RESEARCH REPORT

Towards an Australian Circular Economy for Solar Photovoltaic Technologies



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About This Report

In December 2023, the Australian PV Institute released Silicon to Solar, a comprehensive report on the status and opportunities for photovoltaics (PVs) in Australia. Since then, Australia has significantly invested in PV manufacturing, battery production and tax incentives for renewable hydrogen and critical minerals.

As Australia and its global partners scale up solar manufacturing and deployment to meet net-zero targets, the volume of PV waste is projected to increase sharply. Australia alone is expected to accumulate more than 1 million tonnes of PV waste by 2035. Addressing this challenge is critical to maximising resource efficiency, minimising environmental harm and maintaining the resilience of clean-energy supply chains. To assist in these efforts, an international group of research partners led by the Royal Melbourne Institute of Technology collaborated on this report to present an assessment of the technical, social, economic and policy landscape for the development of a PV circular economy in Australia and an identification of circular economy development pathways over the coming decades.

We intend for this report to inform Australian policymakers, decisionmakers and stakeholders in relevant industrial sectors about the opportunities and challenges for developing a PV circular economy. We address many of the pressing policy design questions that are emerging in Australia as the Commonwealth and individual states and territories advance policies to incentivise a shift towards circularity with respect to PV waste.

RAND Education, Employment, and Infrastructure

This work was conducted in the Infrastructure and Justice Program of RAND Education, Employment, and Infrastructure, a division of RAND that aims to improve educational opportunity, economic prosperity, and civic life for all. For more information, visit www.rand.org/eei or email eei@rand.org.

The Royal Melbourne Institute of Technology

Royal Melbourne Institute of Technology (RMIT) is an international leader in technology, design, enterprise and innovation. In its commitment to driving impact across social, environmental and economic dimensions, the University places particular emphasis on research-industry collaborations designed to generate scalable, cross-sectoral solutions to complex challenges.

Funding

Funding for this research was provided by the Australian Commonwealth Department of Industry, Science and Resources through the International Clean Innovation Researcher Networks (ICIRN) grant programme. ICIRN grants support technologies that are needed to deliver greenhouse gas emission reductions and renewable-energy goals. The programme is intended to support Australian researchers to build networks with global experts to develop renewable-energy and clean technologies.

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Ylias Sabri, principal investigator, led the International Clean Innovation Researcher Networks project from which this report originated, provided strategic direction and approved high-level report decisions, and is the colead author of Chapter 5. James Bond, lead RMIT editor and project coordinator, scoped and developed the full report and chapter structure, including the identification and coordination of chapter-level expert contributing authors; he also led the quality assurance processes at RMIT. Alejandra Nunez Madrigal, editorial and research coordinator, coordinated the author contributions, compiled and prepared the consolidated manuscript, and supported reference and content resolution throughout. Venkatakrishnan Balasubramanian, techno-economic analysis lead and technical reviewer, led the techno-economic modelling and scenario analysis for PV recycling; was lead author of Chapter 9; contributed to Chapters 2, 3 and 5; and reviewed the report for system-of-units consistency.

We acknowledge the contribution of two peer reviewers—Michael Wilson of RAND and M. Akbhar Ramdhani of Swinburne University of Technology—and the RAND quality assurance manager for this project, Tom LaTourette.

This report is dedicated to the memory of Dr. Sergio Martín-Martinez, University of Castilla-La Mancha, in recognition of his valued contributions to this work and his dedication to advancing understanding of the effective design and deployment of renewable energy systems. He will be missed.

Summary

After two decades of exponential growth in the deployment of photovoltaic (PV) technology, Australia now finds itself at a critical inflection point in its energy transition. Australia leads the world in per capita PV deployment—more than 40.6 gigawatts have been installed across more than 4 million systems. Yet, the lifespan of those systems is not infinite.

A Decision Point for Australia

Cumulative end-of-life (EoL) PV waste is projected to reach approximately 1.1 million tonnes by 2035 and then double or triple in the subsequent 15 years to 2050 (Figure S.1). As of this writing, the infrastructure, regulation and market mechanisms that are required to manage this growth in EoL waste do not exist at scale. The PV installation spike of 2018 to 2024 means that there is a coming wave of PV decommissioning, and it will arrive regardless of whether infrastructure, markets or policies are in place to handle it. Given that PV panels have a typical lifespan of 25 to 30 years, there is a rapidly closing window of opportunity to plan and begin implementing a comprehensive national response to PV waste. Each year of inaction increases the infrastructure deficit, entrenches linear disposal pathways and permanently locks critical materials out of circular pathways because they cannot be recovered once they are downcycled or disposed in a landfill.

The Lack of a Viable Market for End-of-Life Solar Photovoltaics

In a properly functioning circular economy, EoL PVs would be collected and processed to recover and reuse the embodied materials. However, three structural barriers prevent market forces alone from creating that circularity:

- **First**, **existing recycling facilities are limited** and operate at low technology-readiness levels with respect to PVs. These facilities rely on mostly mechanical methods that limit the recovery of high-value materials, such as silver and silicon, and often downcycle panels into construction aggregate, permanently destroying their embodied value (Chapters 3 and 5).
- **Second**, although 45 to 65 per cent of decommissioned panels remain suitable for reuse (Chapter 6), **Australia lacks the collection logistics, certification frameworks and marketplace infrastructure** to capture that value. Logistics costs alone can constitute up to 60 per cent of total reuse and recycling scheme costs.
- **Third**, **the high cost of recycling EoL PVs** using existing infrastructure and technologies relative to disposal reduces the financial incentive to recycle. For example, recycling a panel costs approximately $28, compared with $4 to $5 for landfill disposal (Chapter 9).

Analysis indicates that action will be needed across a broad variety of stakeholders to overcome these barriers and build a sustainable EoL PV market that advances the principles of circularity. In the absence of advances in EoL PV waste processing, the scaling of infrastructure and logistics to efficiently manage EoL waste, and regulatory or financial incentives, decisionmaking about EoL PVs will default to disposal. This represents a potential missed opportunity for Australia.

FIGURE S.1

Solar Photovoltaic Waste Projections, 2025–2040

Solar PV Waste Projections, 2025–2040

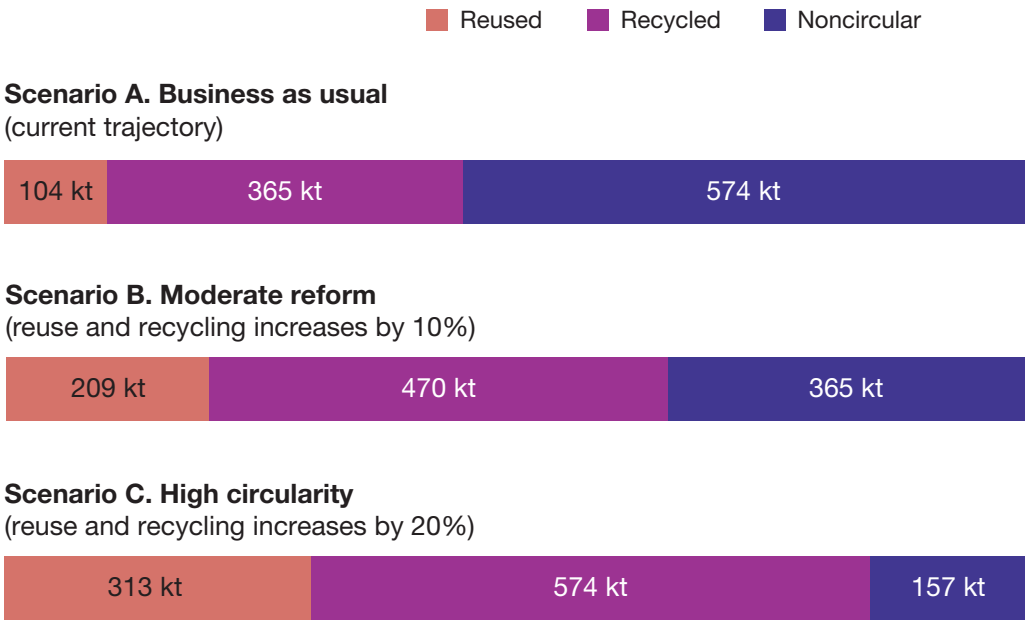
Where does ~1 million tonnes of decommissioned solar PV go over the next 15 years? The answer depends on the investment and policy choices made now.

Disposal Pathways, by Scenario

Scenario	Reused	Recycled	Noncircular
A. Business as usual	10%	35%	55%
B. Moderate reform (+10%)	20%	45%	35%
C. High circularity (+20%)	30%	55%	15%

Cumulative Material Fate, by 2040

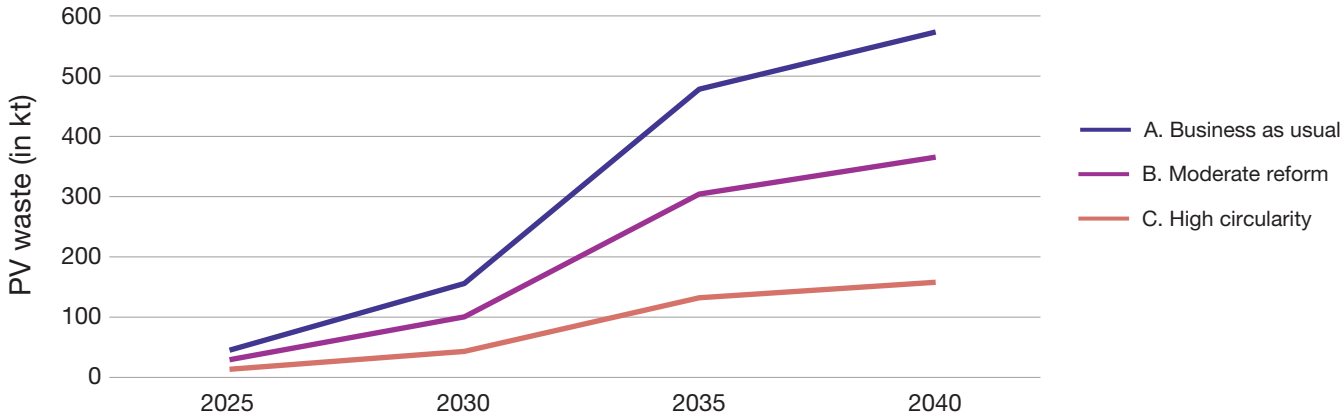
~1 million tonnes of PV panels are decommissioned across all scenarios. Scenario differences lie in the proportion of reuse, recycling and noncircular decommissioning pathways, such as landfilling and stockpiling.



SOURCES: The cumulative waste data projections are based on the latest industry data from Florin, Salim, and Madden, 2023; historical installation rates across Australian postcodes calculated by the Australian PV Institute (undated-b); and Blue Tribe Company, interview with the authors, 2025.

Cumulative Noncircular PV Waste, from 2025

Accumulation over time from 2025 (*not* accounting for historical waste)



The Critical Window (2030 to 2035): Installation spikes from 2018 to 2024 drive a decommissioning surge starting around 2030. Infrastructure must be ready.

The Cost Gap

$28 per panel to recycle
$4 to $5 per panel to landfill

Without policy, the market defaults to disposal.

Employment Multiplier

9.2 jobs per 10,000 tonnes (with recycling)
2.8 jobs per 10,000 tonnes (with landfilling)

There are 3.3x more jobs from recycling than disposal.

Recoverable Value

$1B+ material value by 2035
~45–65% of decommissioned panels suitable for reuse

A reused panel has 133x more value than a recycled panel.

Sovereignty context and mitigating the unavoidable wave of waste: The three scenarios send very different amounts of PV waste to landfill and other noncircular pathways, even though the same volume of panels is decommissioned in each. Higher reuse keeps more panels in service, and higher recycling keeps more materials in use. For example, Scenario C increases reuse and recycling by 20% over Scenario A, which equates to 73% less cumulative noncircular waste by 2040 (157 kt compared with 574 kt). In turn, this reduces the circular economy infrastructure investment needed to accommodate PV waste in the future. With China currently dominating the PV supply chain at the global level, an enhanced circular economy infrastructure also reduces import dependencies and builds domestic capabilities.

NOTE: This infographic models only PV panels installed before 2025 and the subsequent waste expected from those panels. It does not include panels installed after 2025 and does not include panel waste accumulated before 2025. Cumulative waste projections (1.0 to 1.2 million tonnes by 2035) include all historical waste. The projections include the following assumptions: (1) the average new panel lifespan (i.e., the number of years until a panel enters decommissioning streams) is 12 years, (2) the average reuse panel operational lifespan is 12 years based on a 25-year design life and average lifespan until decommissioned, and (3) a panel's weight is 25 kilograms. kt = kilotonne.

Pathways to a Circular Photovoltaic Economy

As detailed in this report, viable pathways exist for Australia to develop an EoL PV circular economy. Table S.1 shows how those pathways are contingent on making gains across five different activity areas spanning innovation, policy, markets, logistics and stakeholder engagement and connects those efforts to the different chapters of this report. Given the interdependencies among these activities, they should be

TABLE S.1
Five Activities That Lead Towards a Circular Economy for Photovoltaics

Activity Area	Horizon I: Build Foundations Now to 2030 **Establish a national regulatory framework by 2027, develop a digital marketplace for secondary panels, launch the first commercial-scale recycling facilities and build workforce capabilities.**	Horizon II: Scale Rapidly 2031 to 2040 **Deploy testing and certification facilities nationwide, expand high-throughput disassembly and integrate with critical mineral supply chains.**	Horizon III: Sustain and Lead Beyond 2040 **Cultivate a competitive circular marketplace with continuous improvement towards 100-per-cent circularity.**
Research and development	Accelerate TRLs for silicon (greater than 99.9-per-cent purity), silver and copper recovery; conduct feasibility studies; and guide RMIT, UNSW and CSIRO capabilities towards commercial readiness (Chapter 5).	Improve cost-effectiveness, integrate with critical minerals and battery storage supply chains, and develop second-life silicon anode pathways for lithium-ion batteries that yield a 10-fold increase in capacity (Chapter 7).	Keep pace with evolving panel design and material composition and enable greater supply-chain situational awareness (Chapter 11).
Policy and regulatory reform	Extend the Product Stewardship Act, set minimum recycling efficiency standards, establish reuse liability indemnification, legislate before the 2028 federal election and align with the EU's EPR framework (Chapter 10).	Mandate stewardship contributions, harmonise cross-jurisdictional standards via the National Cabinet, and advance workforce development programs, including safe panel removal standards to ensure reusability (Chapter 10).	Continually refine policy, harmonise international circular economy standards and wind down incentives as the market becomes self-sustaining (Chapter 11).
Market scaling	Launch a digital marketplace for secondary panels, establish national reuse certification on the Circular PV certificates foundation and build consumer and industry awareness (Chapters 3 and 8).	Expand processing capacity, develop domestic PV module remanufacturing, scale certified reuse markets and develop insurance products for reused panels (Chapter 8).	Maintain a self-sustaining competitive circular marketplace with retail enterprises based on reuse and support continuous improvement towards 100-per-cent circularity (Chapter 11).
Logistics	Establish EoL collection and storage, design jurisdiction-specific models (e.g. modular, decentralised, mobile models in Queensland; regional, fixed models in Victoria), and provide each metro facility with access to 5,000 to 10,000 tonnes of PV waste per year (Chapter 6).	Deploy testing and certification facilities nationally, expand high-throughput disassembly capacity and integrate with battery waste streams (Chapter 6).	Maintain a mature, efficient national logistics network and fully circular supply chain that includes cross-waste-stream economies of scale (Chapter 11).
Stakeholder engagement	Build community and council relationships, launch public awareness campaigns, and establish solar reuse and recycling trade associations (Chapter 8).	Scale stakeholder engagement; provide technical and further education training and university workforce training; establish vocational pathways for installers, testers and recycling technicians; and deepen international partnerships (Chapters 8 and 11).	Achieve recognition for Australia as a global continuing education excellence centre, continually upskill the PV workforce and distribute equitable benefits across metropolitan, regional and remote communities (Chapter 8).

NOTE: CSIRO = Commonwealth Scientific and Industrial Research Organisation; EPR = extended producer responsibility; EU = European Union; RMIT = Royal Melbourne Institute of Technology; TRL = technology readiness level; UNSW = University of New South Wales.

pursued using a phased approach. That is why Table S.1 maps each activity area to three planning horizons that are aligned with Australia's Net Zero 2050 plan (and explained in more detail in Chapter 11). This matrix approach to planning can aid in identifying different types of activities that could be undertaken by different actors over different time scales as part of a broader long-term strategy towards PV circularity.

