SCOPING STUDY:

SOLAR PANEL END-OF-LIFE MANAGEMENT IN AUSTRALIA

Authors
Rong Deng, Verity Tan, Chence Niu, Renate Egan (University of New South Wales)
Email: rong.deng@unsw.edu.au

Design
Hillary Lang Design

Cover photo
Neoen Australia

First published
March 2024
This project received funding from Neoen Australia and Australian Centre of Advanced Photovoltaics.

ACKNOWLEDGEMENT

The authors of this report would like to thank Neoen Australia and ACAP for providing funding to undertake this important research project.

Neoen Australia has been contributing to Australia's energy transition for over a decade, with 3.75 gigawatts (GWs) of solar wind and grid-scale storage capacity in operation or under construction in February 2024. As a long-term owner and operator of its projects, Neoen manages a project across its entire life cycle, including decommissioning and end of life (EoL).

While Neoen's first utility-scale solar projects in Australia are currently only five years into their 25+ year lifecycle, the company is committed to understanding the challenges of PV recycling and to playing its part in developing solutions. As part of its long-term commitments to deliver renewable energy to the ACT Government it has commissioned this study to contribute to knowledge sharing across government, as well as the renewable energy and waste industries.

The Australian Centre for Advanced Photovoltaics (ACAP) is a dynamic, world-leading national centre where solar photovoltaic research institutions across Australia collaborate.

Federally funded by the Australian Renewable Energy Agency (ARENA) since 2013, and led by the University of New South Wales, ACAP's broad range of research work continues to drive Australia's international lead in solar technology and development, as global economies transition to renewable energy. Our strong pipeline from research to industry makes us a world leader in solar power technology development.

Disclaimer

The work received funding from the Australian Renewable Energy Agency (ARENA). The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.

The authors would like acknowledge Ms. Lisa Stiebel, Mr. Jean-Christophe Cheylus, and Ms. Mikaela Georgiadis from Neoen Australia, Prof. Vinayak Dixit and Dr. Nathan Chang from UNSW, representatives from Veolia Australia and New Zealand, and Transport Canberra and City Services (ACT Government) for their essential contributions to this research in various capacities ranging from project conceptualization to early-stage methodology development and report review.

EXECUTIVE SUMMARY

End-of-life management is becoming an increasingly important consideration in the solar industry.

Australia has committed to reduce its CO_2 emissions by 43% by 2030 compared to 2005, then to reach net zero emissions by 2050. A significant uptake of solar photovoltaics (PV) will play a vital role in achieving this target. However, this brings the challenge of managing the millions of tonnes of solar panel waste at the end of the 25-year lifetime. This scoping study, *Solar Panel End-of-Life Management in Australia,* provides an in-depth analysis of the current PV recycling landscape, market opportunity, best practice and most cost-effective strategies to manage solar panels end of life in Australia.

The cumulative volume of end-of-life solar panels in Australia is expected to reach 1 million tonnes by 2035, and the total material value from end-of-life solar panels is projected to surpass $1 billion. As a result, establishing domestic PV waste management facilities in Australia presents an opportunity for resource recovery. Recycling offers a gateway to reducing landfill, enhancing circular economy initiative, and job creation.

Initially waste volumes are expected to come from rooftop solar, particularly in Queensland, New South Wales and Victoria, and near-term action is needed to prevent this waste going to landfill. The report maps potential locations for PV waste management. Optimal locations to establish large-scale PV waste management facilities are in the five big cities in Australia: Sydney, Melbourne, Brisbane, Perth and Adelaide. These facilities are projected to manage more than 70% of the country's waste panels within a 150km radius, with an annual supply of 4,000 to 10,000 tonnes of panels before 2030, and a doubling of supply expected in the future. These locations, along with a few regional facilities, will provide comprehensive nationwide coverage.

The analysis highlights Australia's potential to develop solar panel recycling and reuse market within 12 years through strategic initiatives. Key recommendations include:

Facility Development: Establish large scale PV waste management facilities (over 5,000 tonnes/year) in five big cities within three years and expand to regional areas within six years.

Regulatory Measures: Enact a nationwide product stewardship program to fund and oversee the management of PV end-of-life to support early-stage industry development.

Collection Accessibility: Create easily accessible drop-off points, and increase public awareness about PV waste management.

Technological Advancement: Promote innovation in scalable, efficient, and comprehensive recycling technologies and develop robust reuse standards and procedures to enable a PV circular economy.

This work was supported by Neoen, who partnered with the Australian Centre of Advanced Photovoltaics (ACAP), hosted by UNSW and co-funded by ARENA, to deliver the scoping study. Research at UNSW was conducted at the School of Photovoltaic and Renewable Energy Engineering and the School of Civil Engineering Research Centre for Integrated Transport Innovation. Neoen contributed primary data from its operation and management in utility-scale PV. In addition, Veolia provided international case studies and insights on the current challenges faced by the recycling industry and what is required to move forward in Australia. In addition, ACT NoWaste, within the Transport Canberra and City Services Directorate of ACT Government, has shared insights in relation to the ACT's waste and circular economy policy context to help inform the project.

CONTENTS

1. INTRODUCTION

Australia has committed to reduce its CO_2 emissions by 43% by 2030 compared to 2005, then to reach net zero emissions by 2050. A significant uptake of solar photovoltaics (PV) will play a vital role in achieving this target. However, this brings the challenge of managing the millions of tonnes of solar panel waste at the end of the 25-year lifetime. This scoping study, *Solar Panel End-of-Life Management in Australia,* provides an in-depth analysis of the current PV recycling landscape, market opportunity, best practice and most cost-effective strategies to manage solar panels end of life in Australia.

This project is be divided into four phases:

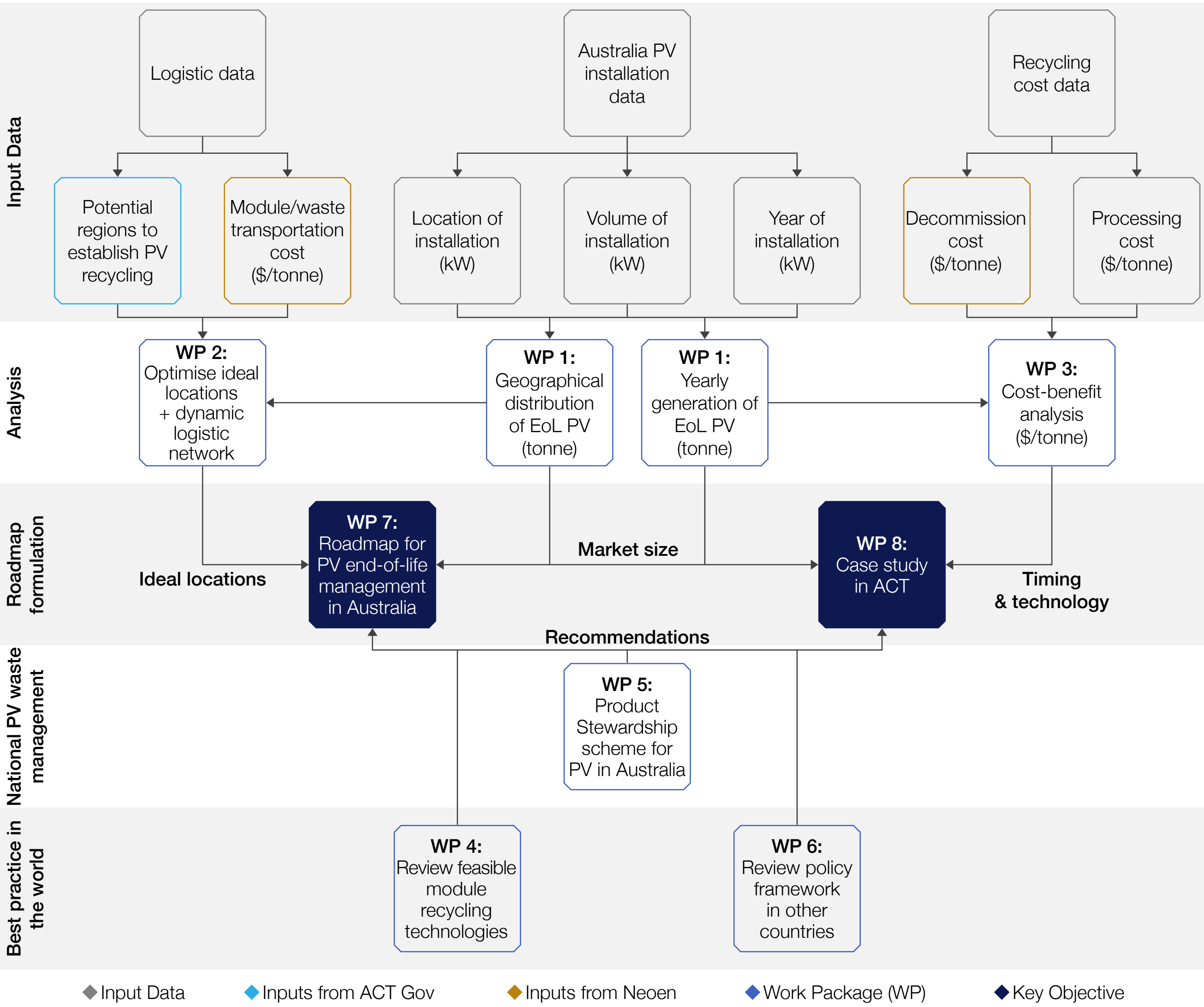
Phase 1 – collect historical PV capacity installation data and PV end-of-life cost data in Australia.

Phase 2 - analyse the volume of end-of-life PV panels (Work Package1), ideal locations and associated logistic networks for dedicated PV waste management facilities (WP2), and the cost of dedicated PV waste management facilities (WP3).

Phase 3 - review the best practice of module recycling technologies (WP4), Australia's national product stewardship scheme which is currently under discussion for PV systems (WP5), and policy frameworks (WP6) to manage end-of-life PV in other countries.

Phase 4 – formulate a roadmap for sustainable management of PV end-of-life in Australia (WP7) and a case study for ACT (WP8) in terms of when, how, and what to do to benefit the most from this emerging PV recycling industry and business opportunities. The detail of the methodology and data analysis flow is shown in Figure 1.

Figure 1
Methodology used in this scoping study.



Neoen has contributed primary data from its operation and management in utility-scale PV. Veolia has provided insights and a case study from the waste management industry to this study. ACT NoWaste, within the Transport Canberra and City Services Directorate of ACT Government, has shared insights in relation to the ACT's waste and circular economy policy context to help inform the project. Research at UNSW was conducted by UNSW School of Photovoltaic and Renewable Energy Engineering and Research Centre of Integrated Transport Innovation (rCITI). Dr Nathan Change of ACAP contributed to the cost-benefit analysis. Prof. Vinayak Dixit at rCITI contributed to the conceptualisation and supervision of the logistic modelling.

The key objective of this project is to formulate a 12-year roadmap (2023-2035) with strategies for the industry to manage solar panel end-of-life in Australia.

The project achieved the following outcomes, for Australia between 2023 and 2035:

- Volume and location of end-of-life solar panels in Australia were assessed.
- Optimal locations, treatment capacities and associated logistic networks were mapped for large-scale PV waste management facilities.
- The cost-benefit analysis of module recycling and reuse technologies was assessed, to understand the technical, investment and market requirements to establish domestic PV recycling industry.
- Best practice of PV end-of-life management policy frameworks and businesses were reviewed.
- A case study for the ACT Region was developed.
- A 12-year roadmap (2023-2035) documented that the industry can take as a step-by-step guide to sustainably deal with PV waste in Australia.

This report is exclusively dedicated to the assessment of solar panels. End-of-life management of inverters, batteries, and other system components are not assessed.

2. SOLAR PHOTOVOLTAIC WASTE PROJECTION IN AUSTRALIA

Australia has been in the top 10 countries in the world for its solar deployment and integration since 1990s. The total installed capacity at the end of 2023 reached 34 GW, meaning Australia has a remarkable, and world leading installation rate of over 1.2 kW of solar per person. Further reductions in the already low-cost electricity from PV and increasing cost of coal and gas generated power will accelerate the growth of PV deployment in Australia to reach the net-zero target. According to AEMO's (Australian Energy Market Operator) projections, the PV capacity is expected to reach 50 GW by 2030 and 138 GW by 2050 [1].

Solar PV waste projection is integral in ensuring effective and sustainable end-of-life management. In this study, end-of-life panels are defined as panels that are uninstalled from their original systems and will no longer serve their original purpose for any reason. This includes both technically failed panels that no longer generate power/generate power below expectation, technically working systems that are removed because they are no longer needed (e.g. house demolition), and technically working panels that are replaced with new panels for high power output or other technical/social/economic reasons.

In Australia, end-of-life planning will be unique compared to the rest of the world as the early installations were predominantly small, residential systems (Figure 2), and are expected to contribute to the early waste stream before the growing volume of utility-scale systems reach their end-of-life.

2.1. Solar panel waste projections methodology

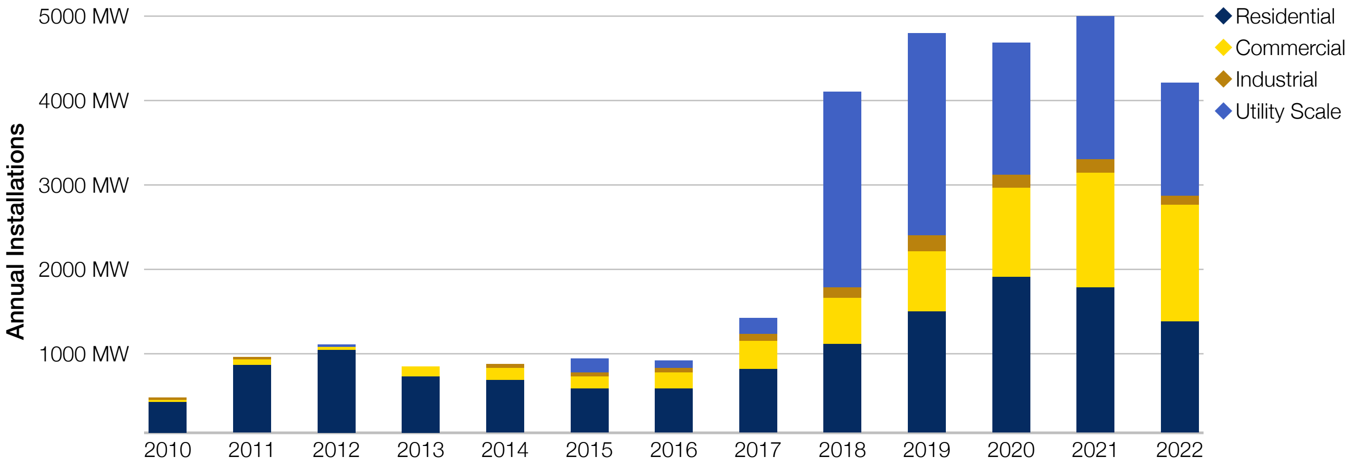
Step 1: We obtained installation data by postcode in kW and over time, from the Australian Photovoltaic Institute (APVI) up to **April 30th, 2022** [3].

Step 2: This data was sorted into small-scale (<=100kW) and large-scale (>100kW) systems; then sorted by Local Government Area (LGA) and states. To sort the postcode data by LGA an Australian Statistical Geography Standard (ASGS) geographic correspondence file from the Australian Bureau of Statistics (ABS) was used [4]. 2018 was the most recent postcode to LGA file to date and is used in this report.

Step 3: The kW data was converted into tonnes using MW/tonne ratios calculated from historic and PV manufacturer's datasheets.

Step 4: Two Weibull lifetime functions were applied to the sorted installation data, one for small-scale systems and one for large-scale systems. These lifetime functions were an output of a journal paper focusing on practical lifetime of solar panels in Australia [5]. From applying these functions, annual and cumulative waste projections per LGA, in both MW and tonnes, for 2023-2035 were achieved.

Figure 2
Annual PV installation by sector in Australia (adapted from APVI), 2010 – 2022 [2].



2.2. Power to weight conversion

Waste is usually measured in tonnes. We account the PV panel efficiency evolution in the past decade and apply the power to weight conversion ratio (averaged from product datasheets) on PV installation data, as shown in Figure 3.

2.3. Lifetime functions

There is strong evidence of early decommissioning of small-scale PV systems in Australia after interviewing several PV installers and domestic PV recyclers. Specifically, the average practical lifetime of these residential modules may be less than the industry standard of 25 years (manufacturer's performance guarantees of 80% power output after 25 years of operation), due to factors including ease of replaceability, limited roof space, fiscal policy, technological improvements, and social behaviors. The statistics and other literature evidence was modelled using Weibull probability functions to better reflect the practical lifetime of solar panels in Australia; a more detailed explanation of the module lifetime characteristic can be found in Tan *et al.* [5]. Historical installation data was sorted into small-scale (<=100kW) and large-scale (>100kW) systems, then applied to different Weibull functions, as shown in Figure 4 below.

For example, at the end of year 10, it is estimated that a cumulative of 23% modules installed in small-scale systems would be decommissioned, due to panel breakage, upgrading to more efficient systems, and other motivations of the homeowners, while 12% of modules in the large-scale system would be decommissioned by year 10. By the end of year 30, 98% of small systems and 86% of large systems would be decommissioned, while the rest may stay operational for longer.

Figure 3
PV module weight to power conversion ratio (t to MW), 2007-2021.

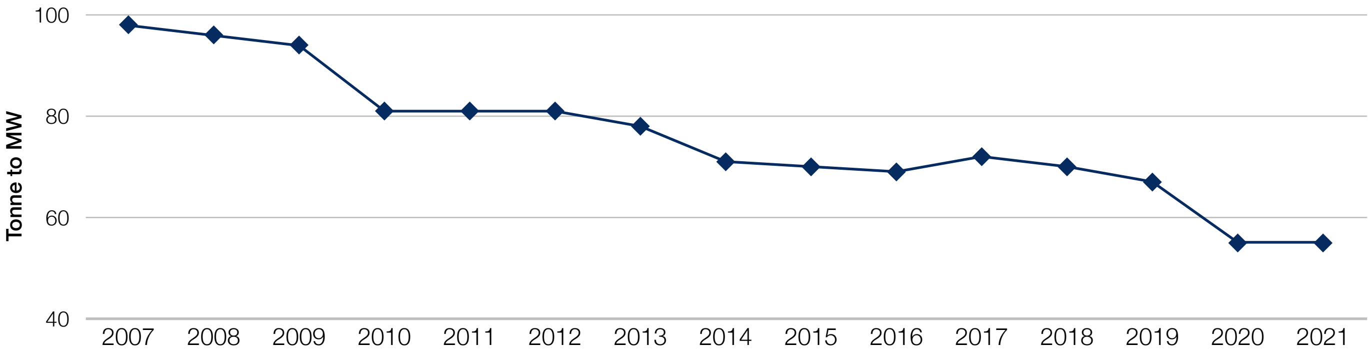
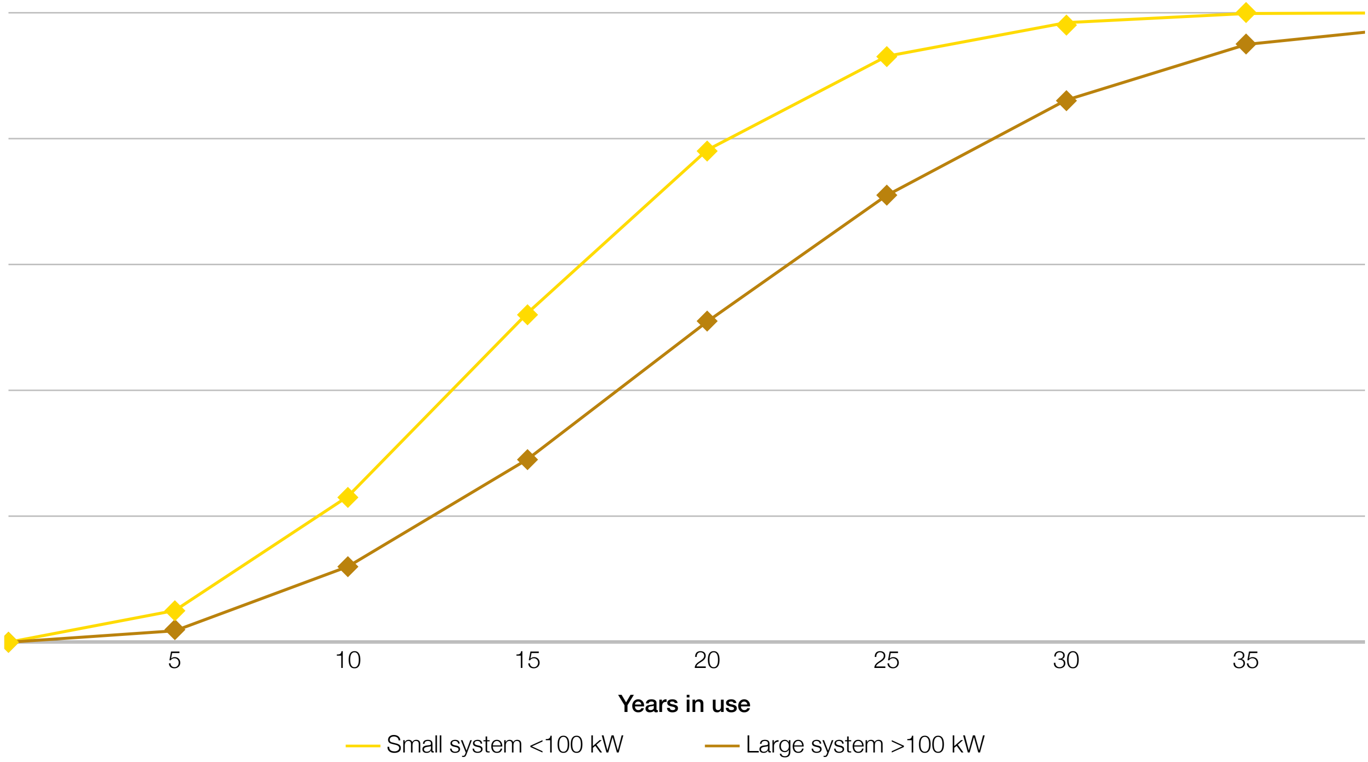


Figure 4
Solar panel lifetime estimates, represented by Weibull functions.



2.4. PV waste generation 2022-2035, Australia overview

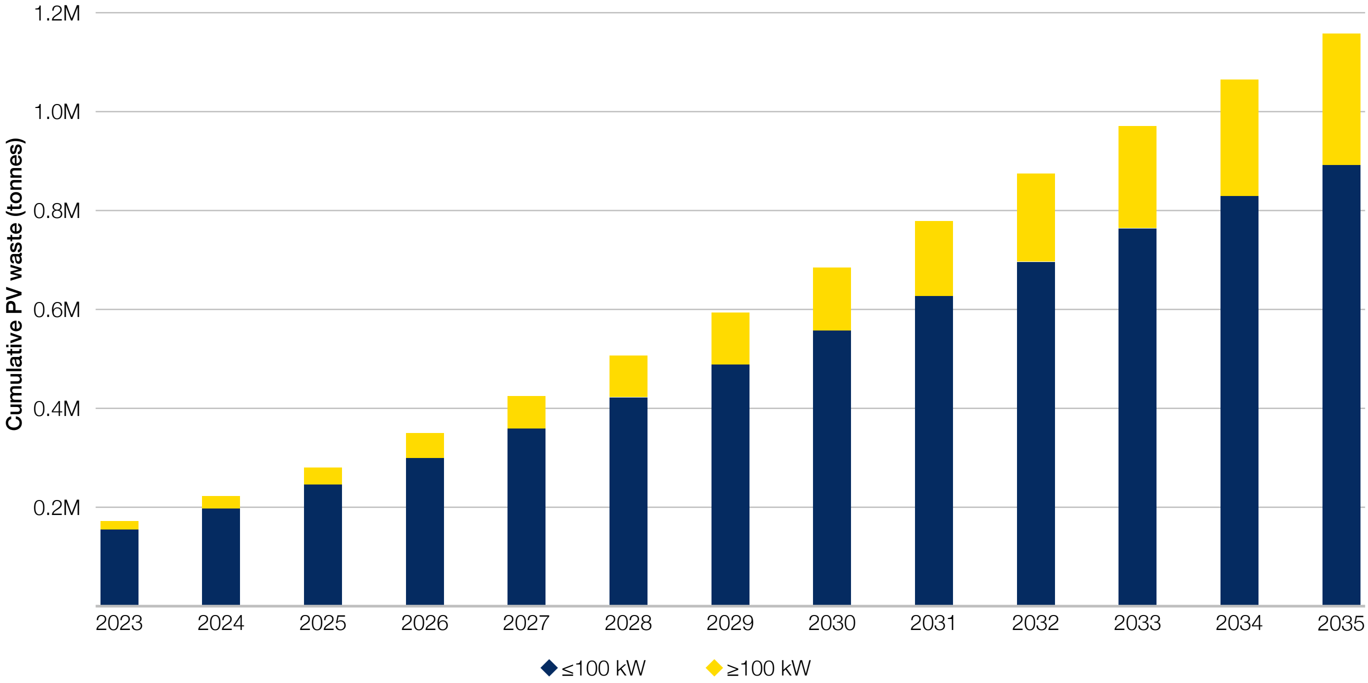
Figure 5 provides the projected cumulative end-of-life solar panels in tonnes from 2022-2035 in Australia, categorised by small- and large-scale systems.

The cumulative volume of end-of-life solar panels is projected to reach 280,000 tonnes by 2025, 680,000 tonnes by 2030, and a significant milestone of 1 million tonnes between 2034 and 2035. On an annual scale, waste volume is expected to surpass 50,000 tonnes in 2025 and could reach approximately 100,000 tonnes, equivalent to 1.2 GW per year, from 2030 to 2035 nationwide.

More than 80% of the decommissioned solar panels will come from small-scale distributed PV systems by 2030 due to early development of Australia's residential PV market (Figure 5). The waste panels from large-scale system are expected to grow faster after 2030.

Figure 5

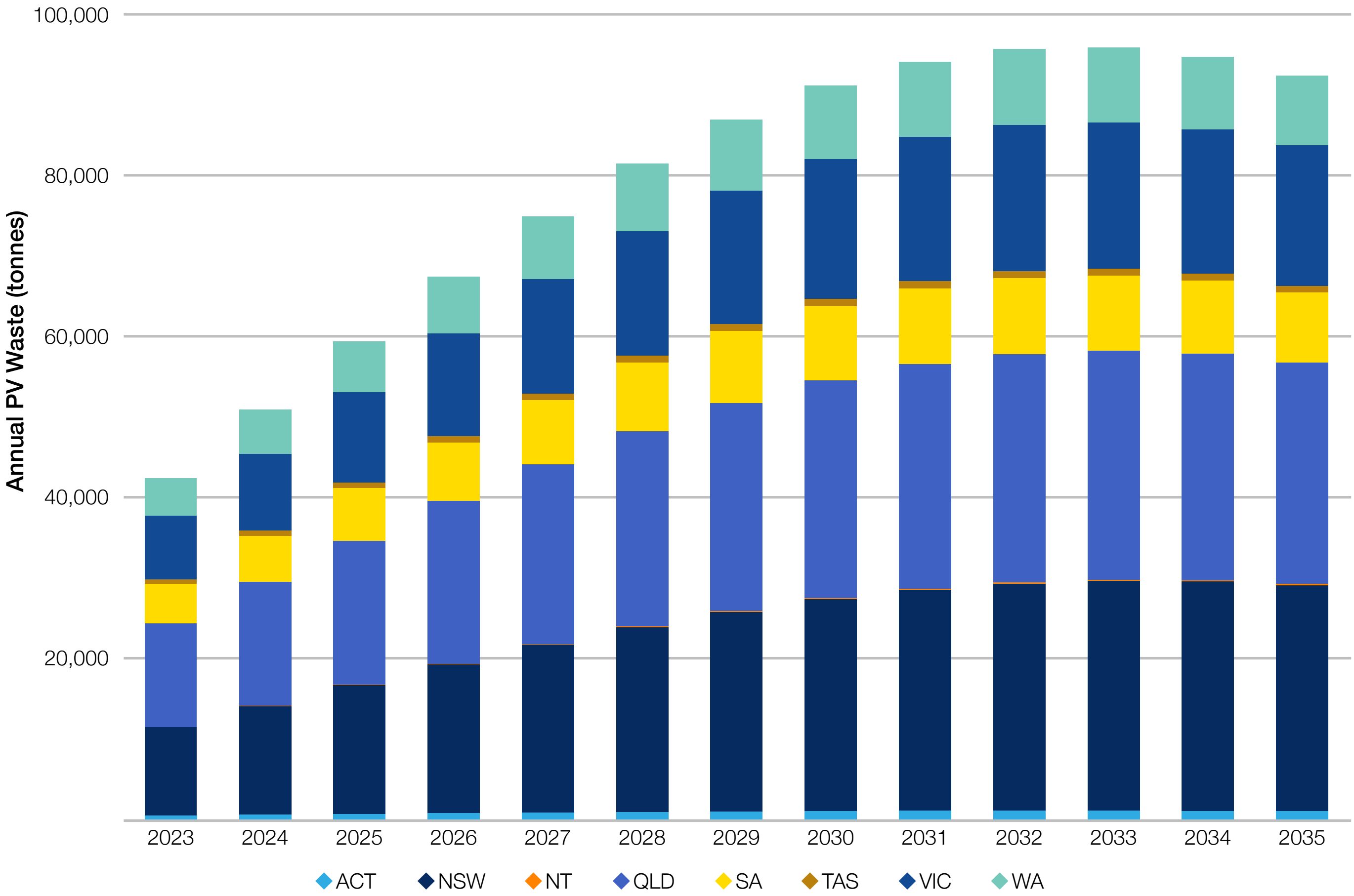
Projected cumulative PV waste in tonnes in Australia from 2022 to 2035, comparison between small and large-scale systems.



Year	Small scale (tonnes)	Large scale (tonnes)
2023	155,754	16,839
2024	197,901	25,572
2025	246,223	36,599
2026	300,260	49,999
2027	359,338	65,799
2028	422,602	83,971
2029	489,052	104,438
2030	557,590	127,073
2031	627,061	151,703
2032	696,304	178,113
2033	764,200	206,050
2034	829,716	235,232
2035	891,942	265,353

Figure 6 shows the projected annual waste generation in each state and territory. **The volume of end-of-life solar panels is expected to grow rapidly in New South Wales, Victoria, and Queensland, which calls for immediate action by the industry to prevent landfilling.** Only small amounts of waste are expected in Tasmania and the Northern Territory.

Figure 6
Annual PV waste in tonnes in each state and territory in Australia.



