundance is similar to lithium.
Tellurium	Tellurium is a key component of some thin-film panels.	Tellurium and tellurium alloys are listed as hazardous waste under Annex VIII of the Basel Convention, which can impede or prohibit the transboundary movements of such waste.
Metal solder and contacts	Metal contacts to extract electricity from the solar cell and solder for interconnecting cells	Metal contacts are typically silver. However, contacts also contain metals such as aluminium, copper, nickel or tin (sometimes various metals are present). Solder may contain lead, tin, bismuth, indium, copper, silver. Depending on the metals used, there may be scarcity or toxicity concerns (eg. see lead and silver sections of the table).
Front and rear glass compositions including fining agents.	Solar panels typically use rolled glass with antimony to reduce photodegradation. Bifacial panels can use different glass compositions for their front and rear.	Antimony and antimony alloys are listed as hazardous waste under Annex VIII of the Basel Convention, which can impede or prohibit the transboundary movements of such waste. Glass and fining agents may present other challenges as detailed in Section 2.3.5.
Phthalates	Phthalates are present in the power cables. They are commonly used to soften vinyl plastics	Phthalates can leach into the environment and can negatively impact hormonal development and reproductive health.
Bismuth (not listed in EU Ecodesign labels)	Bismuth is used for solders in SHJ cells and some other niche PV technologies.	Although bismuth in general is abundant and non-toxic, current global production is less than silver. Increased uptake of SHJ and tandem cells could create supply chain concerns for Bismuth.

Action 7: Knowledge Building

With limited solar panel recycling activities in Australia, governments should explore opportunities for overseas partnerships to bring PV recycling expertise to Australia and build local capability in the short-term (see Section 2.3.3) . In particular, collaboration with EU Member States could allow Australia to leverage their experience with PV product stewardship for policy implementation, technology development, capability building, and establishing collection, transport, and recycling infrastructure.

To assist with these partnerships, the government should identify solar panel recycling as a critical strategic industry for Australia, and ensure streamlined paths to visas for solar PV recycling experts from regions with established PV recycling activities such as Europe, the US and China. For the longer-term, it will be essential to develop educational programs and help support building and the training of a local workforce on solar panel recycling. Education programs are also required for both consumers and installers to build awareness of PV waste management, and reduce premature retirement of functioning PV systems.

Action 8: Research and Development

Funding research and development for end markets will be beneficial for unlocking offtake options and stimulating demand for materials recovered from EoL PV, improving the business case for PV recycling. To this end, future Cooperative Research Centres Project (CRC-P) rounds can include PV waste management as a funding priority.

Firstly, research is required to understand the variability in solar panels currently installed in Australia, because of its direct impact on logistics and recycling processes. This is required to identify the composition of materials used in solar panels so that the most appropriate recycling methods can be used, and to identify suitable end markets given the potential mixed nature of panel components in recovered materials.

A second key area of research and development will be identifying end markets for materials with limited offtake options, and offtake options to improve PV circularity. This could also improve the commercial viability of using recovered materials in manufacturing or other industrial processes. Key materials to target for research and development will be silicon and glass, given the challenges identified in Section 2.3.5. For example, recovered silicon is metallurgical grade, which is currently used in the production of aluminium alloys.

A third research area will involve the development of commercially viable recycling processes specific to solar panels to ensure a high-value recovery of materials and to maximise the potential to return recovered materials to the PV supply chain.

6 IMPLEMENTING PV CIRCULARITY IN AUSTRALIA

Drawing on Section 5, Table 12 presents an implementation plan for specific sub-actions to improve PV circularity in Australia.