Building a PV circular economy will likely require a whole-of-nation approach. For example, product stewardship frameworks can help create a level playing field for stakeholders throughout Australia and establish clear expectations for manufacturers. In addition, the National Cabinet has an important role to play in facilitating interstate coordination and collaboration, and organisations, such as the Australian Renewable Energy Agency, can both support infrastructure development and help monitor the PV EoL waste marketplace. Meanwhile, state and territory governments would have a role to play in implementing jurisdiction-specific EoL waste collection programs, enforcing landfill bans and managing planning approvals for new infrastructure. Local councils can operate collection points and educate consumers. The PV industry can contribute to EPR schemes and promote innovation in design for circularity. Particularly over the long term, research and development (R&D) within Australian research institutions will be critical for advancing recovery technologies towards commercial readiness.

Key Near-Term Policy Recommendations

Although developing a robust and sustainable PV circular economy will necessitate years of planning and investment, three interdependent actions require immediate attention. Given their interdependences, these actions should be implemented in the following sequence:

1. **Establish a national PV circularity framework by mid-2027.** As identified in Chapter 10 of this report, the absence of a national regulatory framework for PV waste management—combined with inconsistencies across states and territories in policy development and implementation—represents a critical gap for circularity. This can be addressed by extending the Product Stewardship Act to cover PV panels, setting minimum recycling efficiency standards and establishing liability indemnification for panel reuse. The pilot product stewardship proposal by the Department of Climate Change, Energy, the Environment and Water (DCCEEW) is the natural vehicle for advancing such a framework, but, to be successful, it must ultimately result in binding regulations, not voluntary guidelines. Moreover, to meet the timetable outlined in Horizon I, this framework would need to be implemented quickly—before the next federal election in 2028.
2. **Fund commercial-scale recycling and reuse infrastructure by 2028.** There is a short-term need to develop the necessary infrastructure to enable a PV circular economy, but, given the emergent nature of the existing market for PV waste, financial incentives will be needed to ensure such development. Coinvestment by states and the Australian Renewable Energy Agency could secure the development of regional facilities in Queensland, Victoria and New South Wales that each have a target processing capacity of 2,500 tonnes of PV waste or more per year. The payback period is estimated to be 7.2 to 8.0 years (see Chapter 9). Published estimates suggest that each facility could support 146 to 335 jobs by 2030 (Deng et al., 2024).
3. **Launch a national PV reuse certification and digital marketplace by 2027.** Build on the Queensland reuse trial and Circular PV certificates to establish a nationally recognised certification system and a digital platform connecting decommissioned panel supply with secondary market demand (see Chapters 3 and 6). Reuse must be the first-priority circular pathway. Additionally, the marketplace needs to generate provenance and condition data to underpin downstream recycling efficiency. To do so, leasing business models—identified in Chapter 6 as commercially promising—should be developed alongside the certification framework.

A Closing Window of Opportunity

The early 2026 announcement from DCCEEW for a National Solar Panel Recycling Pilot confirms that the Australian federal government has recognised the problem of EoL PV waste. However, the pilot alone will not resolve the structural market failure, mandate producer responsibility or fund the infrastructure needed before the pending 2030 to 2035 decommissioning surge. Accelerating action on PV waste would, therefore, necessitate rapidly translating the findings from the pilot into legislation and a funded national infrastructure programme.

Australia's technical and commercial capability for advancing a circular economy for PVs is well established, suggesting that accelerating circularity could be feasible given the right enabling conditions. For example, RMIT leads international research-industry collaborations in PV recycling, separation technologies and remanufacturing; UNSW researchers have developed mechanical recycling methods capable of achieving high rates of material recovery; and CSIRO brings national capability in materials science and process engineering (see Chapters 5 and 7 for more on these collaborations). Additionally, the techno-economic assessment in Chapter 9 demonstrates commercially viable returns under existing TRLs without breakthrough R&D. The Queensland reuse trial in 2025 and the Circular PV Alliance's Circular PV certificates demonstrate global-leading operational innovation that policy has not yet matched (for more details, see Chapter 3).

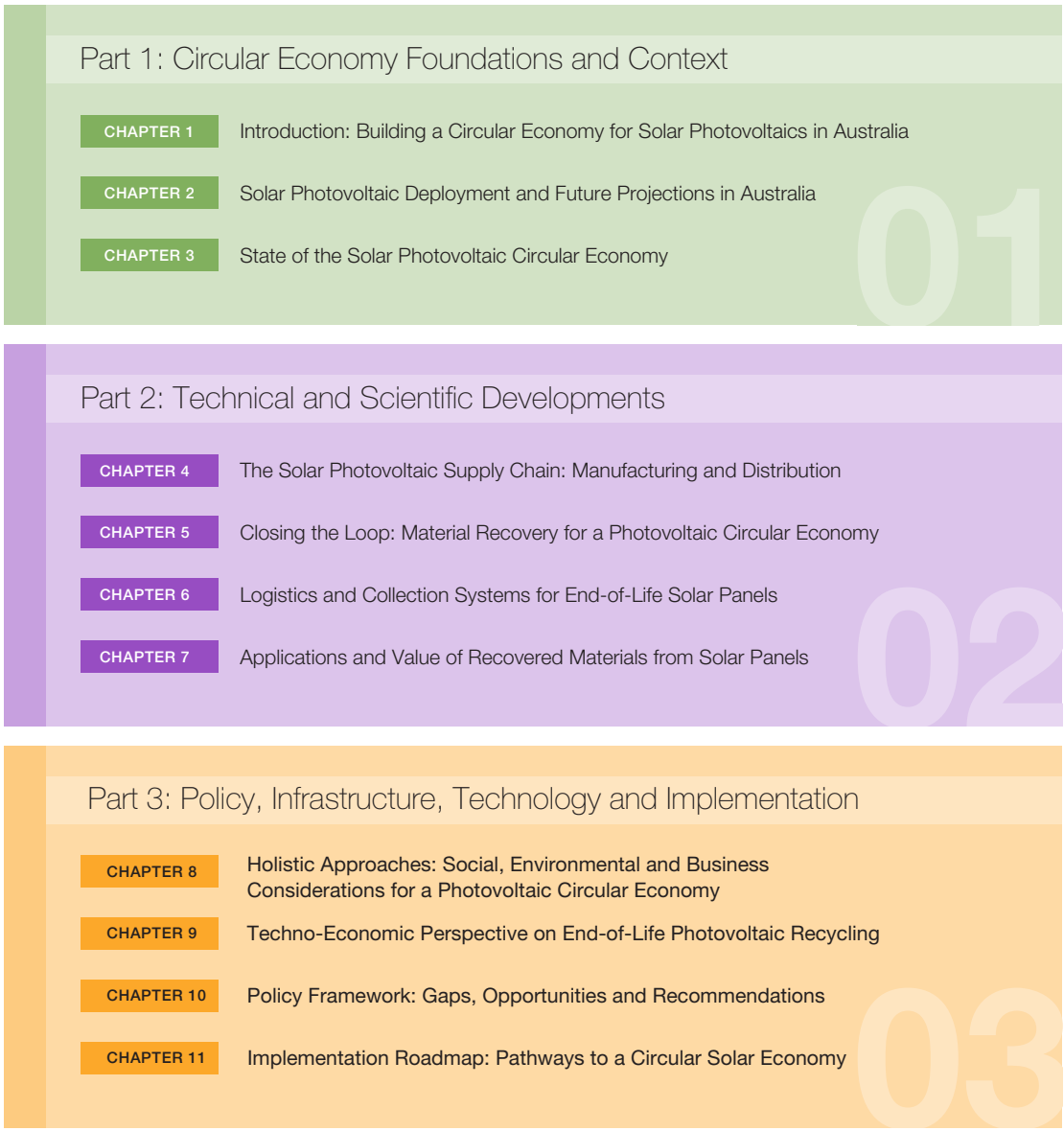
It is also important to recognise that a successful transition to circularity will require more than just R&D and market expansion. As a whole-of-nation challenge, achieving a successful transition will necessitate implementing solutions that are not only technically and economically sound but also equitable. The costs and benefits of the circularity transition should be shared among different actors and communities. In particular, Australia's First Nations communities should be engaged early, and regional communities should not bear disproportionate environmental costs while metropolitan centres capture economic returns. This is not a peripheral consideration but rather a prerequisite for the social licence required to successfully build the large-scale infrastructure that will enable PV circularity.

How to Read This Report

The report is organised into three integrated parts (Figure S.2). Technical solutions cannot succeed without supportive policy frameworks, and policy frameworks cannot be effective without understanding technical constraints and social dynamics. Thus, we have organised the report as follows:

- Part 1 (Chapters 1 to 3) provides circular economy foundations and context, rationales for action, and baseline assessments.
- Part 2 (Chapters 4 to 7) describes technical and scientific developments across the value chain, from manufacturing to material recovery to downstream applications.
- Part 3 (Chapters 8 to 11) describes policy, infrastructure and implementation requirements integrated with social, economic and regulatory analyses. Chapter 11 is the integrating chapter, bringing all six activity areas into a coherent roadmap with specific actions, timelines and responsible actors across three planning horizons.

FIGURE S.2
Organisation of the Report



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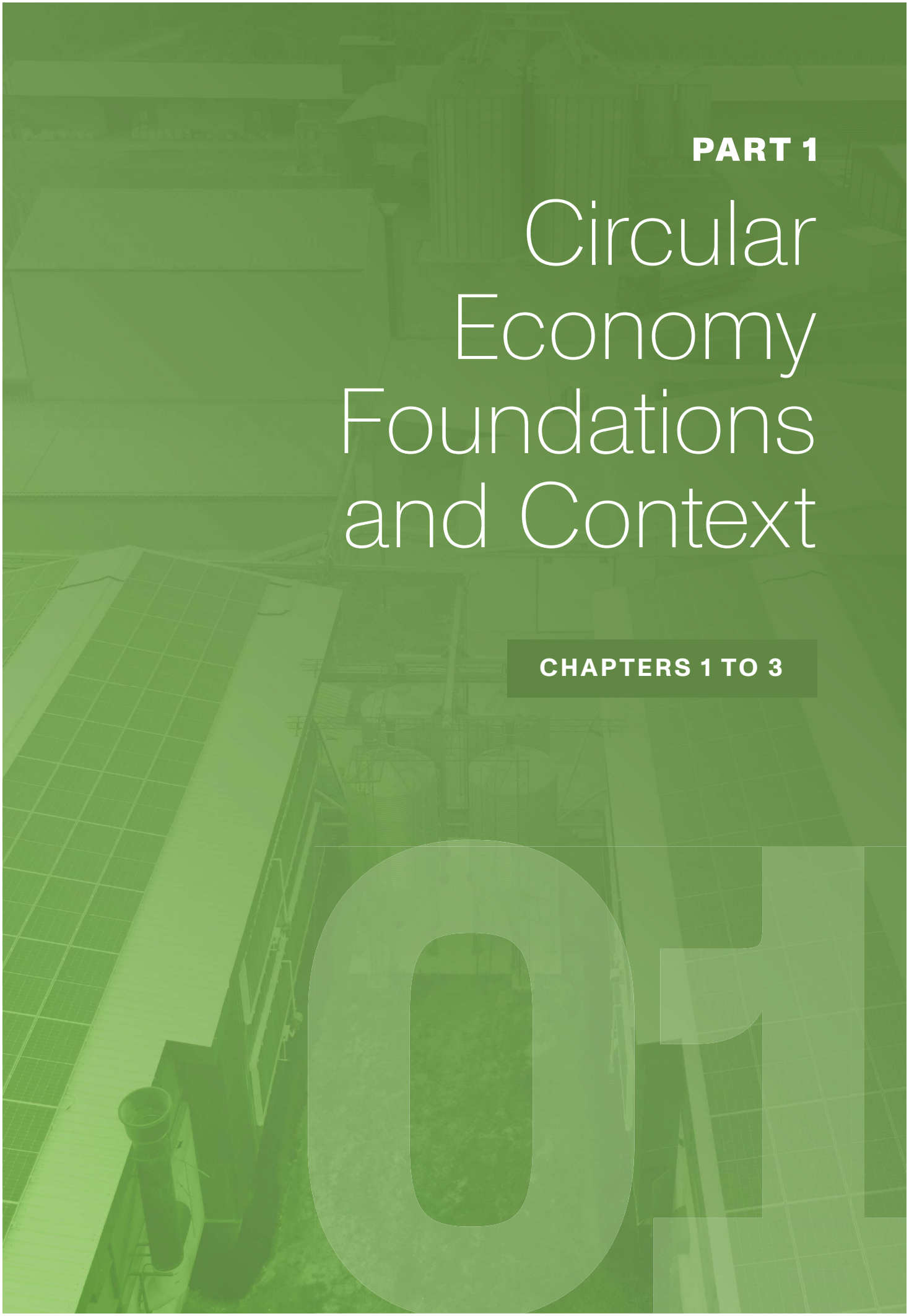
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PART 1

Circular Economy Foundations and Context

CHAPTERS 1 TO 3

01

CHAPTER 1

Introduction: Building a Circular Economy for Solar Photovoltaics in Australia

Benjamin L. Preston

> Landfilling these panels is not just environmentally irresponsible; it is an act of profound economic negligence, akin to burying a strategic mineral reserve.
>
> **Smart Energy Council**

In December 2023, the Australian PV Institute (APVI) released *Silicon to Solar* (Vaqueiro Contreras et al., 2023), a comprehensive report about the status of and opportunities for photovoltaic (PV) manufacturing in Australia. After its publication, Australia's Treasury announced a $22.7 billion investment in the Future Made in Australia initiative to maximise the industrial and economic benefits of the clean-energy transition and accelerate the move to net zero (Australian Public Service Commission, undated; Carouso, 2024). Australian investment is targeting PV manufacturing, battery production and tax incentives for renewable hydrogen and critical minerals. Core to the policy is clean-energy manufacturing, which, in the context of PV manufacturing, is underpinned by the Solar Sunshot initiative aimed at supporting innovative PV manufacturing facilities in Australia across the solar supply chain (Australian Renewable Energy Agency, 2025).

With such significant investment being made in clean-energy manufacturing, it is vital that circular economy considerations are central to future investments and policies. An approach that considers the whole-of-life ecosystem of PVs will minimise waste and enhance domestic capacity by ensuring that materials are available for manufacturing processes at scale, thus supporting long-term economic resilience and supply-chain security. However, the limited domestic PV manufacturing and recycling



infrastructure in Australia, combined with high rates of domestic PV panel installation, creates distinct challenges for the application of circular economic principles across states and territories.

As Australia and its global partners scale up solar manufacturing and deployment to meet net-zero targets, existing residential panels will reach their end of life (EoL), increasing the volume of PV waste. Australia alone is expected to accumulate more than 1 million tonnes of PV waste by 2035, 2 million by 2040 and more than 3 million by 2050 (Deng et al., 2024), although estimates vary depending on assumptions and estimation methods. Addressing this challenge is critical to maximising resource efficiency, minimising environmental harm and maintaining the resilience of clean-energy supply chains.

Given Australia's extensive history of deploying PVs throughout the country and projections of both rooftop and utility-scale solar development,[1] fostering a circular economy can generate a variety of benefits for regional economies and national security. This report examines the technical solutions, policy frameworks, constraints and social dynamics involved in realising a circular economy in Australia.

The Emerging Global Circular Economy

Over the past decade, the global shift towards sustainability has driven growing interest in the pursuit of a circular economy. A *circular economy* is an economic, environmental and business model that seeks to minimise waste and maximise the use of energy and materials. In contrast with a *linear economy*—which conforms to a life cycle of take-make-dispose (Kaur and Singhal, 2024)—the circular economy emphasises keeping products, materials and resources in use for as long as possible.

[1] In contrast to *rooftop solar*, which refers to PV panels installed on the rooftops of buildings (often to offset energy costs), *utility-scale solar* refers to solar projects, such as solar farms, that generate large amounts of power that is sold and integrated into the electricity grid.

Closing the loop can involve a variety of strategies, ranging from extending the life of products to reusing products to recycling materials. These strategies can reduce the environmental impact associated with the procurement and use of products, including demand for extractive materials, energy consumption and greenhouse gas (GHG) emissions, and disposal of waste in landfills. At the same time, developing a circular economy might necessitate new infrastructure and businesses that generate new jobs and economic opportunities. For example, estimates of the economic benefit for Australia from a circular economy are on the order of $210 billion by mid-century (Schandl et al., 2024). This win-win dimension is why businesses and policymakers around the world are increasingly interested in creating the enabling conditions for the circular economy.

The circular economy model is particularly relevant to the clean-energy sector (Department of Climate Change, Energy, the Environment and Water [DCCEEW], 2024a). The transition to renewable-energy sources (such as solar and wind) and battery storage technologies is fundamental to efforts to reduce GHG emissions that contribute to climate change. However, clean-energy technologies depend on a wide variety of critical minerals and materials—such as lithium, cobalt, copper, nickel and aluminium—that are extracted from the environment and processed into consumer and industrial products.