	ACT	NSW	NT	QLD	SA	TAS	VIC	WA	Total
2023	469	10,948	28	12,889	4,893	559	7,924	4,611	42,321
2024	567	13,463	42	15,390	5,725	640	9,570	5,475	50,872
2025	664	16,004	57	17,854	6,528	715	11,202	6,316	59,340
2026	757	18,483	72	20,199	7,272	781	12,762	7,102	67,428
2027	843	20818	88	22,350	7,932	836	14,196	7,805	74,868
2028	918	22,938	103	24,243	8,489	878	15,458	8,400	81,427
2029	980	24,779	116	25,824	8,926	905	16,511	8,868	86,909
2030	1,027	26,289	128	27,053	9,232	918	17,323	9,195	91,165
2031	1,056	27,429	137	27,904	9,401	915	17,875	9,373	94,090
2032	1,069	28,177	144	28,365	9,432	898	18,157	9,401	95,643
2033	1,063	28,523	148	28,438	9,330	868	18,172	9,283	95,825
2034	1,041	28,473	149	28,139	9,103	827	17,929	9,029	94,690
2035	1,004	28,048	148	27,496	8,766	776	17,449	8,654	92,341

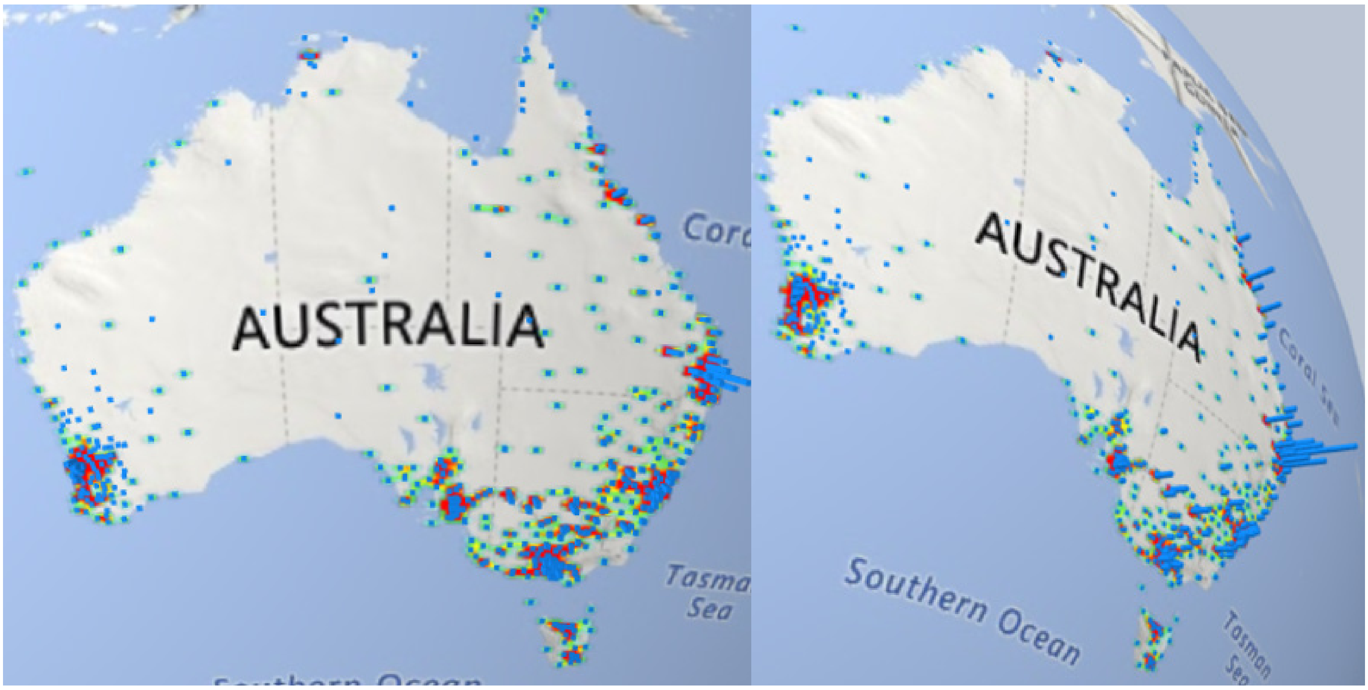


Figure 7
3D bar maps showing projected cumulative PV waste (in tonnes) generated in each LGA in 2030. The height of the blue bar indicates the expected volume, and the red region indicates a centralized area with a high waste volume. If there is no blue bar, it means there will be low or negligible waste solar panels in that area by 2030. The 3D map was rotated to facilitate a better visualisation of the waste volume.

Figure 7 shows the projected cumulative waste solar panels generation from each LGA in Australia in 2030[1]. The height of the blue bar indicates the expected volume, and the red region indicates a centralized area with a high waste volume. If there is no blue bar, it means there will be low or negligible waste solar panels in that area by 2030.

The end-of-life solar panels are highly concentrated near the largest cities in Australia, including Sydney, Melbourne, Brisbane, Perth, and Adelaide while remain negligible in most remote areas in Australia by 2030. **This suggests that the PV recycling industry in Australia should begin with the major cities and then expand to regional Australia.**

Based on annual and geographical PV waste volume forecast, we classify high PV waste areas into three groups, with reference to Table 1:

Class 1: current high waste areas, where annual PV waste is projected to be the highest, which requires immediate action.

Class 2: emerging high waste areas, where annual PV waste generation will emerge between 2025 to 2030, which requires infrastructure planning now.

Class 3: future high waste areas, where annual PV waste will surge between 2030 to 2035, which requires long-term planning.

Table 1
High PV waste areas in Australia.

Class 1	Class 2	Class 3
Sydney, NSW	Murrumbidgee, NSW	Toowoomba, QLD
Brisbane, QLD	Balranald, NSW	Canberra, ACT
Gold Coast, QLD	Dubbo, NSW	
Moreton Bay, QLD	Mildura, VIC	
Melbourne VIC	Whitsunday, QLD	
Adelaide SA	Townsville, QLD	
Perth WA	Sunshine Coast, QLD	
	Western Downs, QLD	

1 LGA based bar maps were created per year for the annual and cumulative waste projections in tonnes in Power Bi. These maps were achieved by obtaining a 2018 LGA shape file from the ABS, converting it to a JSON file using Map Shaper, then importing it into Power Bi alongside the waste projections.

2.5. Comparison with E-Product Stewardship in Australia Report

We further compared the solar panel waste volume forecast in Australia with E-Product Stewardship in Australia Evidence Report [6]. The key difference is the lifetime assumption:

- E-product stewardship report uses the Weibull function with an average lifetime of 22.5 years for all system types. The function is referenced from *E-waste Statistics: Guidelines on Classifications, Reporting and Indicators, second edition* [7]. No clear methodology is provided.
- This report uses two Weibull functions, (1) with an average lifetime of 15 years for small-scale systems (<= 100kW), and (2) with an average lifetime of 20 years for large-scale systems (>100kW). Weibull functions were developed by weighting three models which capture decommissioning due to power decrease, damage, and technical failures, and economic motivation [8]. Details can be found in Progress Report 1.

Due to higher early-replacement assumptions used in the model used herein, and more relevant to Australian PV Market, the waste volume in early years is much higher than the Evidence report.

2.6. Limitation

This waste projection shared here relies on historical PV installation data as of April 30th, 2022. While future PV installations will contribute to waste generation, this analysis does not include them, because future PV installation forecasts do not provide location information necessary for accurate geographical distribution mapping. Figure 9 below shows the differences in waste volume projection when considering future installations [9]. Future waste volume especially after 2032 is likely to be underestimated in this study. However, we believe a 28% uncertainty is reasonable as the future PV installation forecast [1] varies by more than 30% in different scenarios in 2035. Using historical data ensures accurate information about installation location and enables high-resolution logistic network optimisation in the next section.

Figure 8
Australia solar panel waste volume forecast, this study vs e-product stewardship evidence report.

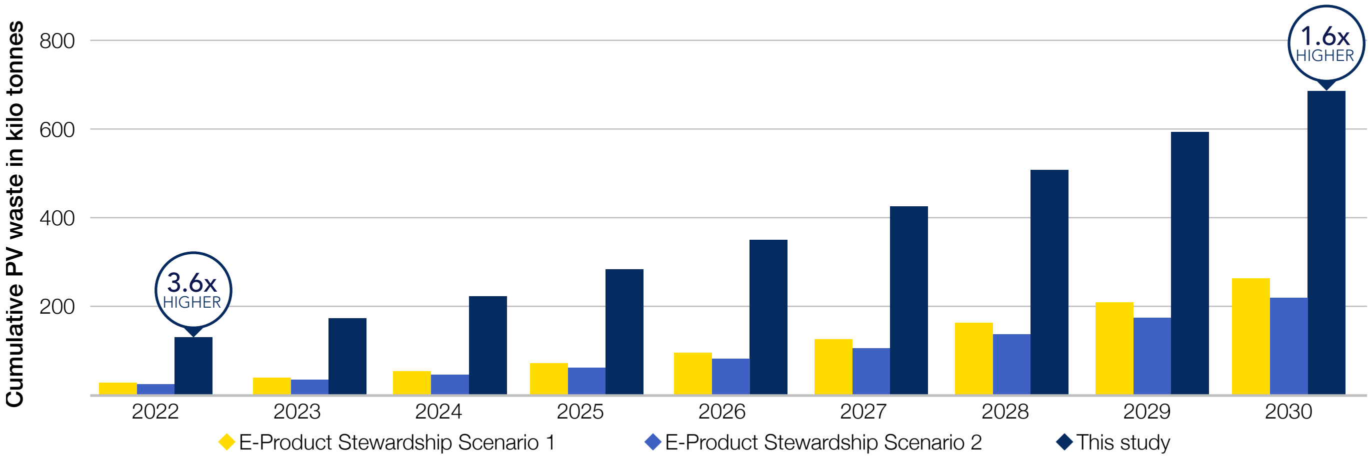
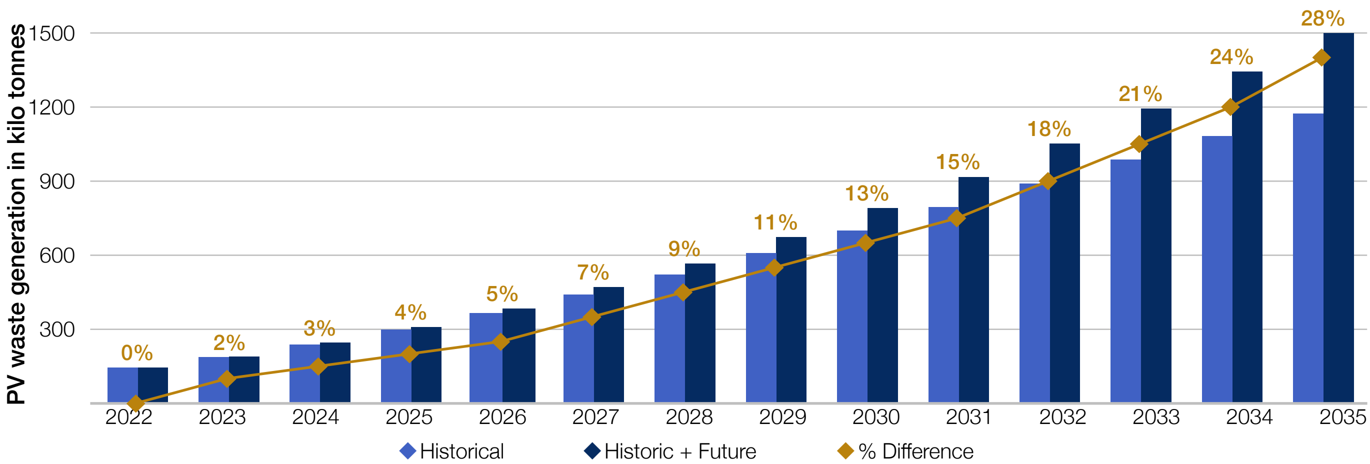


Figure 9
Waste volume forecast uncertainties.



2.7. Summary of waste projections

- The cumulative volume of end-of-life solar panels is projected to reach 280,000 tonnes by 2025, 680,000 tonnes by 2030, and a significant milestone of 1 million tonnes between 2034 and 2035. On an annual scale, waste volume will surpass 50,000 tonnes in 2025 and will reach approximately 100,000 tonnes, equivalent to 1.2 GW per year, from 2030 to 2035 on a national scale. This projection is four times higher than earlier predictions because it accounts for the pre-mature decommission of residential solar panel systems.
- The waste volume is growing rapidly in Queensland, New South Wales and Victoria, which calls for immediate actions to prevent waste going to landfill.
- More than 80% of waste solar panels will be generated from small-scale distributed PV systems by 2030, attributable to the earlier evolution of Australia's residential PV market.
- The end-of-life solar panels generated by 2030 is highly concentrated near the largest cities in Australia, including Sydney, Melbourne, Brisbane, Perth, and Adelaide. In contrast, the volume will remain negligible in most remote areas of the country in the same period. This suggests that the PV recycling industry in Australia should begin with the major cities and then expand to regional Australia.

3. OPTIMAL LOCATIONS FOR LARGE-SCALE PV RECYCLING IN AUSTRALIA

The emerging volumes of PV waste in Australia call for immediate action to establish dedicated PV waste management facilities. These facilities should be strategically located near regions with high waste volume to minimise logistic costs and ensure sustained incoming waste volume. This will optimise the efficiency of the recycling facilities and help prevent landfilling of the waste. This section explores the optimal locations for recycling and reuse in mainland Australia[2].

3.1. Methodology

The study used a geographical resolution per local government area (LGA). It is assumed that there will be a collection point at the centre of each LGA where system owners, solar farm operators, electricians, who remove panels from the system, could drop off end-of-life panels[3]. The quantity of end-of-life panels at collection point each year[4] is regarded as the "origin" and is then transported to the nearest large-scale facility (recycling or reuse) based on a logistic network optimisation.

Potential PV waste management facilities were identified on mainland Australia using a grid size of 55km x 55km, as “candidates” (Figure 10). Transport via trucks ($0.09/tonne•km [10]) is assumed as the only interstate/intrastate transportation method, with no cross-border charges expected to be applied. The road networks are obtained from OpenStreetMap (OSM) data sets using a Python package called OSMnx [11]. All candidate sites are located on main truck roads.

The PV waste generation is dispersed as shown in Figure 7. Therefore, we did three separate models and optimised them separately:

- Eastern Australia (NSW, ACT, VIC, QLD and SA).
- Western Australia
- Northern Territory

2 Tasmania and other islands have been excluded from this simplified analysis as the study only considers transportation via truck road.
3 Although the assumption made in this study is simplified, it is important to acknowledge that there may be multiple collection points within a single LGA, or several LGAs may share a single collection point. These collection points could include but not limited to solar distributors, warehouses, local councils, or existing waste collection sites owned by waste management companies.
4 This is obtained from the LGA based waste generation data in Section 1. While a 100% collection rate is unrealistic, the simplified assumption enables the mapping of optimal locations and logistic networks.

The logistics network was then optimised from all origins to all potential sites subjected to minimised total cost from 2023 to 2035 in each scenario, i.e., the optimal locations and network is not optimised based on annual waste volume but optimised **for the 12-year period**.

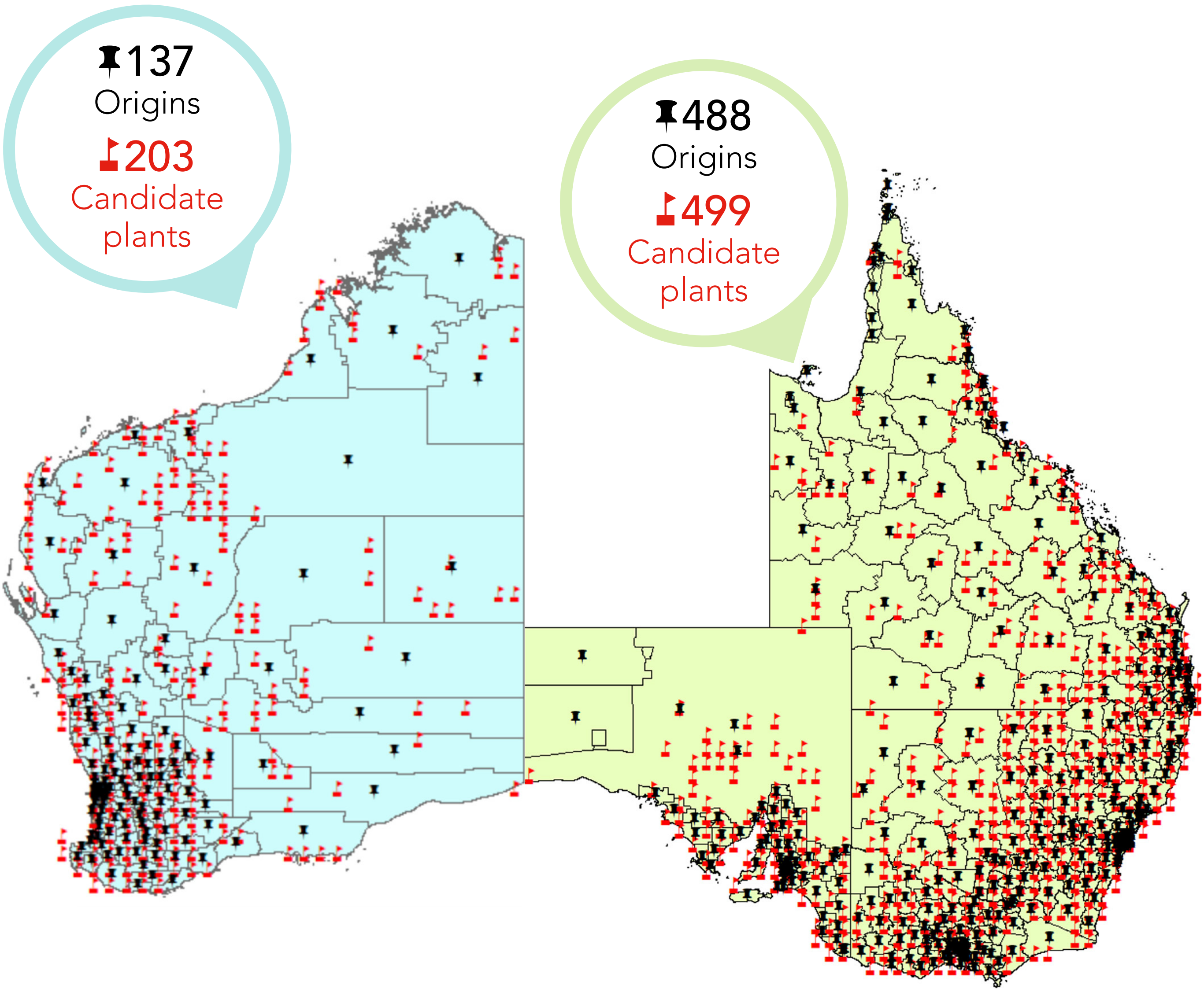
This logistic problem was formulated as a mixed integer linear programming (MILP) problem. The equations can be found in Appendix A.

The total logistic cost sums the logistic costs in every year from all origins to their optimal treatment sites. The model further considers CAPEX to establish a new facility, OPEX, and initial site opening cost. These cost assumptions are simplified to set boundaries for the model, the cost of recycling will be further analysed in Section 4. The following equations 1 to 5 were used to identify the optimal sites and calculate associated optimal logistic solution, subject to **minimum overall cost**.

The objective function has four components. The first component represents the total freight cost of the solar panel waste delivery. The second component represents the capital cost of the waste plants. The third and fourth components represent the total fixed operational cost and the waste operational cost of each plant, respectively.

There are several end-of-life pathways for solar panels that can help avoid landfill, including recycling, reuse, reuse after repair, and reuse after refurbishment. Both recycling and reuse of end-of-life solar panels require treatment at a centralised facility. Recycling typically involves component separation and material recovery, while reuse requires testing and re-certification [12]. Therefore, recycling and reuse are assumed to share the same logistic network, and the results in this section are generally applicable for both. When selecting the optimal location for the facility, a lower capacity bound of 1000 tonnes/year of waste solar panels was set as a requirement. This means that the candidate facility must have access to at least 1000 tonnes/year of waste in order to be considered as an optimal location.

Figure 10
Logistics network optimisation model for Eastern Australian and Western Australia.



3.2. Eastern Australia

Figure 11 displays the optimal locations in Eastern Australia, represented by circles with sizes corresponding to the estimated treated volume in 2023, 2029, and 2035. The optimal logistic solution changes over time based on annual waste volume. Table 2 provides details on all nine proposed PV waste management facilities, including their locations and expected waste volume under the optimal logistic network solution in 2023, 2029 and 2035.

The map showcases proposed locations for solar panel recycling centres, with circle sizes indicating the expected volume of panels to be processed at each site. The coloured zones around each circle delineate the LGAs allocated to transport their solar panel waste to the nearest centre, optimizing for logistical efficiency. For instance, by 2035, the Brisbane recycling centre is projected to be the largest, accommodating waste from 32 LGAs.

Figure 11
Optimal locations for large-scale PV waste management facilities in Eastern Australia in 2023, 2029 and 2035.

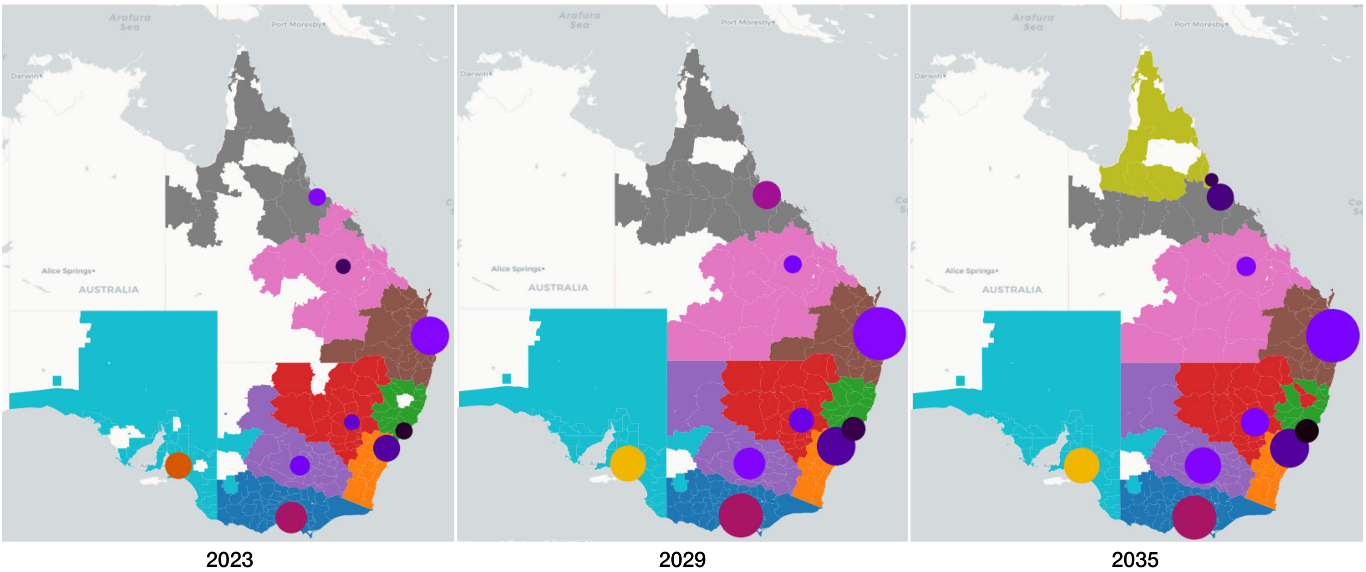


Table 2
Optimal locations to establish large-scale solar panel waste treatment facilities in Eastern Australia. The table shows the name of the location, the expected treated volume and number of LGAs that will send panels here, sorted by expected waste volume from the highest to the lowest. Expected waste volumes are rounded to the nearest thousand, or to the nearest 500 if under 3,000.

Location	Expected waste volume (tonnes per year)		
	2023	2029	2035
Brisbane, Queensland	10,000	20,000	20,000
Melbourne, Victoria	7,000	14,000	14,000
Sydney/Penrith, New South Wales	5,000	10,000	11,000
Adelaide/Adelaide Hills, South Australia	5,000	9,000	9,000
Dubbo/Wellington, New South Wales	2,500	7,000	9,000
Townsville, Queensland	2,000	5,000	5,000
Newcastle, New South Wales	2,000	4,000	5,000
Murrumbidgee, New South Wales	1,500	4,000	4,000
Central Highlands, Queensland	1,500	2,000	2,500

3.2.1 Metropolitan

To minimise total end-life-life management cost, dedicated PV waste management facilities will be needed in the four major cities in Eastern Australia: Brisbane, Melbourne, Sydney and Adelaide, to prevent solar panels from ending up in landfill. Metropolitan facilities will have access to more than 70% of the PV waste generated by 2030 (as shown in Figure 12). The waste volume for metropolitan facilties are expected to double in the next five years. This finding is consistent with the previous section, which shows that small-scale systems, usually centralised in metro areas, will dominate the end-of-life market before 2030, and large-scale systems will catch up afterwards.

Australia has a unique advantage in starting a new PV end-of-life industry in major cities, as more than 70% of PV waste is centralised near metro regions with supporting infrastructure, including aluminum smelting and recycling, glass recycling and manufacturing, and downstream metal refiners. Our first recommendation is to establish large-scale PV recycling/reuse infrastructure in metropolitan areas because such facilities can access more waste volumes to sustain the recycling business.

3.2.2 Sites in regional/remote Australia

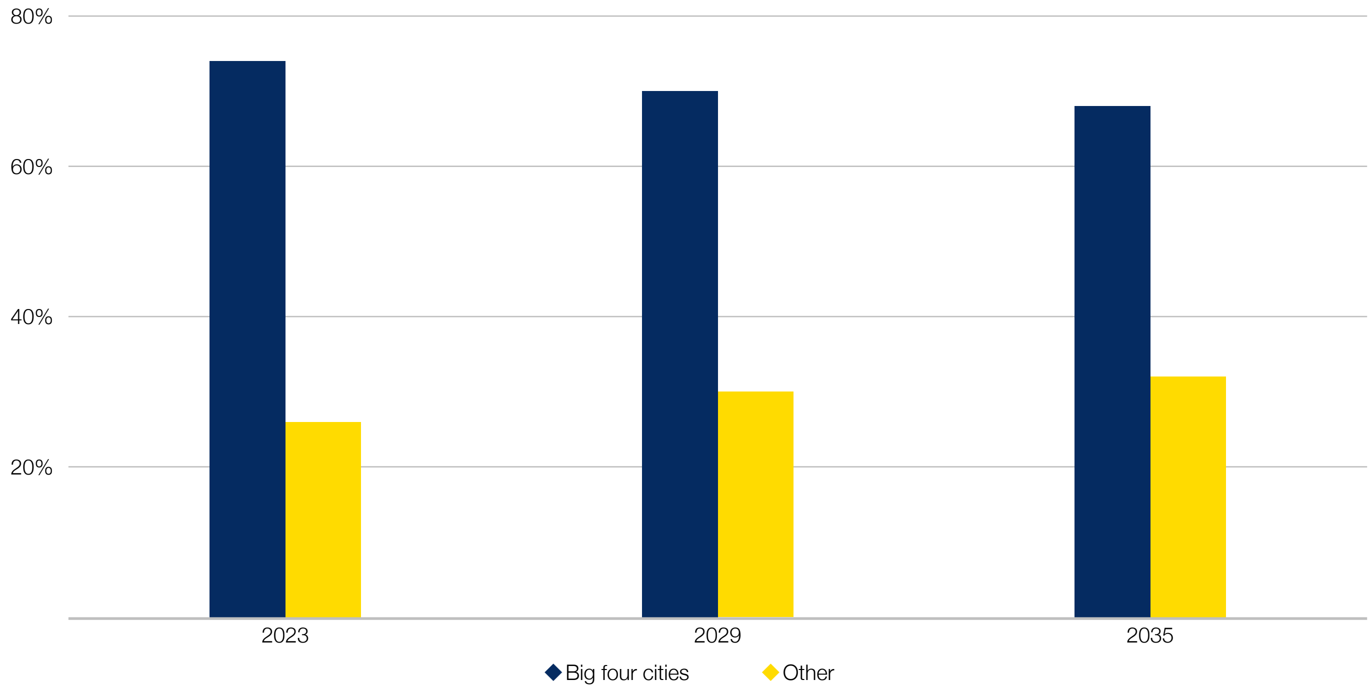
Utility-scale PV systems are located in rural and regional areas and will have needs for recycling. The earliest solar farms in Eastern Australia have been operational since 2016/17 and the need to recycle faulty panels/arrays, and the volume of faulty panels can be expected to increase as the solar farms transit into mid-life (about 10 years). Dubbo/Wellington, Murrumbidgee and Central highlands have large-scale solar farms that were installed before 2018, therefore will have the demand for local PV recycling especially after 2028.

Townsville has a mix of small-scale and utility-scale solar installations. With waste treatment demand in North Queensland expected to rise after 2029, a new site near Ingham, about 100km from Townsville, could be considered.

The Newcastle site is situated in an area with a relative high population density, similar to that of big cities. As such, it is an ideal location for the treatment of panels from small-scale rooftop systems in the surrounding councils. However, the expected incoming volume will be much lower than four major cities.

The model was re-run for three more iterations with varied grid sizes and running time limits. The first six sites were consistently selected, indicating their crucial importance. The last three sites varied among Newcastle, Murrumbidgee, Central Highlands, Gympie Shire, Tweed Shire, Western Downs, Balranald, with an expected capacity of less than 2000 tonnes/year by 2030, and 2000 – 7000 tonnes/year in 2035. All these regional/remote locations are viable to establish large-scale PV recycling.

Figure 12
Comparison of PV waste treatment facilities big four cities in Eastern Australia and other regions.



3.2.3 Transportation distance and cost

As shown in Figure 13, **the average transportation distances to all four metropolitan facilities are less than 150 km under the optimal logistic network by 2030. A facility in Sydney/Penrith can potentially collect 5,000 tonnes/year in 2023 to 2025 and more than 10,000 tonnes/year waste solar panels after 2029 from its surrounding 100 km, making it the best location among all optimal locations.** Regional facilities collect panels from a wider coverage, resulting in higher transportation distance and cost. The average transportation distance to five regional facilities is approximately 200km.

Figure 14 shows the cost of collecting all expected waste panels to each site. Total PV waste collection cost in Eastern Australia will increase from just over $500k, to over $1 million from 2023 to 2035 under the optimal logistic network. This equates to a weighted average transportation cost of $12-13 per tonne of waste solar panels, or $0.6 per panel. These figures represent the cost of transporting each panel from its origin to the ideal location, as determined by the optimal logistics solution.

Figure 13
Average PV waste transportation distance under the optimal logistic arrangement.