Table 12: Summary of Policy and Action Pathways for Improving PV Circularity in Australia

Action	Responsible stakeholders	Timeline
National co-ordination of PV waste management by establishing a National PV Waste Management Taskforce	DCCEEW with input from state and territory governments	2024
Development of a National PV Waste Action Plan to be incorporated into the National Waste Policy and National Waste Policy Action Plan	DCCEEW, state/territory governments, local councils, solar industry stakeholders, Taskforce on Consumer Energy Resources	2025
Implement harmonised state-wide landfill bans on sending PV waste across Australia for both PV panels and PV laminate stacks, establish logistics and collection centres across Australia, enabling 'reverse logistics' where possible.	DCCEEW, state and territory governments, local councils	2025
Implement the e-stewardship program for PV recycling with incentives to achieve a minimum 80% material recovery outcome. **Ensure a pathway for liable entities to establish direct partnerships with PV recyclers to meet their obligations.** **Adopt the National Framework on Recycled Content Traceability and incentivise high-value material recovery.**	DCCEEW, state and territory governments	2025
Establish good-practice PV recycling and testing capability near major Australian cities with large volumes of end-of-life PV panels	DCCEEW, state and territory governments, PV recyclers	2025
Establish PV panel and solar glass manufacturing in Australia under the SunShot Program, with bonus production credits for manufacturing PV materials from recovered end-of-life PV panels.	DCCEEW, Australian Renewable Energy Agency, state and territory governments	2026
Develop new standards for decommissioning, handling, transport, and storage of PV for repair, reuse and recycling. Develop new standards and guidelines for reuse of solar panels including testing requirements and covering export opportunities.	Clean Energy Council, Smart Energy Council, Industry stakeholders	2026
Implement environmental labelling and panel standardisation to reduce variability between panels	PV recyclers, manufacturers, Smart Energy Council, Clean Energy Council, IEA PVPS	2027
Research and Development for commercially viable 'good practice' PV recycling and develop domestic end-markets for recovered materials	Australian Renewable Energy Agency, state governments.	ongoing

Education and training for improved consumer and installer awareness, and silicosis safety training for recyclers.	State governments, industry bodies	ongoing

APPENDIX A. POLICY DIALOGUE WORKSHOP SUMMARY

A summary of the policy dialogue workshops is presented in Table 13 below.

Table 13: PV circularity policy dialogue workshop summary

Workshop Topic	Number of Attendees	Key Outcomes
PV Product Stewardship **August 2023**	49	• General agreement on the need for PV recycling in Australia. • PV product stewardship should incentivise high material recovery rates. • The EU's Ecodesign measures provide insight into material consumption, performance, recyclability, and repairability.
PV Recycling Drivers and Challenges **October 2023**	33	• Key drivers for PV recycling were identified as expected waste volumes, material scarcity, and regulation. • Key PV recycling challenges are profitability and lack of incentives. • A representative from EU-funded project Photorama highlighted the diversity of PV products on the market as a recycling challenge.
Recycling Technology for a PV Circular Economy **December 2023**	35+	• JinkoSolar's 12 megawatt PV recycling pilot plant achieved high recovery rates >95% using thermal/chemical processes. • Product stewardship should align with the waste hierarchy and include waste reduction and reuse. • The Product Stewardship Centre of Excellence presented five characteristics for effective product stewardship based on evaluation of over 100 schemes in Australia.
Logistics Challenges in Australia **February 2024**	39	• Most PV recyclers implement a reverse logistics model, differentiating between small-scale and large-scale systems to economise on collection. • Collaboration between consumers, installers, and local council is beneficial for reverse logistics. • Regional, remote, and very remote areas experience high transport costs required for proper disposal. • End-markets for recovered materials is a challenge for PV recyclers. Offtake may require exporting, reducing profits.
Reuse Opportunities in Australia and Reducing Unnecessary End-of-Life PV Waste **April 2024**	45	• Reuse issue with exports to developing countries are not regulated (questions were raised about the potential relocation of waste under guise of reuse) • Ongoing discussion about testing required for safety and performance (no consensus on the need for wet leakage, which could affect economics of reuse while others identified this as being critical to ensure safety) • The Small-scale Technology Certificate scheme is impacting case for reuse. When it ceases in 2030, will improve business case for reuse.

APPENDIX B. PV RECYCLING TECHNOLOGY OVERVIEW

B1. Disassembly

Disassembly involves the mechanical removal of the junction box, cable, and aluminium frame.[77] The frame may be cut beforehand to allow it to tear away more easily.