The rapid growth in the deployment of clean-energy technologies in Australia and around the world has created significant demand for such materials. For example, Australia has recently seen an annual growth of approximately 5 to 6 gigawatts (GW) in its renewable-energy capacity (Clean Energy Council, 2024). As a result, utility-scale solar capacity in Australia grew by 90 per cent from 2020 to 2023, and wind power output grew by around 40 per cent (Ember, undated). This rapid growth is mirrored in energy markets around the world, driving up the demand for clean-energy infrastructure and, as a result, prices for critical materials. The resulting competition is making access to critical minerals an economic and national security issue (Department of Industry, Science and Resources, 2023), exacerbating geopolitical tensions and incentivising new extractive techniques for their acquisition (LaTourrette et al., 2025).

In addition to the critical mineral supply chain, growth in the deployment of clean-energy technologies has important implications for waste management. Similar to all products, clean-energy technologies will eventually reach the end of their useful life. As a result, the exponential growth in clean-energy technology will ultimately translate into exponential growth in clean-energy waste. Recent studies indicate the potential for EoL solar waste in Australia to reach approximately 685,000 tonnes by 2030 and 1.2 million tonnes by 2035 (Monaghan, 2025). This looming waste management challenge is important for other nations as well. The United States, for example, is projected to install 1,600 GW of PVs by 2050—roughly 20 times the number installed in 2020 (Office of Energy Efficiency and Renewable Energy, 2021). Consequently, the United States is projected to generate 1 million tonnes of waste from PVs by 2030 and 54 to 160 million tonnes by 2050 (Mirletz et al., 2023). In the absence of a plan for addressing this waste, the default strategy will be to send clean-energy waste, which includes potentially toxic components (Mirletz et al., 2023), to landfills or combine it with other household electronic waste (e-waste).

A circular economy approach to clean energy addresses these risks by creating opportunities to recover significant critical materials from Australia's clean-energy supply chains while reducing the environmental footprint of critical materials extraction. The approach includes designing PV panels, wind turbines and batteries with longer lifespans; improving repairability; and allowing for greater recyclability. For instance, next-generation battery designs are being developed to use fewer critical materials and to allow easier recovery of components at EoL (United Nations Conference on Trade and Development, 2025). Similarly, recycling facilities are being developed to reclaim valuable metals from decommissioned PV panels and wind turbine blades (Baumgurtel et al., 2025). Circular strategies also encourage the use of secondary raw materials—recycled inputs—instead of virgin materials, reducing the pressure on ecosystems and mining communities.



In addition to reducing environmental impacts, a circular energy economy can strengthen energy security and economic resilience (Sohail, Ullah, and Sohail, 2025). By recovering materials from used technologies and reintegrating them into new production cycles, countries can reduce their dependence on volatile international supply chains and resource-exporting nations. This is particularly relevant for Australia, the European Union (EU), the United States and other regions that import most of their critical raw materials, value-added products or both (Villalobos et al., 2022; Department of Industry, Science and Resources, 2023; Park, Tracy, and Ewing, 2023). Moreover, new circular business models (CBMs)—such as product-as-a-service or equipment leasing—can lower upfront costs and incentivise companies to maintain and refurbish clean-energy infrastructure more efficiently (Schandl et al., 2024).

Ultimately, integrating circular economy principles into the clean-energy transition is essential for achieving a truly sustainable and just energy future. It ensures that, while countries reduce their reliance on fossil fuels, they can also minimise the unintended environmental and social consequences of new technologies. As the world scales up clean-energy deployment to meet climate targets, embedding circularity into energy systems will not only conserve resources but also unlock innovation and long-term economic value. Hence, rather than being a barrier to progress, a mature circular economy can help ensure that the clean-energy revolution is genuinely sustainable from start to finish.

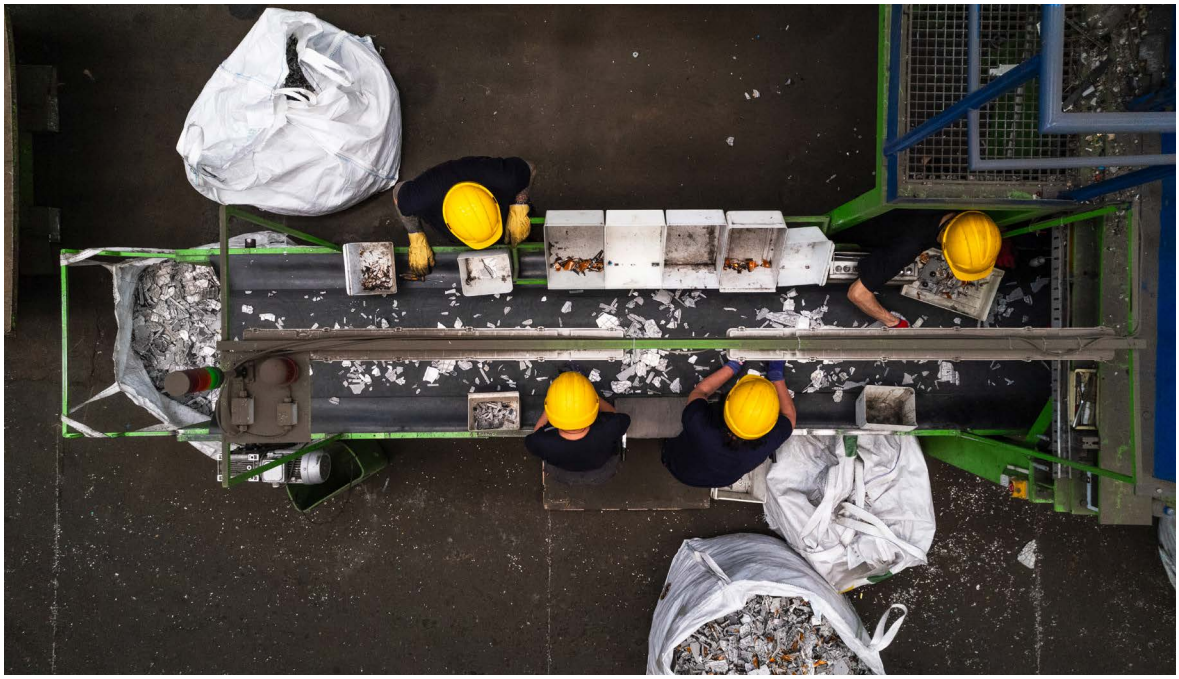
A fundamental benefit for Australia in developing a PV circular economy is the diversion of future EoL PV waste from landfills. In the absence of a regulatory prohibition or circular economy for PV waste, the estimated 1.2 million tonnes of waste from PVs by 2035 would likely find its way to Australia's solid waste landfills. Moreover, given that the geographic distribution of PVs is concentrated in certain areas, particularly in and around Australia's capital cities and utility-scale development regions (Deng et al., 2024), landfills in those areas would receive the bulk of Australia's PV waste. Australia is already facing pressure because of declining landfill space and rising levies for waste disposal (McCabe and Clarke, 2017). For example, in November 2024, the New South Wales Government declared Greater Sydney to be on the brink of a waste crisis, with landfill space projected to run out by 2030 (Pittorino, 2025). Landfill diversion enables other forms of recycling and reuse that can reduce carbon emissions and preserve the value of embodied materials within the Australian economy (Deng et al., 2024).

Economic Opportunity

One of the more compelling policy justifications for a PV circular economy is the opportunity it presents to grow the Australian economy. This could be achieved through two primary mechanisms. First, a circular economy would allow Australian businesses and consumers to avoid the opportunity costs associated with the disposal of EoL PV waste. Specifically, the generation capacity and the embodied materials and energy within PV panels are removed from the Australian economy on disposal, and they must be procured through other means. The cost of disposing EoL panels in landfills is estimated to be $4.50 per panel (Baumgurtel et al., 2025). Although recycling PV panels is more expensive than disposal (approximately $28 per panel), advances in technology, the scaling up of the recycling industry and policy interventions (e.g. bans) can reduce this cost gap (Quinn, 2023). In addition, reusing EoL PV panels to extend their life can generate even greater economic benefits. An industry study notes that the 'economic value of a reused PV panel is 133 times greater than a recycled panel', underlining how reuse drives far higher returns (McGregor, 2023, p. 5). For example, reinstalling all available used panels by 2035 could raise total PV capacity by up to 17 per cent (Clean Energy Council, 2025).

Second, a circular economy would necessitate the development of a new industry across Australia, adjacent to the clean-energy economy, to facilitate the circular economy. This development would include the expansion of existing businesses or the establishment of new businesses to manage PV waste logistics, reuse and recycling, and material processing and recovery. Recovering and reusing panel materials would require significantly more jobs than would be needed to simply dispose of the panels. One analysis finds that 9.2 jobs are created per 10,000 tonnes of waste recycled versus only 2.8 jobs per 10,000 tonnes landfilled (Access Economics, 2009). The development of PV waste management facilities in Australia is expected to generate 146 to 335 jobs per facility by 2030, increasing to 355 jobs by 2035 (Deng et al., 2024). By contrast, the techno-economic assessment in Chapter 9 assumes five to six full-time staff for on-site operations at each 2,500-tonne facility. In addition, a thriving second-hand PV market would extend the life of existing panels at a fraction of the cost of new panels while avoiding disposal costs (Deng et al.,





2024). For example, the company Second Life Solar estimates that redeploying 8 GW within Australia of still-serviceable panels could generate $38.4 billion in economic output by 2030 and $167.8 billion by 2045 (McGregor, 2023).

Material Recovery

A significant opportunity for Australia's economic and national security is the contribution that a PV circular economy could make towards bolstering the nation's critical mineral supply chain. Australia has some of the world's largest reserves of cobalt, lithium, manganese, rare earth elements, tungsten and vanadium (Hughes, 2023). It also has extensive expertise in mining and mineral extraction (Department of Industry, Science and Resources, 2023). However, the Australian government faces a challenge common to most Organisation for Economic Co-operation and Development (OECD) countries, which is the need for a more complete critical mineral value chain that spans material extraction, processing and refining, downstream manufacturing and other value-added applications (Department of Industry, Science and Resources, 2023). As of 2026, China dominates the critical mineral processing industry. Materials extracted in Australia are often exported to China for processing, and then Australian consumers import finished, value-added products manufactured overseas that are derived, in part, from Australian resources.

Australia's *Critical Minerals Strategy 2023–2030* explicitly identifies circular economy approaches as an opportunity for constructing a more complete domestic critical mineral value chain and as necessary for balancing resource extraction and processing with a commitment to net zero emissions by 2050 (Department of Industry, Science and Resources, 2023). One element of this strategy is the low-cost and low-emissions domestic recovery of materials found in PV panels. For example, given projected waste volumes, diverting PV panels away from landfills is estimated to save more than $1 billion by the mid-2030s (Baumgurtel and Merwe, 2024; Clean Energy Council, 2025). A typical 20-kilogram (kg) crystalline silicon (c-Si) panel contains roughly 70-per-cent glass, 18-per-cent aluminium, 4-per-cent silicon,

2-per-cent copper and 0.05-per-cent silver by weight (Xu et al., 2018; Ziemińska-Stolarska, Pietrzak, and Zbiciński, 2021). Much of this material is readily recoverable and recyclable. Glass and aluminium have long been integrated into commercial recycling operations in Australia. Even the smaller, more-valuable components (such as copper and silver) can be recovered with high efficiency. Hence, given commodity prices in 2024, one 20 kg panel is estimated to yield between $20 and $25 worth of materials in total (Baumgurtel and Merwe, 2024). This is comparable to the cost of recycling, suggesting that recycling PV panels is already at or near the break-even point. As the efficiency of material recovery improves and the scale of recycling efforts expands, the benefits of PV panel recycling will continue to rise. In conjunction with integrated supply chains and greater domestic processing capacity, the recycling of EoL PV panels is positioned to offset a significant fraction of the materials used in construction and manufacturing in Australia.

Objectives of This Report

Our objectives in this report are to enhance the understanding of those working in or interested in PVs or clean-energy sectors regarding the opportunities associated with developing a circular economy for PVs in Australia. In addition, we detail the technological, social and economic constraints associated with developing such a circular economy.

To that end, in Chapter 2 we provide detailed estimates of existing and future deployments of PVs in Australia and their implications for future EoL waste streams. To place these projections in context, in Chapter 3 we elaborate on the state of the PV circular economy in Australia. In Chapters 4 through 7, we describe analyses of the core components of a future circular economy supply chain, including supply-chain issues, material recovery, logistics and collection systems, and applications of PV reuse and recycling. In Chapter 8, we present the social and environmental factors that need to be reviewed to develop business models and innovative scenarios for adopting a circular economy within Australia's PV industry, and in Chapter 9, we provide a techno-economic perspective on EoL PV recycling. In Chapter 10, we identify policy gaps that need to be addressed to shift the industry towards circularity, and in Chapter 11, we introduce a future pathway for developing the circular economy. The appendixes provide additional information about the methods and data we used for the techno-economic assessment (TEA) in Chapter 9 and the infographic about PV waste projections.

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CHAPTER 2

Solar Photovoltaic Deployment and Future Projections in Australia

Alejandra Nunez Madrigal, Pabasara Wijeratne, Venkatakrishnan Balasubramanian, and Nieves Espinosa

> As the installation of panels in Australia increased exponentially in the early 2000s, there will be a rapid increase in the number of panels reaching the end of their 25–30-year lifespan within the next few years. Approximately 90% of existing PV systems in Australia could ultimately end up in landfill if regulatory and technological advances are not made.
>
> **Australian PV Institute**



With a total capacity of more than 40.6 GW, Australia has the top position in the world in terms of adopting solar per capita. Building-attached PVs (BAPVs) occupy the predominant share of installed capacity, while building-integrated PV (BIPV) installations remain minimal.[1] However, the success of PV adoption brings an inherent challenge: PV waste. It is estimated that, by 2050, there will be 2.5 million tonnes of PV waste in Australia. In this chapter, we present data on forecasted PV waste volumes and strategies for waste diversion as Australia's early systems approach the end of their 25- to 30-year operational life.

The State of Solar Deployment in Australia

As of 31 March 2025, Australia has successfully installed more than 4.09 million PV systems, contributing to a total capacity of more than 40.6 GW and underscoring the country's commitment to advancing sustainable energy solutions (APVI, undated-a). Most PV systems in Australia are imported, and only a few manufacturers operate within the country (Vaqueiro Contreras et al., 2023). The three main types of PV panels available to Australian consumers and businesses are monocrystalline, polycrystalline and thin film panels (Dallaev et al., 2023). The Australian PV market includes both grid-connected and off-grid installations. Australian grid-connected solar installations are predominantly BAPV, which represent the largest share of installed capacity (Table 2.1). Utility-scale ground-mounted PV rank second, contributing significantly but with more variability over time. In contrast, BIPV installations remain minimal, reflecting limited uptake in the built environment. When compared with grid-connected systems, off-grid PV installations represent only a small fraction of the overall PV market.

[1] *BAPV* refers to the use of PVs to retrofit existing buildings, such as installing PV panel arrays on a rooftop. *BIPV* refers to the replacement of traditional building materials with PV materials (e.g. solar windows, solar roof tiles) in the construction of new buildings.

Figure 2.1 illustrates the trends in grid-connected PV installations in Australia across various sectors over the past decade (from 2014 to 2023). Residential BAPVs (i.e. rooftop solar installations) remains a significant and mature segment, although their growth has plateaued slightly since peaking around 2020. As of 2023, residential BAPVs accounted for the second-highest installed capacity, indicating widespread adoption in households. BAPVs in commercial buildings emerged as the leading segment of solar deployment in 2023, reaching the highest installed capacity among all categories. Industrial BAPV installations continue to represent the smallest share of BAPV deployment; the capacity has remained low and relatively flat, with only a modest increase in 2023. The utility-scale ground-mounted segment has experienced high volatility. It saw a rapid surge between 2017 and 2019, followed by a dramatic drop in 2020, a partial recovery in 2021 and a decline through 2023. Despite these fluctuations, utility-scale projects remain an important part of the national solar portfolio.