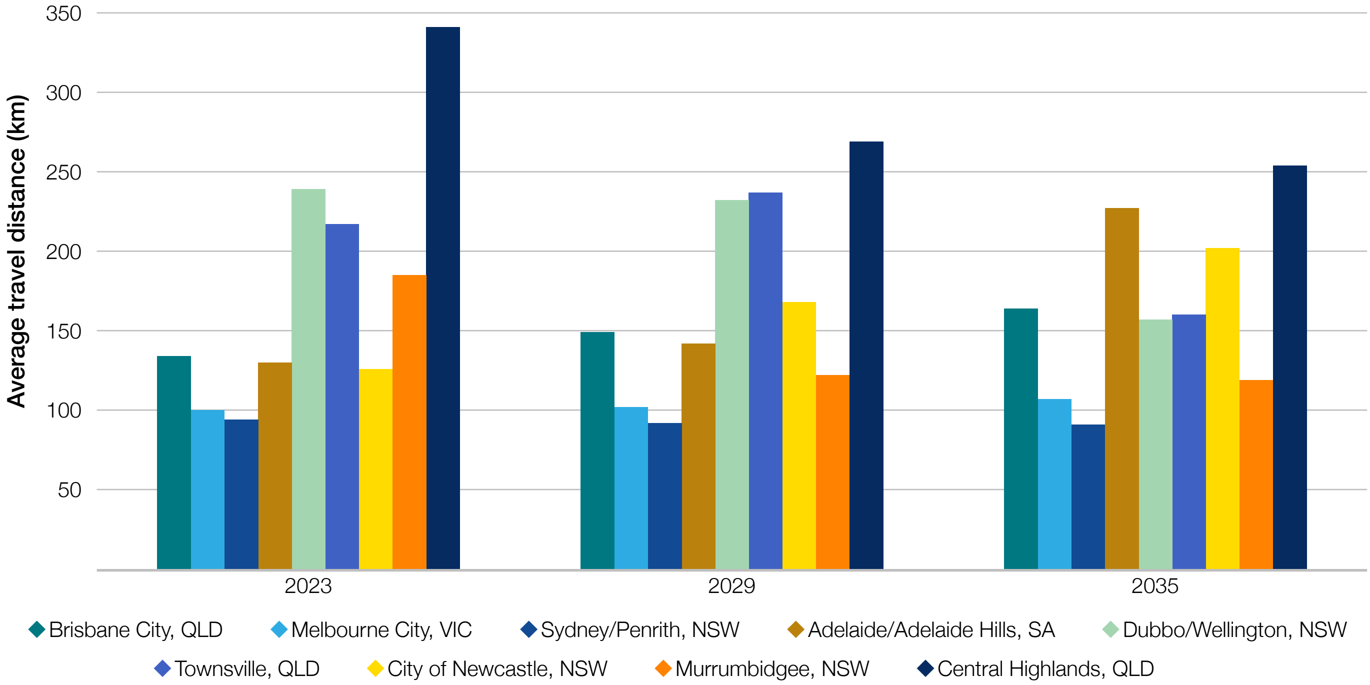
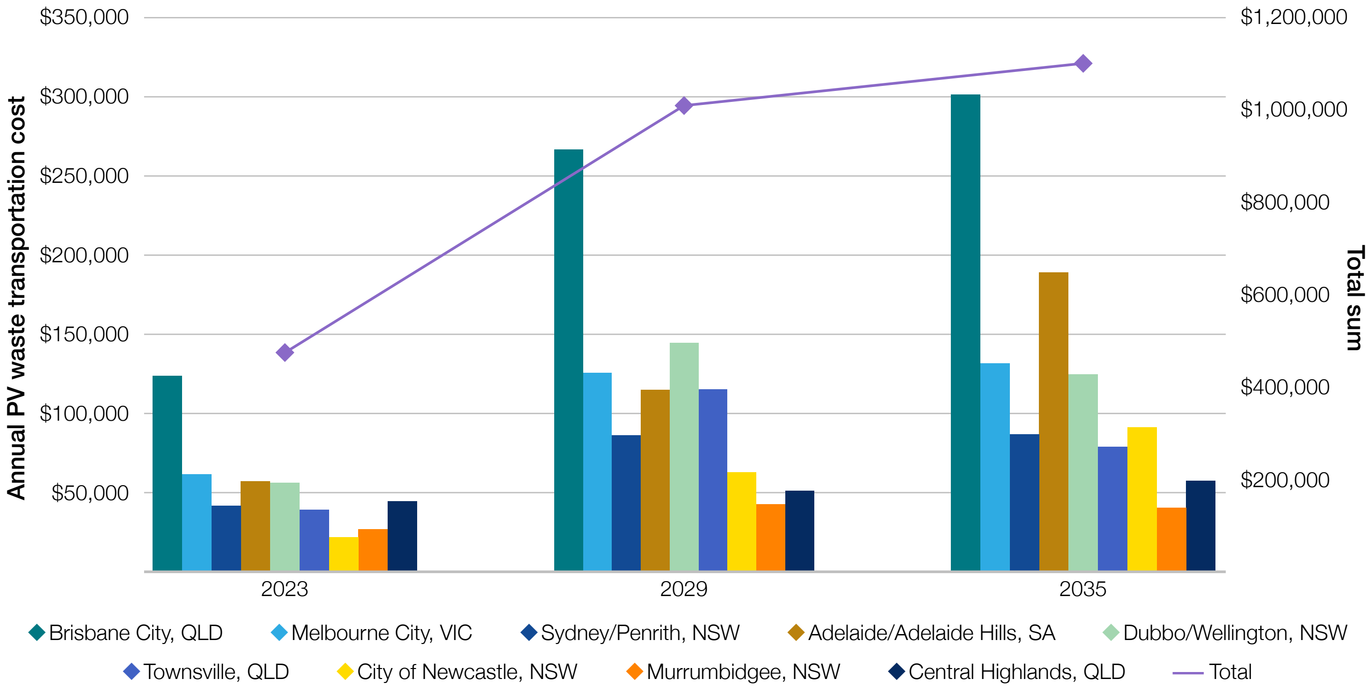


Figure 14
Annual waste transportation cost for all facilities in Eastern Australia under the optimal logistic arrangement.



3.3. Western Australia

In Western Australia, the most efficient locations for large-scale photovoltaic (PV) waste management facilities have been identified as Perth and Busselton. The Perth facility is projected to be the state's primary collection point, handling an estimated 3,000 to 4,000 tonnes of waste solar panels annually during 2023-2025, with an expected increase to 7,000-8,000 tonnes annually by 2030-2035. This expansion aligns with the anticipated rise in waste solar panels, particularly from the southern regions post-2025. To effectively manage this increase, Busselton has been designated as an optimal secondary site, geared to process waste from 20 local government areas (LGAs) in the south, with a capacity of 1,000 tonnes annually through 2024 to 2035. Alternatively, this southern waste stream could be integrated into the Perth facility.

The proposed facilities are expected to have an average transportation distance of 100-120km with average costs around $10 per tonne, slightly lower than those observed in Eastern Australia.

Due to the large and dispersed nature of Western Australia, we investigated the total transportation costs of having two centralised facilities compared to more isolated sites. It was found that expanding from 2 to 7 sites leads to a mere 5% reduction in total freight costs, which is relatively insignificant. On the other side, smaller facilities would not only necessitate greater initial capital investment, but also foster unnecessary competition. Such competition among these sites could lead to reduced operational efficiency across the board, undermining the overall effectiveness of the waste management system.

Based on our analysis, **we recommend that the optimal location to establish a large-scale PV waste management facility in Western Australia is Perth**. The facility should have a treatment capacity of 3,000 tonnes/year starting in 2023-2025, with a capacity expansion plan (double the treatment capacity) in place for the next 5 years. In addition, a smaller facility might be established in Busselton and begin operating in the late 2020s to manage PV waste generated from the southern region of Western Australia. These measures will ensure that Western Australia has a sustainable end-of-life management plan for solar panel waste.

Figure 15
Optimal locations for large-scale PV waste management facilities in Western Australia by 2035.

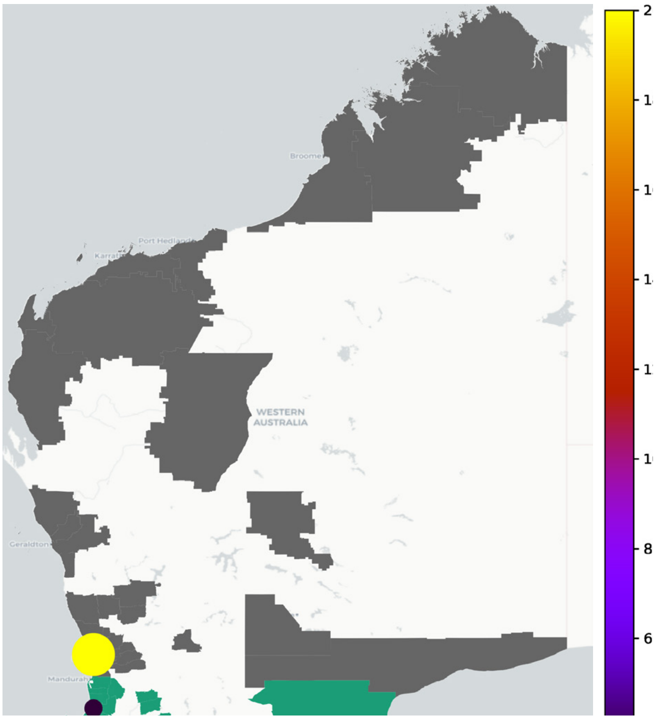


Table 3
Optimal locations to establish large-scale solar panel waste treatment facilities in Western Australia.

Location	Expected waste volume (tonnes per year)		
	2023	2029	2035
Perth, WA	3,500	7,000	7,000
Busselton, WA	1,000	1,000	1,000

3.4. Northern Territory

In the Northern Territory, the volume of end-of-life panels is low, with 28 tonnes expected in 2023 and a steady increase to 150 tonnes in 2035. This volume forecast is consistent with a previous study focusing on the Northern Territory [13]. Given the modest volume, it may not be feasible to establish a dedicated centralised PV waste management facility due to economies of scale, which we will explore further in the next section. Additionally, the use of mobile PV recycling platforms [14], although effective in material separation, is not advisable due to logistical challenge of transporting separated materials to distant waste management infrastructures for processing materials like glass or aluminium.

To address the management of waste solar panels in NT over the next decade, we propose two alternative strategies:

1. Setting up local collection points with interstate transportation to other states for large-scale recycling treatment.
2. Exploring local reuse opportunities, such as reusing the old solar panels in farming or off-grid applications.

3.5. Limitation

This section provides a modelling analysis of the optimal locations for solar panel waste treatment facilities based solely on the waste volume expected from each LGA in mainland Australia from 2023 to 2035. It should be noted that the results presented in this section do not consider the presence of existing solar panel recycling companies in Australia, including PV Industries [15], Reclaim PV [16], Scipher Technologies [17], Elecsome [18], Lotus Energy Recycling [19], and Solar Recovery Corporation [20] etc. This is because these companies are not currently taking large volumes, but have exapansion plans. Details on their treatment capacity and collection network are commercial in confidence and subject to change, making it unsuitable for inclusion in the modeling process.

The outcomes presented herein can be regarded as recommendations for potential locations where Australia could establish such a facility in each year. It is intended for the industry to consider these suggestions as they plan their business development strategies.

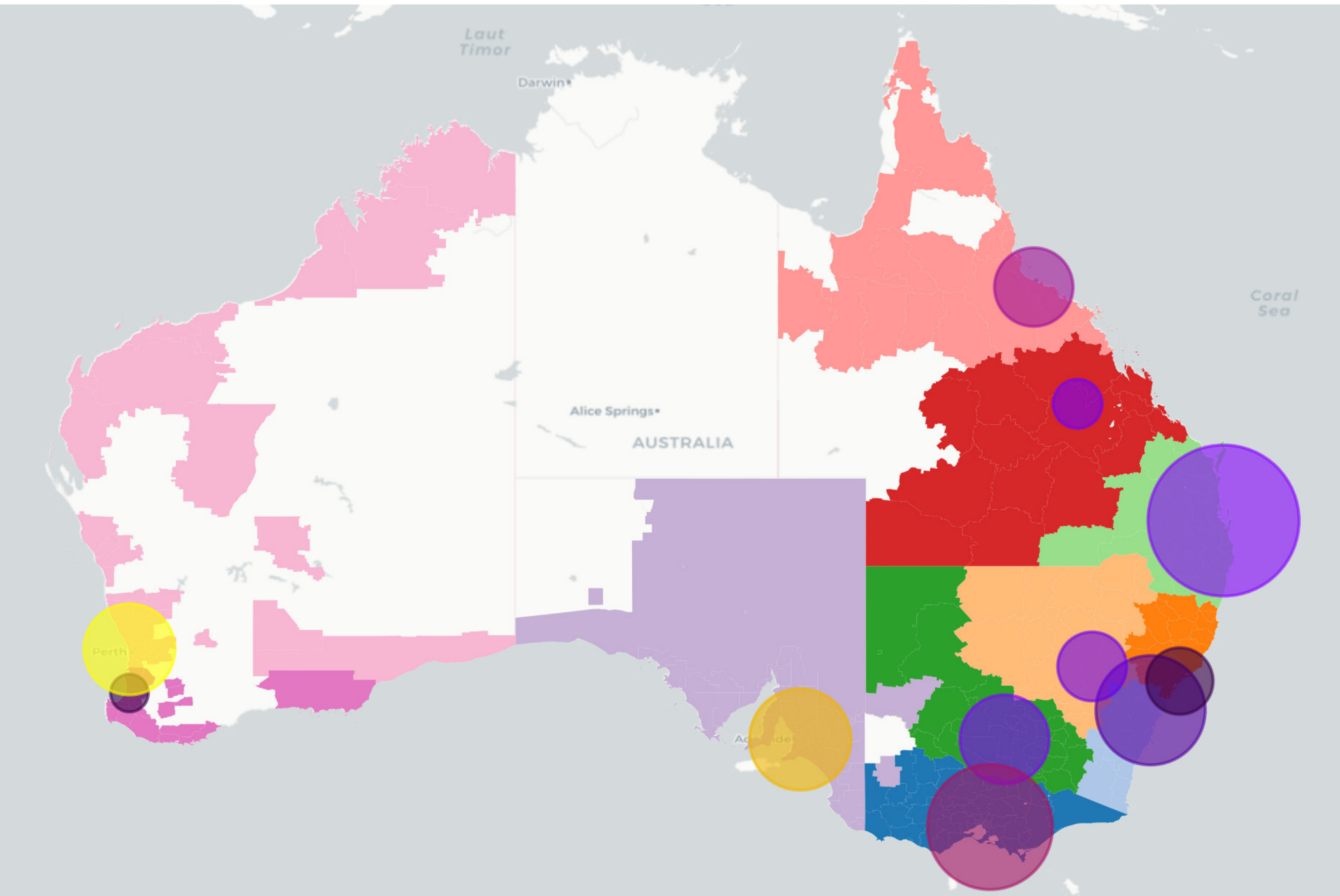
3.6. Summary of logistic modelling

Strategic placement of large-scale PV waste management facilities near high waste volume regions is vital to minimize logistical costs and ensure a steady inflow of waste. The optimal logistic solution for mainland Australia is shown in Figure 16.

By 2030, Australia should establish large-scale PV recycling/reuse waste management infrastructure (>5,000 tonnes/year treatment capacity) in metropolitan areas to treat mostly rooftop systems, rather than focusing on regional areas that target decommissioned solar farms. Brisbane, Sydney, Melbourne, Adelaide and Perth should establish dedicated PV waste management facility right now to divert them from landfilling. These metropolitan facilities will have access to more than 70% of the PV waste generated by 2030 within its 150km radius.

To complement metropolitan facilities, additional sites in Dubbo/Wellington, Townsville, Newcastle, Murrumbidgee, Central Highlands and Busselton can provide comprehensive national coverage as shown in Figure 16. These facilities should aim for a treatment capacity of around 2,000 tonnes per year by 2030 and 2,000 to 7,000 tonnes per year by 2035. Other favourable regional/remote locations include Ingham, Gympie Shire, Tweed Shire, Western Downs and Balranald.

Figure 16
Optimal locations to establish large-scale solar panel waste treatment facilities in Australia.



4. COST BENEFIT ANALYSIS OF SOLAR PANEL RECYCLING AND REUSE

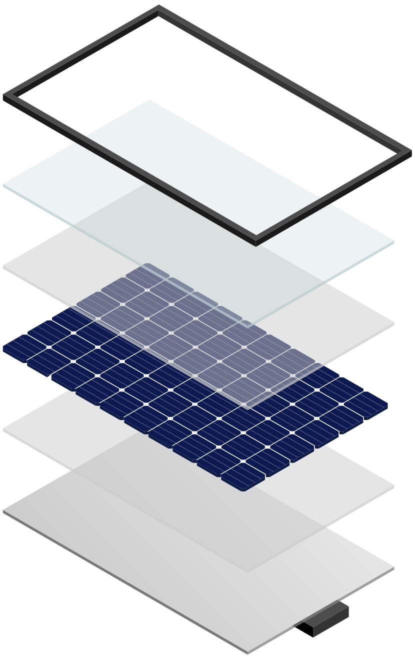
4.1. Economic value of solar panels

Solar panels contain a variety of valuable materials. They are a valuable resource, rather than a "waste" even at its end-of-life.

Figure 17 shows the sandwich structure of a traditional crystalline silicon photovoltaic module. Solar cells in the middle convert sunlight into electricity, and solar cells contain valuable materials such as high-purity silicon and silver. This layer is approximately 4% of the total weight but 40%-50% of the value. A tempered glass sheet and a backsheet (which is sometimes another tempered glass sheet) encapsulate this photoelectronic active layer using EVA as the glue, to prevent it from environmental damage during operation. Aluminium frames and a junction box are attached to the outside of the panel, to provide extra mechanical strength and a terminal to output electricity.

Table 4 shows the breakdown of the component and value in a typical 20-kg crystalline silicon solar panel. All $ in this section refer to Australian dollars[5]. Crystalline silicon solar panel occupied more than 90% of the Australian PV market, therefore following sections will focus on this type of panels.

Figure 17
Configuration of a silicon photovoltaic module.



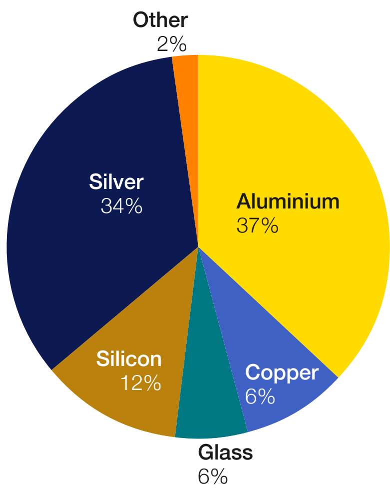
On average, $22.6 worth of materials can be potentially recovered from a typical 20-kg solar panel, resulting in a material value of over $1000 per tonne of solar panels. Extrapolating this data, **the total material value from all end-of-life solar panels generated in Australia by 2033 is projected to exceed 1 billion dollars.**

When solar panels are reused, their selling price can be considerably higher. We found some private trading records, showing second-hand panels were sold for $40 to $130 per panel. Transparent market price information, specifically related to qualified solar panel reuse in significant volume, are not yet available.

By transitioning to recognising solar panels as valuable resources or assets rather than mere "waste," there will be an improvement in both consumer and industry engagement in developing the domestic PV end-of-life management market, effectively diverting them from being disposed of in landfills.

Table 4
Weight and value composition of major materials in a typical crystalline silicon photovoltaic panel [21], [22].

Component	Material	Weight	Price ($/kg)
Solar cells	Silicon	3-5%	3.1 - 3.8
	Silver	0.03%-0.05%	746 - 1084
Ribbon	Copper	0.8%	7 - 10
	Tin	0.1%	22
	Lead	0.01%	3
Frame	Aluminium	16-20%	2.1 - 2.8
Glass	Glass	67-70%	0.06 - 0.13
Junction box	Copper	0.3%	7 - 10
Encapsulant	EVA	6-7%	Negligible
Backsheet	PVF/PET	3-4%	Negligible



5 Exchange rate assumption: 1 USD = 1.4 AUD.

4.2. PV recycling and reuse technologies

4.2.1 How does solar panel recycling work?

Even though the silicon solar cell structure has changed dramatically to achieve higher efficiency, the configuration of the module has barely changed since the 1980s. Based on this structure, solar panel recycling can be viewed as reverse manufacturing a panel, following three key steps: detaching the frame and junction box, delaminating the "sandwich" structure to get glass, solar cells, backsheet, ribbons or the mixture of them, and then extracting high-purity valuable material.

The following case studies underscore Veolia's PV recycling efforts in France and Germany, demonstrating that a solution can only be developed when stakeholders from the entire value chain are convened to collaboratively address the challenge.

Case study: Solar Panel End-of-life Recovery by Veolia

Veolia is positioned across 10 geographical zones globally with experience in developing the collection logistic, separation and processing, and valorisation of waste electronic and electrical equipment.

The recommended activities to fully recycle or recover all valuable materials from Photovoltaic equipment and solar panels consists of:

- Re-use of panels or refurbishment of damaged panels for second life use with suitable applications.
- Recycling and creating loops of secondary raw materials at different stages:
  - Step 1: Base Dismantling: basic removal of aluminium frame.
  - Step 2: Base Delamination: separate the glass from the solar cells.
  - Step 3: Complex Separation: separate silicon (Si) and silver (Ag) from the solar cells.
  - Step 4: Material Specific Refining: advanced refinery of Si and Ag, and potential other materials.

Veolia France - Rousset (Bouches du Rhône)

Veolia France worked with centralised eco-organisation Soren (ex-PV CYCLE France) to process and recover crystalline silicon as well as other components (aluminium, copper, glass) from solar panels.

Strong focus on optimising the carbon footprint of the whole process on top of the recovery of materials: energy recovery, optimisation of logistics with the choice of location in the South of France.

- First in Europe.
- 5,000 tonnes per year capacity.
- 95% recovery rate.

Veolia Germany

Veolia Germany developed a highly efficient and special process for the recycling of end-of-life photovoltaic (PV) modules - in final development stage.

Together with partner companies from the public and private sector operating along the PV module recycling chain, all PV module components are completely separated for the first time. This way, pure silicon, silver and glass, among other things, can be made available to the manufacturing industry again. Around 5,000 tonnes of disused PV modules are to be processed in the demonstration plant and the pilot will run until the end of January 2025.

Veolia has learnt from this experience that the main conditions for solar panel recycling activity to be commercially viable are:

- National or geography-based schemes in place to ensure sufficient volume for viable collection and processing to work financially.
- Incentives on recycling and recovery or restrictions on disposal to landfill to ensure the recycling and recovery alternative are viable.
- Understanding the variability in panel types in Australia as it impacts both logistics and recycling process (manual handling required, specific care needed for decommissioning and transport required for re-use, variability in materials and polymers used are impacting the process and commodities management, etc).

Veolia has provided insights of current challenges to move faster with the actions that would help moving forward in Australia:

Table 5
Challenges and opportunities to move forward the PV recycling industry in Australia.

Challenges	Opportunities What our industry needs to move forward in Australia
Technical challenges: • Separating components before crushing • Clearing out glues and polymers • Poor glass & material quality	Identification of the outcome we want to achieve with recycling to guide the choice of technologies, scale up the resources needed, refined the logistics arrangement.
Landfill is closer and less expensive	Regulation alignment on landfill restrictions/levies
Limited downstream logistics for second raw material use and value of recycled materials	Regulation alignment on waste export Commitment from off-takers
Limited financial sustainability without stakeholder commitments (solar industry players and governments)	Industry stewardship schemes and/or incentives to guarantee sustainable logistics and processing
Low logistics and plant performance due to panels variability	Scalable and consistent feedstock to optimise logistics and processing

The choice of recycling technology for solar panels depends on the type and condition of the panel and the end-use applications of recovered materials. Severely damaged panels, for example, are typically recycled using crushing methods. Below is a brief overview of the key steps in the solar panel recycling.

Detaching the frame and junction box

The aluminium frame of a solar panel, sealed with adhesive like silicone, is mechanically clamped to its laminated components. Similarly, the junction box, also bonded with silicone adhesive, is attached to the module's backsheet and wired to the internal busbars. To disassemble these components, mechanical methods are used: external force detaches the frame, and blade cutting removes the junction box. This straightforward process requires adaptable equipment for various panel sizes and conditions, ensuring efficient and quality disassembly.

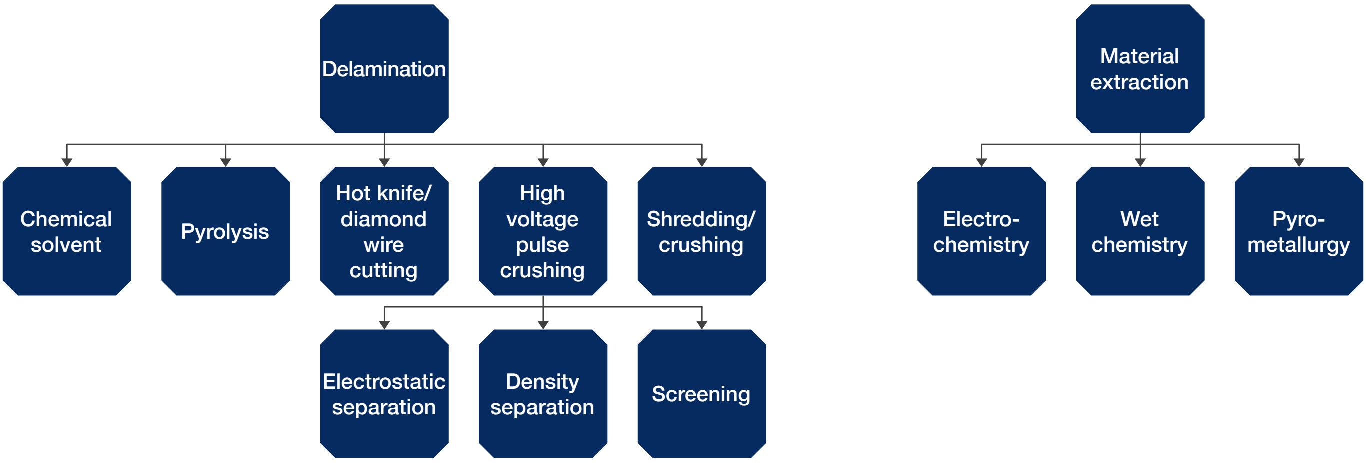
Delamination

The rest of the module can be viewed as a five-layer "sandwich" composed of glass, EVA (encapsulant), solar cells, EVA, and a backsheet or a piece of glass (as shown in Figure 17). The crosslinked EVA encapsulant acts as an adhesive, ensuring the long-term outdoor durability. However, this strong adhesion poses challenges for component disassembly during recycling. Various methods have been developed to address this challenge, as shown in Figure 18. The ultimate goals here are to separate parts for material recovery, ensure downstream material quality, prevent environmental contamination, and concentrate valuable materials for efficient recovery.

Shredding and crushing break the module into smaller fragments. Elastic and adhesive EVA and backsheet typically remain in larger pieces, flexible copper ribbons maintain their strip form, and brittle silicon is grounded into powders along with silver. An alternate approach, high voltage pulse crushing, submerges the module in a liquid and applies an electrical discharge pulse to selectively break at joint interface. After crushing, the fragments are sorted by screening then density separation, allowing materials of different densities to float or sink with a flowing gas or liquid medium. Fine powders can be further sorted using electrostatic separation, based on their conductivity. While this method yields high overall recycling rates (>95% by weight) with low energy demand [23], [24], it can compromise material purity. For instance, silicon powders contaminate metal and glass. Some suggest using the resulting low-purity mixture in construction materials such concrete or asphalt [25], [24], [26].To enhance the crushing efficiency, i.e. to weaken EVA's adhesive strength and recover more valuable materials like silicon, silver and high-quality glass, additional treatments such as low-temperature cryogenic treatment or supercritical CO_2 treatment can be employed.

Instead of crushing the whole panel, hot knife/diamond wire cutting, or water-jet grinding can keep the glass sheet intact and clean. Hot knife cutting involves using a heated blade in parallel to the glass sheet to soften and melt the encapsulant, allowing for the separation of the solar cells from the glass sheet. Diamond wire cutting uses the same principle. Water-jet grinding uses high-pressure water to scrap the backsheet, encapsulant, and solar cells from the intact glass sheet. These techniques offer several advantages: (1) they yield in clean, whole pieces of glass that can serve as raw materials for glass manufacturing; (2) they prevent highly contaminated glass, which comprises 70% weight of the panel and could otherwise incur additional treatment cost; and (3) they allow for a relatively small fraction of material to be sent to the next stage material recovery.

Figure 18
Feasible silicon solar panel recycling technologies.



Pyrolysis decomposes the adhesive EVA at high temperatures (approximately 500 °C), cleanly separating components and enabling the extraction of high-purity materials. This process has two stages: the initial phase, where the EVA experiences a significant 20% weight loss between 210°C and 350°C, and the final phase, occurring between 400°C and 515°C, resulting in nearly 100% weight loss [27], [28]. However, pyrolysis is energy-intensive and costly.

Chemical solvents like toluene, hexane, cyclohexane, D-limonene, and KOH-ethanol can dissolve EVA to obtaining high-purity glass of a quality suitable for direct use [29]. Chemical delamination can also be employed after crushing. However, the consumption and disposal of organic solvents cause environmental concerns and high costs.

Material recovery

Material recovery encompasses advanced refining treatments on separated module components to extract high-purity materials, especially silver, silicon, and copper. These treatments span pyrometallurgical, hydrometallurgical, and electrochemical techniques and usually involve high energy and/or chemicals. Each solar panel contains only small amounts of these precious materials, which are intertwined with other components. Until now, it has not been cost-effective to recover them.

There are two business approaches for material recovery. The first involves sending all laminates to general material refinery facilities, such as those processing printed circuit boards. This method benefits from economies of scale but may be less efficient due to the refinery's potential unfamiliarity with PV materials like silicon, EVA, and backsheet. The second uses specialised PV material recovery facilities, designed specifically for handling PV components.

ROSI, a French start-up company, showcases the second approach at scale. Their commercial demonstration highlights a crucial, previously unaddressed aspect of Australia's PV recycling industry.

ROSI: A French Start-up Redefining Value-Added PV Recycling at Scale

ROSI is a technology start-up company, who has developed dedicated material recovery techniques to deeply separate the materials laminated in the end-of-life PV panels. ROSI can recover the high-purity silicon, silver fingers, and copper, which are typically hardest materials to extract, from solar cells. The processes are based on physical, thermal, and soft chemistry processes. Beyond extracting high-value materials from end-of-life panels, ROSI has developed a patented process for reintegrating them into a number of industries, from solar to semiconductors. The company's main revenue will come from reselling them.

In a recent development, ROSI, in collaboration with Envie 2E Aquitaine, has been chosen by Soren - the producer responsibility organization governing PV module collection and recycling in France – for the revalorization of end-of-life photovoltaic (PV) modules in France. This partnership allows a high-quality recovery of valuable raw materials from the PV value chain with a low environmental impact.