B2. Delamination

Panel delamination methods are summarised in Table 14 and discussed further thereafter:

Table 14: Summary of delamination methods for PV panels[42]

Delamination method	Recovered products	Glass recovery ($\%_{weight}$)	Relative throughput	Energy/chemical consumption
Mechanical (shredding/crushing)	Glass cullet, mixture of silicon and metal (and/or plastic) powder	80-91%	High	Low
Mechanical (hot knife)	Glass sheet, solar cells, ribbons[78]	98%	High	High
Thermal	Glass sheet, solar cells, ribbons	100%	Low	High
Chemical	Glass sheet, solar cells, ribbons	100%	Very Low	Very high

B.2.1. Mechanical Delamination

Mechanical delamination involves the physical separation of the glass from the solar cells. The high throughput of mechanical processes makes it commercially attractive compared to thermal or chemical delamination methods. The products of mechanical delamination will typically require further thermal treatment such as pyrolysis[79] to remove EVA residues. Further, the backsheet will need to be removed from the solar cells before proceeding to the next recycling stage. This can be done by heating the panel to soften the EVA and then

[77] R. Frischknecht, K. Komoto, T. Doi 2023, Life Cycle Assessment of Crystalline Silicon Photovoltaic Panel Delamination With Hot Knife Technology, IEA PVPS Task 12, International Energy Agency (IEA) PVPS Task 12, Report T12-25:2023. ISBN 978-3-907281-41-3.
[78] Ribbons are a thin conductor used for the electrical interconnection of solar cells.
[79] Heating in the absence of oxygen.

manually peeling off the backsheet. Alternatively, the backsheet can be removed by incineration by a licensed plant.

Two methods for mechanical delamination are described below.

- **Hot knife delamination** uses a heated knife to soften the EVA as it cuts the glass sheet away from the solar cells.[80] The process takes around 50 seconds per panel.[77] This can recover 98% of the glass by weight in a single step.[42] Figure 17 shows a production tool for hot knife delamination.
- **Shredding and/or crushing** breaks the panel into particles that can be sorted based on physical size. The larger particles tend to be recoverable glass, while the smaller particles tend to be silicon and metals requiring further treatment. This method can recover 80-91% of glass by weight.[81]

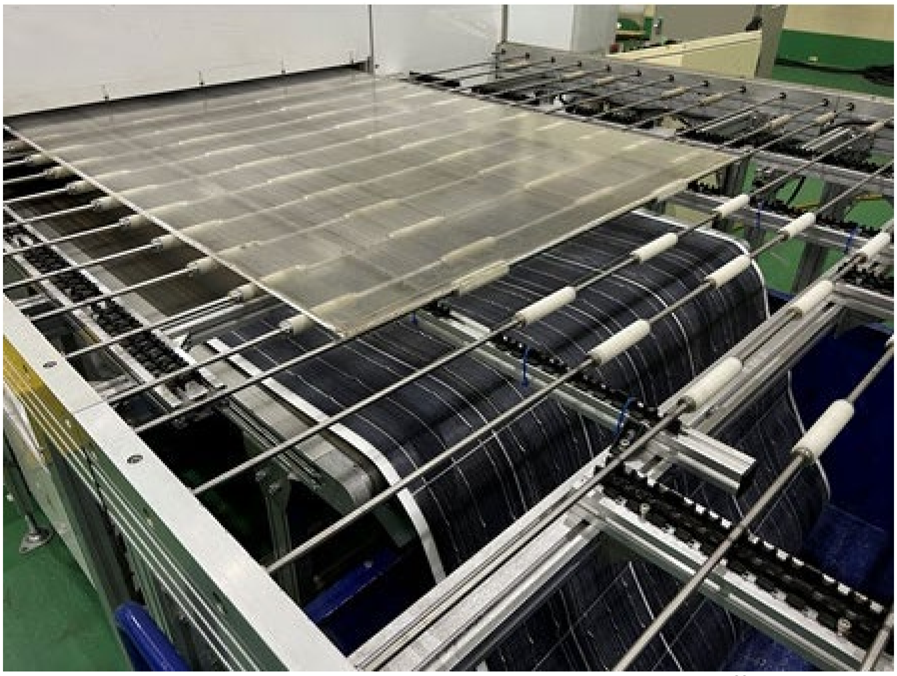

Figure 17: Recovered materials from hot knife delamination[82]