TABLE 2.1

Installed Photovoltaic Capacity in Australia, in Megawatts

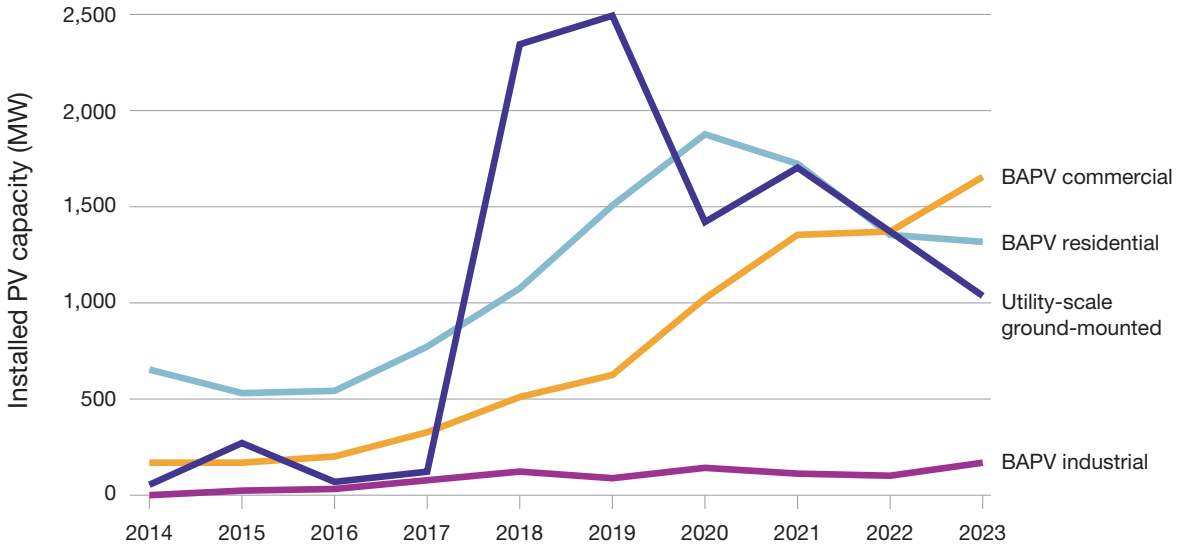
Application		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Grid-connected	BAPV	825	722	780	1,184	1,695	2,223	3,056	3,201	2,829	3,145
	BIPV	—	<1	<1	—	—	—	—	—	—	—
	Utility-scale	63	273	60	123	2,359	2,510	1,422	1,713	1,377	1,053
Off-grid	Residential	12	16	26	—	37	25	25	24	34	13
	Other	3	—	36	—	—	—	—	5	—	24

SOURCES: Features information from APVI, 2015; APVI, 2016; APVI, 2017; APVI, 2018; APVI, 2019; APVI, 2020; APVI, 2021; APVI, 2022; APVI, 2023; and APVI, 2024.

NOTE: A dash (–) indicates that values were not reported.

FIGURE 2.1

Grid-Connected Building-Attached Photovoltaics and Utility-Scale Installations in Australia, from 2014 to 2023



SOURCES: Features information from APVI, 2015; APVI, 2016; APVI, 2017; APVI, 2018; APVI, 2019; APVI, 2020; APVI, 2021; APVI, 2022; APVI, 2023; and APVI, 2024.
NOTE: MW = megawatt.

Volume Forecasts: How Much Photovoltaic Waste Will Australia Have to Deal With and When?

Australia is approaching a critical inflection point in PV waste generation as early systems near the end of their 25- to 30-year operational life. Cumulative waste from decommissioned PV modules is projected to reach 2 to 3 million tonnes by 2050, and these figures have the potential to double under high-uptake scenarios (Tan, Deng, and Egan, 2024). The bulk of this waste will consist of glass and aluminium—for instance, projections for 2047 alone include 541,209 tonnes of glass and 116,483 tonnes of aluminium—but there will also be substantial quantities of copper and steel (Mahmoudi, Huda, and Behnia, 2019). These numbers underscore an immediate need for proactive policy frameworks and scalable infrastructure.

Waste volumes are anticipated to peak around the mid-2040s, coinciding with the life-cycle end of PVs that were manufactured during the installation surge in the early 2000s (Mahmoudi, Huda, and Behnia, 2019). Forecasts suggest that cumulative PV waste could reach between 1 and 8 million tonnes by 2060, and the most pronounced increase might occur during the 2040s (Mahmoudi, Huda, and Behnia, 2019). This escalation is not due solely to PVs' natural life-cycle completion; early decommissioning from weather damage, technological upgrades and system repowering also contribute significantly. Similar early retirement trends have been observed in other sectors, including power generation and construction (Fonseca et al., 2013; Fofrich et al., 2020; Mahmoudi, Huda, and Behnia, 2021a; Spišáková, Mésároš, and Mandičák, 2021; Jahan et al., 2022; Fonseca et al., 2023; Shui, Xu, and Luo, 2024).

These projections are underpinned by assumptions about module longevity and degradation patterns. Although linear degradation rates of 0.5 to 1.0 per cent per year remain the standard for c-Si modules (Vázquez and Rey-Stolle, 2008; Andersen et al., 2016; Jordan et al., 2017; Theristis et al., 2023), emerging research increasingly incorporates exponential decay and stress-based models (Zhang et al., 2012; Abunima and Teh, 2020; Nivelle et al., 2021; Alimi, Meyer, and Olayiwola, 2022; Karatas and Gottschalg, 2023;



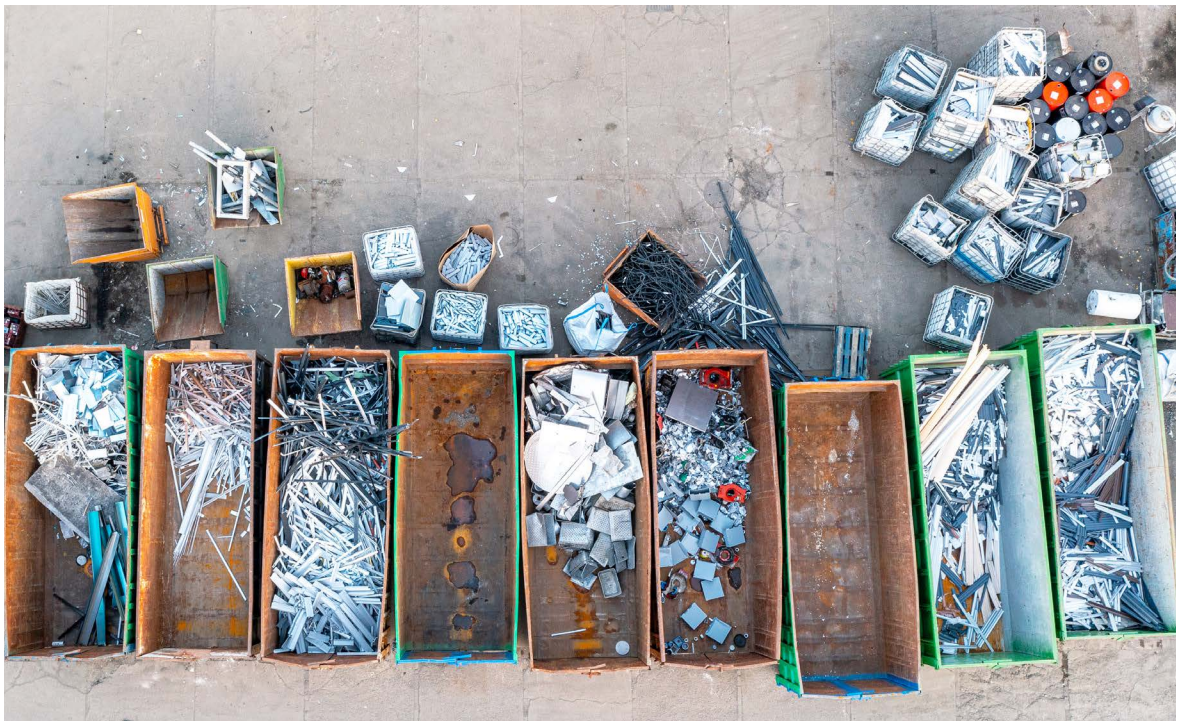
Nam et al., 2025). Factors that are exacerbated by environmental conditions, such as cell cracking and encapsulant browning, are shaping more-probabilistic and more-nuanced lifespan assessments (Jordan et al., 2017; Karatas and Gottschalg, 2023; Theristis et al., 2023).

Australia has developed national forecasting tools based on historical installation data and assumed recovery rates; these tools yielded the projection of 2 to 3 million tonnes of PV waste by 2050 (Tan, Deng, and Egan, 2024). Other countries apply different modelling techniques; for example, India and South Korea use Weibull distribution functions to capture both regular and premature module failures. Researchers forecast that there will be 6.64 million tonnes of PV waste in India by 2040 (Kim and Park, 2018; Jain, Sharma, and Gupta, 2022; Sharma, Mahajan, and Garg, 2024). On a global scale, PV waste could reach 60 to 78 million tonnes by 2050, underlining the magnitude of this issue (Farrell et al., 2020; Venkatachary et al., 2020; Mahmoudi, Huda, and Behnia, 2021a; Ndalloka et al., 2024; Vinayagamoorthi et al., 2024; Yu et al., 2022).

The implications are twofold: Although Australia faces a substantial EoL PV waste burden over the next two decades, this challenge also presents a significant economic and environmental opportunity. If managed strategically, materials recovered from recycling PV waste could meet up to 100 per cent of domestic PV demand for critical inputs, such as silver and aluminium, by 2050 (Tan, Deng, and Egan, 2024), with potential economic returns estimated at $1.2 billion (Mahmoudi, Huda, and Behnia, 2019). Realising this potential would require immediate investment in robust, future-ready recycling systems.

Waste Diversion Potential

Australia's large-scale uptake of PV technology will, inevitably, generate a significant volume of EoL panels and inverters over the coming decades. *Waste diversion* refers to the ability to prevent these materials from entering landfills by redirecting them towards reuse, refurbishment or material recovery



pathways. The strategic importance of this diversion lies not only in reducing environmental harm but also in unlocking material value, reducing reliance on virgin resources and fostering domestic recycling and repair industries (Chowdhury et al., 2020; Florin et al., 2020).

Projections suggest that Australia could accumulate more than 1.16 million tonnes of PV waste by 2035, rising to more than 2.5 million tonnes by 2050 (Madden, Florin, and Salim, 2023; Deng et al., 2024). Without a national mandate for EoL management, most PV panels risk disposal via landfill or stockpiling, particularly in states without e-waste bans (Thou, 2024). As of 2024, landfill bans on PV panels are only in place in Victoria and South Australia, and national-level product stewardship remains under development (Chhillar et al., 2024; DCCEEW, 2026).

Solar panels contain valuable materials—including aluminium, copper, silver and high-purity silicon—alongside potentially hazardous substances, such as lead, antimony and fluorinated polymers. Diverting PV waste through reuse and high-value recycling reduces the environmental impact of virgin extraction and supports circular economy outcomes (Chowdhury et al., 2020; Komoto et al., 2022).

Several studies estimate that more than 90 per cent of materials in PV modules are technically recoverable under advanced recycling processes (Vaqueiro Contreras et al., 2023; Komoto et al., 2022). PV modules are composed of recyclable materials, such as aluminium frames, high-purity glass, copper wiring and silver conductors. Diverting these panels from landfills can mitigate the GHG emissions associated with raw material extraction and energy-intensive refining. For example, recycling aluminium consumes approximately 5 per cent of the energy required for primary smelting (International Aluminium, 2024).

The economic rationale for waste diversion is strengthening. Until 2023, Reclaim PV was one of Australia's few dedicated PV panel recyclers; it demonstrated that, with suitable infrastructure, the recovery of valuable materials (such as silver, silicon and copper) was technically feasible. However, the company ceased operations after being placed into liquidation in September 2023, highlighting the financial and logistical challenges facing the emerging PV recycling sector (Peacock, 2023). Still, a recent analysis estimated that, by 2040, the market value of recoverable materials from EoL panels could exceed $1 billion, highlighting the scale of the opportunity if robust recovery pathways are developed (Salim et al., 2023).

Beyond recycling, functional panels also offer reuse potential in off-grid systems, community electrification and export markets (Florin, Salim, and Madden, 2023; Ashby, 2024). However, Australia lacks a reuse certification framework or consistent technical standards to test and verify second-hand panels, limiting diversion opportunities and contributing to premature disposal (Jensen and Remmen, 2017; Ashby, 2024).

Unlocking the waste diversion potential of PV systems requires a coordinated policy response that integrates circular economy principles with energy-transition planning. With the right measures, Australia can avoid a significant future waste burden while positioning itself as a leader in solar sustainable practices. The essential strategies that need to be in place to maximise the waste diversion potential of PV systems in Australia are as follows:

- national stewardship legislation with clear targets for diversion, reuse and recovery
- investment in recycling infrastructure, including the development of regional recycling facilities equipped to handle increasing volumes of PV waste
- established standards for testing and certifying reused panels to facilitate second-life applications
- digital traceability tools to track product condition, ownership and destination post-decommissioning
- design incentives that reward recyclable materials and modular construction.

Conclusion

PV installations in Australia will continue to grow; thus, it is critical that, in parallel, there is a growth in strategies to manage the waste that will be generated from these installations in the coming years. The information presented on waste diversion potential shows the market value of directing EoL panels into recovery and reuse channels that will provide economic and environmental benefits to Australia.

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CHAPTER 3

The State of the Solar Photovoltaic Circular Economy

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> A circular economy for photovoltaic (PV) systems requires changes across the whole supply chain including promoting circular design and manufacturing of high-quality systems, maximising product lifetimes through maintenance, repair and reuse, establishing high-value recycling, and reducing landfilling.

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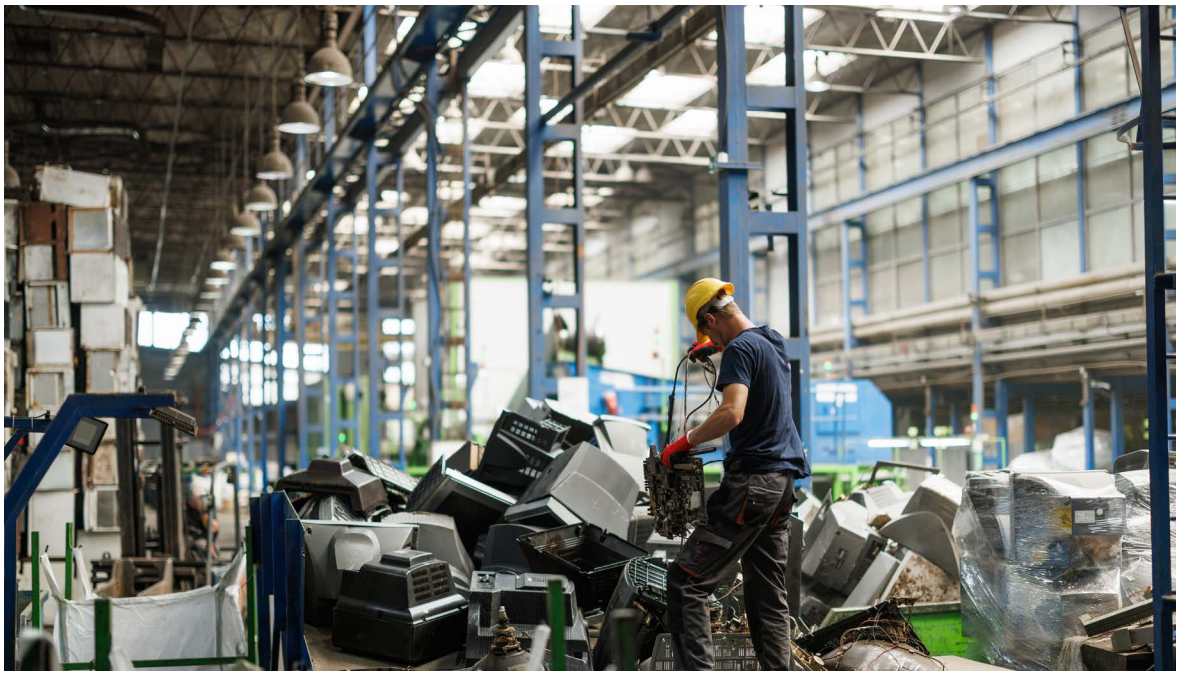
As Australia has significantly increased its PV deployments, challenges emerge with their associated waste. Chapter 2 introduced the state of PV deployment as of March 2025 and briefly described solutions for diverting PV waste from landfills. These solutions explore circular strategies that involve recycling, reusing and redesigning. The circular economy includes these and additional strategies that can represent the best approach for waste diversion.

Research on the circular economy applied to the PV sector is becoming a critical factor in maximising the environmental and economic benefits of solar energy. In this chapter, we present opportunities for integrating circular economy strategies into different stages of the PV life cycle and describe how overseas and Australian companies are already implementing circular solutions, including an Australian case study of the world's first PV certification.

Opportunities for Circularity

The surging demand for PV installation helps to solve energy challenges and supports the transition to a low-carbon society; however, the increased use of PVs also exacerbates social and ecological problems. By 2050, the cumulative mass of EoL PV modules is expected to reach 80 million tonnes globally. Uptake of PV panel recycling faces major challenges because existing approaches for recycling are fragmented and inconsistent despite the Basel Convention's regulation of the transboundary movement of hazardous and nonhazardous waste and classifications for reuse, repair and recycling (Basel Convention, 1989). Transitioning to a circular economy in the PV panel recycling industry is, therefore, essential for achieving long-term sustainability, conserving resources and protecting the environment.