4.2.2 The missing link in PV recycling in Australia

Australia presently lacks a dedicated entity specialising in solar panel material recovery, like ROSI. Existing recycling companies can manage the delamination of modules, but the commodities are then sent to material recovery facilities that lack specialization in PV laminates, thus potentially compromising value and output yield. The ROSI model serves as an instructive case, shedding light on the added value a specialized PV laminate material recovery firm could bring to Australia's domestic PV recycling industry value chain. This could be achieved through comprehensive treatment of all panels or by serving as a high-specialty destination for laminates originating from other PV recyclers.

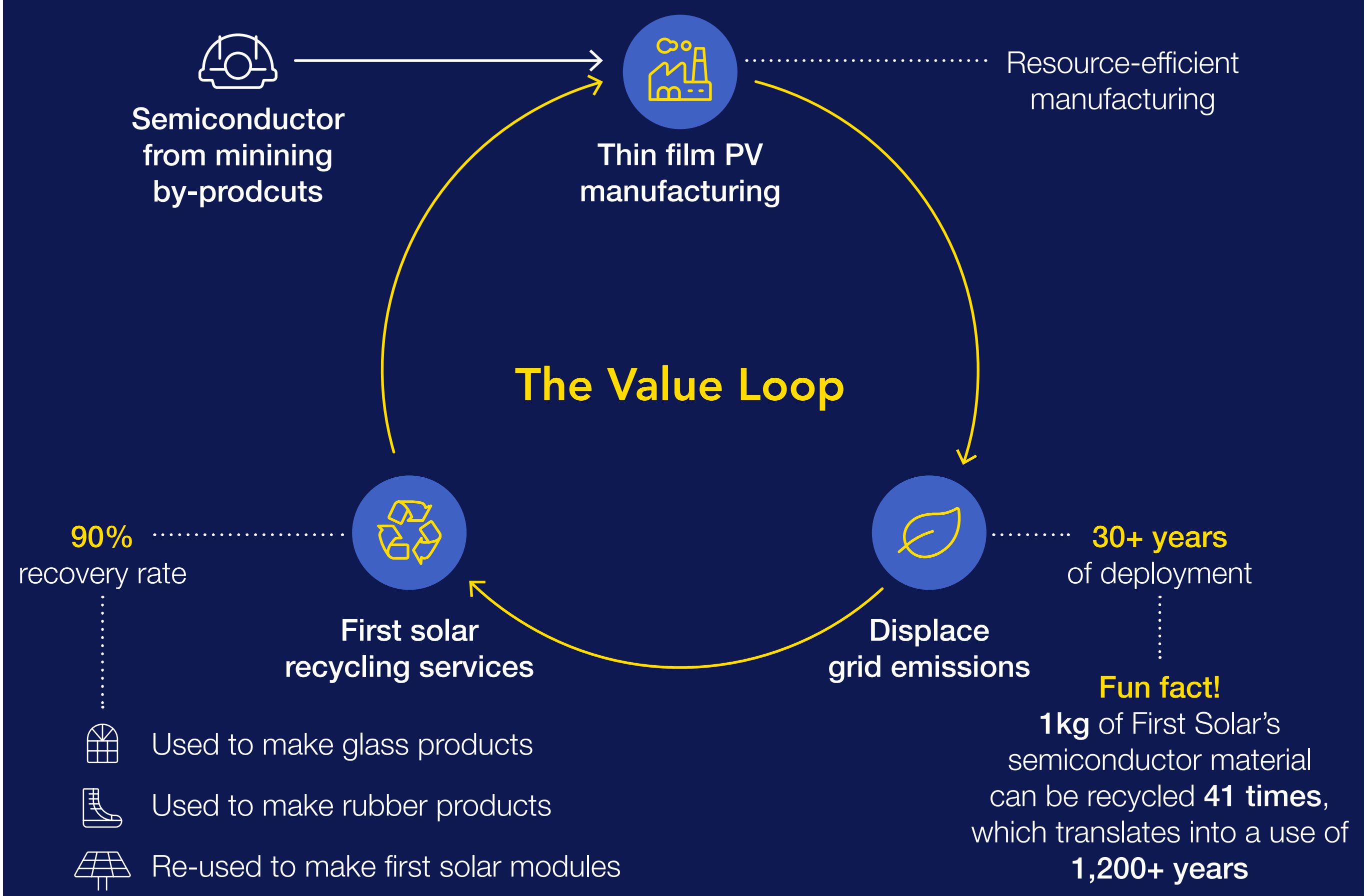
4.2.3 Manufacturer self-managed recycling

Panel manufacturers can also self-manage end-of-life recycling. This approach not only embodies the principles of environmental stewardship but also aligns with the circular economy model, where materials are recovered, recycled, and reintegrated into the manufacturing process. First Solar stands out as a noteworthy example of manufacturer self-managed recycling efforts, with its comprehensive and globally extended recycling program.

First Solar pioneer in-house PV recycling

First Solar is the only solar manufacturer with global in-house PV recycling capabilities.

First Solar voluntarily established the industry's first global solar panel recycling program in 2005 and has been investing in recycling technology improvements ever since. First Solar currently operates recycling facilities in Ohio, Malaysia, Vietnam, and Germany. First Solar offers collection and recycling service for its CdTe panels around the world. First Solar modules are designed for high-value recycling to maximize material recovery at end-of-life and recover more than 90% of module materials for reuse, providing high-quality secondary resources for new solar panels, glass, rubber, and aluminium products.



4.2.4 Reuse, repair, and refurbishment

Reuse involves inspection, repair (if necessary), testing, and recertification for safety and performance [30]. Some defects are repairable, such as replacing junction box and cables, repairing backsheet, repairing mounting clamps, and replacing bypass diodes. Those with more significant defects such as broken glass, defective frame, or significant edge delamination should be redirected to recycling [12], [31]. Electroluminescence (EL) imaging serves as a vital tool in defect detection, including cracks, broken cell interconnections, and shunts.

Some retired panels, despite degradation, remain fully functional and can be directly reused. This approach extends the life of older, less efficient panels, avoiding environmental impacts from recycling or landfilling, but it comes with the trade-offs of repair costs and the missed opportunity to install newer, more efficient panels [32]. While reusing modules in developing regions offers access to clean energy, it poses long-term disposal risks. Most of these regions lack the infrastructure or economic capacity to recycle modules, increasing the likelihood of landfilling eventually[31].

4.3. Recycling and reuse process description for the cost-benefit analysis

PV recycling processes can be divided into three broad categories: bulk material recovery, full recycling, and aluminium frame recycling only. This report focuses on three recycling processes that have well-documented costs in published literature. The selected processes serve as representative examples within their respective categories.

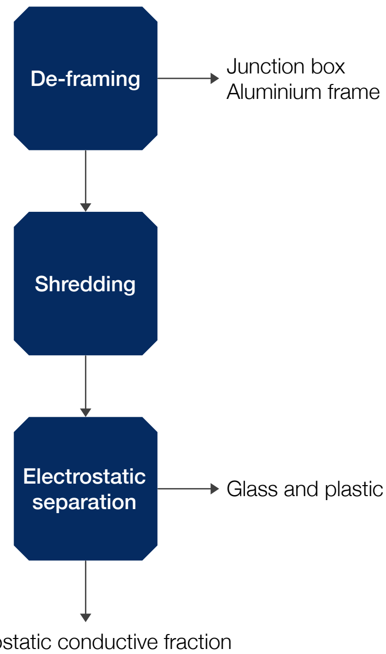
Option 1

Bulk material recovery, or delamination only. The recycling facility removes aluminium frames and junction boxes, delaminates panels, and then send fractions with value materials (silicon, silver, copper) to downstream recycler for metal refinement.

The first process consists of module deframing, shredding, and concentrating valuable materials using electrostatic separation [33]. This has two outputs: a valuable mixture of silver, copper, aluminium and silicon (electrostatic conductive fraction), and a mixture of mostly glass, silicon and polymers (electrostatic non-conductive fraction). The valuable mixture accounts for only approx. 3% weight of the total module, which can be forwarded to the downstream industry for further refinement.

This option requires lower capital investment but would require further downstream recycling to recover all valuable materials, key cost and revenue assumptions are extracted from [33].

Figure 19
Flow diagram of recycling process 1.



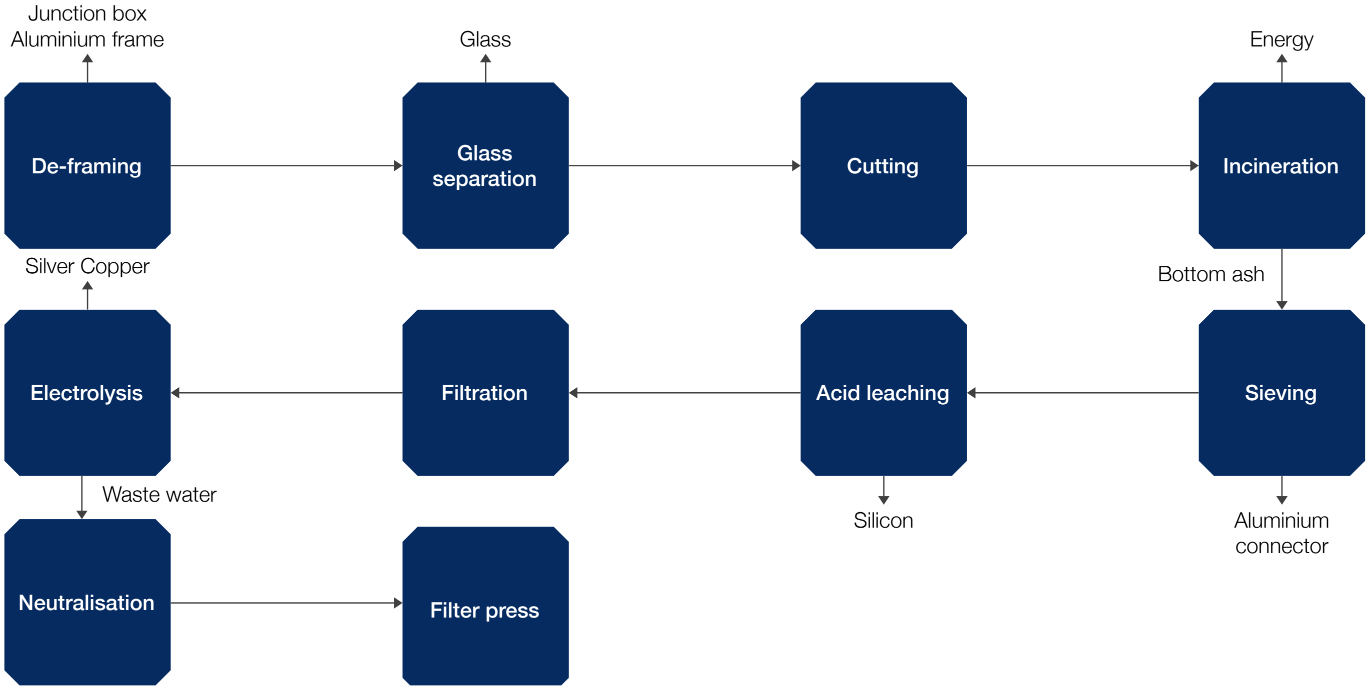


Figure 20
Flow diagram of recycling process 2.

Option 2

Full recycling, the recycling facilities delaminates panels and recycle all valuable materials.

The processes being modelled is the Full Recovery of End-of-Life Photovoltaic (FRELP) process, which has an annual capacity of 8,000 tonnes/year and operated by the company Sasil. It is the most well-established full value recovery recycling process for silicon solar panels [34].

The FRELP process targets value recovery, the process flow is shown in Figure 20. Initially, a robotic system separates the aluminium frame, junction box and cabling which are sent to secondary facilities for dedicated recycling. What is left is the PV laminate, or sandwich, which contains EVA layers, solar cells, glass and polymers. Glass is separated from the laminate using a high-frequency cutting knife within an elevated temperature furnace. Optical separation is then used to separate glass into similarly sized pieces and removes contaminants. The remaining laminate is cut into small pieces and incinerated to produce energy and ash containing silicon and various metals. The ash is then sieved to separate aluminium connectors originally contained in the laminate. Acid leaching is used to dissolve metals and leave a residue that can be filtered to recover the silicon fraction. Electrolysis is then employed, which yields copper and silicon from the metallic oxides within the remaining solution. The FRELP process allows for almost complete recovery of material. Over 95% of the glass, aluminium, silver and silicon are recovered from panels.

This option requires higher capital investment but can recover all valuable materials to be reused in the local economy, key cost and revenue assumptions are extracted from [33].

Option 3

Aluminium only, the recycling facility only takes apart aluminium frames and junction boxes from panels and leave the rest “unattended”.

Option 4

Reuse after in-house performance testing.

Due to limited research and practice on solar panel reuse, we propose a simple method for cost-benefit analysis that assumes the same inspection and testing procedure used at the end of the module manufacturing can be applied to module reuse.

According to IEC61215, all solar panels must undergo IV (current-voltage), EL, and insulation resistance tests before leaving the factory. The panels are then sorted into bins based on their testing results to ensure that each bin contains panels that generate identical power and current before sending to distributors.

Figure 21
Flow diagram of option 4 panel reuse.

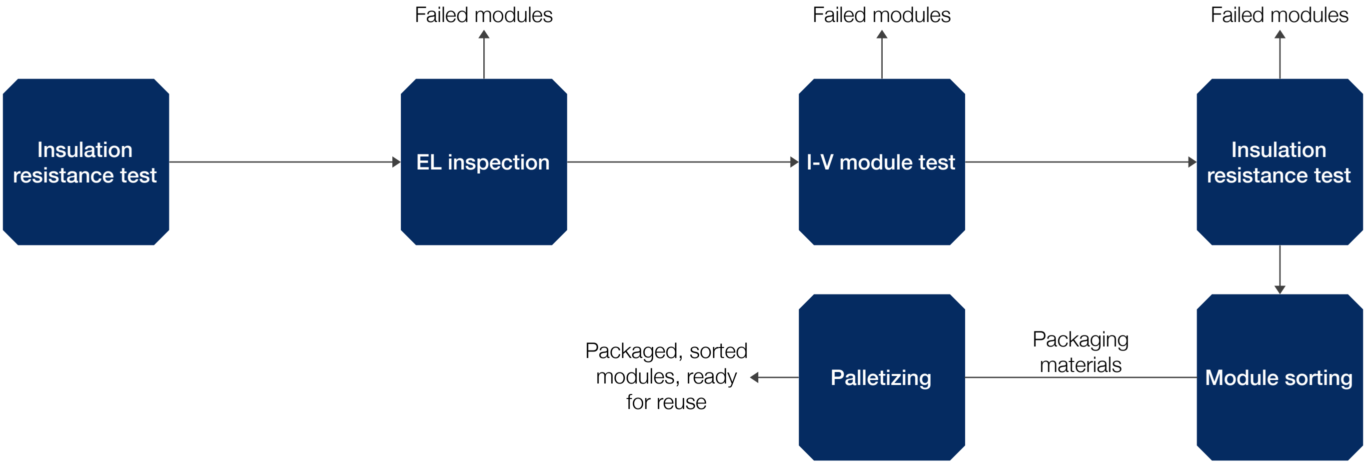


Table 6
Key cost-benefit assumptions for four options analysed.

	Option 1	Option 2	Option 3	Option 4
Equipment	$1.07m	$17.8m	$0.22m	$0.4m
Maintenance	12% as annual equipment cost	12% as annual equipment cost	12% as annual equipment cost	12% as annual equipment cost
Transportation	$16.2 per tonne	$16.2 per tonne	$16.2 per tonne	$16.2 per tonne
Utilities, materials and waste treatment	$118 per tonne	$91 per tonne	$107 per tonne	$45 per tonne
Materials sales revenue	$655/tonne $512/tonne (low revenue)	$1168/tonne	$300 $180/tonne (low revenue)	N/A
Labour	30 employees at 10,000 tonnes/year full capacity	25 employees at 4,000 tonnes/year capacity	Minimum 4 employees at 1,000 tonnes/year capacity	Minimum 5 employees at 1,000 tonnes/year capacity
Land and building	Starting from $164,700 per year	Starting from $329,400 per year	Starting from $82,350 per year	Starting from $82,350 per year

We assume that the same testing procedure can be used for panel reuse (see Figure 21). Upon arrival at the waste management facility, the panels will undergo performance and fault testing through an inspection line. EL tests will detect significant faults and defects within the panel, while IV will measure the panels' power output for sorting based on power/current rating. The final insulation resistance test will exclude panels with electrical risks from reuse. Any panels with significant quality issues will be excluded, and the functioning panels will be sorted and packaged for resale/reuse. The cost data is obtained from solar panel manufacturing cost in 2020 (module inspection costs 0.003$/W at 1GW capacity [35]), then recalculated for proposed reuse facility scale.

4.4. Cost benefit analysis methodology

Key cost-benefit assumptions for analysing four distinct recycling and reuse options include: equipment investment, operational expenses, labour requirements, and potential revenue streams from material sales. The assumptions are based on a comprehensive analysis incorporating various operational scales and financial models, as summarised in Table 6 with explanation in the subsequent text.

The costs associated with utilities, transportation, and material sales revenue scale directly with the volume of panels processed. Conversely, equipment costs, labour expenses, and building costs rise at a nonlinear rate as operational capacity increases, reflective of economies of scale benefits.

Equipment cost encompasses the equipment and their ancillaries, which is depreciated over a 10-year using the straight-line method.

The average transportation cost per tonne is assumed to be $16.2 with average transportation distance of 180km (from 3.2.3 Transportation distance and cost).

Utilities, materials and waste treatment data is obtained from Dias 2022 [33] and NREL 2020 [35]. This is high for option 1 and 3, because both leave large amounts of materials "unattended", and there is a cost associated with it.

The recycling yield and material recovery revenue for option 1, 2 and 3 are taken from [33]. The revenue for option 3 only includes $2.1/kg revenue from aluminium frame sales, $9.8/kg revenue from copper cables sales. In addition, $9.8/kg revenue from conductive fractions is accounted for option 1; $0.091/kg for clean glass, $3/kg for silicon, and $916/kg for silver are accounted for option 2.

We also modelled a low-revenue scenario for option 1 and 3, because option 1 will generate non-conductive fractions, and option 3 will generate PV laminates, which the market price is unknown, and the authors claimed, "finding of suitable companies willing to buy recovered glass was challenging and, to date, unsuccessful". In a pessimistic scenario, it would cost $0.15/kg for recyclers to get rid of these materials, reducing the total revenue. The revenue for option 4 is difficult to estimate as both the reuse rate and reuse price are unavailable.

Labour count for option 1, 2 are estimated based on news from recently opened PV recycling facilities [36], [37]; option 3 and 4 are estimated based on interview with a recycler. Salary assumption is $60,000 per employee, and 10% for benefits.

Land and building costs for the waste infrastructure are estimated based on Australia's average industry land leasing, at $122/m^2 for non-premium metropolitan locations. Another 35% of the land leasing cost are added to account for building utilities. The minimum factory sizes are assumed to be 1,000 m^2, 2000 m^2, 500 m^2, 500 m^2 for all four options respectively at 1,000 tonnes/year capacity. Additionally, a 1,000 tonnes/year treatment capacity would require an additional 200 m^2 space to temporarily store panels waiting to be processed[6].

There is an important revenue stream being excluded from Table 7: a gate fee when disposing any type of waste in Australia. This fee is typically assessed per tonne and varies across different waste categories. Due to the lack of a clear waste classification and a product stewardship scheme specifically for solar panels, the gate fee for this type of waste is currently unavailable.

However, by conducting a cost-benefit analysis, we can gain insights into what a reasonable gate fee might entail, even though the specific details are not yet accessible.

A scaling factor was applied to equipment and labour cost to count for the cost difference when the factory is operating at different scale compared to the reference value:

$$I = I_m \times \left(\frac{Q}{Q_m}\right)^{0.6}$$

Where donates the investment in fixed assets, and represents the reference value of and treatment quantity respectively; 0.6 is the economies-of-scale benefit index.

The full capacity is 8,000 tonnes/year for one set of recycling tools and 6,000 tonnes/year for one set of reuse tools (operating 24 hours, 365 days a week, including scheduled shutdown for maintenance). Any scale below the full capacity would assume constant CAPEX (meaning it is not possible to purchase half of a tool). The scaling factor is applied to equipment at higher than 8,000 tonnes/year and labour cost (at any capacity).

A discount rate at 7% is applied to all Net Present Value analysis, following Australian Government cost-benefit analysis guidance [38]. To simplify our analysis, we have excluded tax considerations. This methodology allows for the application of different discount rates in future cost-benefit analyses. The primary objective of this section is to examine costs across various operational scales, with the aim of making informed technological recommendations. However, the analysis can be adapted to include different discount rates for varied cost-benefit analysis applications.

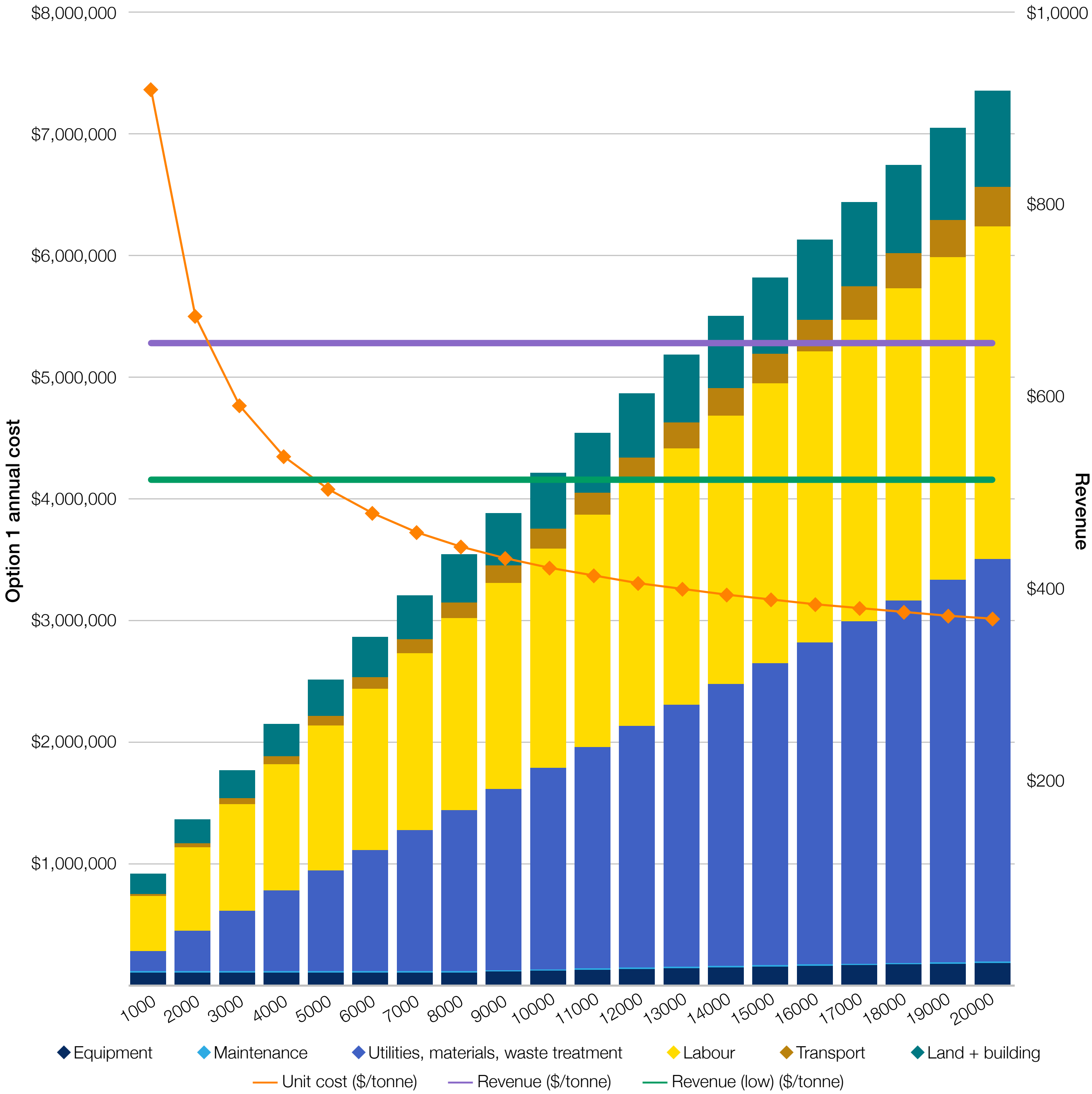
6 It is assumed that 10% of annual capacity would be temporarily stored at the facility. To safely handle the storage and movements, each pallet should not exceed 2m height, which is equivalent to approx. 50 panels in a stack with total weight of 1 tonne. The size of a panel is about 2 m^2. Therefore, the storage space for 100 tonnes of panels (10% of 1000 tonnes) would be 2 m2 * 100 pallets = 200m2.

4.5. Cost breakdown of PV recycling and reuse, at different operating scales

Figure 22 to Figure 25 show the cost breakdown of four different end-of-life options across operational scales ranging from 1,000 to 20,000 tonnes per year. These figures illustrate the facility's total annual costs, which consider a 10-year straight-line equipment depreciation, represented by the stacked bars with the left-hand axis. The lines in the graph indicate the unit cost and unit revenue per tonne, with values corresponding to the right-hand axis. The revenue is determined from the recycling yield, material purity and material price for each option, regardless operational scale; therefore, the revenue is shown as a straight line. The intersection of the cost and revenue lines indicates the point of cost breakeven.

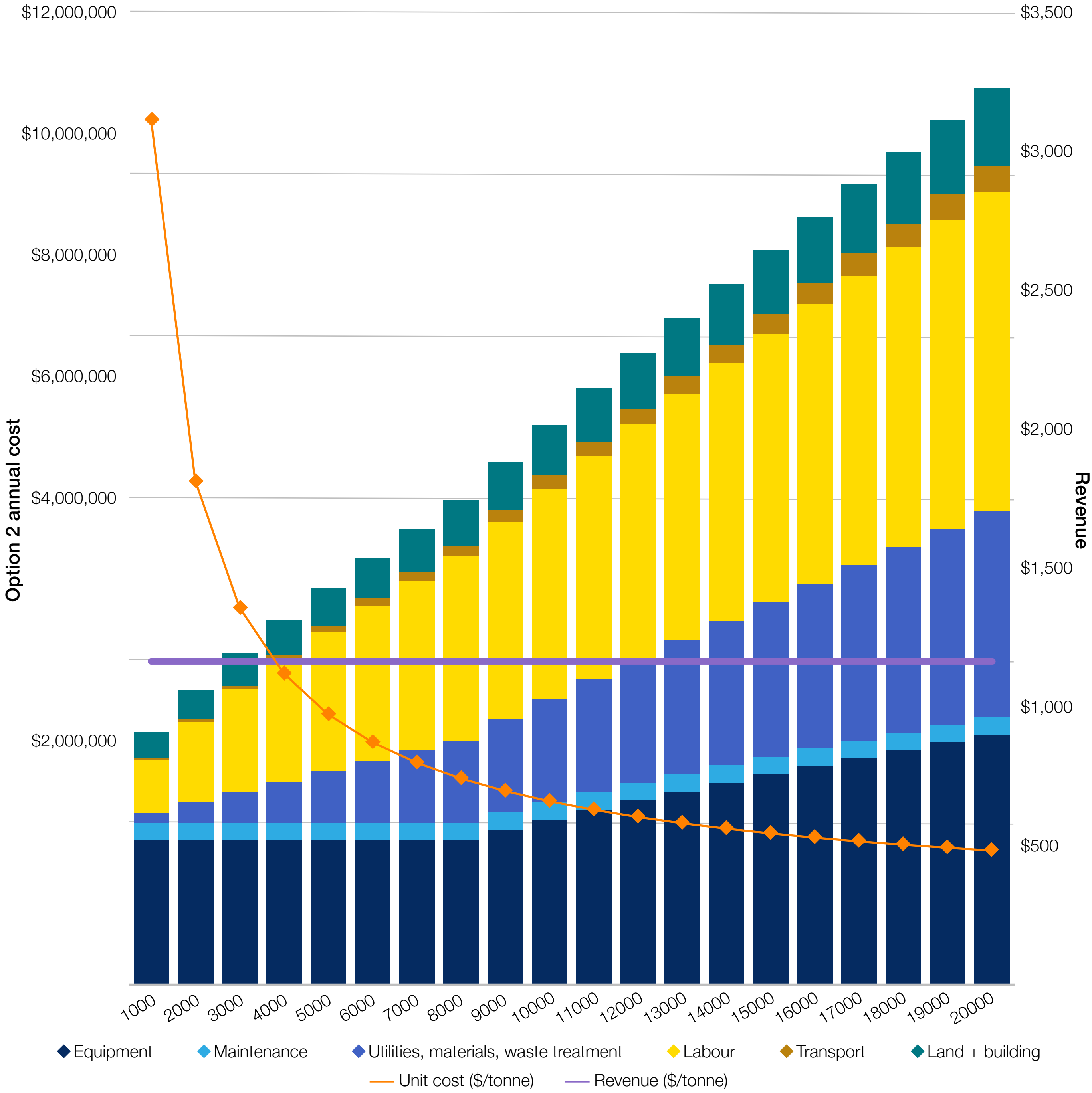
For option 1 (Figure 22), CAPEX (mainly equipment) is negligible compared to operating cost every year, such as utilities, materials and waste disposal and labour, at any operation scale. The cost breakeven can be achieved at over 2,500 tonnes/year. However, recyclers should consider the risk of not finding a suitable market to sell the electrostatic non-conductive fractions, which contain a mixture of glass, polymers, and silicon. In this case, the breakeven can be achieved at over 5000 tonnes/year.

Figure 22
Breakdown of annual cost structure for Option 1 electrostatic recycling at different operation capacity.