[80] Latunussa C., Ardente F., Blengini G., Mancini L., Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels, 2016, http://dx.doi.org/10.1016/j.solmat.2016.03.020
[81] Granata G., et al., Recycling of photovoltaic panels by physical operations, 2014 https://doi.org/10.1016/j.solmat.2014.01.012
[82] R. Frischknecht, K. Komoto, T. Doi 2023, Life Cycle Assessment of Crystalline Silicon Photovoltaic Panel Delamination With Hot Knife Technology, IEA PVPS Task 12, International Energy Agency (IEA) PVPS Task 12, Report T12-25:2023. ISBN 978-3-907281-41-3.

B.2.2. Thermal Delamination

Thermal delamination involves heating panels to 300-600˚C to remove the adhesive encapsulation layer between the glass and solar cells, allowing for the separation of these two components. Prior to this, lower levels of heating will allow the backsheet to be manually peeled away.[42,83] If thermal delamination is conducted in an inert gas environment, the encapsulation layer decomposes.[84] In an oxygen environment, the layer is burned off.

B.2.3. Chemical Delamination

Chemical delamination involves dissolving the adhesive encapsulation layer, typically over a long period ranging from 30 minutes to 10 days[85]. Chemical delamination has been demonstrated with various solvents and can be accelerated using ultrasonic radiation, although it still has a lower throughput compared to mechanical or thermal delamination. Currently, the low throughput and high chemical consumption of this process makes it commercially unattractive.

B3. Silicon and Metal Separation

Leaching and etching are two approaches for separating silicon and metals, described below.

Leaching is typically used for powders containing metals, silicon, metallic ashes from shredding and/or thermal treatment (described above). This process dissolves the metals (silver, aluminium, and copper) in nitric acid or a mixture of nitric acid and hydrochloric acid. Metallurgical grade silicon residue remains undissolved and therefore filtration of the resulting mixture enables separation.

Etching uses a high pressure, chemical spray to remove electrodes, passivation layers/anti-reflective coating,[86] and to remove the emitter and doped layers of the solar cell (containing high concentrations of phosphorus, boron or aluminium). The process enables the potential

[83] Dobra T, Vollprecht D, Pomberger R. Thermal delamination of end-of-life crystalline silicon photovoltaic panels. Waste Management & Research. 2022;40(1):96-103. doi:10.1177/0734242X211038184
[84] Products of decomposition are acetic acid, propane, propene, ethane, methane, and other combustible oils and gases
[85] This time period can vary based on several factors including the solvent used and acceleration from heating, agitation, or ultrasonic radiation.
[86] Some etching processes remove this mechanically

recovery of high-purity, solar-grade silicon wafers as it can target the surface layers of the cell. However, this is more time-consuming and chemically intensive than leaching, detailed above.[87,88]

B4. Metal Extraction

The leaching process leaves metals in the solution following the extraction of silicon. Metal extraction is key in recovering valuable materials such as silver, and removing toxic materials such as lead from the waste stream. Some metal extraction approaches include:

- **Electrolysis**, which involves passing a current through the solution to attract positive metal ions towards the cathode, where they gain electrons to form a deposit of pure metal.
- **Precipitation**, which involves introducing a precipitating reagent to the solution. This reacts with metal ions to form an insoluble particle, which can be removed by filtration or settling.

Metal replacement involves introducing a more reactive metal to the solution, which reacts preferentially and replaces the less reactive metal in the compound. An example of this is the use of zinc powder for the recovery of silver.