Although the rapid expansion of PV installations in Australia presents a critical challenge, it also provides a significant economic opportunity if the EoL PV panels can be considered a resource instead of waste. Landfilling EoL PV panels means forfeiting PVs' recoverable resource value while increasing dependence on mining virgin materials and missing critical industrial and employment opportunities (Hoffman, 2025). The potential long-term liabilities from landfilling PV waste include the leaching of



hazardous materials into the environment, which can affect human health and the environment (Sinha et al., 2014; Peplow, 2022; Vinayagamoorthi et al., 2024). From an environmental perspective, landfilling PV panels results in estimated emissions of 0.059 kg of carbon dioxide (CO_2) per kilowatt-hour (kWh), whereas sending them to be recycled can reduce emissions to 0.046 kg of CO_2 per kWh by avoiding those emissions associated with virgin material production (Faircloth et al., 2019; Singh et al., 2021; Dias et al., 2022).

Environmental Benefits of Applying a Circular Economy to the Photovoltaics Sector

From a holistic perspective, the environmental impacts of PV panels start with the mining of the materials used in PV modules. Life-cycle assessment (LCA) studies have addressed GHG emissions throughout PV life-cycle stages, showing that the main sources of these emissions occur at the PV material and module production stage because of their fuel and electricity requirements (Fthenakis and Kim, 2011). Therefore, solutions that can reduce GHG emissions at these stages are key. PV EoL solutions, such as reuse strategies, help avoid the need for new PV module production (Kastanaki, 2025), while resource recovery strategies extend the materials' life cycles and reduce the need to mine new materials. Materials recovered from PV panels, such as glass and copper, can also be reintroduced in construction materials (Goh et al., 2024).

The transition to a circular economy for PV systems offers substantial environmental and economic benefits, including a 30-to-50-per-cent reduction in solar GHG emissions (Wikoff, Reese, and Reese, 2022) and energy savings from material recovery; for example, recycled aluminium requires only 5 per cent of the energy that is used to mine virgin materials, and it maintains the same quality (Ansanelli et al., 2021). These sustainability advantages coincide with significant market opportunities. The PV repair sector alone is projected to reach $9 billion by 2025, and achieving economic viability for mechanical recycling depends on reducing processing costs by approximately 30 per cent through technological advances and facility optimisation (Deng et al., 2019; Heath et al., 2020; Heath et al., 2022).

As mentioned previously, it is estimated that, by 2035, Australia will accumulate around 1 million tonnes of EoL PV panels, and the total value of recoverable materials is expected to exceed $1 billion (Deng et al., 2024). The economic opportunity lies in recovering valuable materials—such as silicon, silver, copper, aluminium and glass—from decommissioned panels (Sica et al., 2018; Deng, 2021). Applying circular economy strategies and principles to the solar industry aligns with global environmental efforts, such as UN Sustainable Development Goals 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production) and 13 (Climate Action) (Goh et al., 2024; Heath and Drahi, 2024). Additional benefits can be found in LCAs, which demonstrate that recycling EoL PV modules reduces cradle-to-grave emissions from PV systems (Singh et al., 2021; Peters, Hauch, and Brabec, 2024; Tan, Deng, and Egan, 2024) and reduces reliance on emissions-intensive primary extraction (Faircloth et al., 2019; Deng, Zhuo, and Shen, 2022; Guo, Cheng, and Song, 2025). Emerging recycling technologies are also being trialled to reduce the carbon footprint of recycling processes themselves (Mathur, Singh, and Sutherland, 2020; Walzberg, Carpenter, and Heath, 2021; Bošnjaković et al., 2023; Rahman and Chowdhury, 2023; Kwon et al., 2025). Comparative studies, such as those conducted in South Korea, indicate that recycling offers a markedly lower carbon footprint than landfill disposal (Sharma, Mahajan, and Garg, 2024; Kwon et al., 2025).

Establishing a robust PV recycling and remanufacturing industry in Australia would not only unlock this resource potential but also create jobs in engineering, logistics, manufacturing and research and development (R&D) (Australian Council of Recycling, 2024; Carroll, 2024a; DCCEEW, 2024a). In addition, Australia has a strong potential to export recycled PV materials and components, capitalising on the emerging green markets for sustainable and circular solar technologies (Vaqueiro Contreras et al., 2022), which would enable Australia to strengthen its position in the global renewable-energy supply chain.

Circularity for Photovoltaic Installations: Certification Case Study

An example of an Australian organisation working to enable circularity for PV technologies is the Circular PV Alliance (CPVA), which developed a certification scheme known as CPVA Certified. Most PV circularity initiatives focus on EoL actions, such as recycling or reuse. But PV panels are owned and operated for decades before they reach that point. CPVA's certification scheme helps integrate circular economy principles across the full life cycle of solar farms with a structured process to find practical, effective ways to embed circularity (CPVA, undated).

CPVA's view is that, if solar farms are to be part of the circular economy, they must be customers of it and contributors to it. Such involvement includes using circular inputs where available. Existing options include recycled metals and concrete aggregates (recycled-content modules are not yet common). CPVA Certified encourages developers to seek out circular products and track reused and recycled content in construction.

Operationally, circularity means keeping equipment in service longer. Repair is one path. A recent project by PV Lab Australia, Australia National University and CPVA—funded by the Australian Capital Territory government—tested the longevity of repairs that were made to cracked backsheet and found that they performed well in accelerated ageing tests. CPVA certification encourages such approaches and highlights the role of operational teams in delivering circular outcomes.

EoL PV panels occur because of panel failures, repowering or decommissioning. Therefore, to receive CPVA certification, developers are asked to define EoL steps; examples include training staff to preserve the condition of panels, planning the storage and bulk transport of panels to minimise damage, and selecting reputable EoL managers that have reuse and recycling capabilities. Such steps help grow the services and infrastructure needed for circularity at scale.

Global Examples of Circular Economies in the Photovoltaics Sector

As the CPVA example shows, circular economy solutions include a variety of approaches at each stage of the PV panel life cycle. The circular economy thus relies on a variety of strategies and frameworks that can be integrated into the PV sector at different scales. In recent years, research studies on PV technologies have developed circular solutions mainly around some of the R-ladder strategies for PV circularity and CBMs (Gentilini and Salt, 2019; Tsanakas et al., 2020; Heath et al., 2022; Madrigal, Iyer-Raniga, and Yang, 2023; Rabaia et al., 2024).[1]

However, proposed solutions vary because one solution can be aimed towards different elements within the PV technology. The reduce strategy, for example, has three possible aims in the context of PV panels:

- Decrease the amount of materials embedded in PV modules (Weckend, Wade, and Heath, 2016).
- Decrease the number of new panels needed (Madrigal, Iyer-Raniga, and Yang, 2023).
- Decrease waste or use resources more efficiently (Shaw et al., 2024).

[1] *R-ladder strategies* are hierarchised models for resource use and waste management. While the number of *R*s differ among models, they usually involve sustainable strategies (e.g. refusing, reducing, repairing, recovering) that are organised hierarchically based on their ability to decrease waste production. For example, *refusing* is often a higher-ranked strategy, while *recycling* is often a lower-ranked strategy.



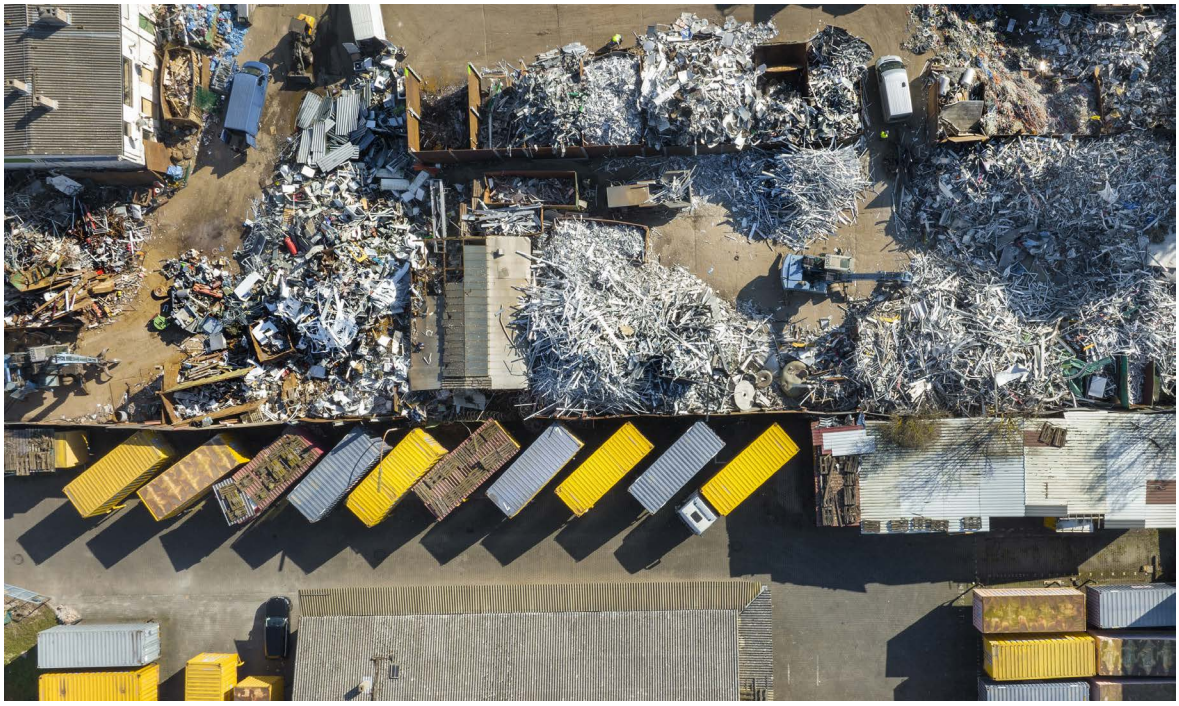
The redesign strategy can be applied in a PV module design with a lifetime of 50 years (Duong, 2023; Dimitriou, Skandalos, and Karamanis, 2024). Nevertheless, these strategies need to be tested in practice, and they require further research before they can be integrated into the market.

A recent innovation in PV circularity is the case of ReModule 1 by Biosphere Solar, a company in the Netherlands that provides the option to purchase a PV module that has been designed with repairability in mind. Its design is modular, and it can be easily disassembled because it avoids the use of lamination processes. Because of its design, the size can be customised, or a customer can choose between 466 Watt-peak (Wp) or 480 Wp PV panels, each with an output warranty of 30 years. Biosphere Solar claims to have made the first repairable and open-source PV panel in the world, and each of the panels has a product passport with manufacturing information and take-back systems in place (Biosphere Solar, undated).

Although recycling is the most used circular strategy (Shaw et al., 2024), recycling and reuse are both feasible solutions to extend the lifespan of PV materials and modules because they are strategies of waste valorisation (Heath and Drahi, 2024; Goh et al., 2024).[2] PV reuse research and practices are gaining momentum. Organisations worldwide are attempting to integrate these solutions into the PV sector, and some countries are undertaking these practices despite a lack of specific regulations (Heath and Drahi, 2024). In Australia, such organisations as the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and CPVA are working on different projects to analyse and standardise reuse and circularity for PV panels (CPVA, undated; Fell and McGregor, 2022). For example, in 2022, a collaboration among Dubbo Regional Council, CSIRO, and the Blue Tribe Company resulted in a PV reuse pilot site that was installed in New South Wales with a 7-kilowatt (kW) PV system that incorporated reused PV panels (Fell and McGregor, 2022).

Another example of PV reuse research and practices involves PV Cycle, a global nonprofit organisation that has been providing advice and consultancy services on PV waste management, including

[2] *Waste valorisation* is the industrial process of transforming waste into useful products through such methods as recycling, reuse and composting.



recycling and reuse strategies, since 2007. They define the waste hierarchy for PV panels as follows (in order of priority):

1. prevention of waste
2. preparing for reuse
3. recycling
4. other recovery
5. disposal (e.g. landfilling) (PV Cycle, 2023).

This waste hierarchy sheds a light on the need to analyse solutions that start with the aim of minimising waste generation and move gradually towards recycling solutions.

PV recycling methods are evolving; many aim to reintroduce recovered materials into the construction sector (Goh et al., 2024) or even use recovered silicon from EoL PV panels in new silicon ingots for batteries and automobile industry materials (Sah et al., 2023). However, these are just a few of the advances in PV recycling; Chapter 5 and Chapter 7 will delve deeper into recent advances and present the latest research.

Conclusion

Circularity for PV technologies is becoming a tangible goal that has the potential to deliver economic and environmental benefits. Design innovations, such as the PV panel developed by Biosphere Solar, offer an ideal model for a circular PV chain, and circularity programs, such as CPVA Certified, bring attention to the system in which PV panels are used, extending the application of circular solutions into the developer's sector. These types of innovations include more than one circular solution, maximising the potential for positive impacts in the environment and the renewable-energy sector.

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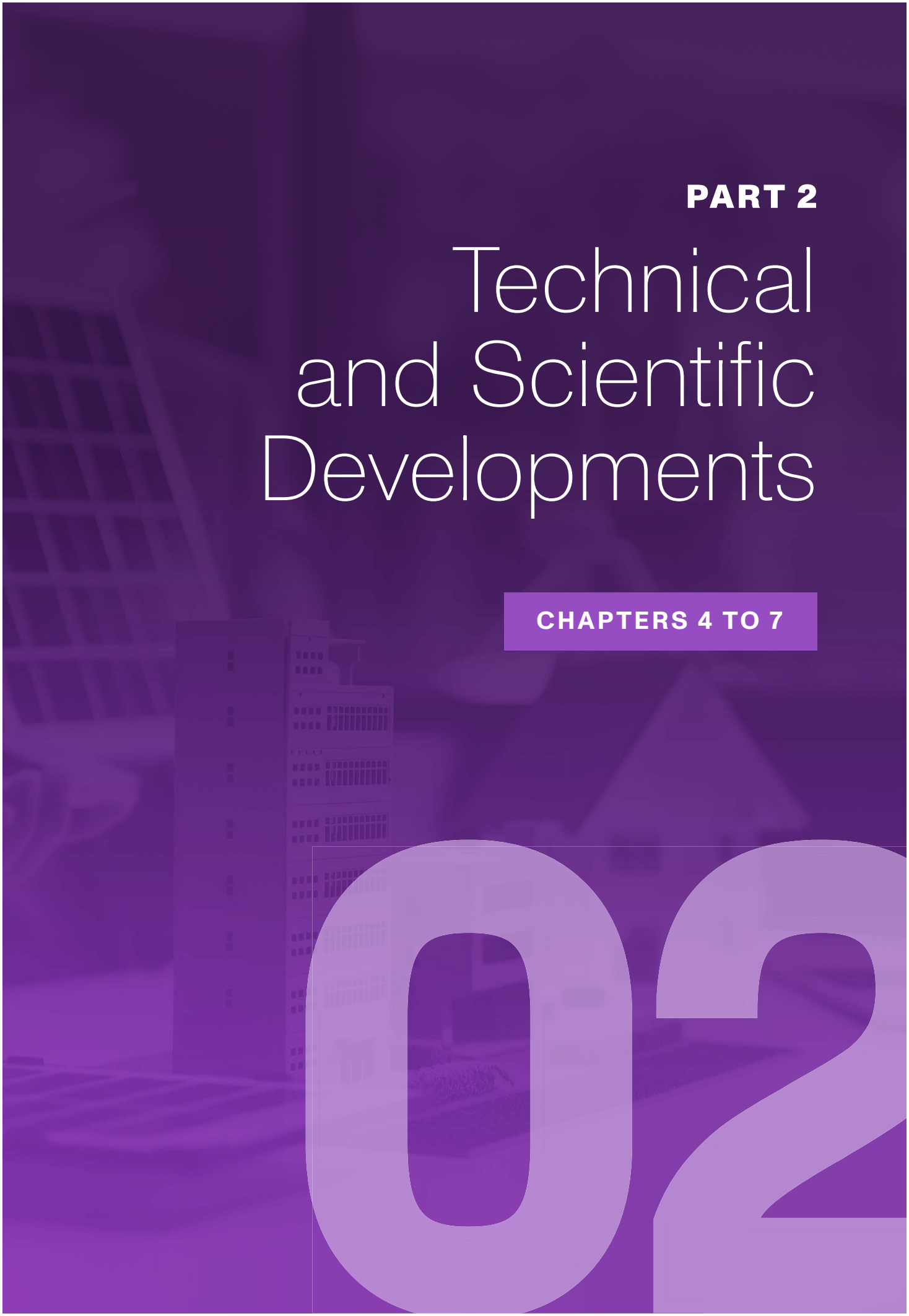
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PART 2

Technical and Scientific Developments

CHAPTERS 4 TO 7

02

CHAPTER 4

The Solar Photovoltaic Supply Chain: Manufacturing and Distribution

Stephen Kennedy, Lathe Jones, Estefanía Artigao Andicoberry, Sergio Martín Martínez, Raquel Villena Ruiz, Andrés Honrubia Escribano, Emilio Gómez Lázaro, Carlos Miralles Sánchez, and Pabasara Wijeratne

> Australia will be competing for supply of PV panels from a global market whilst at the same time disposing of perfectly functional solar panels.
>
> **James McGregor, The Blue Tribe Company**

Over the past decade, global PV manufacturing has shifted significantly from Europe, Japan and the United States to China, which now accounts for more than 70 per cent of worldwide capacity (International Energy Agency [IEA], 2022b). Although China remains dominant, other markets, such as Europe, India and the United States, continue to play important roles, and emerging economies, such as those of Cambodia, Vietnam, Thailand, the Philippines and Saudi Arabia, are increasing their involvement in solar manufacturing (International Renewable Energy Agency [IRENA], 2024). Annual global capacity reached 1.3 terawatt (TW) in 2025 (IEA, 2026), up from 400 GW in 2021 (IEA, 2022b), reflecting growing global demand for solar energy.