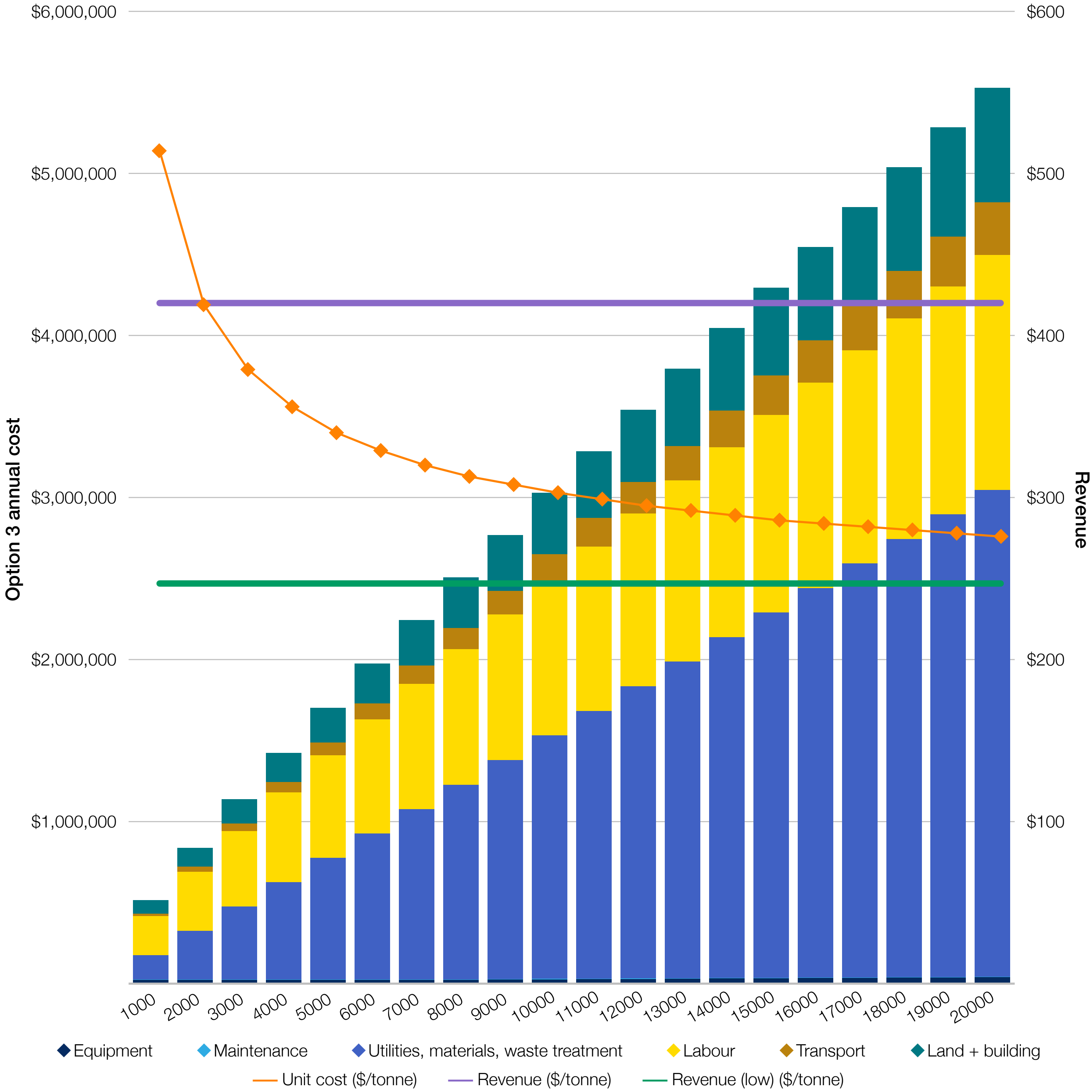
Option 2 (Figure 23) requires significant capital investment, about $17.8 million, to establish full recovery facilities. Option 2 is not economically feasible for less than 4,000 tonnes/year capacity. With lower processing capacity and high idle time, the unit cost per tonne would be significantly high therefore not recommended for small to mid-scale waste management facilities. Labour cost is still the highest expense.

Figure 23
Breakdown of annual cost structure for Option 2 FRELP process at different operation capacity.



Option 3 only needs small upfront investment in equipment, at approximately $220k. However, the main problem with option 3 is that it relies on outsourcing the recycling of the PV sandwich to a third-party downstream recycler, and that entity may not exist. In the absence of an appropriate recycling entity, Option 3 only recycles less than 20% of the module's weight, leaving 80% unaddressed, which does not align with the target of 80% recovery rate from all waste streams by 2030, as set forth in Australia's National Waste Policy Plan. In light of these factors, Option 3 cannot be considered a sustainable long-term solution for managing large quantities of end-of-life solar panels (Figure 24).

Figure 24
Breakdown of annual cost structure for Option 3 only recycle aluminium frames and junction boxes at different operation capacity.



The cost of panel reuse testing on automated panel testing facilities ranges from $177 to $473 per tonne, equivalent to $3.5 to $9.5 per panel tested for reuse (Figure 25). This is approximately half the cost of recycling and requires a relatively low capital investment. However, these figures only cover testing. If only 10% of panels are reusable, the cost per reused panel increases tenfold, with the remaining 90% still requiring recycling.

In summary, option 1 has a lower capital investment and is economically feasible at a lower operation capacity but finding a material recovery facility (MRF) to treat the glass/polymer mixture can be challenging. On the other hand, the FRELP process can recover all valuable materials from solar panels with high material yield and purity, resulting in higher revenue. However, due to its high capital investment, it is only feasible for large facilities (>5,000 tonnes/year) that can access a sustained incoming waste volume.

Figure 25

Breakdown of annual cost structure for Option 4 reuse after inspection at different operation capacity.

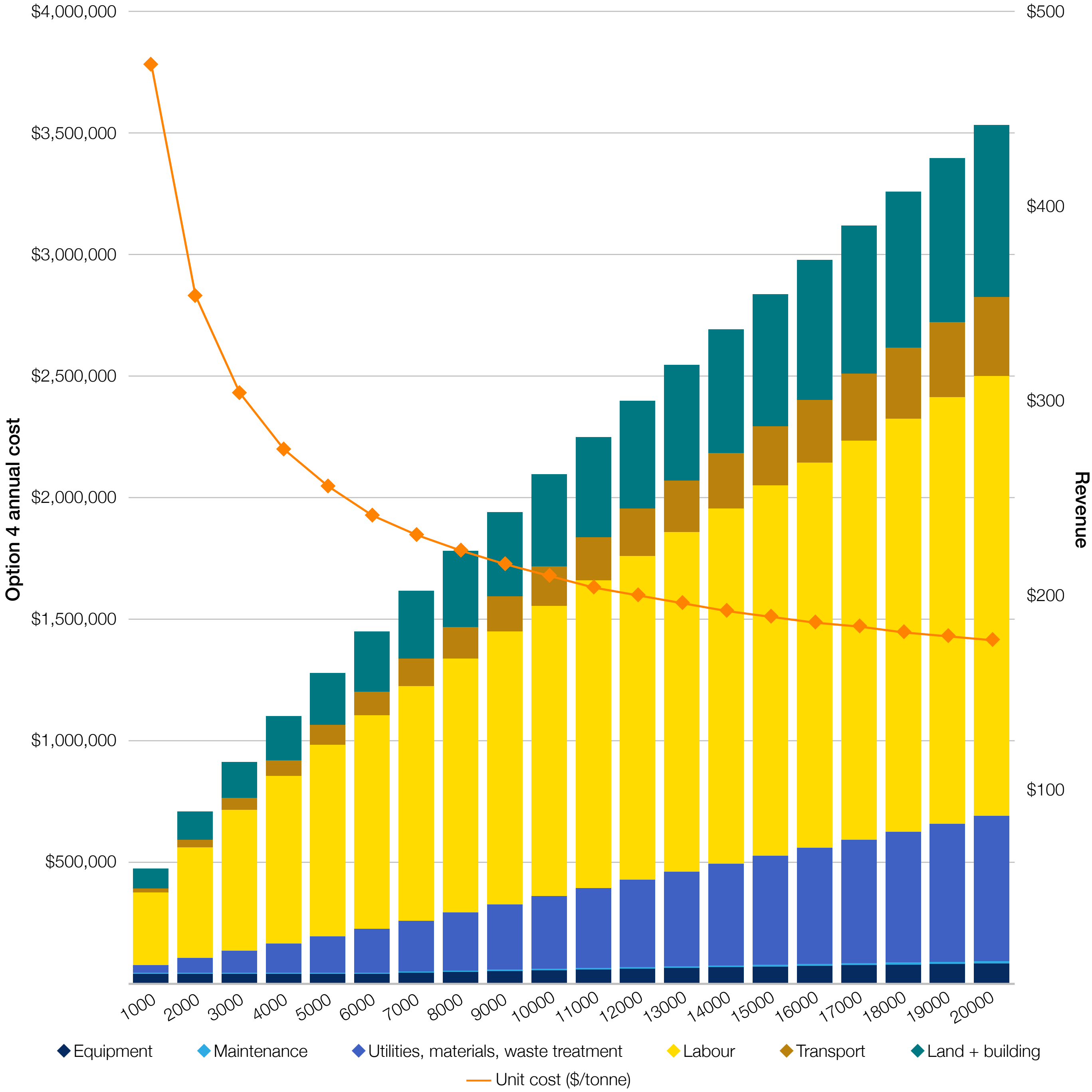


Table 7
Summary of capital investment, minimum feasible scale and revenue for four options.

	Capital cost	Revenue	Minimum economic feasible scale	Unit cost at 5,000 tonnes/year
Electrostatic recycling	Low – Medium	Low-medium	2,500 tonnes/year	$503/tonne
Full material recovery	Very high	High	4,000 tonnes/year	$978/tonne
Frame only	Low	Low-medium	3,000 tonnes/year	$382/tonne
Reuse after inspection	Low	N/A	N/A	$249/tonne

Table 8
NPV and payback time for option 1 and 2. Values are rounded to the nearest thousands.

Scale	Option 1		Option 2	
	Payback time	NPV	Payback time	NPV
2,000 tonnes	-	-$713k	-	-$13,450k
3,000 tonnes	5 years	$987k	-	- $8,733k
5,000 tonnes	2 years	$4,714k	9 years	$1,308k
8,000 tonnes	1 year	$10,852k	5 years	$17,161k

The previous analysis was a simple breakeven analysis which did not take into account the time value of money. A more detailed analysis using NPV was used to further understand the investment payback time for different technology options at different processing capacity.

Table 4 illustrates the net present value (NPV) and payback time for Option 1 and Option 2, considering a 10-year facility lifespan, 7% discount rate at various operating scales. At a low operating capacity of 2,000 tonnes per year, both options yield negative NPV values, indicating that they are not financially viable and would lead to a loss in value. Considering the time value of money, **Option 2 full recovery facility is only recommended at sites that can access more than 5,000 tonnes of PV waste annually.**

Our analysis, as detailed in Table 2, indicates that starting from 2023, metropolitan facilities are projected to handle between 5,000 to 10,000 tonnes of PV waste annually, while regional and remote facilities may process between 1,500 to 2,500 tonnes annually, assuming a 100% collection efficiency. However, in the nascent phase of Australia's PV end-of-life market, there is a lack of both a robust logistic network for waste collection and mandated collection rates. This situation, as underlined by insights from Sections 2 and 3, presents a challenge in reaching the minimum scale of operation deemed economically feasible. Without an optimized national logistics framework, guaranteed collection rates, and the development of market competition, PV waste management facilities may face a shortfall in waste input. This discrepancy risks facilities operating below their economically viable thresholds.

In the current market stage, where ideal conditions for PV recycling operations—such as optimal logistics and collection efficiency—are not immediately attainable, **it is necessary to implement a nationwide gate fee for solar panels**. This fee is crucial for maintaining the financial health of PV recycling businesses. However, care must be taken to set this fee at a level that encourages recycling without discouraging the continued use of still-functional panels. **An initial gate fee of around $500 per tonne, with a variance of ±50%, is suggested**. This fee takes into account the likelihood of recycling companies managing an inflow of 500 to 2,000 tonnes of waste annually on their own. **Such a fee would help cover operational costs of PV recycling.**

To supplement the income from the gate fee and enhance profitability, recyclers should actively seek out buyers for the recycled materials or develop innovative recycling solutions that can extract valuable materials more efficiently. By doing so, recyclers can generate higher revenue streams.

Establishing this gate fee will provide the burgeoning market the necessary time to expand its logistics infrastructure. Additionally, it will allow new entrants to sustain their operations while they establish a reliable waste supply chain. This two-pronged approach—securing operational costs through gate fees and seeking additional revenue through material off-takers—ensures a gradual and sustainable growth of the PV recycling industry.

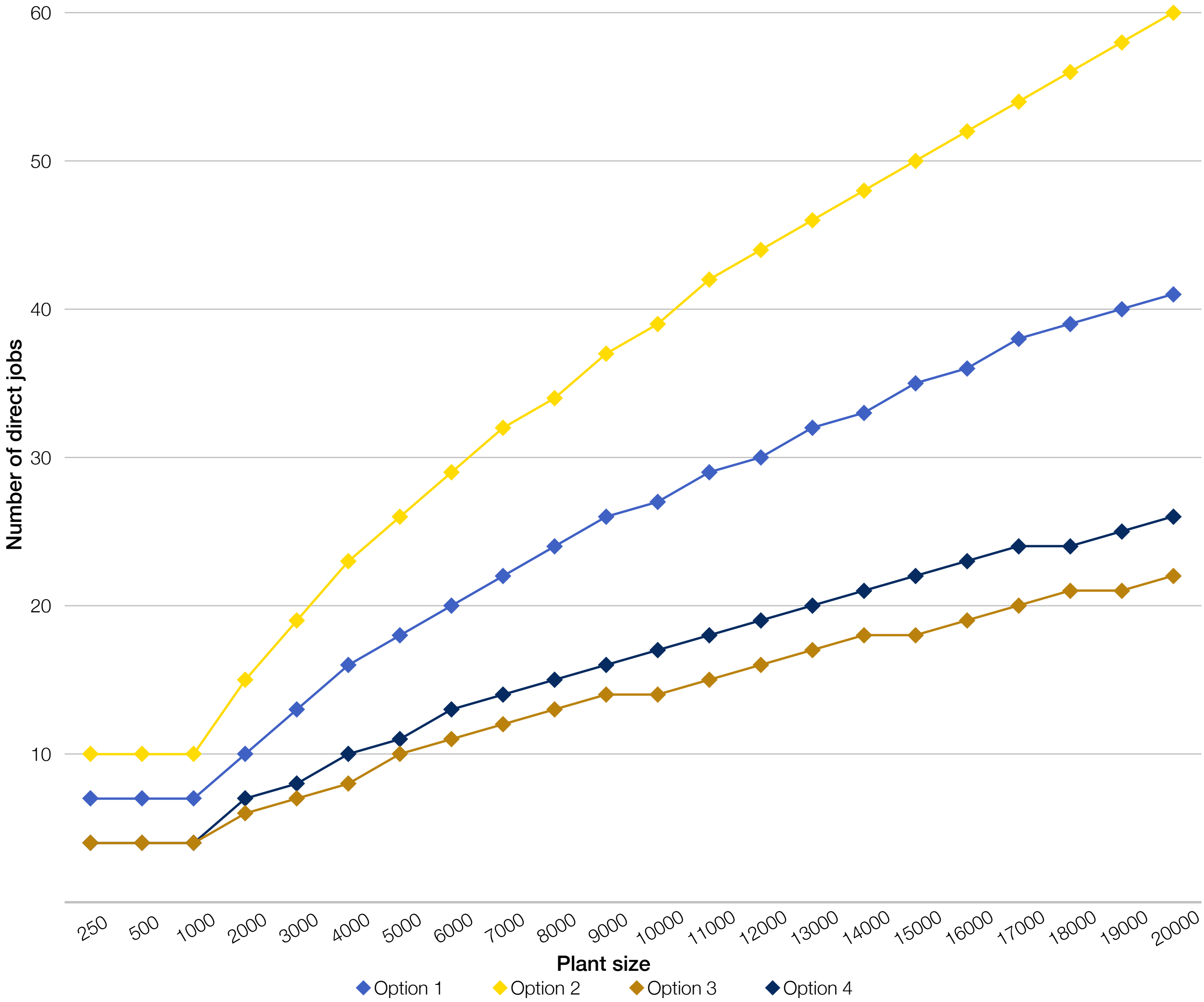
A product stewardship for PV systems will be implemented in Australia in 2025, where manufacturers shoulder the financial responsibility for the disposal costs of panels, ultimately passing these costs onto consumers. For instance, in 2023, with an estimated 40,000 tonnes of waste solar panels and a gate fee of $500 per tonne, this would translate to an additional cost of $0.005 per watt for manufacturers, effectively setting aside 1% of the panel's cost for end-of-life management.

Early incentives could be critical for ensuring viable recovery pathways, fostering long-term positive outcomes, and mitigating the risks of stockpiling and illegal dumping.

In line with Section 3 findings, most regional facilities may find it difficult to process over 5,000 tonnes of waste panels annually. Hence, a strategic approach would be to establish mid-scale facilities employing delamination (type 1 technology) and forming partnerships with type 2 facilities in metropolitan area for further material refinement, rather than investing in comprehensive, high-capital equipment in each regional facility.

Lastly, the development of specialized PV waste management facilities is expected to generate local employment. As projected in Figure 26, based on the recommendations of Section 3, PV recycling/reuse industry will **create 146-335 jobs in Australia by 2030**, up to 355 jobs by 2035. This only considers the direct labour, including management and operational staff, at the recycling/reuse plants, with additional employment opportunities likely in logistics monitoring and administration.

Figure 26
Number of jobs created by new dedicated PV waste treatment facilities at different operation capacity.



4.6. Challenges and opportunities

Challenges

Scale challenge

Operating at scale is the key to drive down the cost. The per-tonne recycling cost can decrease from $919 to $683 if the facility's processing capacity expands from 1,000 tonnes/year to 2,000 tonnes/year. Instead of relying on subsidies to compensate for the cost gap, recycling businesses should meticulously design their waste collection network. This will ensure a steady inflow of waste material, critical for maintaining business sustainability. The insights from Section 2 and 3 of this report can provide some insights for the industry to overcome this challenge.

End-market challenge

There has been a constant challenge in finding a suitable end-market for all recovered materials, especially for glass, which constitutes 70% weight of the panel. Current solutions involve repurposing the glass as a substitute for sand in concrete and bricks. There are two main reasons: firstly, during the shredding process, the glass recovered from solar panels becomes contaminated with iron or other metallic components, making it unsuitable for direct use as glass manufacturing feedstock without additional sorting and cleaning procedures. Secondly, the breakdown of glass particles into very fine sizes (less than 1mm in diameter) poses difficulties for reprocessing. The challenge extends beyond glass, as the highly mixed nature of the components makes it challenging to find markets for their use, ultimately resulting in the need for disposal. This situation is contrary to the initial objective of achieving recycling rates exceeding 80% while preserving material value and diverting waste from landfills.

Reuse challenge

Key technical barriers exist for panel reuse in Australia. Firstly, the Clean Energy Council (CEC) maintains an approved list for installation, but older panels are typically excluded, making room for newer ones. To enable panel reuse, the standard should be revised to allow for the inclusion of older panels. Secondly, the power ratings of older panels differ from newer ones. This creates a challenge when connecting panels in a string within a PV system, as the current mismatch can lead to severe damage and reduced power output. The mismatch can be mitigated by microinverters but adding significant cost. Thirdly, there is a lack criteria or standards for panel reuse. Before being sold as second-hand products, panels should undergo safety and quality testing, and the resulting data should be available to buyers to establish trust. The absence of such testing criteria in Australia currently favours the adoption of new panels over second-hand ones.

Opportunities

Low-cost innovative full recovery technology

Full material recovery technologies offer the potential for high overall recycling yields by recovering both bulk and valuable materials. However, their implementation poses challenges due to the substantial capital investment required. For example, the capital expenditure (CAPEX) for Full Recovery Enhanced Leaching Process (FRELP) amounts to $17.8 million. This high CAPEX makes it difficult for most facilities to adopt such technologies. Reductions in these costs are crucial: halving the CAPEX would allow a recycling operation to become viable at 3,000 tonnes per year, while a reduction to a quarter could lower the threshold to 2,000 tonnes annually. For facilities processing 5,000 tonnes per year, a 50% CAPEX reduction could boost the 10-year IRR from 9% to 28%, and reducing CAPEX by 75% could see IRR increase to 61%. **Australia needs more innovative solutions to recover all materials from solar panels while keeping the cost low.**

Australia's solar panel recycling industry currently lacks a dedicated entity focused on material recovery, a gap highlighted in section 4.2.2. However, government support is fostering progress in this area. The New South Wales Government's $10 million fund aims to reduce solar panel and battery system landfilling and facilitate the state's shift to renewable energy within a circular economy [39]. Similarly, Breakthrough Victoria's $10 million investment in solar recycling innovations indicates a movement towards scalable solutions. These government-led initiatives are laying the groundwork for the necessary infrastructure to address the country's increasing solar waste.

Potential second-hand panel market

In a circular economy model, reuse is prioritised over recycling. Cost-benefit analysis demonstrates that the expense associated with logistics for reuse is lower than that of recycling. However, reuse might require additional re-certification, re-installation and transportation to customers, which the cost is not yet available before such market exists. Given that early decommissioned panels from rooftop systems are expected to dominate the Australian PV end-of-life market in the coming decade, a significant portion of these panels are likely to still be functional and suitable for repurposing elsewhere. With the advantages of an environmentally preferable outcome, lower costs, higher revenue, and an adequate supply of panels, the possibility of establishing a domestic second-hand panel market in Australia becomes feasible. However, further in-depth research is needed to understand the technological and market requirements necessary for the realization of such a market.

4.7. Limitation

This section has a few limitations to consider. Firstly, there is a conflict between reuse and recycling. If a larger proportion of panels are reused, it may divert them away from recycling, making it more difficult to achieve the expected operational scale of the recycling facility and potentially resulting in economic losses. This contradiction is not accounted for in the simplified analysis conducted here. Secondly, as the industry accumulates experience and treated volumes increase, there will be lessons learned that can impact costs. This learning factor has not been included in the analysis conducted so far. These limitations indicate areas where further analysis and consideration are necessary to provide a more comprehensive understanding of the dynamics and potential outcomes in the industry.

4.8. Summary of cost-benefit analysis

From the cost-benefit analysis, current recycling technologies, including transportation costs, range from $500 to $1,000 per tonne, covering transportation, before accounting for the revenue from sold materials. This estimate assumes that the recycling facilities handle approximately 5,000 tonnes of panels each year. Among the various cost components, equipment investment and labour account for the majority of expenses. On the other hand, the cost of reuse testing falls within the range of $130 to $380 per tonne, including transportation to the testing site. Other costs for reuse, such as re-certification, re-installation, transportation to customers, are not covered in the analysis as the data is not available. Although reuse is the most desirable option, it poses practical challenges, such as ensuring compliance with existing Australian PV installation standards, which must be adequately addressed.

For recycling, the delamination-only recycling technology proves to be economically feasible at an operational capacity of 3,000 tonnes per year or higher. To achieve the target of an 80% material recovery rate, recyclers must actively seek domestic end-markets that can utilise the recycled solar glass and plastics. On the other hand, full recovery technology holds promise for achieving high recycling rates and revenue by recovering both bulk and valuable materials. However, this technology currently requires significant capital expenditure (CAPEX) investment and more suitable for large-scale operation (>5,000 tonnes per year). Australia currently lacks such facility, and urgently needs more innovative solutions to recover all materials from solar panels while keeping the cost low.

In a fledgling market with numerous new market entrants and intense competition, operating under the optimal logistic arrangement poses challenges, making it difficult for anyone to access a sufficiently high volume of waste to achieve the minimum economically feasible operating scale. To ensure the sustainability of dedicated PV recycling businesses, a nationwide gate fee for solar panels becomes necessary. We believe that a gate fee of approximately $500 per tonne (with a variation of ±50%) represents a reasonable starting point for establishing the market. Instead of relying on subsidies to bridge the cost gap, recycling businesses should strategically design their waste collection networks to achieve the minimum feasible scale, thereby securing a sustainable business model. As the market matures, the gate fee can be gradually reduced.

We flag that additional subsidies may be necessary for PV waste facilities located in regional Australia. Compared to metropolitan areas, regional facilities would not access high volumes of waste as metropolitans (see Section 2 and 3). Consequently, operating at a smaller scale can result in higher costs. However, it is worth noting that establishing waste management facilities in regional areas can offer valuable local job opportunities, presenting a trade-off that should be considered. Another recommendation is to encourage Type 2 dedicated full recovery facilities in metropolitan, where Type 1 facilities in regional areas can partner with, to send off their mixed laminates to the full recovery facilities.

5. PV END-OF-LIFE POLICY FRAMEWORK

5.1. Australia

5.1.1 National context: product stewardship for photovoltaic systems in Australia

There has been a consistent and large increase in household PV systems in Australia, resulting in an increase upwards revision of the projected PV material requiring management. **Currently, there is no National PV waste legislation or stewardship program in Australia.**

In 2016, the Commonwealth Government listed solar photovoltaic systems (photovoltaic panels, inverter equipment and system accessories, for domestic, commercial, and industrial applications) on the product stewardship 'priority list.' This indicates PV systems need urgent **product stewardship** action and encourages industry to reduce the negative environmental and human health impacts of products, as well as conduct business more sustainably.

What is product stewardship?

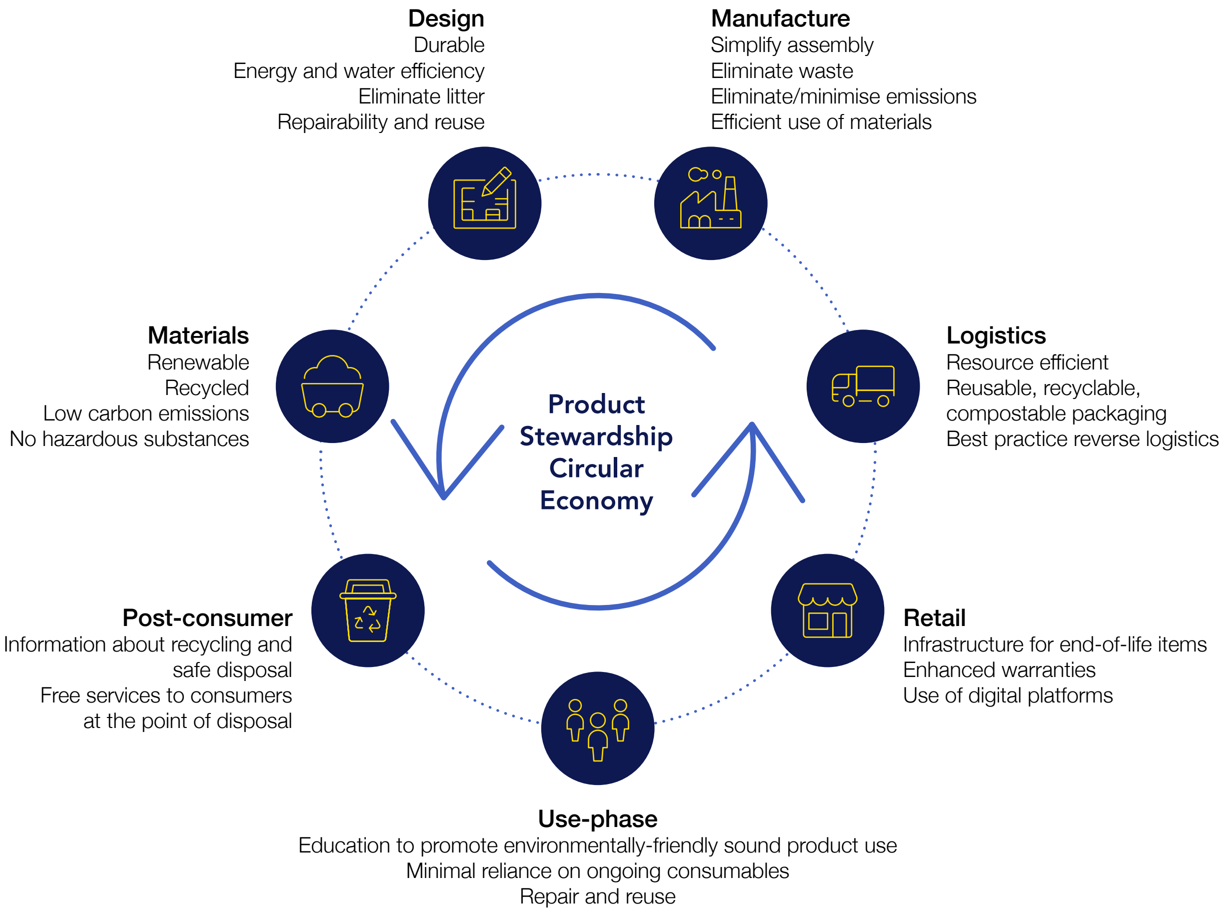
According to Australia Government Department of Climate Change, Energy, the Environment and Water [40],

"Everyone who imports, designs, produces, sells, uses and disposes of products has a shared responsibility to reduce the environmental and human health and safety impacts of those products."

Product stewardship schemes promote the responsible handling of products and materials throughout their entire lifespan, including their disposal at the end of their useful life. These initiatives can be implemented voluntarily, mandated by regulations, or established through collaborative efforts with the industry.

For example, the National Television and Computer Scheme (NTCRS) is a co-regulatory product stewardship scheme to manage TV and computer products end-of-life in Australia. Companies who import or manufacture television and computer products over certain thresholds are liable under the scheme and are required to pay for a proportion of recycling through membership in a co-regulatory arrangement[42]. These arrangements are responsible for day-to-day operation of the scheme, including organising collection and recycling of e-waste on behalf of liable party members.

Figure 27
Product Stewardship infographics from DCCEEW [41].



Regulatory product stewardship for PV systems in Australia

The national product stewardship scheme for PV systems aligns with

- National Waste Policy: Less Waste, More Resources 2018[43]:
  - Improve material collection systems and processes for recycling.
  - Improve the quality of recycled material we produce.
- National Waste Policy Action Plan 2019[44]
  - Target 3: 80 per cent average resource recovery rate from all waste streams following the waste hierarchy by 2030.

In support of the action 3.05 of the National Waste Policy Action Plan (Annexure 2022)[45] to **identify a preferred stewardship scheme for PV systems by June 2023 and implement it by 2025**, the Product Stewardship Centre of Excellence was engaged by the Australian Government in November 2021 to facilitate a co-design process with stakeholders from all governments, business sector and waste and resource recovery industry for an industry-led stewardship scheme to divert PV systems from landfill. The goal was to will prevent hazardous substances from leaching into the environment and increase recovery of valuable materials, including critical minerals.

However, the Australian Government does not consider there has been sufficient progress in the industry-lead scheme and announced its intention to develop a **regulatory product stewarship scheme for** PV systems (including solar panels) and household electronics at the Environment Ministers Meeting (21 October 2022 [46]). In response, the Department of Climate Change, Energy, the Environment, and Water has reinstated the E-Stewardship Reform Working Group under the Resource Recovery Reference Group. This working group has consulted recyclers, peak bodies, regulators, industry stakeholders and state territory governments, and is responsible for advising on the design of the scheme. The scheme objectives are[47]:

- **Reduce waste going to landfill**, especially hazardous materials found 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
- Support Australia's transition to a more **circular economy**
- Foster **shared responsibility** across the life-cycle of covered products.