[87] Huang W H., et al., Strategy and Technology to Recycle Wafer-Silicon Solar Panels, 2017, https://doi.org/10.1016/j.solener.2017.01.001

[88] Park J., et al., An eco-friendly method for reclaimed silicon wafers from a photovoltaic panel: from separation to cell fabrication, 2016, https://doi.org/10.1039/C5GC01819F

APPENDIX C. GLOBAL PV CIRCULARITY POLICIES

C1. China

China's National Development and Reform Commission (NDRC) has recently announced plans to establish a recycling system for retired solar PV panels and wind turbines by 2025.[89] Alongside this announcement, the NDRC released industrial standards and rules for the decommissioning, dismantling, and recycling of wind and solar PV assets. These standards provide design objectives for manufacturers, where products should be lightweight, easily dismantled, and easily recycled. The NDRC also encourages equipment producers to provide their own recycling services, or to cooperate with third party service providers. Further, the guidelines place the onus of decommissioning wind and solar assets on generators, with the resulting waste subject to a landfill ban.[90] Given the dominance of Chinese solar panels in the global market, any changes to the design of solar panels in China will greatly impact future recycling efforts of PV around the world.

Prior to the NDRC's announcement, there was no distinct obligation for handling end-of-life crystalline silicon PV panels. China's only other legislation governing PV waste was a national standard for the recycling and reuse of thin-film PV panels used in building constructions.[91] The standard covers collection, transportation, and treatment of waste panels. It also included standards for recovering and processing of valuable materials, and the safe handling and disposal of hazardous materials.[92]

C2. Japan

There is currently limited legislation in Japan for PV recycling, and PV panels must be treated under the Waste Management and Public Cleaning Act. In 2022, Japan introduced a levy to ensure that generators with over 10 kW capacity had sufficient funds for proper decommissioning and disposal of PV assets at EoL. This was introduced via an adjustment to

[89] https://www.pv-tech.org/china-to-build-solar-recycling-system-by-2025/
[90] https://www.pv-magazine-australia.com/2023/08/21/china-plans-recycling-system-for-wind-turbines-solar-panels/
[91] GB/T 38785-2020
[92] https://doi.org/10.1016/j.chemosphere.2023.139840

their Feed-in-Tariff scheme, which was transitioned to a Feed-in-Premium (FiP) scheme, effective from 1st July 2022.[93] Under the scheme, generators receive a premium for electricity sold on the market via the regular bidding process. Through the FiP process, a certain amount is withheld from the generator and managed by a third party during the final 10 years of the 20-year subsidy period to ensure funds for suitable disposal. Withheld funds are released to the generator upon submission of "documents showing that the disposal of facilities can be reliably anticipated".[94] [93]

C3. United States of America

While the United States of America has no federal regulations governing PV waste management, there are some state-level schemes in place. Namely, Washington has implemented take-back requirements for PV manufacturers at panel EoL, with no added cost to system owners. California has classified PV as universal waste,[95] which reduces the compliance requirements for handling products at EoL when compared to hazardous waste. Universal waste cannot be disposed of in household bins or landfill and must be taken to a designated handler or recycler.[96]

PV waste policies are being considered in several states including Illinois, Hawaii, Arizona, North Carolina, and New Jersey.

C4. India

In late 2022, India added the management of solar PV waste to the E-Waste Management Rules, which is an EPR applied to various electrical products. According to the rules, solar equipment and material producers must register in the E-waste portal and ensure any waste from production is properly processed.[97] Downstream waste is also tracked via the portal, with EPR certificates provided to producers by the recycler.[98]

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[93] Agency for Natural Resources and Energy (ANRE), Haikitou hiyou trumitate gaidorain (Guidelines for Decommissioning and Other Reserves), 2021
[94] Takeuchi N., Higuchi W., Yoshida N. The Renewable Energy Law Review: Japan, The Law Reviews, 2023
[95] The universal waste classification reduces regulation governing material handling at product EoL when compared to hazardous waste. This includes storage, transport, and recycling.
[96] Department of Toxic Substances Control, Universal Waste, 2022
[97] Mishra G., Government Adds Solar Panels to Ambit of E-Waste Management Rules, Mercom, 2023
[98] E-Waste Management System: Portal under E-Waste (Management) Rules, 2022, Government of India Ministry of Environment, Forest and Climate Change