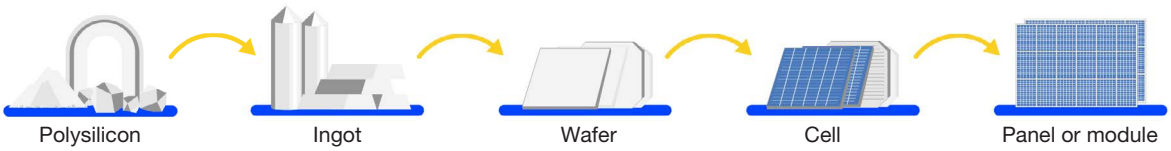
In this chapter, we discuss the supply chain for manufacturing and distributing PVs.

Understanding the Supply Chain

A *supply chain* refers to the series of interconnected processes involved in the production and delivery of a product, from sourcing raw materials through manufacturing or service execution to transportation and delivery to the customer. The key stages in the PV supply chain are depicted in Figure 4.1.

PV modules are made of cells using various technologies. Production begins with refining high-purity polycrystalline silicon (polysilicon) that is derived from metallurgical-grade silicon (MG Si), a commodity obtained from high-purity quartz. About 12 per cent of the world's MG Si is refined into polysilicon for the solar industry. The polysilicon is melted to grow monocrystalline silicon ingots, which are sliced into thin wafers. These wafers are processed into solar cells, interconnected, and assembled between glass

FIGURE 4.1
Key Stages in the Main Manufacturing Process for Solar Photovoltaics



SOURCE: Adapted from IEA, 2022b, p. 7 (CC BY 4.0).

and plastic sheets to form c-Si modules. Currently, China dominates more than 80 per cent of all manufacturing stages—from refining polysilicon, to creating ingots and wafers, to producing solar cells and, finally, PV modules.

Ultimately, the modules need to be placed on mounting structures (also known as racking), and some of these structures include more sophisticated designs that allow for sun-tracking. The energy produced by a PV module is direct current that is almost always converted to alternating current using an inverter.

Global Production Capacity: Key Figures and Trends

The global PV manufacturing landscape is heavily concentrated in China, which dominates both capacity and technological development. According to Wood Mackenzie's 2024 ranking of PV panel manufacturers (Table 4.1), seven of the top ten manufacturers are headquartered in China, and Canadian Solar,

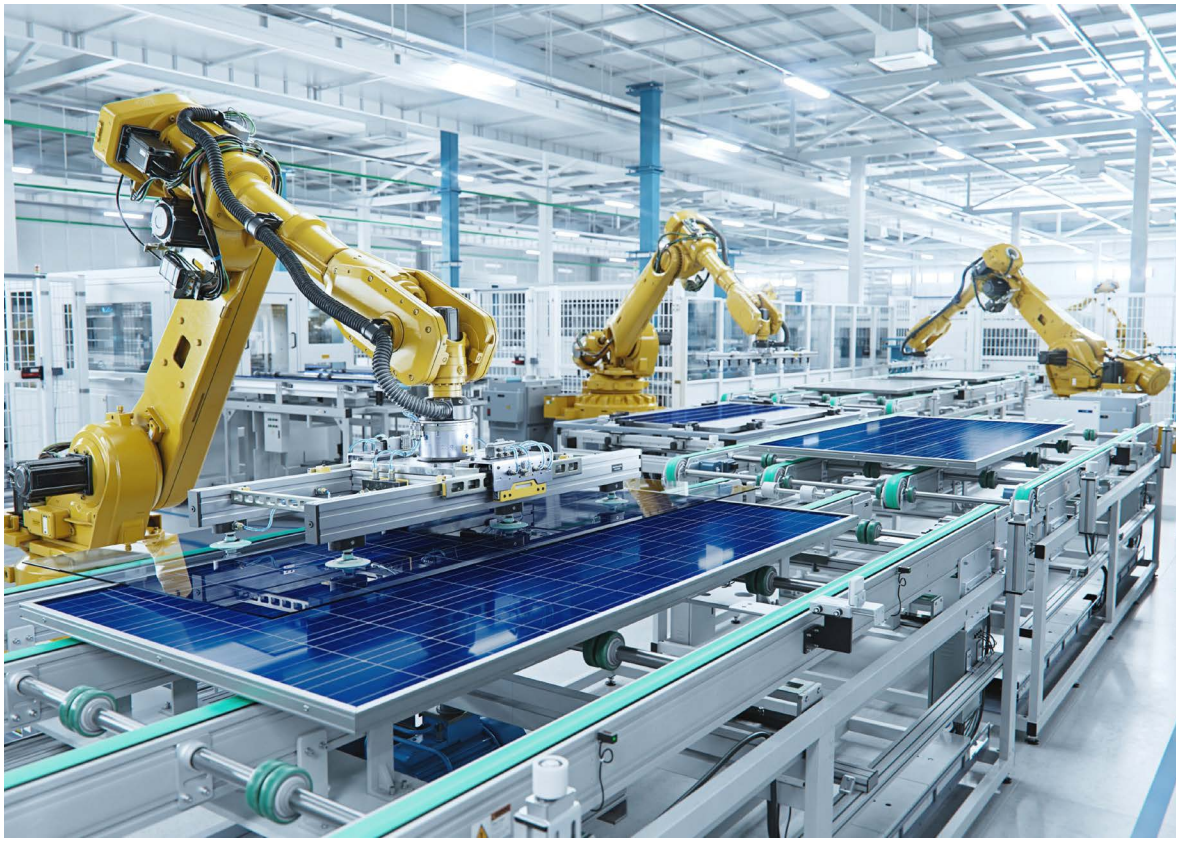


TABLE 4.1
Wood Mackenzie's 2024 Ranking of Photovoltaic Panel Manufacturers

Rank	Manufacturer	Headquarters
1	Jinko Solar	Shanghai, China
2	JA Solar	Shanghai, China
3	LONGi Green Energy	Xi'an, China
4	Canadian Solar	Kitchener, Canada
5	Trina Solar	Changzhou, China
6	DMEGC Solar	Hengdianzhen, China
7	Astronergy	Haining, China
8	Boviet Solar	Bắc Giang City, Vietnam
9	Risen Energy	Ninghai, China
10	Qcells	Seoul, South Korea

SOURCE: Features information from Wood Mackenzie, 2025.

which is technically headquartered in Kitchener, Canada, bases most of its manufacturing operations in China (Wood Mackenzie, 2025). These firms exhibit strong vertical integration, supporting more than 50 per cent of their module production through internal cell capacity, and some can produce wafers or even manage entire supply chains from polysilicon refinement to module production. All top ten manufacturers utilise tunnel oxide passivated contact technology, achieving efficiencies up to 23 per cent when converting sunlight into electricity. Leading producers in 2023 were Jinko (78.5 GW shipped), LONGi (66.4 GW shipped), Trina (65.2 GW shipped) and JA Solar (53.1 GW shipped) (IRENA, 2024).

In 2023, global investment in PV manufacturing reached US$80 billion, and approximately 90 per cent of this investment was allocated to China, doubling the previous year's investment and significantly undercutting costs by 30 to 65 per cent compared with Western markets (IEA, 2022b). China's module capacity reached 1 TW per year in 2023, accounting for about 80 per cent of global production capacity. A polysilicon surplus enabled China to produce enough material for approximately 85 GW of modules as of March 2024, contributing to an annual capacity exceeding 1 TW per year (Feldman et al., 2024). Furthermore, China accounts for more than 95 per cent of global wafer manufacturing investments and nearly all polysilicon capacity expansion.

Although China maintains its dominance, the United States and India are experiencing growth; technological advancements and market expansion are expected to bolster their manufacturing sectors. In addition, many companies are building manufacturing bases in the United States and India to limit their exposure to trade barriers. The EU remains reliant on China for PV manufacturing, importing €22 billion worth of PV products in 2022, while its limited exports are mainly directed towards neighbouring countries (Figure 4.2). Conversely, India is rapidly expanding its PV manufacturing capacity, reaching 44 GW in 2023 and aiming for a total capacity of more than 125 GW by 2027 through government incentives and industry investments (Solar Power Europe, 2024).

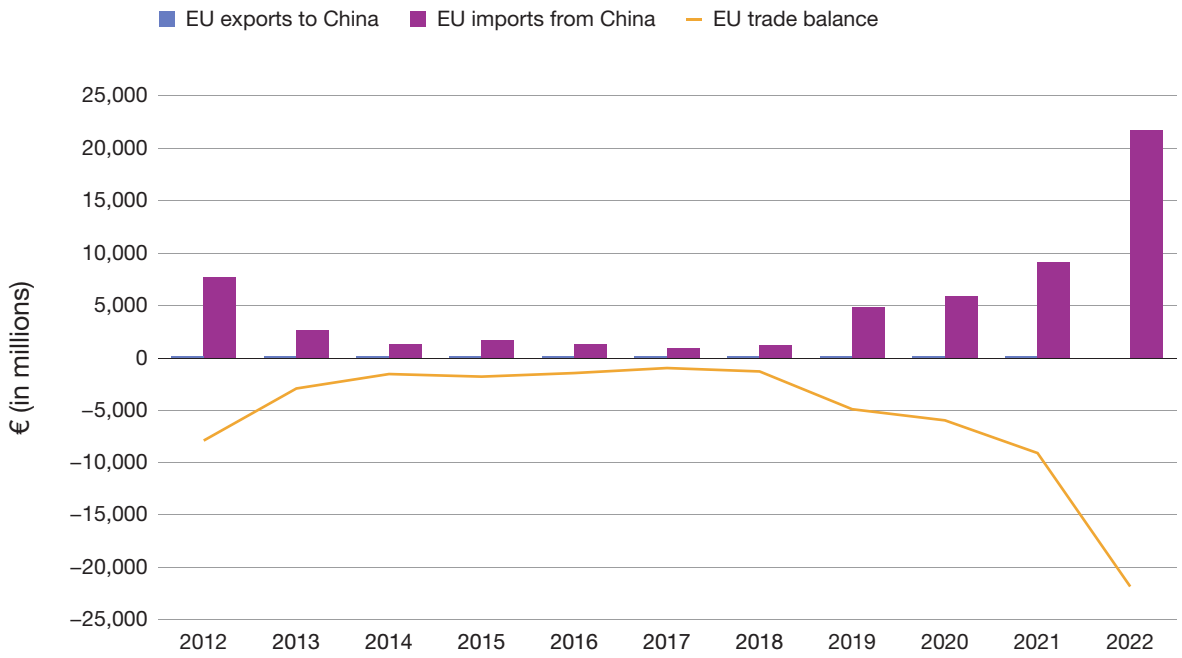
Overview of Photovoltaic Manufacturing in Australia

Australia's PV module manufacturing capacity is in its early stages; as of this writing, it does not produce PV cells on a commercial scale. The Commonwealth of Australia's Solar Sunshot programme, announced

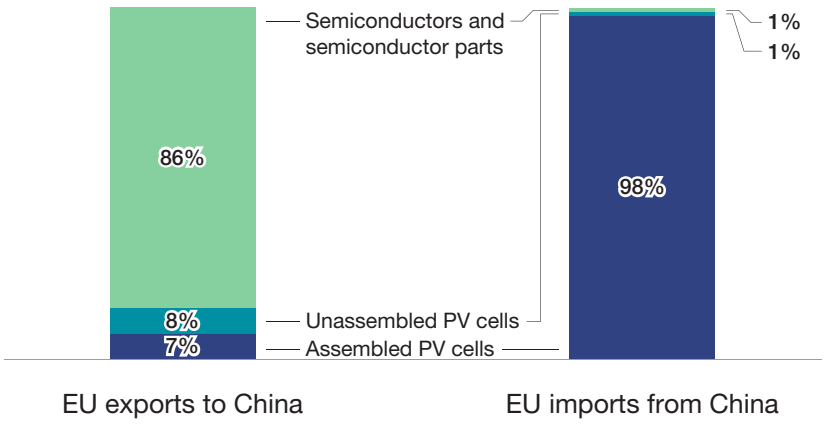
FIGURE 4.2

Trade in Photovoltaics Between the European Union and China

Panel A. European Union Trade with China



Panel B. Share of Traded Goods with China in 2022



SOURCE: Adapted from Chatzipanagi et al., 2023, p. 60 (CC BY 4.0).

in March 2024, plans to invest $1 billion to boost PV module manufacturing, with the aim of achieving 1 TW of installed PVs in Australia by 2050. The investment is modest, given that Australia recorded a trade deficit of approximately $7.3 billion in finished PV panels and components between 2017 and 2021 (IEA, 2022b).

Tindo Solar is the only Australian company that produces PV panels from imported components. Their production facility in Adelaide, South Australia, produces 150 MW annually, but the company has announced plans to build a gigafactory capable of producing 1 GW of panels per year (Tindo, 2024). In June

2025, the company was awarded $34.5 million to, among other things, conduct a feasibility study for the 'Gigafactory'. The feasibility study is not expected to be complete until July 2033 (Tindo, undated).

Sources of Photovoltaic Materials

The supply chains of key materials for PV manufacturing and assembly flow to China, where more than 80 per cent of manufacturing takes place (IEA, 2022b). Virgin materials remain predominant in supply chains because EoL recycling procedures have not matured enough to enable secondary sourcing to meet the manufacturing ramp-up (IEA, 2022b; Sanathi, Banerjee, and Bhowmik, 2024).

Materials of interest for possible supply-chain constraints are aluminium, solar-grade silicon (SoG-Si), silver and copper; other materials, such as plastics and glass, are not as difficult to source and do not represent a significant economic cost ratio of the PV module (SoG-Si and silver make up approximately two-thirds of the module cost) (IEA, 2022b).