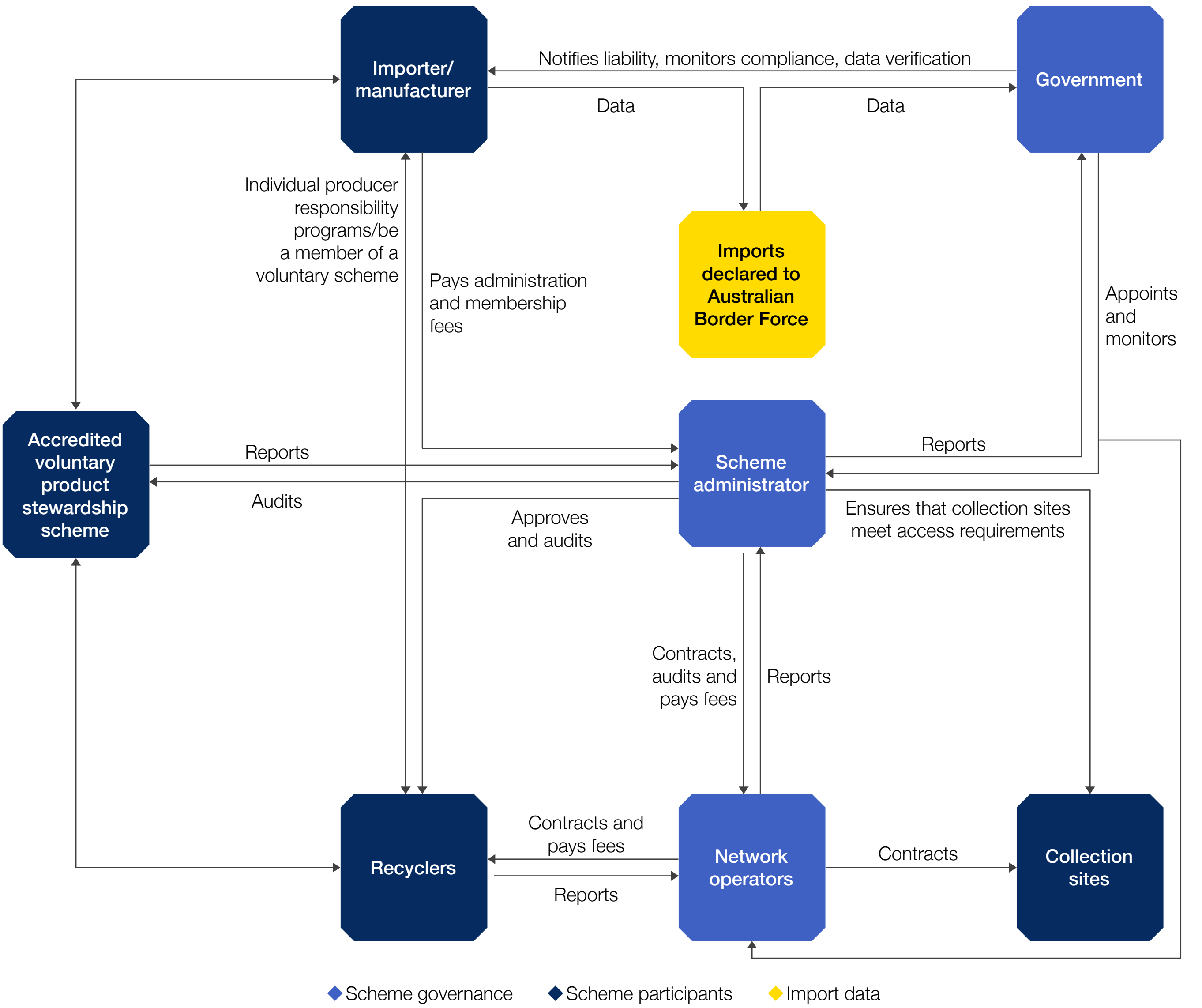
A scheme proposal was released in June 2023 for public consultation. In this proposal, it is proposed that small electronic waste and PV systems (panels, racks and inverters) are covered under one regulatory scheme, but different waste classes. Liability associated with large-scale PV systems (>100kW) could be transferred from importers or producers of in-scope products to large-scale system owners, allowing different options to manage the liability. Furthermore, the scheme will regulate collection, recycling and public education and encourage re-use and repair.

Figure 28 shows the proposed scheme design. In simple words:

- **Liable party**: Importers or manufacturers of regulated products above a certain threshold, responsible for registering with the scheme administrator, **paying fees**, and can run their own recycling programs to reduce liability.
- **Scheme administrator**: Oversees the scheme's outcomes, **manages** risk, audits, ensures public access, receives and submits reports, contracts with network operators to meet scheme outcomes **but does not handle physical recycling activities**.
- **Network operation**: **Manage** collection, transportation, and recycling services within assigned areas, are appointed by the government, contract with and report to the scheme administrator, and ensure recycling meets standards.
- **Consumers**: **Free public access** to drop-off services. For PV systems, the collection part of the scheme will be provided only to qualified electricians to ensure safe handling.

It should be noted that the scheme has not yet been finalised; therefore, all details discussed in the proposed scheme are subject to change. The final scheme is expected in 2025.

Figure 28
Proposed scheme design[48].



In our discussions with several key stakeholders within the Australian market, it has been observed that a significant portion of end-of-life panels from distributed systems are not subjected to domestic recycling or reuse. The collectable waste volume is much lower than projected in Section 2. Instead, these second-hand panels are frequently exported to developing nations for further reuse. Such practices, however, this may have detrimental impacts on receiving countries that must then manage the waste arising. The **Basel Convention** was established to control international movements of hazardous waste and other wastes so that they are disposed of, or recycled, in a way that protects human health and the environment. An anticipated amendment to the Basel Convention, expected to come into effect in 2025, **will specifically regulate the cross-border movement of solar panels** [48]. This amendment is expected to significantly increase the volume of solar panel waste to be managed domestically, highlighting an urgent need for Australia to enhance its waste management strategies in response to the upcoming regulatory changes.

5.1.2 State and Territory management of Solar PV systems and other E-waste

Victoria

Victoria has (as of 1st July 2019) banned all e-waste from landfills, including PV panels, solar battery systems and inverters under Waste Management Policy (E-waste) 2018[49]. In this policy, AS/NZS 5377:2013, Australian and New Zealand Standard, Collection, storage, transport and treatment of end-of-life electrical and electronic equipment, applies.

The specified electronic waste includes rechargeable batteries, cathode ray tube monitors and televisions, flat panel monitors and televisions, information technology and telecommunications equipment, lighting and photovoltaic panels.

South Australia

In 2013, South Australia was the first government to ban e-waste from landfill, alongside investing in recycling infrastructure. However, their definitions of e-waste are designed to support the National Television and Computer Recycling Scheme (NTCRS), so PV systems are exempted from the ban to date [50].

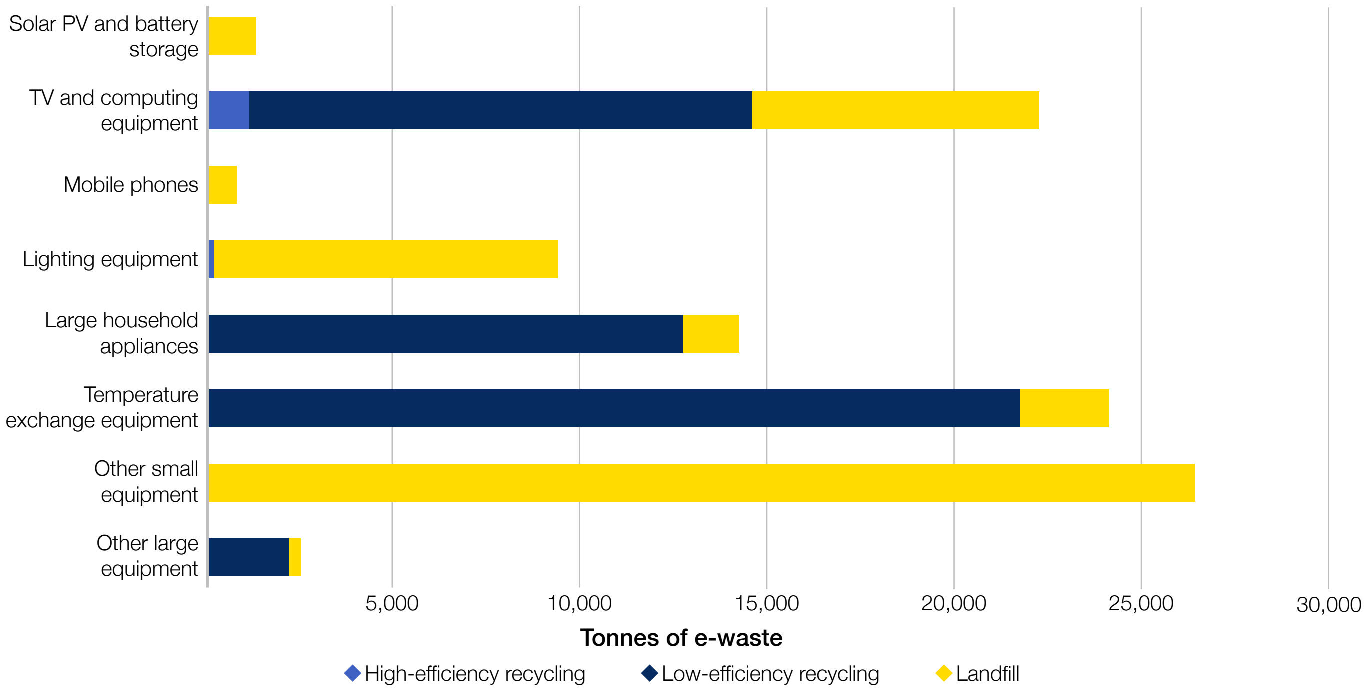
Queensland

In the DRAFT Queensland E-products Action Plan 2022-2032 [51], solar PV and battery storage waste is identified as the fastest growing waste stream to over 17,000 tonnes by 2030. However, the fate of solar PV and battery storage was landfill in 2019, none was recycled or reused (Figure 29).

The 10-year action plan lists several actions to *"Stop recyclable e-products ending up in landfill"*. The actions specifically to PV include:

- State planning approvals for utility PV to require fully funded end-of-life solutions including setting durability, reuse, material recovery and landfill diversion targets (1-2 years).
- Ban the disposal of electrical and electronic equipment including PVs from landfill where industry-funded product stewardship schemes are in place and available (5-10 years).

Figure 29
Fate of e-waste in Queensland, 2019 [Queensland E-products Action Plan 2022-2032].



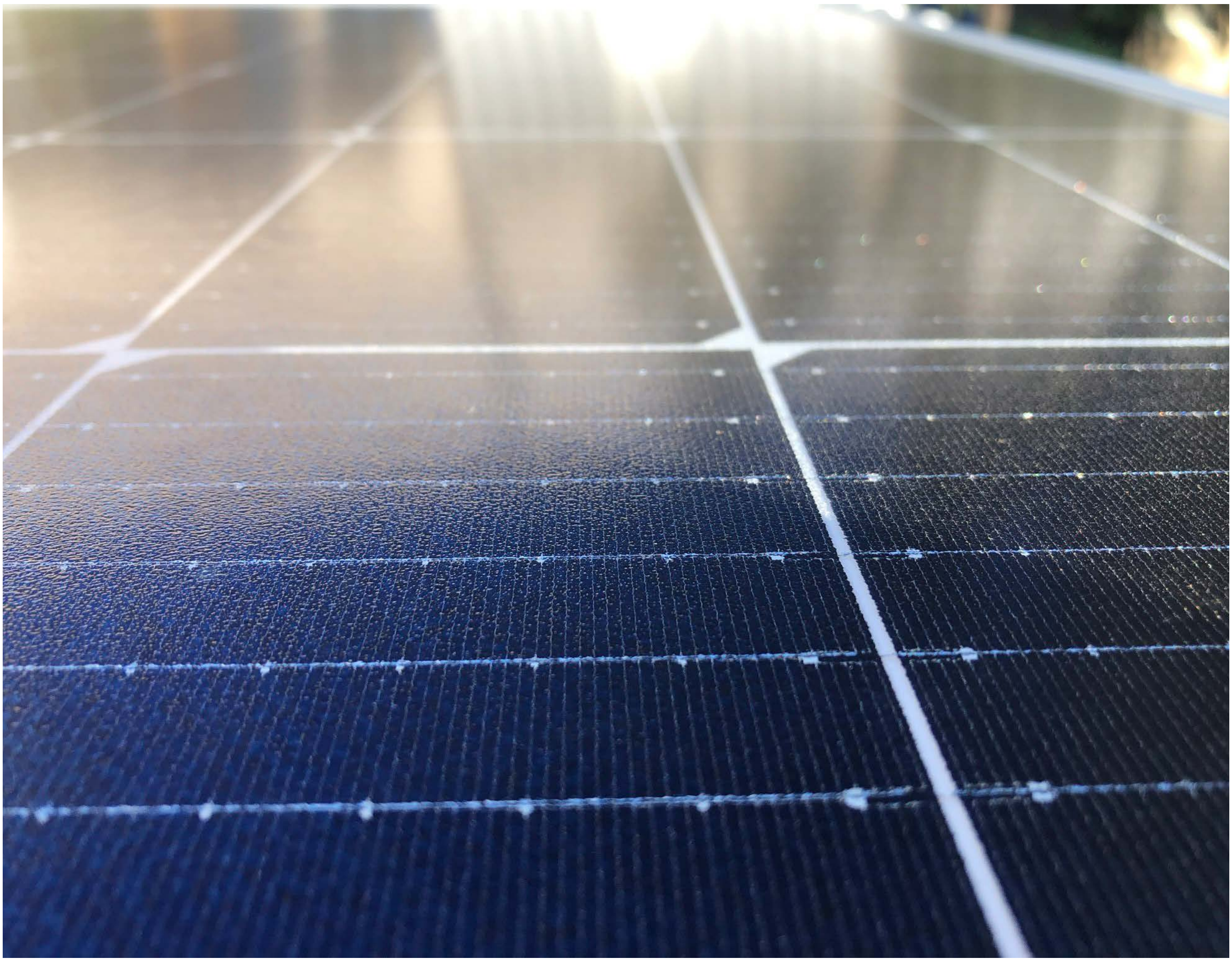
Western Australia
PV have been identified as a national product stewardship priority, and Western Australia anticipates action for these products and systems in the future. Collection may be included in retailed and/or installer take-back activities due to the size and installation requirements of PV.

In the latest e-waste to landfill ban in Western Australia consultation paper [52], The e-waste categories that is in the focus of the current landfill ban includes: screens, IT and telecommunications, lighting and lamps, large household appliances, batteries, temperature exchange equipment and medical devices. Future phases of the ban will capture photovoltaics, small household appliances and monitoring and control equipment.

Australia Capital Territory
In August 2023, the ACT Government released the ACT Circular Economy Strategy and Action Plan 2023-2030 [53] which identifies emerging and problematic waste as a key focus area for the circular economy in the ACT. The Strategy identifies the emergence of solar photovoltaic systems, along with battery storage systems, textiles, and e-waste as problematic waste streams and it also identifies that new problematic waste streams are likely to appear in future. The ambition identified in the Strategy for these types of waste streams is for a circular economy where industry works proactively to prevent the creation of problematic waste, with nationally regulated product stewardship schemes in place in instances of industry inaction for whole of life product management.

New South Wales
The NSW Government has committed $10 million to Circular solar trials grants program[39] which will stimulate increased collection activities across supply chains through the trial of recovery logistics models and reduce the generation of unnecessary solar panel and battery waste to landfill by drawing on collaboration across the supply chain.

States and territories that have not identified restrictions on PV landfill and are expected to participate in nationally led product stewardship measures for photovoltaic systems.



5.2. Solar panel waste management by other countries

The European Union has adopted PV-specific end-of-life regulations since 2012. Discussions are underway in various regions globally regarding the adoption of Extended Producer Responsibility (EPR) for PV end-of-life management, but detailed information regarding specific plans and implementations is currently unavailable.

Table 9 summarises approaches to manage PV end-of-life in PV leading countries/regions from IEA PVPS Task 12 "Status of PV Module Recycling in Selected IEA PVPS Task12 Countries" report [54].

Best practice of collectively joining existing producer compliance schemes and operating their own take-back and recycling systems are further elaborated in boxes below.

Table 9
PV end-of-life management policy framework in PV leading countries/regions.

Country/region	Approach
European Union	Waste Electrical and Electronic Directive (WEEE Directive 2012/19/EU) is the European Union's governing directive concerning E-waste, including waste solar panels. Since 2012, all EU members have implemented the PV regulation into national law, requiring all PV panel manufacturers in the EU market to either operate their own take-back and recycling systems or join existing producer compliance schemes. Manufacturers are financially liable for end-of-life management under the extended producer responsibility (EPR). The legal requirements for PV waste collection and recycling include minimum recycling and recovery rates of 85% and 80% respectively. However, individual EU countries have the authority to establish additional standards and recovery rates beyond these minimums. It is the responsibility of each country to develop policies and infrastructure to meet these targets and ensure compliance.
United Kingdom	Industry-managed take-back and recycling scheme. However, the participation rate is low.
United States	No federal law exists in the US, but Washington introduced an EPR regulation for solar panels. California passed a regulation effective from January 2021, allowing EoL PV modules to be managed as universal waste instead of hazardous waste. Other states are considering similar policies, and industry-led EoL PV recycling programs exist. However, many states lack current EoL PV policies.
Japan	In Japan, PV panels are included under general waste management regulations. A guideline for promoting the proper end-of-life treatment of PV modules was published in 2018. Various governmental bodies have assessed how to handle PV waste and there is a reserve of money created from feed-in-tariff for PV that has been created to deal with future PV recycling.
India	India had included PV waste under E-waste management rules in 2023. This places PV modules under the Extended Producer Responsibility framework.
Korea	On 28 August 2019, the Ministry of Trade, Industry, and Energy and the Korea Photovoltaic Industry Association, as a representative of PV manufacturers, signed an agreement to include PV panels in the EPR list. This agreement implies that EPR will be enforced in the PV industry in 2023.
China	At present, China's policies and regulations on PV module recycling and EoL management are under development. However, China has established a PV recycling centre in collaboration with research and industry in 2022. The centre aims to assess the current and future recycling potential of PV panels, conduct research and analysis on PV recycling, and introduce life cycle management practices to enhance resource efficiency and reduce carbon emissions associated with solar panels. There are a variety of methods and feasible technical routes in the recycling technology of PV modules in China.

A Glance into PV Waste Management in France

France is a leader when it comes to processing photovoltaic waste.

In France, the transposition of the directive 2012/19/EU was made into French law in 2014 by the Décret n° 2014-928 of the French code of the environment, which sets the minimum recovery rate of PV panels to be 85% and the recovery of materials to be 80%.

According to the Environment Code, producers fulfill their obligations by collectively establishing approved eco-organisations. Producers include photovoltaic panel manufacturers, remote sellers, importers, introducers, third-party vendors, and resellers under its own brand, who places photovoltaic panels on the French market. Producers are responsible for governing these organisations, transferring their obligations to them, and providing financial contributions (eco-contribution) in return.

The eco-contribution is a visible environmental contribution applied to each new photovoltaic panel and making it possible to finance and develop current and future collection, sorting and recycling operations, paid to the eco-organisation, which ranges from 0.36 - 1.22€ for a standard silicon panel.

The eco-organisations play a crucial role in managing end-of-life products on behalf of the producers. They serve as mechanisms of solidarity and efficiency, bringing producers together around a common interest.

Soren, the only non-profit French PV industry Producer Responsibility Organisation, coordinates the decommissioning of solar panels all over France with its partners, which consequently has a monopoly on PV module waste management. Soren manages both collection and recycling by operating private tendering procedures that enable the centralisation of PV waste management in France. The map below shows all collection and processing centres in France.

Since 2015, Soren (formerly PV Cycle France) has collected more than 16,000 tonnes waste solar panels throughout mainland France and the overseas territories. Soren expects 20,000 tonnes in 2025. The figure below shows annual used PV panel collection (in tonnes) in France. According to Soren, 94% average recovery rate has been achieved for crystalline silicon solar panels.

Soren and its partners provide two methods for solar panel recycling:

Processing of crystalline photovoltaic panels by grinding. It makes it possible to sort all the components of the panels in order to reintegrate the secondary raw materials:

1. Receiving panels at the processing center.
2. The pre-dismantling.
3. Grinding of laminates, screening and refining of fractions.
4. Air separation.
5. Densimetric or flotation separation.
6. Eddy current separation.

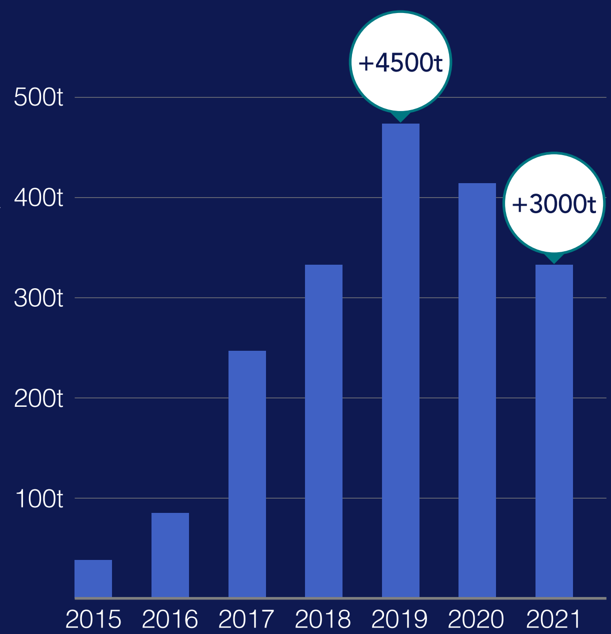
Processing of crystalline photovoltaic panels by delamination. Hot blade delamination allows recycling with very high added value to recover as many components as possible from photovoltaic solar panels, in particular flat glass and strategic metals (silicon, silver and copper):

1. Receiving panels at the processing center
2. The pre-dismantling.
3. Delamination
4. Thermal process
5. Gentle chemical treatment

Soren and its service providers prioritise traceability to ensure high-quality recycled materials and valuable outlets. This traceability spans from waste collection to recovery stages, assuring equipment holders that their disposals meet expectations and providing manufacturers with fractions that meet their requirements.

In June 2023, Soren partners with ROSI, the specialist solar recycling company that offers an industrial solution to economically recover high-purity silicon, silver and copper from end-of-life PV modules, to extract and reuse 99% panel materials in new module manufacturing. Soren and its partners have been at the forefront of achieving an ultimate circular economy in the photovoltaic sector.

More information on Soren's activities can be found from Soren's annual activity report and website [56].



5.3. Summary of regulatory framework

In 2025, Australia anticipates the establishment of a nationwide product stewardship system for managing end-of-life photovoltaic products. This system is expected to align with existing waste regulations and certain state-level regulations. As part of this scheme, producers will be mandated to pay an upfront fee to manage the end-of-life process for solar panels. This fee will be allocated towards collection, recycling, and administration costs. In addition, an anticipated amendment to the Basel Convention will regulate the cross-border movement of solar panels, expected to come into effect in 2025. This amendment aims to manage solar panel waste domestically by making exporting such waste illegal, likely increasing the volume of waste to be processed within Australia. Consequently, all end-of-life panels in Australia will need to be recycled or reused locally, as landfill disposal and exporting will no longer be permissible options.

Drawing from international precedents, Europe's regulation of solar panels under the Waste Electrical and Electronic Equipment (WEEE) Directive, which specifies collection and recovery targets, offers a successful model. This regulatory framework has led to a transparent and efficient recycling process, with detailed disclosure of material recovery information at accredited facilities. Such transparency is crucial for effectively monitoring waste flows and the recycling rate of waste solar panels, highlighting the importance of regulatory oversight in ensuring the accountability and sustainability of waste management practices.

We propose that only organisations that can offer traceability should receive this fee. This is to ensure the production of high-quality recycled materials and to identify valuable outlets, thereby maximizing the benefits to the local economy.

6. A CASE STUDY FOR PV WASTE MANAGEMENT IN ACT

In August 2023, the ACT Government released the ACT Circular Economy Strategy and Action Plan 2023-2030 which identifies emerging and problematic waste as a key focus area for the circular economy in the ACT. This section will focus on the ACT and CRJO (Canberra Region Joint Organisation) and provide recommendations for effective PV waste management in this region over the next decade. CRJO is a collective of local governments located in South-Eastern NSW and surrounds the ACT (Figure 30).

6.1. Waste volume

Figure 31 shows the projected annual solar panel waste generation in CRJO councils to 2035. ACT is anticipated to have the highest amount of solar panel waste, surpassing the combined waste generated by all other councils. The waste is estimated to increase from around 500 to 1,000 tonnes per year between 2025 and 2030, where the majority of the waste stream consists of panels from small-scale systems, accounting for over 80%. However, both ACT and CRJO's waste contribution remains relatively small compared to NSW, constituting approximately 10% of the total waste in ACT and NSW.

Figure 30
CRJO Membership Boundary Map and annual solar panel waste generation (tonnes).

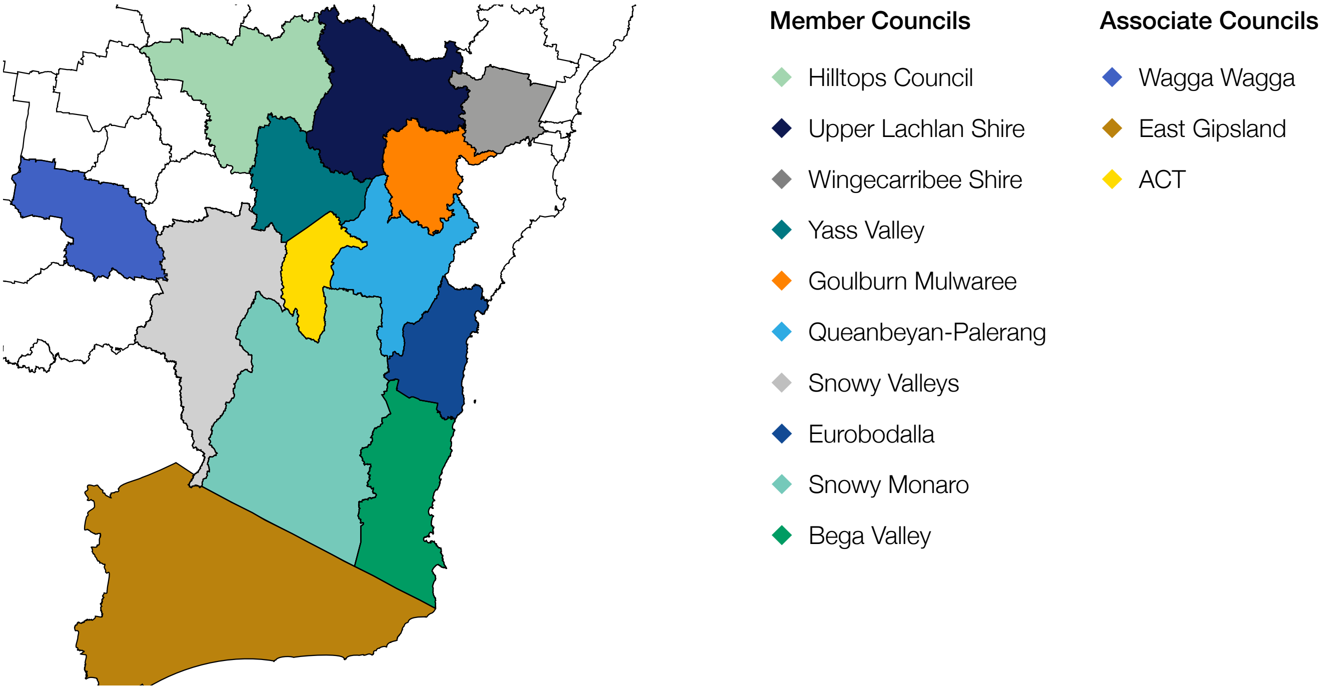
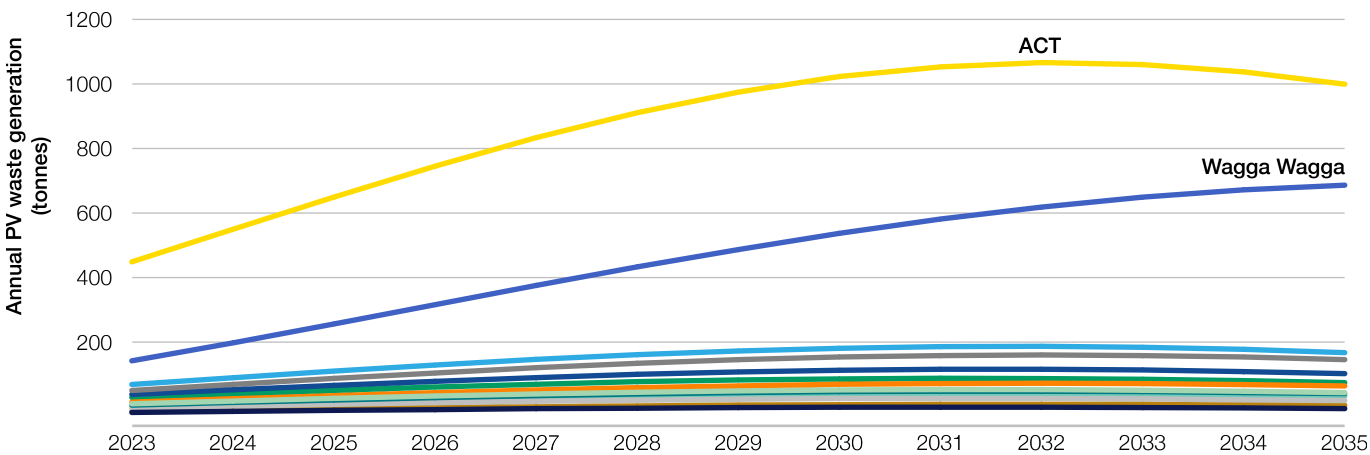


Figure 31
Annual solar panel waste generation in ACT and CRJO councils. (tonnes).



6.2. Setting up PV waste management facility in ACT

Three scenarios were established with insights from ACT NoWaste:

Scenario 1: Facility set up in ACT, receiving all waste panels generated within CRJO.

Scenario 2: Facility set up in the ACT, receiving waste panels from ACT and nearby NSW councils.

Scenario 3: Facility set up in the ACT, receiving panels from ACT, NSW, QLD, VIC and SA.

Using the same methodology described in Section 3, we modelled scenario 2 and 3 by pre-selecting ACT as one location and then run the model to determine other locations and associated transportation network.

Under the ACT's Waste to Energy Policy[55], the thermal treatment of waste including, incineration, gasification and pyrolysis will not be permitted in the ACT. New facilities, proposing thermal treatment of waste, by means of incineration, gasification, pyrolysis or variations of these for energy recovery, chemical transformation, volume reduction or destruction will not be permitted in the ACT. Therefore, we only modelled delamination only recycling technology (option 1) and reuse (option 4) in ACT.

The three scenarios were compared to the optimal logistic solution identified in Section 3, which suggested that the waste solar panels generated in ACT should be transported to Sydney facility for central treatment.