APPENDIX D. ADDITIONAL CONSIDERED POLICY OPTIONS

D1. Eco-modulated EPR Fees

The e-stewardship scheme remains open to the implementation of eco-modulation for extended producer responsibility (EPR) fees, where producers are issued a bonus (a fee discount) or penalty (a fee premium) based on whether their product meets certain design criteria. This can provide a financial incentive and increase price competitiveness for product designs that meet specified criteria such as recyclability, repairability, durability, and environmentally sustainable production.

Table 15 summarises some desirable design characteristics for circular-friendly PV, should the scheme opt for eco-modulation of EPR fees.

Table 15: Design characteristics for circular PV

Design Characteristic for PV Circularity	Advantages	Drawbacks
Panel standardisation	• Easy to assess compliance and works to reduce the number of variations in panel designs on the market, thereby improving the ease of PV panel recycling	• Potential to stifle innovation • Challenging to bring new products to market
Recycled content	• Decreased use of virgin materials • Some manufacturers may already be using recycled content	• May be difficult to assess compliance, especially given much of manufacturing occurs overseas • Annual PV waste volumes are insignificant relative to annual production.
Antimony-free glass	• Supports use of glass cullet by Australian manufacturing	• May decrease durability or performance as the antimony is added to solar glass to combat photodegradation
Low or no fluorinated content in backsheets	• Can simplify recycling processes by reducing health and safety challenges	• May decrease panel durability, leading to increased waste creation
Durability	• Extends operational life, decreasing PV waste generation • Easy to assess compliance using warranties as a proxy	• Market is trending towards increased durability as a point of difference already. Early retirement is often due to other factors such as economics and STC incentives
Embedded emissions	• Targeting the use of green electricity throughout the supply chain	• Can be challenging to assess and may introduce complexity such as companies purchasing carbon offsets
Higher efficiency	• Increased energy yield over the life of a PV system, which can decrease material requirements and waste generation • Easy to assess based on performance guarantees	• Higher efficiency technologies may introduce new material challenges, by using scarce materials, or increasing material demand for silver. This can create challenges in terms of using recycled materials to manufacture new PV panels

Eco-modulation fees can often be difficult to implement in practice as they create an additional administrative burden for scheme operators while also often failing to trigger meaningful design changes from producers.[66,99,100] This can occur for various reasons, including:

- Bonuses and penalties may make up a relatively small proportion of the product price.
- Costs for product design or manufacturing changes reduce the benefit of financial incentives.
- Producers often consist of local entities, including importers, sellers, and assembly companies. These entities may have limited influence regarding product design criteria, particularly with manufacturers who sell to global markets.

It is worth noting that no jurisdiction has implemented eco-modulation fees for PV. This may present additional challenges for eco-modulation, as detailed below:

- Given the long operational life of PV, eco-modulated fees implemented in the present may target design criteria that are not accurate or reflective of future recycling processes when panels enter the waste stream.
- Eco-modulation could increase panel variations on the market, which can present challenges for recyclers, as detailed in Section 0.

However, it is also worth noting the PV industry is very price competitive, which increases the potential for eco-modulated EPR fees to influence importer purchase decisions, should products with the desired design characteristics already exist on the market.

A report studying potential implementation of eco-modulated fees in the United Kingdom suggested three characteristics for successful implementation of eco-modulation, drawing on knowledge from markets with existing schemes:[99]

- **Simplicity.** Eco-modulation criteria should be easy to understand and implement. Complicated processes and design criteria will likely deter producers from

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[99] Magalini F., et al., DSS+ Defra report on implementing eco-modulation into the UK's WEEE system, 2022
[100] Laubinger F., Brown A., Dubois M., Borkey P., Modulated fees for Extended Producer Responsibility schemes (EPR), OECD Environment Working Papers No. 184, https://dx.doi.org/10.1787/2a42f54b-en

implementing changes. The scheme should target design criteria that are readily achievable with manufacturing processes and products currently on the market.