Aluminium

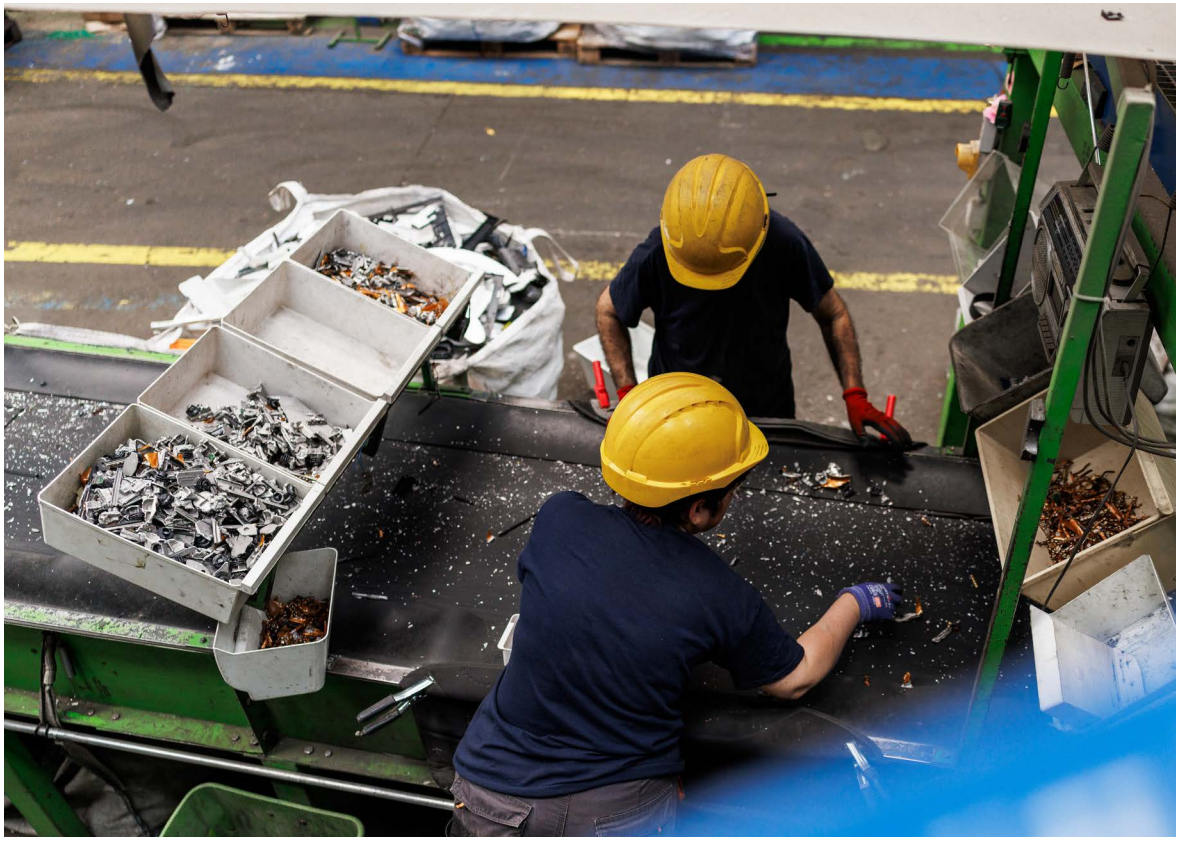
Australia has four aluminium smelters and is the world's sixth-largest aluminium producer (1.6 million tonnes per year), refining local bauxite ore to alumina and then processing it into elemental aluminium. More than 98 per cent of Australian bauxite ore is exported to China instead of being processed into aluminium onshore; $17 billion of bauxite was exported worldwide from Australia in 2024 (Department of Industry, Science and Resources, 2025). On a global level, primary aluminium production is dominated by China (44 million tonnes per year), followed by India and Russia; thus, China is able to supply its own aluminium demand locally. However, China still needed to import aluminium in 2024 because of the 45 million tonnes cap on primary aluminium production imposed by the Chinese government in 2017 (Department of Industry, Science and Resources, 2025).

Silicon

Silicon is an abundant element, and the supply of raw material quartzite (silicon dioxide as sand or pebble quartz) is plentiful and cheap worldwide. Australia produces high-quality silica sand, primarily for the glass industry. Silicon dioxide is converted to SoG-Si, which is at least 99.999-per-cent pure, in an energy-intensive, specialised process that is applied to a monocrystalline silicon ingot (IEA, 2022b). The supply of high-quality SoG-Si from manufacturing facilities is, thus, more critical than sourcing the raw material (silicon dioxide), and this market is dominated by China, which has invested heavily in facilities to produce more than 80 per cent of global silicon materials (U.S. Geological Survey, 2024, pp. 160–161).

Silver

Silver, although present in relatively small quantities in PV modules, is the most expensive material in silicon-based solar cells (Davidsson and Höök, 2017; IEA, 2022b). The primary sources of silver are from mine sites in Mexico, China and Peru (U.S. Geological Survey, 2024; Department of Industry, Science and Resources, 2025). Fifty per cent of silver is co-mined from copper or lead and zinc deposits in these three countries, and the relatively distributed nature of silver production ensures secure supply chains for PV manufacturing (U.S. Geological Survey, 2024). Although only approximately 3.2 to 8 grams of silver are required per m^2 of a PV module, PV manufacturing is price sensitive to silver; in 2020, PV manufacturing accounted for 12.7 per cent of global silver annual production (Hallam et al., 2023).



Copper

Copper is abundant, but production needs to meet the demand from multiple areas of emerging renewable technologies (Kamran, Raugei, and Hutchinson, 2023). Production of copper ores is most prevalent in Chile, Peru, the Democratic Republic of the Congo and China. Australia exported 765 kt (kilotonnes) of copper in the 2024–2025 financial year on a global production of more than 28,000 kt. Refinery production of pure copper is concentrated in China (almost one-half of the worldwide supply), which processes imported ores in addition to its domestic mine supply, ensuring that PV manufacturing supply is met from domestic sources. Copper has a long lifetime and high recyclability, meaning that secondary (recycled) sources will become more available over time (U.S. Geological Survey, 2024, pp. 64–65; Department of Industry, Science and Resources, 2025).

Projected Availability of Metals for Photovoltaics

IEA projections assume a global total installed PV capacity of 6.7 TW by 2030 in order to enable the world to reach a net zero carbon emissions target by 2050.[1] Achieving this scale of deployment implies annual PV capacity additions on the order of 630 GW by 2030, which represents more than a quadrupling of the capacity additions observed in 2020 (IEA, 2022b). These rates of capacity expansion have significant implications for the sustainability of clean-energy supply chains because the demand for raw materials could surpass mining and refining production capacity (IEA, 2022b).

[1] These values are based on IEA's Net Zero Emissions by 2050 scenario (IEA, 2021).

Materials that could be constrained in availability or subject to cost pressures are silicon (SoG-Si and polysilicon), copper (cables, wires, ribbons and inverters), and silver (electronic contacts and silver paste). Other manufacturing components, such as glass, plastics and polymers, are not projected to be constrained in supply, although the price of aluminium might be subject to market fluctuations.

In 2022, the IEA noted that polysilicon was the only 'bottleneck' in an 'otherwise oversupplied supply chain' (IEA, 2022b), but the availability of materials in the coming decades should also be considered. In 2023, silicon, aluminium and copper were designated as *critical raw materials* (Chatzipanagi et al., 2023) in the EU, while in the United States, they are classified as *near-critical materials* (U.S. Department of Energy, 2023). China classified aluminium and copper as *strategic minerals* in 2016 (Andersson, 2020).

Silicon is abundant in its mineral form, although specialised, energy-intensive manufacturing procedures could constrain its conversion to high-purity SoG-Si and polysilicon (Davidsson and Höök, 2017; IEA, 2022b). China's share of global polysilicon manufacturing will soon reach almost 95 per cent—a significant concentration in one country (IEA, 2022b). Polysilicon intensity (i.e. the amount of SoG-Si needed in each PV cell) dropped by a factor of six between 2004 and 2020 because of advances in cell configurations and manufacturing procedures.

Copper is a critical element for renewable-energy technologies beyond PVs because of its excellent conductivity (Kamran, Raugei, and Hutchinson, 2023). By 2030, PV demand for copper could be between 2 and 8 per cent of global production levels in 2012, although the available resources should be able to meet copper demand because of its recyclability.

There is some uncertainty about the future availability of silver, which is considered the material of most concern, because it depends on progress in reducing silver material intensity (Davidsson and Höök, 2017). The silver intensity of cells was reduced by a factor of three between 2009 and 2018 because of improvements in manufacturing and PV cell configurations (Laugharne and Yucel, 2018). However, such significant reductions are unlikely from 2025 onwards; estimates project a further one-quarter reduction in the future. The share of silver production used in solar could rise from 12.7 per cent in 2020 to more than 30 per cent in 2030 (IEA, 2022b). Cumulative silver demand could constrain large-scale PV cell production; however, reductions in silver intensity with new technologies (e.g. using copper or aluminium in place of silver and employing new printing techniques), along with decreasing demand in non-PV sectors, should alleviate this constraint. Taken together, and consistent with the scenario analysis of Lo Piano, Saltelli and van der Sluijs (2019), the most likely outcome is not absolute material scarcity but periods of supply-chain pressure that are driven by the timing of deployment relative to efficiency gains and recycling uptake. Although extreme combinations of rapid capacity growth and slow material-intensity reduction can result in cumulative overshoot scenarios, the central assumption across published scenarios suggests that continued reductions in material use and increases in EoL recovery would substantially mitigate long-term constraints.

The future importance of an EoL recycling industry is key here; its contribution to recycling from 2041 to 2050 could be more than 60 per cent for silver, more than 30 per cent for silicon and more than 20 per cent for copper and aluminium (IEA, 2022b).

End-of-Life Determination Methods

Understanding End-of-Life in Photovoltaic Panels

PV modules are subject to inevitable degradation and failure. The modules have an annual failure rate ranging from 0.15 to 0.25 per cent, while the primary structural components often remain intact (Mao et al., 2024). The IEA estimates that 45 to 65 per cent of modules are suitable for reuse, recovery and

renovation (Pascual et al., 2021). Consequently, adopting standardised design protocols for PV panels is crucial to facilitate their reuse by equipment manufacturers, thereby enhancing circularity within the industry (El-Khawad, Bartkowiak, and Kümmerer, 2022).

The rate of PV panel ageing is highly dependent on both the specific type of PV panel and the geographical conditions in which it operates (dos Santos et al., 2021). With regard to the PV panel type, most manufacturers provide information on the maximum annual decline in electricity output under standard operating conditions. This decline is typically in the range of 1 to 5 per cent in the first year and 0.2 to 0.8 per cent from the second year onwards, as a linear function (Walker and McDevitt, 2025). Recent studies have reported degradation rates of approximately 0.6 to 0.7 per cent each year (Virtuani et al., 2019; Da Fonseca et al., 2020). With regard to operational conditions, researchers have concluded that the ageing effect of PV panels is highly dependent on environmental conditions. Table 4.2 summarises several modes and degradation rates across different countries. Leading causes of degradation include high humidity, extreme ambient temperatures and considerable day-night temperature variations; these causes are reported in Kim et al. (2021) and shown in Table 4.2. According to the National Renewable Energy Laboratory, the most-common degradation and failure modes are

TABLE 4.2
Degradation Rates Reported from Various Countries

Country	Source	Module Type	Degradation Rate (% per Year)	Cause of Degradation
Spain	Martín-Martínez et al., 2019	Poly-Si solar cell	0.8–1.1	Wind speed
Italy	Lovati et al., 2019	Poly-Si solar cell	0.8–1.1	PV-cell shading
Greece	Gaglia et al., 2017	Poly-Si solar cell	0.9–1.13	Ambient temperature, solar irradiation and wind speed
Poland	Jurasz, Dąbek, and Campana, 2020	Poly-Si solar cell	>0.9	Elevated air temperature
India	Chandel et al., 2015	Mono-Si solar cell	1.4	High cell temperature and humidity
Southern India	Thotakura et al., 2020	Poly-Si solar cell	1.3	Air temperature and high irradiance
Thailand	Tongsopit et al., 2019	Poly-Si solar cell	1.5–4.9	Humidity and moisture
Northern Thailand	Dechthummarong et al., 2010	Poly-Si solar cell	1.5	Delamination of EVA sheet
Japan	Teah et al., 2019	Poly-Si solar cell	1.15	Ambient environmental factors
Singapore	Jordan et al., 2019	Poly-Si solar cell	2.0	Ambient temperature
Republic of Korea	Park et al., 2019	Poly-Si solar cell	1.3	Corrosion and discolouration
Scotland, United Kingdom	Dhimish and Alrashidi, 2020	Poly-Si solar cell	1.05–1.16	Extreme low temperature and humidity
Australia	Dhimish and Alrashidi, 2020	Poly-Si solar cell	1.35–1.46	Extreme high temperature and moisture

SOURCE: Adapted from Kim et al., 2021, Table 1.

NOTE: EVA = ethylene-vinyl acetate. EVA is an encapsulant film commonly used in PV panel manufacturing to provide a protective, weather-resistant bond between the solar cells, glass and backsheet.

hot spots (33 per cent), ribbon discolouration (20 per cent), glass breakage (12 per cent), encapsulant discolouration (10 per cent), cell breakage (9 per cent) and potential-induced degradation (8 per cent) (Jordan et al., 2017).

Quantitative Approaches to End-of-Life Estimation

Building on the understanding of EoL considerations in PV panels, this section explores quantitative methods to estimate a panel's lifespan, incorporating performance degradation and economic factors (Bouraiou et al., 2018; Gagliardi and Paggi, 2018; Hocine and Samira, 2019; Sahouane et al., 2019).

In this regard, PV panel efficiency under standard conditions can be calculated as

$$\eta_{25\,^{\circ}\mathrm{C}} = \frac{MPP}{G.S},$$

where G equals irradiance (in W/m^2), S equals the PV panel's surface (in m^2) and MPP equals the maximum power point (in W).

However, when considering the ageing effect, AE, the above formula becomes

$$\eta = \eta_{25\,^{\circ}\mathrm{C}} \frac{AE}{100}.$$

The ageing effect must incorporate the cumulative effects of degradation to a PV module's EVA, glass and wires rather than assuming a linear function. In this regard, the standard ageing effect, AE_{ST}, incorporates EVA, glass and wires as independent ageing factors over n number of years:

$$AE_{ST} = 100 - n_{year}\sqrt{AE_{EVA}^2 + AE_{glass}^2 + AE_{wires}^2}.$$

Although glass ageing is independent, EVA ageing and wire ageing depend on glass ageing and glass and EVA ageing, respectively. Thus, the actual ageing effect, AE_{AT}, becomes

$$AE_{AT} = 100 - n_{year}\sqrt{AE\left(AE_{glass}\right)_{EVA}^2 + AE_{glass}^2 + AE\left(AE_{glass}, AE_{EVA}\right)_{wires}^2}.$$

In a purely economic scenario, an important parameter to determine the actual EoL is based on economic benefits for a maximum investment payback, $Max(Inv_{PB})$, which can be calculated as follows:

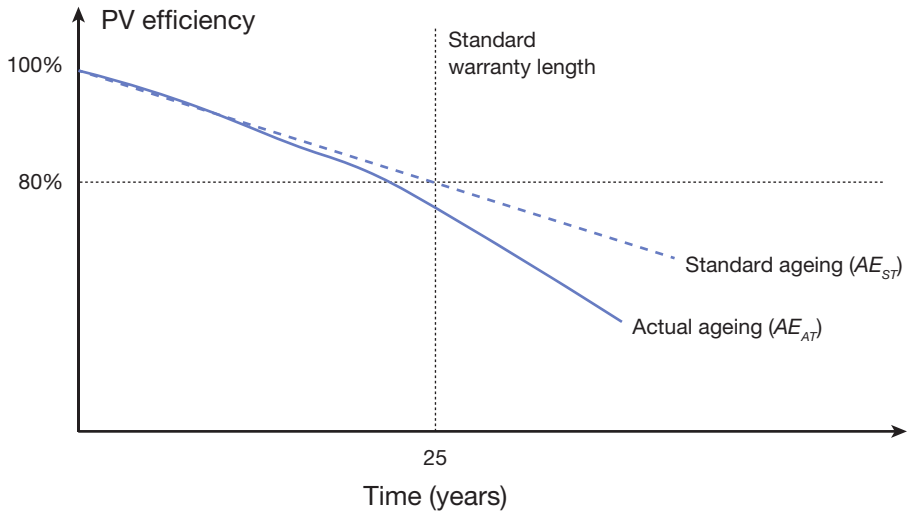
$$Max\left(Inv_{PB}\right) = B_{Eg}\, n_{year} - Inv_{PV},$$

where Inv_{PV} is the initial investment in purchasing PV panels, and the benefit, B_{Eg}, under standard conditions, can be calculated as

$$B_{Eg} = \sum_{n_{year}=1}^{n_{year}=fixed\ lifetime} Eg_{/year} AE_{AT}.$$

Figure 4.3 illustrates the difference between the ageing effect under standard conditions and the actual ageing effect under a harsh climate. Note that AE_{ST} and AE_{AT} begin to diverge long before the average 25-year warranty of a PV panel.

FIGURE 4.3
Standard Ageing Versus Actual Ageing of a Photovoltaic Panel



SOURCE: Adapted from Hocine and Samira, 2019, p. 228.

End-of-Life Feedstock Material Flows

When PV modules enter the EoL phase, they can become a valuable source of feedstock for various industrial applications (Farrell et al., 2020). *Feedstock material flows* refer to the movement and transformation of materials recovered from PV modules at the end of their operational life (Woo, 2020; Bakker, 2024). The recycling process of PV waste begins with the collection and transport of decommissioned or defective modules to specialised facilities where they are inspected and classified by product type (e.g. c-Si, thin-film) (Tsanakas et al., 2020). The panels are dismantled, and the aluminium frames, junction boxes and wiring are recovered as recyclable materials (Savvilotidou, Antoniou, and Gidarakos, 2017; Chowdhury et al., 2020). The module comprises layers of laminated glass, silicon cells, encapsulants and metals, which undergo mechanical, thermal or chemical treatment to separate the materials (Chowdhury et al., 2020). The recovered materials, now refined into usable forms, can be potentially reintroduced into various value chains, including PV manufacturing, electronics and construction (Chowdhury et al., 2020; Bulińska, Sujak, and Pyzalski, 2025; Wei et al., 2025). For example, tempered glass, which accounts for approximately 70 per cent of a PV module's weight, can be reused in the glass industry or in construction materials (Bulińska, Sujak, and Pyzalski, 2025; Wei et al., 2025), and silicon wafers can be processed into MG Si or SoG-Si for new PV modules or electronic components (Tao and Yu, 2015; Lee, Duffy, and Allen, 2025). Despite the high recovery potential of PV waste, inevitably, some residual components, such as contaminated plastics or fine particles, must be safely landfilled or incinerated (Lisperguer et al., 2020). This EoL feedstock material flow supports a circular economy by minimising waste and reducing the need for virgin raw materials.