Scenario 1

When only considering waste arising from CRJO, the optimal solution is to establish one centralised waste management facility in ACT. This facility would collect waste from all 13 councils within the CRJO, with an average travel distance of 170km. The annual waste volume is projected to increase from approximately 1,200 tonnes in 2023 to 2,600 tonnes in 2029 and 2,700 tonnes in 2035. As a result, the associated transportation costs for waste will also rise from $13,000 to $30,000 in 2029, and $34,000 in 2035, respectively.

Figure 32
Map showing Scenario 1 and 2 optimisations. Scenario 1 has 13 origins and 97 candidate plants. Scenario 2 has 130 origins and 215 candidate plants. The origins and candidates in Scenario 3 are the same as Figure 10 and not shown here.

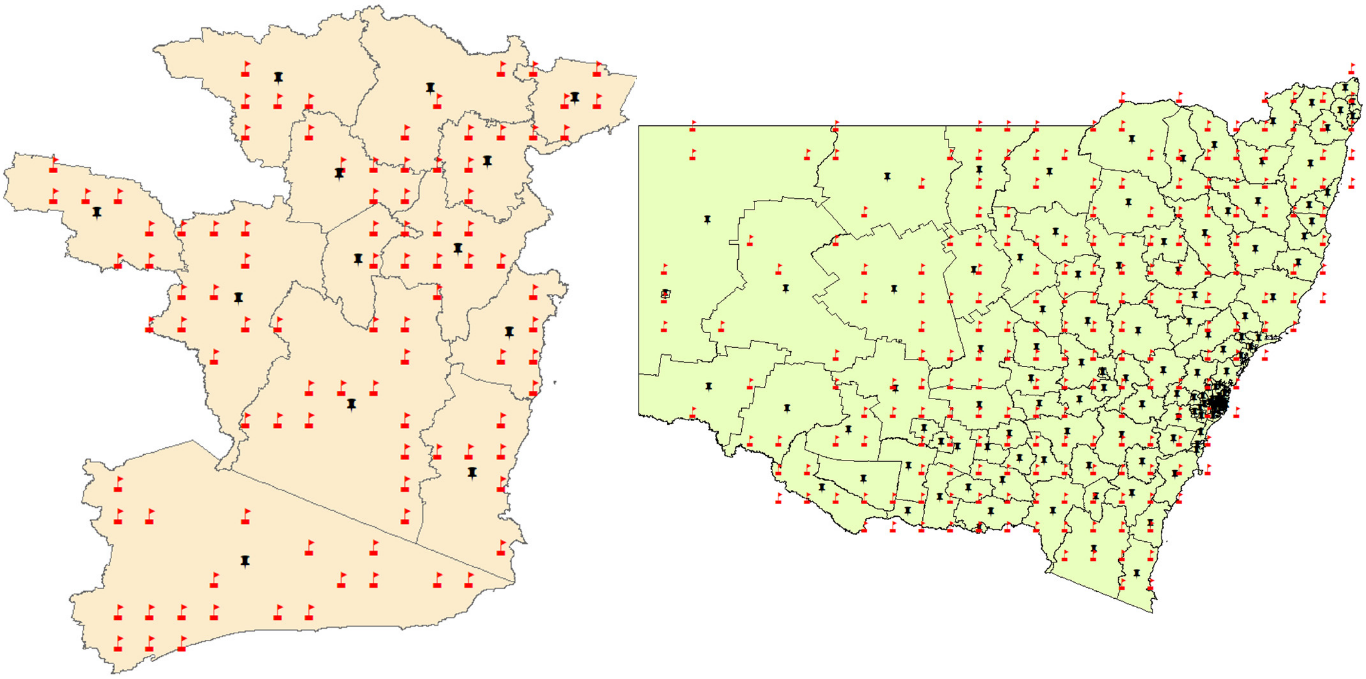
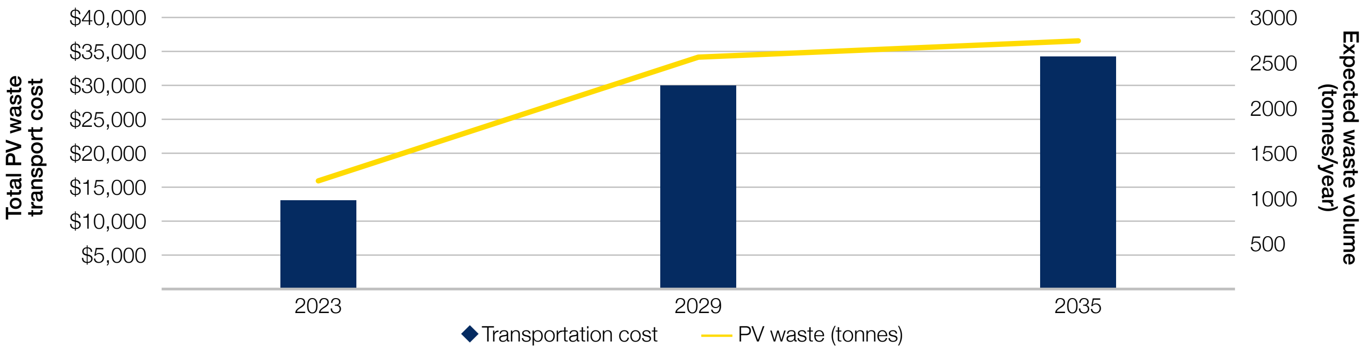


Figure 33
Total transportation cost and expected waste volume when all solar panel waste from CRJOs is treated in ACT.



Scenario 2

When considering waste arising from receiving panels from ACT and NSW, 5 optimal locations were identified, shown in Table 10. In this case, ACT will collect panels from 11 neighbouring councils: ACT, Bega Valley, Cootamundra-Gundagai Regional, Eurobodalla, Goulburn Mulwaree, Hilltops, Queanbeyan-Palerang Regional, Snowy Monaro Regional, Snowy Valleys, Upper Lachlan Shire, and Yass Valley. The average travel distance is 185 km from neighbouring councils the proposed facility in ACT. Similar to Scenario 1, the ACT facility is expected to receive approximately 1,000 tonnes/year waste solar panels starting in 2023, then double to approximately 2,000 tonnes per year in 2030-2035.

Scenario 3

When considering location set up in the ACT, receiving panels from ACT and NSW, 10 optimal locations were identified, shown in Table 11. In this case, ACT will collect panels from 21 neighbouring LGAs: ACT, Bega Valley, Coolamon, Cootamundra-Gundagai Regional, Eurobodalla, Goulburn Mulwaree, Hilltops, Junee, Kiama, Oberon, Queanbeyan-Palerang Regional, Shellharbour, Shoalhaven, Snowy Monaro Regional, Snowy Valleys, Temora, Upper Lachlan Shire, Wagga Wagga, Wingecarribee, Yass Valley, Towong. Similar to Scenario 1, the ACT facility is expected to receive approx. 1,000 tonnes/year waste solar panels starting in 2023, then double to approx. 2,000 tonnes per year in 2030-2035.

Optimal scenario

Under the optimal logistic network arrangement in Section 3, all PV waste generated in ACT should be sent to Sydney for centralised treatment.

Table 10
Optimal 5 locations to establish PV waste management facilities in NSW, including ACT, and the expected treated volume.

Location	Expected waste volume (tonnes per year)		
	2023	2029	2035
Sydney	5,440	11,542	11,708
Murrumbidgee	1,903	5,379	7,330
Dubbo	1,758	4,464	5,762
Tweed	1,296	2,486	2,383
ACT	1,004	1,888	1,873

Table 11
Optimal 10 locations to establish PV waste management facilities in Eastern Australia, including ACT, and the expected treated volume.

Location	Expected waste volume (tonnes per year)		
	2023	2029	2035
Melbourne, VIC	6,059	12,221	11,965
Brisbane, QLD	5,857	10,547	7,388
Sydney, NSW	5,045	10,102	11,232
Adelaide, SA	4,736	8,699	8,362
Townsville, QLD	2,393	5,961	6,687
Gympie, QLD	2,198	5,705	4,296
Murrumbidgee, NSW	1,886	6,717	6,906
Western Downs, QLD	1,624	4,500	6,143
ACT	1,589	3,558	3,941
Dubbo, NSW	1,347	3,534	3,726

6.3. Cost for ACT to establish PV waste management facility

For all three scenarios, **in 2023,** the waste volume at the ACT facility would be significantly lower than 2,500 tonnes/year, the minimum economic feasible scale, **and would not be recommended**. By 2029, projections indicate that the ACT facility would handle varying volumes of PV waste under three different scenarios: 2,500 tonnes, 2,000 tonnes, and 3,500 tonnes annually. This adaptation involves establishing facilities with capacities aligned to these volumes, requiring land sizes between 1,200 to 1,500 m² and employing between 13 to 16 direct labours.

Figure 34 shows PV waste generated in ACT will contribute to 38%, 52%, and 28% of the total treated volume at the ACT facility in the three proposed scenarios, with the remainder coming from neighbouring councils. Although the per-panel recycling cost for all three scenarios is higher than the optimal scenario, the revenue generated from material sales can nearly cover all expenses. This indicates that while the facility in the ACT may operate at a higher cost compared to sending the waste to Sydney, there is still potential for the facility to make a profit by selling all the recovered materials, ensuring the sustainability of the business.

However, the realisation of abovementioned scenarios relies on two crucial factors:

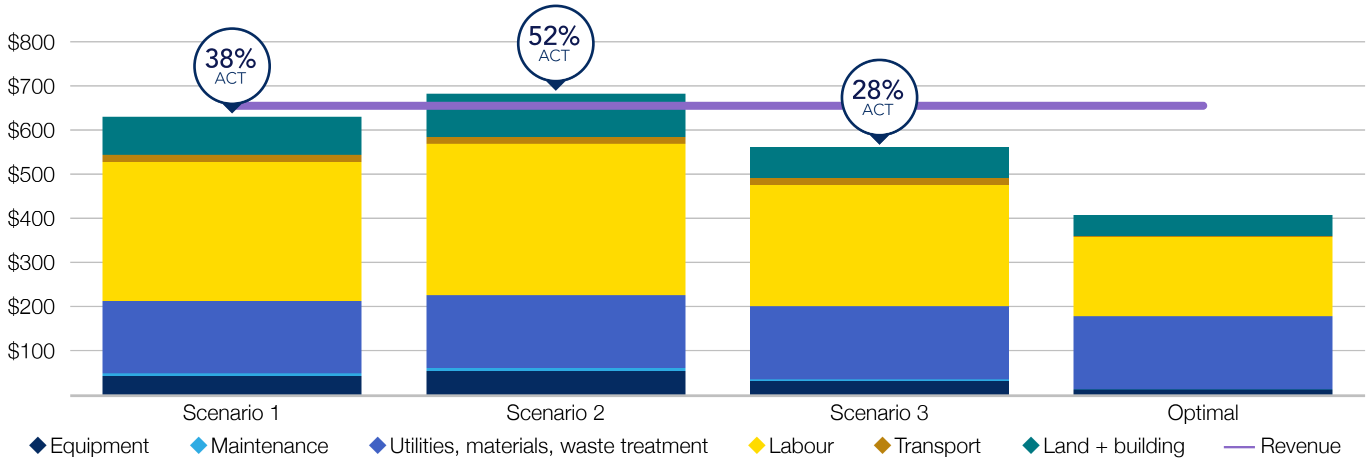
1. The incoming waste must reach the anticipated volume, which is heavily contingent on the collection rate and access issues in regional areas. It is essential to highlight that the optimisation of the logistic network assumes a 100% waste collection rate, as discussed in Section 3.
2. A market must exist for the sale of recycled materials such as aluminium, copper cables, a mixture of valuables (silicon, copper, silver, plastic), and solar panel glass.

The establishment of these two factors presents an opportunity for local job creation and economic growth within the ACT. Nevertheless, businesses may encounter challenges in maintaining marginal profitability. To support and facilitate PV waste management in the ACT, the local government can provide financial assistance through various means, including:

- Capitalising on opportunities for job creation and economic growth.
- Implementing a gate fee system, where recycling facilities are paid per tonne of recycled panels.
- Taking the lead in panel collection and transportation to relieve the burden on recyclers.
- Offering discounted land and building options to encourage the development of local waste management solutions.

Regarding the establishment of a dedicated reuse facility for the three proposed scenarios, the unit cost per tonne is estimated to be between $250 and $300. However, the reuse facility would also need to consider the two crucial factors and technical challenges as discussed earlier. ACT would require a compelling incentive now to establish such a facility, as the current market, economics, and technology are not favourable. The feasibility of establishing a reuse facility in ACT relies heavily on policy factors, such as robust subsidies, to make it a viable option.

Figure 34
Cost breakdown for PV waste treatment facility in ACT in 2029, compared to sending PV waste in ACT to Sydney for treatment[7].



7 In the optimal scenario, all waste generated in ACT will be sent to Sydney for treatment, incurring a transportation fee of $18 per tonne (assuming a 280 km distance between ACT and Sydney). This scenario considers only waste generated inside ACT, which results in a lower overall transportation cost compared to scenarios 1, 2, and 3.

6.4. Final recommendations

Therefore, in addition to participating in the national product stewardship as outline in its 2022 Circular Economy Strategy, we recommend ACT:

In the next 6 years:

1. Re-direct waste panels to nearby PV recycling facilities, e.g. Sydney.
2. Pending the outcome of the development of a national regulated product stewardship scheme for solar panels, and once its parameters are known:
   a. Establish logistic networks. This includes setting up collection points, and educating (even incentivising) system owners, solar farm operators, and electricians, to drop off end-of-life panels at dedicated collection points.
   b. Act to improve the collection rate in regional and remote councils around Canberra, because they will contribute to more than 50% of the incoming waste volume if ACT had its own PV waste management facility.
3. Encourage industrial solutions that repurpose recycled solar panels materials into local products or those in nearby states. The primary focus should be on the glass, accounting for 70% of a panel's wright. This can potentially attract PV recycling businesses to ACT.

In the next 6-12 years:

1. Consider launching a mid-scale recycling/reuse facility for PV waste in ACT and surrounding councils. This would entail a $1.2 million investment and could generate 13-16 jobs. Efficiency can be boosted by leveraging insights from PV recycling centres developed in major cities over the first 6 years.
   a. If ACT lacks a PV recycling facility and aims to attract businesses, the local government could consider offering infrastructure grants or other forms of support to attract businesses. Such incentives would encourage the development of innovative recycling solutions within the territory.
   b. If several facilities already exist in CRJOs by this time, an additional facility might lead to operational inefficiencies due to increased competition and split waste volumes.

7. A 12-YEAR ROADMAP TO ACHIEVE A PV CIRCULAR ECONOMY IN AUSTRALIA

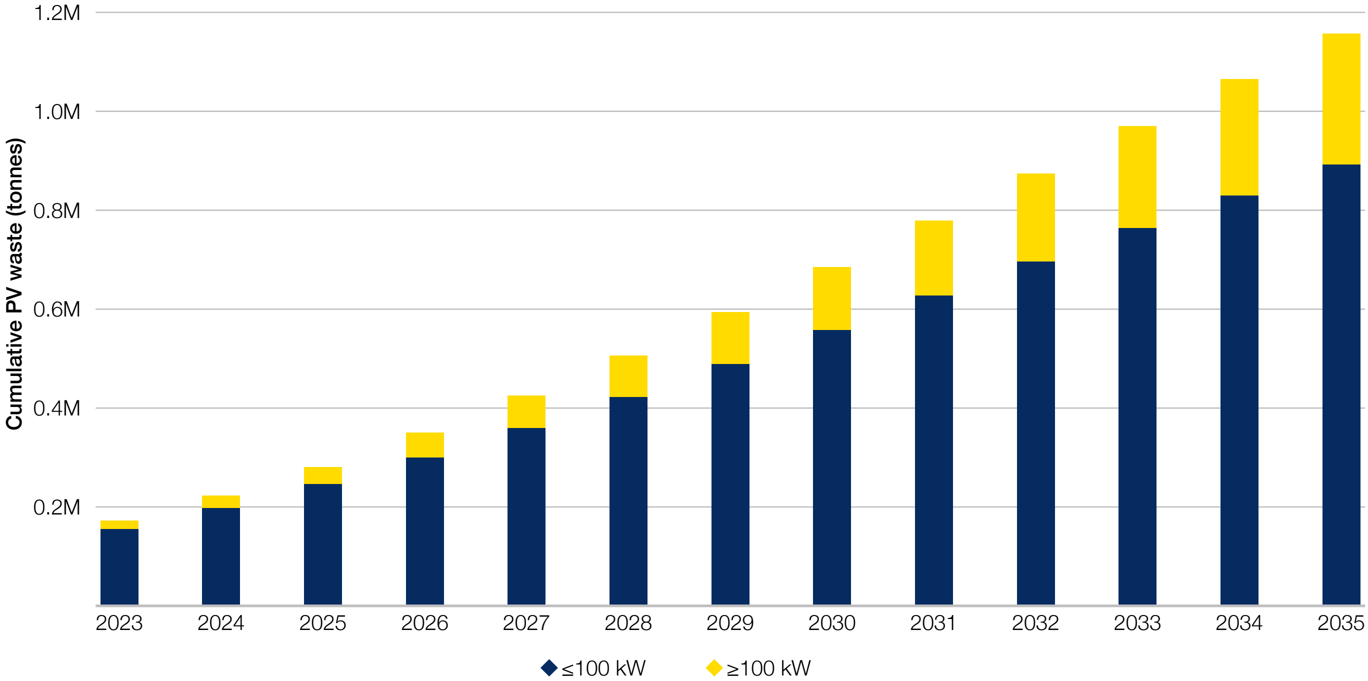
End-of-life management is crucial for the sustainability of the solar industry. This report has provided a clear perspective on some vital questions:

What is the volume of end-of-life panels in Australia?

The trajectory for PV waste generation in Australia is evident. The cumulative volume of end-of-life solar panels is projected to reach 280,000 tonnes by 2025, 680,000 tonnes by 2030, and a significant milestone of 1 million tonnes between 2034 and 2035. On an annual scale, waste volume is expected to surpass 50,000 tonnes in 2025 and could reach approximately 100,000 tonnes, equivalent to 1.2 GW per year, from 2030 to 2035 nationwide. Significantly, more than 80% of the decommissioned solar panels by 2030 are projected to emanate from small-scale distributed PV systems, attributable to the earlier evolution of Australia's residential PV market.

Figure 35

Projected cumulative PV waste in tonnes in Australia from 2022 to 2035, comparison between small (<=100kW) and large-scale (>100kW) systems.

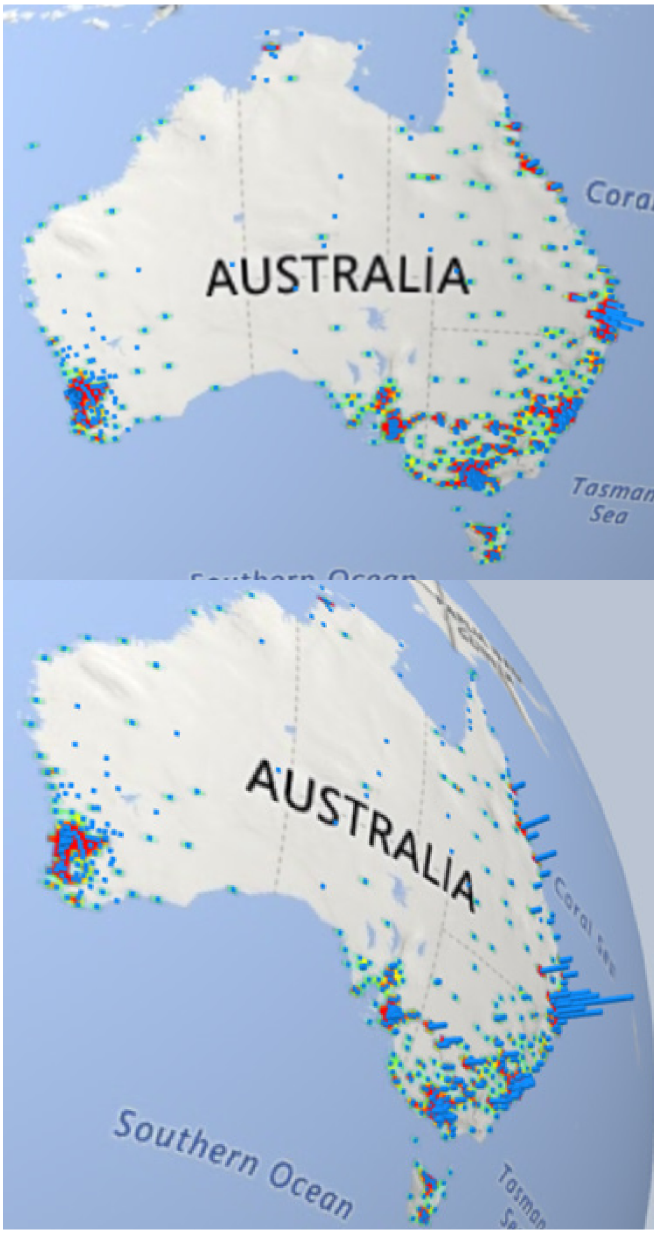


Year	Small scale (thousands of tonnes)	Large scale (thousands of tonnes)
2023	156	17
2024	198	26
2025	246	37
2026	300	50
2027	359	66
2028	423	84
2029	489	104
2030	558	127
2031	627	152
2032	696	178
2033	764	206
2034	820	235
2035	892	265

When and where will the issue of waste start to escalate?

This study reveals that the challenge of managing PV waste is more immediate than previously anticipated, with waste volumes emerging within the next 2 to 3 years, particularly in New South Wales, Victoria, and Queensland. This finding contradicts earlier forecasts, which predicted significant volumes of PV waste would not appear until post-2030. Initially, the majority of waste solar panels are expected to concentrate in major Australian cities—Sydney, Melbourne, Brisbane, Perth, and Adelaide. Following this period, from 2030 onwards, the PV waste volumes is anticipated to grow faster in regional and remote areas as large-scale PV systems reach the mid or end of their lifecycle.

Figure 36
3D bar maps showing cumulative PV waste (in tonnes) generated in each LGA in 2030. The height of the blue bar indicates the expected volume, and the red region indicates a centralized area with a high waste volume. If there is no blue bar, it means there will be low or negligible waste solar panels in that area by 2030. The 3D map was rotated to facilitate a better visualisation of the waste volume.



Based on waste projections, a three-tiered classification emerges:

Class 1: current high waste areas, where PV waste is the highest in the country, which requires immediate action.

Class 2: emerging high waste areas, where annual PV waste generation will grow rapidly between 2025 to 2030, which requires infrastructure planning now.

Class 3: future high waste areas, where annual PV waste will grow between 2030 to 2035, which requires long-term planning.

Table 12
High PV waste areas in Australia.

Class 1	Class 2	Class 3
Sydney, NSW	Murrumbidgee, NSW	Canberra, ACT
Brisbane, QLD	Balranald, NSW	Toowoomba, QLD
Gold Coast, QLD	Dubbo, NSW	
Moreton Bay, QLD	Newcastle, NSW	
Adelaide, SA	Whitsunday, QLD	
Melbourne, VIC	Townsville, QLD	
Perth, WA	Sunshine Coast, QLD	
	Western Downs, QLD	
	Mildura, VIC	

Where should large-scale PV waste management facilities ideally be located to best handle the anticipated waste volumes?

Strategic placement of large-scale PV waste management facilities near high waste volume regions is vital to minimize logistical costs and ensure a steady inflow of waste. The designated locations and the corresponding waste volumes that optimize logistical cost-efficiency are shown in Table 13. The sites in major cities are projected to access 5,000 – 10,000 tonnes of waste panels per year now and the volume will double in the next 6 years. The sites in regional and remote Australia are projected to access 1,000 – 3,000 tonnes waste panels per year now. An accompanying map shows each site's coverage area.

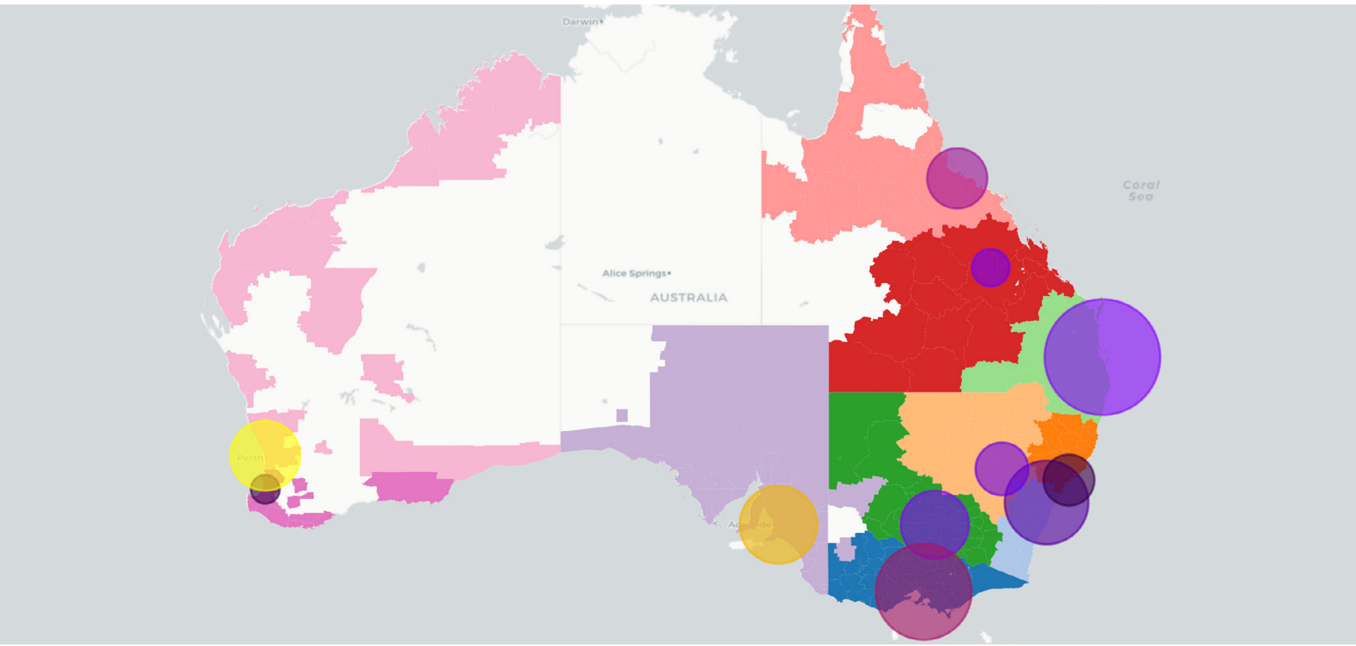
Metropolitan facilities are expected to manage over 70% of Australia's solar panel waste, primarily from end-of-life rooftop systems. Each of these potential sites can access sufficient waste volume within its 150km radius.

To complement metropolitan facilities, additional sites in Dubbo/Wellington, Townsville, Newcastle, Murrumbidgee, Central Highlands and Busselton can provide comprehensive national coverage. Other favourable regional/remote locations are Ingham, Gympie Shire, Tweed Shire, Western Downs and Balranald.

Table 13
The optimal locations to establish large-scale solar panel waste treatment facilities in Australia and expected treatment volume. Expected waste volumes are rounded to the nearest thousand, or to the nearest 500 if under 3,000.

Location	Expected waste volume (tonnes per year)		
	2023	2029	2035
Brisbane, Queensland	10,000	20,000	20,000
Melbourne, Victoria	7,000	14,000	14,000
Sydney/Penrith, New South Wales	5,000	10,000	11,000
Adelaide/Adelaide Hills, South Australia	5,000	9,000	9,000
Perth, Western Australia	3,500	7,000	7,000
Dubbo/Wellington, New South Wales	2,500	7,000	9,000
Townsville, Queensland	2,000	5,000	5,000
Newcastle, New South Wales	2,000	4,000	5,000
Murrumbidgee, New South Wales	1,500	4,000	4,000
Central Highlands, Queensland	1,500	2,000	2,500
Busselton, Western Australia	1,000	1,000	1,000

Figure 37
The location of these optimal sites and areas that each site will cover. Blank area on the map indicates the annual waste generation in the LGA is less than 5 tonnes/year. The size of the circle corresponds to the expected waste volume; bigger circles indicate higher projected annual treatment volume. The coloured zones around each circle delineate the LGAs allocated to transport their solar panel waste to the nearest centre, optimizing for logistical efficiency.



Are solar panels recyclable? Reusable?

Solar panels are made of materials like aluminium, glass, silicon, silver, and copper, and they can be recycled when they reach the end of their life. Therefore, panels should be viewed as valuable resources rather than waste. On average, over $20 worth of materials can be recycled from a typical 20-kg solar panel. By addressing current technical challenges in solar panel recycling, Australia can potentially unlock a cumulative material value of $1 billion by 2035.

In Australia, the recycling of solar panels is approached through two primary methods: (1) mechanical delamination, a process that separates the panels into bulk materials; the fractions containing valuable materials are then forwarded to existing material recovery facilities for further processing. (2) Dedicated full material recovery facilities focus exclusively on recycling solar panels through comprehensive processes designed specifically for this purpose, aiming for higher recycling rates and revenue. Both methods will have to meet the 80% material recovery rate under the National Waste Policy. The first method has already been implemented in Australia; the second method will be developed in the future.

The cost of recycling solar panels currently ranges from $500 and $1,000 per tonne, covering transportation and before accounting for the revenue from sold materials. This estimate assumes that the recycling facilities handle approximately 5,000 tonnes of panels each year. The major expenses in the recycling process are the capital expenditures required for facility setup and the ongoing labour costs.

The recycling sector faces significant challenges: (1) Finding markets for recycled solar panel materials, especially glass (70% of panel weight), is challenging. Currently they are mainly used as a sand substitute in construction materials because Australia does not have solar manufacturing industry that would make use of the recycled glass. The challenge extends beyond glass, as the highly mixed nature of the components and fine particle size make it challenging to find markets for their use. (2) There is also a lack of specialized recovery solutions for the solar panel laminate. Given these challenges, alongside the high costs of recycling and a limited market for the recycled materials, there is a pressing need for more innovative recycling solutions in Australia. These solutions should aim to efficiently reclaim all materials from solar panels at lower costs, addressing the existing gaps in the process.

Given that early decommissioned panels from rooftop systems are expected to dominate the Australian PV end-of-life market in the coming decade, a significant portion of these panels are likely to still be functional and suitable for repurposing elsewhere. The cost of panel reuse testing is $130 - $380 per tonne, or $6 – 20 per panel including manual handling and transportation. After testing, reused panels might need to be re-certified and transported to customers, and the cost varies depending on the application. Although reuse is more desirable in the waste management hierarchy, second-life old panels pose safety concerns under the current AS/NZS 5033 solar standard, restricting their reuse in grid-connected systems. Reuse testing and assurance procedures are necessary to establish domestic panel reuse market.