- **Transparency.** Design criteria should be easily verifiable and developed in consultation with producers and recyclers to ensure viability. Criteria should also be flexible enough to avoid stifling product innovation or impeding other product characteristics.

Harmonisation. Eco-modulation schemes should align with other laws and regulations, both locally and internationally. Eco-modulation fees for PV in Australia should seek to align with local and international eco-design initiatives, such as the proposed Ecodesign and energy labelling requirements for PV in the EU. As PV manufacturers serve global markets, aligning legislation across markets may increase the efficacy of eco-modulated fees, particularly as Australia is a relatively small PV market in relation to global demand.

D2. Classification of PV Waste

There were mixed views among stakeholders for the need for the classification of PV waste. Clear guidance is required from the DCCEEW for the classification of PV waste. This includes guidance for toxic materials such as lead, antimony, and cadmium that may be present in very small concentrations, and a potential differentiation between physically damaged panels versus panels with no evidence of physical damage. Guidance should also seek to align with the Basel Convention, which significantly constrains the export of hazardous waste.

Classification of PV waste should consider balancing the requirements for the safe handling, storage and management of PV waste, while minimising unnecessary costs and the challenges of assessing a large number of variations in PV panel designs over decades. In particular, panels with no physical damage (broken glass, scratched backsheet, etc.) will likely be suitable for relaxed storage requirements, compared to current regulations in Victoria, which place restrictions on the outdoor storage of solar panel waste. Visual inspection would be sufficient to assess physical damage.

D3. Research and Development for PV Durability, Repairability, and Recyclability

Given challenges facing the durability, repairability, and recyclability of PV, there is scope for research and development to improve panel design with the aim of facilitating these outcomes.

Due to Australia's lack of PV manufacturing, international collaboration will allow input from global stakeholders with PV manufacturing capability, including potential collaboration with major manufacturers. Engaging these stakeholders will be key to unlocking commercially viable panel designs addressing these circularity challenges.

In line with the circularity framework in Section 1.2, design outcomes should be prioritised as follows:

1. Durability (R1)
2. Repairability (R4)
3. Recyclability (R8)

Design outcomes should seek to avoid impeding higher priority circularity strategies. For example, increased panel recyclability should not decrease durability or design life.

D.3.1. Durability

Improved panel durability will seek to decrease faults that result in PV panels entering the waste stream prior to the end of their design life, as outlined in Section 1.4.1. It is worth noting that manufacturers are already seeking to increase panel durability, as indicated by longer product and performance offerings for newer panel models.

Designing panels with a focus on increased durability of external components such as the glass, frame, and backsheet may mitigate faults such as glass breakage, cell cracking, interconnection faults and backsheet degradation. It is worth noting that such design considerations should seek to avoid impairing panel performance and functionality.

Further, research and development into reduced panel degradation could improve the design life of PV. This will increase usage before panels enter the waste stream and could serve to lower the rate of PV replacement.

D.3.2. Repairability

Design for repairability aims to facilitate panel repair when faults or damage occur. Research and development could also explore technologies to facilitate repair of common PV faults such as delamination, broken glass, or broken solar cells. Some literature has suggested improvements to repairability through modular or dismantlable panel designs, which allow easy access to individual components for replacement or repair.[101,102] Such designs may increase manufacturing costs,[102] which may inhibit consumer uptake. A key limitation of repairability will be the long lifetime of PV panels, and the substantial changes in both physical and electrical characteristics between manufacturers and over time, limiting the opportunity to replace components such as cells. Panel standardisation may assist with reducing the number of variations in spare-parts needed for panels.

D.3.3. Recyclability

Products designed for recycling aim to improve the speed and ease of dismantling, increase the recycling rate and purity of recovered materials, and reduce waste. The IEA PVPS program has developed 'design for recycling' guidelines for PV panels.[103] Recommendations from the design for recycling guidelines are summarised below. Research and development may seek to explore commercially viable design for recycling options that do not inhibit the durability or repairability of PV panels.