The following case study underscores Veolia's PV recycling efforts in France and Germany, demonstrating that a solution can only be developed by gathering all the stakeholders from the value chain.

Case study: Solar Panel End-of-life Recovery by Veolia

Veolia is positioned across 10 geographical zones globally with experience in developing the collection logistic, separation and processing, and valorisation of waste electronic and electrical equipment.

The recommended activities to fully recycle or recover all valuable materials from Photovoltaic equipment and solar panels consist of:

- Re-use of panels or refurbishment of damaged panels for second life use with suitable applications.
- Recycling and creating loops of secondary raw materials at different stages:
  - Step 1 - Base Dismantling: basic removal of aluminium frame.
  - Step 2 - Base Delamination: separate the glass from the solar cells.
  - Step 3 - Complex Separation: separate silicon (Si) and silver (Ag) from the solar cells.
  - Step 4 - Material Specific Refining: advanced refinery of Si and Ag, and potential other materials.

Veolia France - Rousset (Bouches du Rhône)

Veolia France worked with centralised eco-organisation Soren (ex-PV CYCLE France) to process and recover crystalline silicon as well as other components (aluminium, copper, glass…) from solar panels.

Strong focus on optimising the carbon footprint of the whole process on top of the recovery of materials: energy recovery, optimisation of logistics with the choice of location in the South of France.

- First in Europe.
- 5,000 tonnes per year capacity.
- 95% recovery rate.

Veolia Germany

Veolia Germany developed a highly efficient and special process for the recycling of end-of-life photovoltaic (PV) modules - in final development stage.

Together with partner companies from the public and private sector operating along the PV module recycling chain, all PV module components are completely separated for the first time. This way, pure silicon, silver and glass, among other things, can be made available to the manufacturing industry again. Around 5,000 tonnes of disused PV modules are to be processed in the demonstration plant and the pilot will run until the end of January 2025.

Veolia has learnt from this experience that **the main conditions for solar panel recycling activity to be commercially viable are:**

- National or geography-based schemes in place to ensure sufficient volume for viable collection and processing to work financially.
- Incentives on recycling and recovery or restrictions on disposal to landfill to ensure the recycling and recovery alternative are viable.
- Understanding the variability in panel types in Australia as it impacts both logistics and recycling process (manual handling required, specific care needed for decommissioning and transport required for re-use, variability in materials and polymers used are impacting the process and commodities management, etc).

What is the regulatory landscape in Australia?

The Australian Department of Climate Change, Energy, the Environment, and Water is leading the product stewardship for PV systems, to be implemented by the end of 2025. This national scheme mandates producers, including manufacturers, importers, and all parties introducing solar panels to the Australian market, to take responsibility for the end-of-life management of these panels. Key aspects of the scheme include establishing recycling benchmarks, enforcing material traceability, and setting criteria for recyclers. Financial responsibility for managing waste will transition from owners of small-scale systems to manufacturers, while owners of large-scale PV systems (over 100kW) have the option to bear the end-of-life liability themselves.

The Basel Convention was established to control international movements of hazardous waste and other wastes so that they are disposed of, or recycled, in a way that protects human health and the environment. An anticipated amendment to the Basel Convention will regulate the cross-border movement of solar panels, expected to come into effect in 2025. This amendment aims to manage solar panel waste domestically by making exporting such waste illegal, likely increasing the volume of waste to be processed within Australia. Consequently, all end-of-life panels in Australia will need to be recycled or reused locally, as landfill disposal and exporting will no longer be permissible options. To support this directive, an upfront fee will be imposed on manufacturers to subsidize accredited recyclers for processing end-of-life panels.

To bridge the cost gap in recycling, relying solely on subsidies is not recommended. The end-of-life industry is encouraged to proactively design efficient waste collection networks, leveraging economies of scale to reduce recycling costs and foster a sustainable business model.

Drawing from international precedents, Europe's regulation of solar panels under the Waste Electrical and Electronic Equipment (WEEE) Directive, which specifies collection and recovery targets, offers a successful model. This regulatory framework has led to a transparent and efficient recycling process, with detailed disclosure of material recovery information at accredited facilities. Such transparency is crucial for effectively monitoring waste flows and the recycling rate of waste solar panels, highlighting the importance of regulatory oversight in ensuring the accountability and sustainability of waste management practices.

What are the opportunities for addressing the emerging issue of EoL panels in Australia?

In understanding the market, industry landscape, and government plans, we can pinpoint essential competencies needed to realise a circular economy for photovoltaics, as well as resource management frameworks required to make it happen.

Table 14
Summary of current challenges and actions that would help establish a sustainable PV end-of-life industry in Australia:

Current barriers in Australia	Why do these barriers exist?	Recommendations to address barriers	How can these recommendations be implemented?
Lack of large-scale technical capability	Recycling PV modules in Australia is straightforward for aluminium frames and junction boxes, but challenging and expensive for materials like glass, silicon, and silver due to lack of advanced recycling technology. Current methods involve manual frame removal and shredding, limiting high-purity recovery. Developing dedicated PV recycling technology remains ongoing in the country as current methods rely on e-waste standards.	Develop technical capabilities and equipment specifically for PV recycling.	An efficient PV recycling approach yields over 95% recycling rates, recovering key materials for PV reuse rather than other sectors. Achieving this involves mechanical, chemical, thermal, or electrostatic separation. Supporting existing Australian PV recyclers and adopting global best practices can enhance material purity and recovery.
Lack of end-markets	Finding markets for recycled solar panel materials, especially glass (70% of panel weight), is challenging. Currently they are mainly used as a sand substitute in construction materials because Australia does not have solar manufacturing industry that would make use of the recycled glass. The challenge extends beyond glass, as the highly mixed nature of the components makes it challenging to find markets for their use. Finding a suitable domestic market for reused panels is also challenging because of their safety and performance concerns.	Collaborate with stakeholders across the value chain to foster the development of new products that integrate recycled materials. Establish robust standards and procedures for panel reuse.	Facilitate stakeholder collaboration to identify and develop domestic material reuse opportunities. Implementing a comprehensive approach for glass recovery, including improved sorting and cleaning processes to reduce contamination and maintain material value, is essential. This also involves adopting innovative methods to repurpose finely broken glass and finding alternative uses for mixed materials to achieve higher recycling rates and landfill diversion.
High cost	At present high recycling expenses hinder PV recycling. Consumers find landfilling cheaper than recycling (i.e., $2/panel to landfill compared to $10-20/panel to recycle). Recyclers face slim margins due to intricate technology, insufficient material returns to offset costs, especially when operating at a small scale.	Provide government funding and grants into R&D / medium scale demonstration pilot	Research into improving recycling processes and recovering materials at a higher purity is critical, so they are suitable to be re-used. For example, UNSW achieved 99% solar cell separation, while Deakin University has developed a highly valuable chemical-free nano silicon extraction. Commercializing, scaling, and government support is becoming more essential. Growing PV recycling demand boosts recyclers' profits, and subsidies could encourage consumer participation.

Current barriers in Australia	Why do these barriers exist?	Recommendations to address barriers	How can these recommendations be implemented?
Lack of enforcement	Currently, PV recycling is not mandated on a federal level, and only Victoria has banned PV panels from being landfilled. There are little incentives for both consumers and PV recyclers, and the environmental consequences of the growing PV waste problem are not reflected in the government's current regulations.	Mandate recycling and place more responsibility on manufacturers	It is essential to establish a product stewardship program for federal recycling mandates or higher landfilling penalizations for PV panels. Following Europe's success, manufacturers should bear responsibility for end-of-life collection and recycling of their products. This might raise initial costs but offers an efficient way to handle PV waste.
Logistical challenges	Given the size of Australia, it is a challenge to coordinate PV recycling at a nationwide scale. This includes utility scale solar farms in regional and remote areas. Coordinating collection points and recycling facilities to take into account the widespread distribution of panels across the country will be a significant barrier.	Develop a streamlined network between manufacturers, consumers and recyclers	Strategies regarding logistics could be addressed through the proposed product stewardship scheme that is currently under consultation. It would be beneficial to set up dedicated disposal/collection sites across the country to account for recycling of rooftop solar panels. For regional and remote solar farms, system owners should create a decommissioning plan, which factors in the most efficient way to recycle decommissioned panels in bulk. Additionally, placing some responsibility with local manufacturers (if established) could help to coordinate a streamlined process.

Industry roadmap - Actions to foster a circular economy for the photovoltaic industry in Australia over the next 12 years.

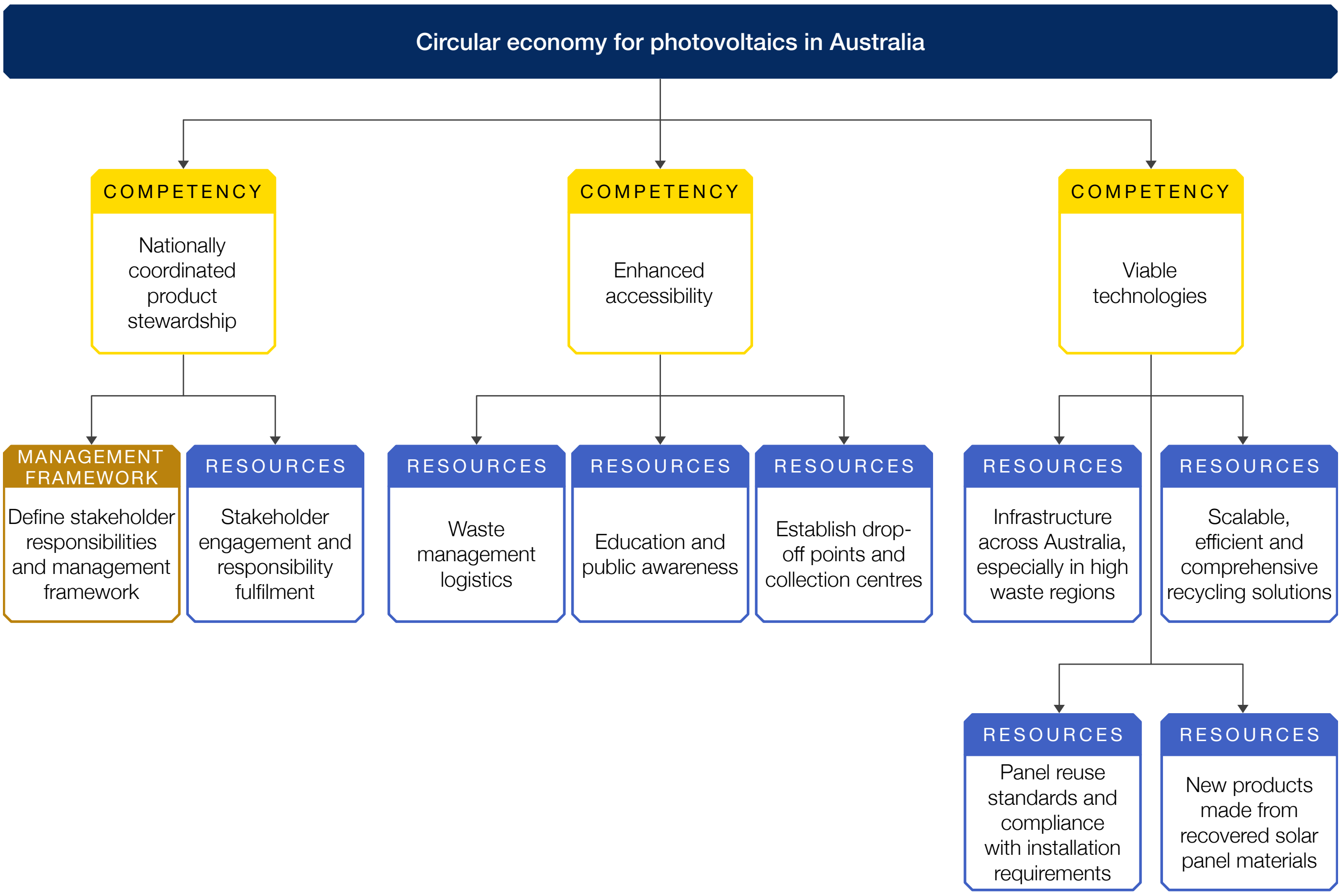
While this study does not prescribe a policy framework, it outlines a 12-year roadmap for the PV and waste industries in Australia. The objective is to address the end-of-life challenges of solar panels and transform them into sustainable business opportunities with positive economic, environmental and social outcomes.

Drawing inspiration from the EU's success in PV waste management, commercial viability can be achieved with the right mix of technology, business models, and regulatory supporting. Figure 38 shows proposed actions for Australia.

A nationally coordinated program of product stewardship serves as the overarching management framework. This comprehensive scheme should define management structures and stakeholder responsibilities, ensuring clarity and accountability throughout the industry. It should set definitive targets for performance measurement, reporting, and traceability, particularly within the waste management sector, while also outlining the roles of producers and owners of large-scale systems. The scheme design should also offer guidance on logistic management responsibilities, specifying whether responsibilities lie with recyclers, local councils, or a designated coordinator. By establishing clear lines of accountability, it encourages all participants in the value chain to actively engage and contribute. Large-scale system owners are encouraged to proactively plan end-of-life management for their existing systems, potentially outside of the scheme's scope. Ultimately, fostering a circular economy requires a collective commitment from all involved.

- Action 1: The national product stewardship scheme should define management structures and stakeholder responsibilities, ensuring clarity and accountability throughout the industry.
- Action 2: Stakeholders should engage in the national product stewardship scheme and ensure responsibilities are met throughout the industry.

Figure 38
Actions to foster a circular economy for the photovoltaic industry over the next 12 years.



Enhanced accessibility is pivotal in achieving high collection and recycling rates. Councils, local governments should be instrumental in setting up drop-off points and raise public awareness. This might include contracting nearby accredited recycling facilities to handle locally generated PV waste. Waste management companies can harness their existing waste collection networks and experience in management and compliance to foster a highly efficient waste collection system. As identified earlier, high collection rates and processing volumes can significantly reduce the cost of recycling, thus enhancing the sustainability of this business sector.

- Action 3: Raise public awareness by creating and distributing informative resources on PV sustainability and end-of-life options for consumers, installers, and industry stakeholders, aiming to reduce premature replacements and divert waste in landfills.
- Action 4: Pending the detailed outcomes of product stewardship (i.e. the condition to become a drop off point), initiate nation-wide drop-off points and collection centres in high solar panel waste regions (Figure 36), leveraging and subsidising existing resources at PV distribution centres, warehouses, and local council large equipment pick-off & drop-off services.
- Action 5: Optimise waste logistics by creating a streamlined network to transport waste efficiently and develop a comprehensive waste tracking and monitoring system.

Innovative technologies are vital for enhancing domestic solar panel waste management capability. There is a need for a coherent, nationwide infrastructure system for collecting and recycling solar panels. This involves establishing multiple recycling centres especially in high-waste areas to reduce logistic cost and advancing scalable, efficient, and comprehensive recycling solutions through continuous R&D and industry collaboration. Improvements in how panels are delaminated, or in how materials like copper, silver, and silicon are separated and recovered will enhance the cost-effectiveness. As these technologies mature and demand for recycling grows, the overall cost of recycling is expected to decrease, making the process more economically attractive. In addition, developing standards for panel reuse, which address performance and safety, is important for ensuring quality and building trust. Lastly, creating new products from recovered materials, such as new solar panels or silicon alloys and battery anodes, is key to a circular economy. Establishing a market for these materials adds value to recycling and encourages its adoption.

- Action 6: Invest in and develop full-recycling technologies tailored to Australia's recycling needs. While current recycling companies handle module delamination, a specialise entity focusing on PV laminate recovery could be beneficial, inspired by the French model.
- Action 7: Drive the circular economy by innovating products from recycled PV materials and explore revenue streams in other circular economy interventions such as reuse and repair.
- Action 8: Develop panel reuse standards. The photovoltaic industry should lead developing panel reuse standards and ensure the standards comply with current PV system installation requirements in Australia.
- Action 9: Establish large-scale (approx. 5000 tonnes/year) PV waste treatment facilities in Brisbane, Sydney, Melbourne, Adelaide, Perth now, with a 2–3-year operational target. These facilities will have access to more than 70% of the country's PV waste by 2030.
- Action 10: Expand PV waste management infrastructures into regional areas, prioritising the establishment of medium-scale facilities in high-waste regional areas.

Table 15
Summary of actions.

	Action	Who	Timeframe
1	The national product stewardship scheme should define management structures and stakeholder responsibilities, ensuring clarity and accountability throughout the industry.	DEECCW	Within the next 2 years
2	Engage in the national product stewardship scheme and ensure responsibilities are met throughout the industry.	All stakeholders.	2-5 years
3	Awareness training. Design and distribute educational materials to raise awareness on PV sustainability issues and end-of-life options for solar panels for consumers, installers, and industry stakeholders.	Local councils, governments, and environmental agencies, Home solar providers	Within the next 2 years
4	Initiate national-wide drop-off points and collection centres in high solar panel waste regions (pending on the outcome of product stewardship)	Local councils, governments, and environmental agencies	2-5 years
5	Optimise waste logistics by creating a streamlined network to transport waste efficiently and develop a comprehensive waste tracking and monitoring system	Waste management companies and logistic providers	5-10 years
6	Invest in and develop full-recycling technologies tailored to Australia's recycling needs.	Research institutes, tech developers and PV industry stakeholders	Ongoing
7	Drive the circular economy by innovating products from recycled PV materials and explore revenue streams in other circular economy interventions such as reuse and repair.	PV manufacturers, research institutes, circular economy innovators, solar panel recycling company	Ongoing
8	Develop panel reuse standards. The photovoltaic industry should lead developing panel reuse standards and ensure the standards comply with current PV system installation requirements in Australia.	PV industry consortiums, standard regulatory body, CEC	Within the next 3 years.
9	Establish large-scale (> 5000 tonnes/year) PV waste treatment facility in Brisbane, Sydney, Melbourne, Adelaide, Perth.	Solar panel recycling company with the support from governments, EPAs and product stewardship scheme	Within the next 3 years
10	Establish a few medium scale PV waste management facilities in regional Australia.	Solar panel recycling company with the support from local councils / governments, EPAs and product stewardship scheme	5-10 years

APPENDIX A

The objective function is as follows:

$$min \sum_t \sum_i \sum_j x_{i,j,t} c_{i,j} m_{i,t} \gamma + \sum_j y_{j,t^*} cost_j + \sum_j \sum_t y_{j,t} O + \sum_t \sum_i \sum_j x_{i,j,t} m_{i,t} \theta \quad (1)$$

The constraints are as follows:

$$\sum_j x_{i,j,t} = 1 \, \forall \, t,i \text{ when } m_{i,t} > 5 \quad (2)$$

$$\sum_j x_{i,j,t} = 0 \, \forall \, t,i \text{ when } m_{i,t} \leq 5 \quad (3)$$

$$Cap_l y_{j,t} \leq \sum_j x_{i,j,t} m_{i,t} \leq = Cap_u y_{j,t} \forall \, t,i \quad (4)$$

$$y_{j,t'} = 1 \text{ if } y_{j,t} = 1 \text{ where } t < t' \quad (5)$$

Here is the notation used in the model:

$c_{i,j}$	The travel cost when LGA i is assigned plant j
$m_{i,t}$	The solar panel waste of LGA i at time t
γ	The freight rate
Cap_u	The upper bound capacity of plant
O	The fixed operational cost per site
Cap_l	The lower bound capacity of plant
θ	The operational cost per tonne
$x_{i,j,t}$	Let $x_{t,i,j}$ =1 if LGA i is assigned plant j at time t, and 0 otherwise
$cost_j$	The capital cost of plant j
$y_{j,t}$	Let $y_{j,t}$ =1 if plant j is implemented at time t
t^*	The last year of the project

Equation 2 means the solar waste of LGA i will be assigned to one plant if the waste is larger than 5 tonnes at time t.

Equation 3 means the solar waste of LGA i will not be assigned to one plant if the waste is smaller than 5 tonnes at time t.

Equation 4 means the solar waste assigned to plant j is smaller than the upper capacity bound and larger than the lower capacity bound at time t.

Equation 5 means if the plant j is established at time then the plant j will always exist.

REFERENCES

[1] "2022 Integrated System Plan For the National Electricity Market," 2022.

[2] RJ Egan and L Koschier, "National Survey Report of PV Power Applications in AUSTRALIA," 2022. [Online]. Available: www.iea-pvps.org

[3] pv-map.apvi.org.au/historical, "Australian PV Institute ."

[4] Australian Bureau of Statistics, "Australian Bureau of Statistics." [Online]. Available: data.gov.au/data/dataset/asgs-geographic-correspondences-2016

[5] V. Tan, P. R. Dias, N. Chang, and R. Deng, "Estimating the Lifetime of Solar Photovoltaic Modules in Australia," *Sustainability (Switzerland)*, vol. 14, no. 9, May 2022, doi: 10.3390/su14095336.

[6] W. and the E. Department of Agriculture, "E-Product Stewardship in Australia Evidence Report," 2021.

[7] V. Forti, C. P. Balde, and R. Kuehr, *E-Waste Statistics Guidelines on Classification Reporting and Indicators*. 2018.

[8] V. Tan, P. R. Dias, N. Chang, and R. Deng, "Estimating the Lifetime of Solar Photovoltaic Modules in Australia," *Sustainability (Switzerland)*, vol. 14, no. 9, 2022, doi: 10.3390/su14095336.

[9] V. Tan, R. Deng, and R. Egan, "Solar Photovoltaic Waste and Resource Potential Projections in Australia, 2022-2050," *Resource, Recycling, Conservation* , 2023.

[10] Australian Government Department of Infrastructure and Regional Development, "Freight Rates in Australia."

[11] G. Boeing, "OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks," *Comput Environ Urban Syst*, vol. 65, pp. 126–139, Sep. 2017, doi: 10.1016/j.compenvurbsys.2017.05.004.

[12] J. A. Tsanakas *et al.*, "Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification," *Progress in Photovoltaics: Research and Applications*, no. June, pp. 1–11, 2019, doi: 10.1002/pip.3193.

[13] D. Mathur, R. Gregory, and T. Simmons, "End-of-Life Management of Solar PV Panels," 2020.

[14] K. Kemp *et al.*, "Innovative device for mechanical treatment of End of Life photovoltaic panels: Technical and environmental analysis," *Resour Conserv Recycl*, vol. 205, no. January 2019, pp. 697–702, 2019, doi: 10.1016/j.wasman.2019.06.037.

[15] "PV Industries." [Online]. Available: pvindustries.com.au

[16] "Reclaim PV Recyling." [Online]. Available: reclaimpv.com

[17] "scipher.com.au/servicesproducts/circular-solar"

[18] "wastemanagementreview.com.au/elecsome-brings-pv-upcycling-to-victoria"

[19] "lotusenergy.io/news-posts/lotus-energy-recycling-plant-opens"

[20] "srcorp.com.au"

[21] R. Deng, N. Chang, Z. Z. Ouyang, and C. M. C. M. Chong, "A techno-economic review of silicon photovoltaic module recycling," *Renewable and Sustainable Energy Reviews*, vol. 109, pp. 532–550, Jul. 2019, doi: 10.1016/j.rser.2019.04.020.

[22] R. Deng, Y. Zhuo, and Y. Shen, "Recent progress in silicon photovoltaic module recycling processes," *Resources, Conservation and Recycling*, vol. 187. Elsevier B.V., Dec. 01, 2022. doi: 10.1016/j.resconrec.2022.106612.

[23] J. Vanek, P. Maule, and K. Jandová, "Development of Recycling of Photovoltaic Systems from the Point of View of Prolonging the Total Service Life of Photovoltaic Modules and Circular Energetic," *ECS Trans*, vol. 99, no. 1, pp. 211–219, 2020, doi: 10.1149/09901.0211ecst.

[24] Sustainability Victoria, "PV Panel Reprocessing: Research into Silicon-Based Photovoltaic Cell Solar Panel Processing Methods, Viable Materials Recovery and Potential End Market Applications," 2019.

[25] G. Ansanelli, G. Fiorentino, M. Tammaro, and A. Zucaro, "A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels," *Appl Energy*, vol. 290, no. November 2020, p. 116727, 2021, doi: 10.1016/j.apenergy.2021.116727.

[26] J. Vanek, P. Maule, and K. Jandová, "Development of Recycling of Photovoltaic Systems from the Point of View of Prolonging the Total Service Life of Photovoltaic Modules and Circular Energetic," *ECS Trans*, vol. 99, no. 1, pp. 211–219, 2020, doi: 10.1149/09901.0211ecst.

[27] J. Park and N. Park, "Wet etching processes for recycling crystalline silicon solar cells from end-of-life photovoltaic modules," *RSC Adv.*, vol. 4, no. 66, pp. 34823–34829, 2014, doi: 10.1039/C4RA03895A.

[28] J.-K. Lee *et al.*, "Simple pretreatment processes for successful reclamation and remanufacturing of crystalline silicon solar cells," *Progress in Photovoltaics: Research and Applications*, vol. 26, no. 3, pp. 179–187, Mar. 2018, doi: 10.1002/pip.2963.

[29] F. Pagnanelli *et al.*, "Solvent versus thermal treatment for glass recovery from end of life photovoltaic panels: Environmental and economic assessment," *J Environ Manage*, vol. 248, no. July, p. 109313, 2019, doi: 10.1016/j.jenvman.2019.109313.

[30] G. A. Heath *et al.*, "Research and development priorities for silicon photovoltaic module recycling to support a circular economy," *Nat Energy*, vol. 5, no. July, 2020, doi: 10.1038/s41560-020-0645-2.

[31] A. van der Heide, L. Tous, K. Wambach, J. Poortmans, J. Clyncke, and E. Voroshazi, "Towards a successful re-use of decommissioned photovoltaic modules," *Progress in Photovoltaics: Research and Applications*, vol. 30, no. 8, pp. 910–920, 2022.

[32] Neethi Rajagopalan *et al.*, "Preliminary Environmental and Financial Viability Analysis of Circular Economy Scenarios for Satisfying PV System Service Lifetime," 2021. [Online]. Available: iea-pvps.org/research-tasks/pv

[33] P. R. Dias *et al.*, "High yield, low cost, environmentally friendly process to recycle silicon solar panels: Technical, economic and environmental feasibility assessment," *Renewable and Sustainable Energy Reviews*, vol. 169, Nov. 2022, doi: 10.1016/j.rser.2022.112900.

[34] C. E. Latunussa *et al.*, "Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels," *Solar Energy Materials and Solar Cells*, vol. 156, pp. 101–111, 2016, doi: 10.1016/j.solmat.2016.03.020.

[35] B. L. Smith, M. Woodhouse, K. A. W. Horowitz, T. J. Silverman, J. Zuboy, and R. M. Margolis, "Photovoltaic (PV) Module Technologies: 2020 Benchmark Costs and Technology Evolution Framework Results," 2020. [Online]. Available: nrel.gov/publications

[36] "French consortium commissions solar module recycling facility – pv magazine International".

[37] "eit.europa.eu/news-events/news/rosi-french-start-supported-eit-innoenergy-raises-eur-74-million"

[38] Australian Government Department of the Prime Minister and Cabinet, "Cost-benefit analysis Guidance Note," 2020.

[39] NSW EPA, "Circular economy boost for solar panels." Accessed: Feb. 11, 2024. [Online]. Available: epa.nsw.gov.au/news/media-releases/2022/epamedia220627-circular-economy-boost-for-solar-panels

[40] Australian Government Department of Climate Change, Energy, the Environment and Water "Product stewardship in Australia." Accessed: Feb. 11, 2024. [Online]. Available: Product stewardship in Australia

[41] Australian Government Department of Climate Change, Energy, the Environment and Water "Minister's Priority List 2022-23." [Online]. Available: dcceew.gov.au/environment/protection/waste/product-stewardship/ministers-priority-list/2022-23

[42] Australian Government, "Recycling and Waste Reduction (Product Stewardship—Televisions and Computers) Rules 2021." 2021.

[43] Australian Government, "National Waste Policy Less Waste, More Resources 2018." 2018. Accessed: Feb. 11, 2024. [Online]. Available: dcceew.gov.au/sites/default/files/documents/national-waste-policy-2018.pdf

[44] Australian Government, "National Waste Policy Action Plan 2019." 2019. Accessed: Feb. 11, 2024. [Online]. Available: dcceew.gov.au/sites/default/files/documents/nationalwaste-policy-action-plan-2019.pdf

[45] Australian Government, "National Waste Policy Action Plan – Annexure 2022." 2022. Accessed: Feb. 11, 2024. [Online]. Available: dcceew.gov.au/sites/default/files/documents/national-waste-policy-action-plan-annexure-2022.pdf

[46] "ENVIRONMENT MINISTERS MEETING – 21 October 2022." 2022.

[47] Australian Government, "Regulation for small electrical products and solar photovoltaic systems." Accessed: Feb. 11, 2024. [Online]. Available: consult.dcceew.gov.au/regulation-small-electrical-products-solar-pv

[48] Australian Government, "Wired for change: Regulation for small electrical products and solar photovoltaic system waste," 2023. Accessed: Feb. 11, 2024. [Online]. Available: storage.googleapis.com/files-au-climate/climate-au/p/prj2748908c878a1b4b81a54/public_assets/Wired%20for%20change%20Regulation%20for%20waste%20small%20electrical%20products%20and%20solar%20photovoltaic%20systems.pdf

[49] Victoria Government Gazette, "Waste Management Policy (E-Waste) 2018." 2018. Accessed: Feb. 11, 2024. [Online]. Available: gazette.vic.gov.au/gazette/Gazettes2018/GG2018G026.pdf

[50] "South Australia Environment Protection (Waste to Resource) Policy 2010." 2010.

[51] Queensland Government, "DRAFT Queensland E-Products Action Plan 2023-2033," 2023. Accessed: Feb. 11, 2024. [Online]. Available: qld.gov.au/__data/assets/pdf_file/0033/365649/draft-e-waste-action-plan.pdf

[52] Government of Western Australia, "E-waste to landfill ban in Western Australia Consultation Paper 2023." Accessed: Feb. 11, 2024. [Online]. Available: consult.dwer.wa.gov.au/waste-policy/ban-on-e-waste-disposal-to-landfill-in-western-aus/user_uploads/e-waste-to-landfill-ban-in-western-australia---consultation-paper---january-2023-2.pdf

[53] ACT Circular Economy Strategy and Action Plan 2023-2030 [Online]. Available: cityservices.act.gov.au/__data/assets/pdf_file/0020/2272331/ACT-Circular-Economy-Strategy-access.pdf

[54] Keiichi Komoto *et al.*, "Status of PV Module Recycling in Selected IEA PVPS Task12 Countries," 2022. [Online]. Available: iea-pvps.org

[55] ACT Government, "ACT Waste-to-Energy Policy 2020-25," 2020. [Online]. Available: cityservices.act.gov.au

[56] "Soren Activity Report 2021 - Soren".