1. **Identification of panel construction and composition** through durable labelling allows for categorisation of panels based on known variations, as detailed in Action 6.2.
2. **Alternative backsheet materials** avoiding the use of fluorine may reduce health and safety concerns during the recycling, which can reduce the complexity of processes required for material recovery.
3. **Metal substitutions** to minimise environmental impacts and facilitate cheaper leaching solutions.

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[101] El-Fayome E., et al., Proposal for Repairable Silicon Solar Panels: Proof of Concept, Energies 2023, 16, https://doi.org/10.3390/en16186492

[102] Majdi A., et al., Fundamental study related to the development of modular solar panel for improved durability and repairability, IET Renewable Power Generation Vol. 15, pg. 1382-1396, 2021

[103] Jose I. Bilbao, Garvin Heath, Alex Norgren, Marina M. Lunardi, Alberta Carpenter, Richard Corkish, 2021, PV Panel Design for Recycling, International Energy Agency (IEA) PVPS Task 12, Report T12-23:2021. ISBN 978-3-907281-27-7.

4. **Minimising encapsulant use or using reversible encapsulants**, given removal is a major challenge for recycling processes.
5. **Alternative sealants for aluminium frames** such as O-ring or U-ring profiles, displayed in Figure 18, are easier to remove without distorting the aluminium frame or breaking the glass, when compared to silicone adhesives currently used.

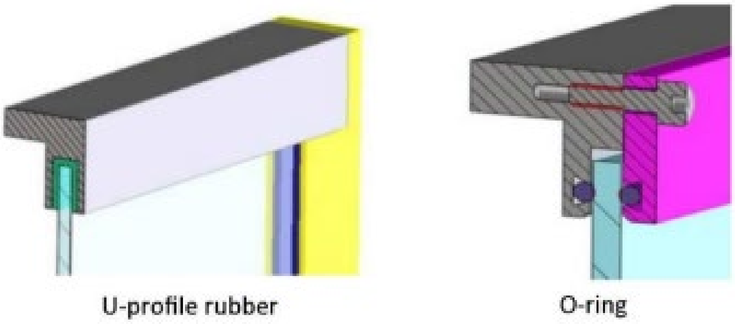

Figure 18: U-profile and O-ring sealants for PV modules[103]

D4. PV Waste Management Support for International Neighbours

Australia has several neighbours with substantially smaller PV markets, primarily Pacific Island Nations. This presents an opportunity for Australia to accept PV waste from these nations for central processing. Importantly, the Waigani Convention allows Australia to receive hazardous waste from Pacific Island Countries who are signatories.[104] Another potential partnership would be with Europe for Asia-Pacific nations falling under European jurisdiction (e.g. New Caledonia), rather than having PV EoL waste in such nations being exported to Europe for recycling. It is noted that considerations and permits may be required under the Basel Convention and Hazardous Waste Act 1989, with the exception of signatories to the Waigani Convention.

D5. Modifications to the Small-scale Technology Certificate (STC) Scheme

As identified in Section 1.4.1, the STC scheme, which incentivises PV uptake, enables early retirement of operational PV panels because they are provided upfront (not for generation) and are also provided for replacement systems, albeit only out to 2030. Given this, the STC scheme should be adapted to incentivise the continued operation of these systems. This could

[104] International hazardous waste conventions, Australian Government Department of Climate Change, Energy, the Environment, and Water, 2022

be achieved by amortising the rebate over the expected life of the system, noting that this may increase the capex outlay for consumers. Alternatively, premature system retirement could incur a penalty proportional to the remaining life of the system for which the rebate applied, which is for each year until the scheme expires in 2030. It is worth noting that premature retirement is difficult to track, given there is limited data on decommissioned rooftop systems. Of course, early system retirement should not be penalised due to failure of system components or faults beyond the control of the consumer or the installer.

Given the STC scheme expires in 2030, such modifications may not be feasible or necessary. The absence of such rebates may alleviate these issues with premature retirement. If another incentive is implemented beyond 2030, it should seek to address premature retirement of small-scale PV systems.