Loss Quantification

Australia will generate more than 90,000 tonnes of PV waste per year by 2035. The most readily recoverable material from PV waste is the aluminium frame, which comprises an average of 18 per cent of the mass of panel waste (Deng et al., 2024). Using the existing price of approximately $2,000 per tonne for recycled aluminium, this market will be worth a little more than $33 million per year in Australia by 2035.



The most abundant material in PV waste is glass, which can constitute 70 per cent of the mass. Australia has a vibrant glass recycling industry; however, the challenge lies in separating the glass from the other components to make it profitable.

Silver is the most valuable component theoretically recoverable from PV waste. PV waste has an average silver content of only 0.04 per cent, but at an existing silver price of approximately $1,600 per kg, this concentration of silver could equate to nearly $58 million per year by 2035. Similarly, recovering the low copper content (0.8 per cent) in PV waste could be worth around $7 million per year, given the existing copper price of $10,000 per tonne.

Recovered silicon remains a challenging component to find a market for in Australia. With an average silicon content of 3.6 per cent, Australia is on track to generate more than 3,000 tonnes per year of silicon from PV waste by 2035. Researchers are currently focused on recovering silicon from PVs and refining it to nanosilicon to make new PV cells or lithium-ion batteries (LIBs) (Eshraghi et al., 2020; Zhang et al., 2021; Hoseinpur et al., 2023). This approach appears poorly aligned with Australia's current industrial capacity because Australia lacks the industrial capacity for silicon refining, PV manufacturing or battery fabrication.

Australia has an overabundance of MG Si. Simcoa, the only producer of MG Si in Australia, produces 52,000 tonnes per year; however, it exports 85 per cent (Simcoa, undated). This equates to a domestic market of 7,800 tonnes of MG Si per year, at an existing spot price of approximately $4,000 per tonne, totalling more than $30 million. Once the valuable metals have been leached from the silicon recovered from PV waste, it is of much higher quality than MG Si and, thus, theoretically, more valuable. However, there is no market in Australia for silicon other than MG Si and finished products, so this increase in value cannot be captured. There is more than enough annual demand for MG Si in Australia to find an end market for all the silicon recovered from PV waste up to and beyond 2035.



Conclusion

The large-scale deployment of PV technologies introduces complex material-flow and supply-chain challenges that extend beyond module manufacturing. Although absolute material scarcity is unlikely to impose a binding constraint in the medium to long term, short-term pressures are expected to arise from supply-chain concentration, limited domestic processing capacity, and a timing mismatch between the rapid deployment of PV modules and the delayed availability of EoL materials. These dynamics emphasise the importance of early investments in recovery and recycling pathways.

From a circular economy perspective, existing EoL practices reveal both structural limitations and transitional opportunities. The use of recovered PV glass as a low-value aggregate or in road-base products represents a significant downgrade in material value and is widely regarded as undesirable. However, given the low rates of PV recycling, such applications as ElecSome's SolarCrete remain among the few examples of functional material recovery that are practicable in Australia. Although such approaches should not be considered a circular end-state, they could serve as interim pathways that divert material from landfill while higher-value reuse and remanufacturing options are developed.

Recovered silicon presents a similar strategic choice. Although researchers have focused on refining EoL PV silicon for use in batteries or new PV cells, this approach is poorly aligned with Australia's industrial capabilities and is unlikely to deliver short-term circular outcomes. In contrast, the use of recovered silicon in aluminium–silicon alloys represents a more practical and scalable pathway that aligns with existing domestic demand, established alloy production routes and the material quality achievable through PV recycling. On this basis, we recommend that PV recyclers and downstream manufacturers prioritise the integration of recovered silicon into the aluminium–silicon alloy value chains as a realistic and value-preserving circular pathway.

Chapter 4 References

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CHAPTER 5

Closing the Loop: Material Recovery for a Photovoltaic Circular Economy

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> Key to realizing high-value, low-cost recycling will be expanding from delamination-focused recycling technology to include recovery of all metals and identifying highest value target markets.
>
> **Photovoltaic Power Systems Programme, International Energy Agency**

Australia's approach to PV recycling occupies a distinctive position within the global landscape, characterised by an emphasis on chemical-free mechanical recovery methods that prioritise environmental safety and regulatory compliance. Although this approach contrasts with the more–chemically intensive processes employed in European and Asian facilities, it reflects Australia's commitment to sustainable innovation and positions the nation as a potential leader in environmentally conscious recycling methodologies. However, the relative immaturity of Australia's recycling infrastructure, coupled with challenges in achieving high-purity material recovery and commercial-scale throughput, necessitates a comprehensive examination of technical processes, emerging technologies and policy frameworks.

In this chapter, we explore advances in recycling technologies, recovered materials quality and standards, and we offer a glimpse into the benefits of PV material recovery by presenting the results of a TEA.

Overview of Photovoltaic Recycling Processes in Australia

Australian PV recycling facilities follow a multistage process: manual dismantling (removal of junction boxes, cables and aluminium frames), mechanical processing (crushing and shredding), and separation techniques (vibratory screening and magnetic separation) to isolate materials (Carroll, 2024b). Two main approaches—mechanical delamination and full material recovery—are used, although the latter is not yet commercially implemented (Deng et al., 2024).

Companies, such as Lotus Energy and PV Industries, lead such efforts. For example, Lotus Energy opened a Melbourne facility (Lotus Recycling, 2020) that can achieve 100-per-cent material recovery without chemicals, processing panels, inverters and mounting systems (Vorrath, 2021). The adaptation of industrial mixers, grinders and milling systems, originally designed for such sectors as mining and e-waste processing, has gained momentum in recent years. For example, in the state of Victoria, ElecSome operates as a dedicated PV panel recycler, employing mineral processing and mining-derived separation technologies supplied by Vortex Industrial Solutions. Its full delamination process was developed through a university and industry collaboration supported by government funding, resulting in two patented processes—one relates to separating PV backsheets and glass to produce fine powder suitable as an additive in construction materials, such as concrete (Sofi et al., 2024), and the other relates to cement compositions incorporating such fine powders to improve strength and durability via waste utilisation (Al Kobaisi et al., 2024). University of New South Wales researchers developed a mechanical method achieving 99-per-cent recovery, focusing on modular panel design (Carroll, 2024b), and the Western Australian government has committed to funding automated facilities expected to process 22,000 panels annually (Government of Western Australia, 2023). In Queensland, Pan Pacific Recycling promotes the recycling and reuse of PV panels and batteries using environmentally friendly methods and aligning with Smart Energy Council Standards.



Chemical-Free Material Recovery

Australian PV recycling emphasises chemical-free recovery. Unlike European or Asian facilities that use chemical baths or thermal treatments, Australian plants use dry mechanical methods, such as shredding, vibratory separation and optical sorting (Komoto et al., 2022). These methods reduce environmental impacts and simplify regulatory compliance, although they limit the recovery of high-value materials, such as silver and pure silicon (Carroll, 2024b). Using these methods, Australia could recover around 68,000 tonnes of PV materials by 2030—mostly glass, aluminium and copper (Madden, Florin, and Salim, 2023).

Australian recyclers and research groups are increasingly exploring the integration of selective chemical and hydrometallurgical methods, often in hybrid combination with mechanical preprocessing, to improve recovery efficiencies and material purity, particularly for silicon and precious metals.

Material Recovery Breakthroughs

The economic viability of PV recycling depends on optimising the recovery of high-value materials and achieving a sufficient processing scale to offset existing cost barriers. Market projections indicate that there is substantial growth potential as waste volumes increase exponentially over the coming decades. This growth potential stems from the concentrated value within a PV module, in which a thin layer representing only 5 per cent of a module's weight contains more than one-half of its recoverable value (Deng, Zhuo, and Shen, 2022). Processing economics are demonstrating emerging profitability; material recovery generates US$13.62 per m^2 against combined private and external costs of US$12.43 per m^2, yielding a profit margin of US$1.19 per m^2. Revenue distribution reflects this value concentration: Aluminium contributes 46 per cent, silver contributes 25 per cent, glass contributes 15 per cent, silicon contributes 11 per cent and copper contributes 3 per cent. By contrast, this report's techno-economic assessment (Chapter 9), which applies Australian-specific price, material-composition and recovery-yield assumptions, finds silver to be the dominant contributor to recovered-material revenue. Silver recovery optimisation presents the most significant opportunity: A 25-per-cent increase in extraction efficiency is projected to raise total revenue to US$16.22 per m^2 (Fortier et al., 2019; Preet and Smith, 2024).

PV modules retain **silver** content ranging from 0.006 to 0.060 per cent by weight and copper concentrations between 0.6 to 1.0 per cent by weight (Dias et al., 2018). Silver recovery achieves exceptional efficiency; mechanical and hydrometallurgical procedures can concentrate up to 94 per cent of silver (Dias et al., 2016), and methanesulfonic acid (MSA) dissolution can reach 99.8-per-cent purity at optimal 90-to-10 MSA-to–oxidising agent ratios (Gernon et al., 1999; Yang et al., 2017).

Copper recovery varies by technique, from 68.6-per-cent recovery with 99.0-per-cent purity using electrostatic separation (Salama et al., 2018) to 99.0-per-cent recovery in optimised hydrometallurgical processes (Nevala et al., 2019). **Lead** removal achieves 93-per-cent recovery through combined hydroxide precipitation and sulfurisation (Jung et al., 2016). These results demonstrate the technical feasibility of high-efficiency metal recovery from EoL PV modules.

Electrodeposition-redox replacement enables the efficient recovery of trace precious metals, allowing the extraction of silver, gold, platinum and tellurium at concentrations ranging from micrograms per litre to milligrams per litre from hydrometallurgical leachates without requiring preliminary purification steps (Cui et al., 2023). To address mass transfer limitations in conventional electrowinning, cyclone electrowinning eliminates concentration polarisation through enhanced convective mass transport, resulting in superior cathodic product quality, improved metal recovery rates and reduced energy consumption (Rivera et al., 2021). Similarly, pulse electrowinning employs alternating current cycles in which metal

deposition occurs during current-on periods, and current-off periods allow ion concentration restoration near the cathode surface, effectively suppressing concentration polarisation and significantly enhancing both current efficiency and deposit quality (Chandrasekar and Pushpavanam, 2008).

Chemical extraction methods have emerged as highly selective alternatives to traditional electrochemical approaches for precious metal recovery from PV waste. Progress in precious metal recovery from e-waste streams demonstrates the potential for these methods to be adapted to PV applications. An aqueous extraction process using 10 millimolar N-Bromosuccinimide/Pyridine solutions operates at room temperature and near-neutral pH conditions, achieving 90-per-cent gold dissolution yields from electronic materials while eliminating harsh chemical requirements (Yue et al., 2017). This mild approach contrasts with silver processing protocols for which concentrated nitric acid (greater than 35 per cent) provides a complete dissolution of both silver and copper within one to four hours at room temperature (Deng, Zhuo, and Shen, 2022). The scalability of photocatalytic systems has been validated through kg-scale experiments, confirming that catalytic materials maintain effectiveness through more than 100 cycles while achieving greater than 99-per-cent dissolution rates for target precious metals (Chen, Xu, et al., 2021). These advances present economic frameworks applicable to PV processing; photocatalytic materials, such as COP-180, require only a US$5-per-gram investment while recovering approximately US$64 worth of gold per gram of catalyst, establishing a 12.8-to-1 value ratio that indicates the potential financial viability for scaled PV precious metal recovery operations (Hong et al., 2020).

Emerging Recycling Technologies

As PV waste volumes are projected to reach unprecedented levels, advanced recycling technologies have emerged to address the limitations of conventional mechanical and pyrometallurgical approaches.

For **pyrometallurgical approaches**, in the past decade, Swinburne University in Australia has been developing an electrically enhanced silicon refining process using slag to coprocess MG-Si and silicon from solar cells (Putera et al., 2024). These innovative methods focus on maximising material recovery rates, improving processing efficiency and enabling the selective extraction of high-value materials from EoL PV panels (Liu et al., 2024).

Another notable technology is **photocatalytic selective recovery**, which extracts seven precious metals (silver, gold, palladium, platinum, rhodium, ruthenium and iridium) using only light and photocatalysts, achieving more than 99-per-cent dissolution and 98-per-cent purity recovery without requiring strong acids, bases or cyanides (Chen, Qiao, et al., 2021; Chen, Xu, et al., 2021).

There is also **supercritical CO_2 technology**, which reduces delamination time to one-third of that at atmospheric pressure, achieving 3.5 times faster processing rates (Lovato et al., 2021), and **microwave-enhanced separation**, which uses trichloroethylene as the most effective swelling agent to reduce EVA layer separation to two hours (Pang et al., 2021). Additionally, **thermal delamination** has evolved beyond basic heating to address polymer removal challenges in PV recycling. Wang et al. (2019) developed a two-stage process removing Tedlar at 150°C for 5 minutes, followed by 500°C pyrolysis for complete EVA removal, achieving more than 99-per-cent polymer elimination.

Alternative approaches include a **laser irradiation method** for gentle EVA separation without cell damage and minimal emissions (Li et al., 2022) and a high-voltage pulse technology that achieves US$0.0019-per-watt processing costs with high recovery rates (Akimoto, Iizuka, and Shibata, 2018). Additionally, **combined chemical-thermal approaches** enable rapid dissolution and mechanical removal of EVA (Xu et al., 2021; Isherwood, 2022) with enhanced solubility techniques that accelerate processing from days to hours (Deng, Zhuo, and Shen, 2022).

Modern PV recycling has evolved from basic material recovery to a sophisticated value-driven process. Automated systems, such as Veolia France's pioneering facility, demonstrate that integrated processes combining grinders, eddy current separators and optical sorters can achieve greater than 95-per-cent material recovery within 1.0 to 1.5 minutes per module (Deng, Zhuo, and Shen, 2022). Because no single sorting technique can fully separate all materials (Deng, Zhuo, and Shen, 2022), advanced systems now integrate multiple sorting technologies with innovative electrowinning processes that couple traditional methods with fuel cells, bioelectrocatalysis, slurry electrolysis, photoelectrocatalysis and electrodeposition-redox replacement (Fathima et al., 2022). These systems represent a shift from mass recovery, which processes PV modules for low-value reuse (Stolz et al., 2017), towards value-recovery processes that focus on reclaiming high-value components, including such critical elements as silicon, silver and copper (Deng, Zhuo, and Shen, 2022).

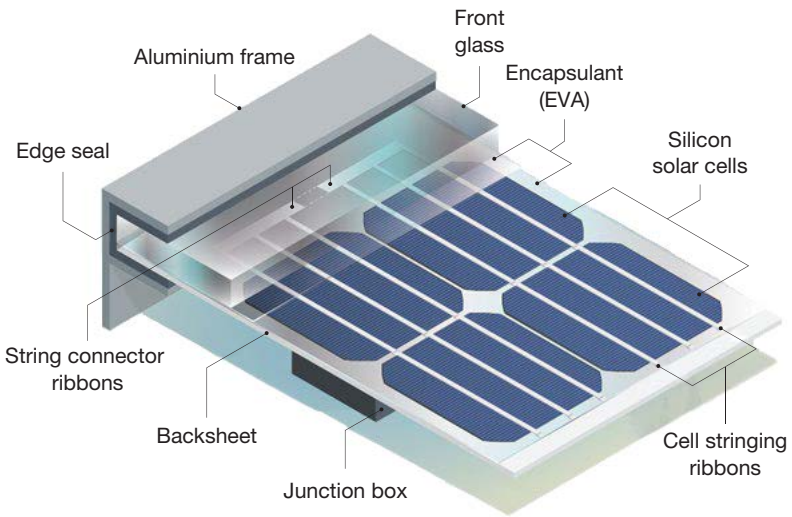
Polymer Synthesis: Challenges for Use in Photovoltaic Panels

Polymers are used for different purposes in PV panels, including the encapsulation of solar cells using EVA, the binding of various layers and protection against environmental effects (Figure 5.1) (Czanderna and Pern, 1996).

EVA is the most widely used polymer with elastomeric and shock-absorbing properties. This makes it a suitable candidate for an encapsulant that can protect the fragile silicon wafer-based solar cells from external mechanical shocks and serve as a transparent adhesive for holding together the different layers of a PV panel: the cover glass, encapsulated solar cell network and polymeric backsheet. Polyurethanes have also been used as an encapsulant, but EVA remains the dominant polymer. For environmental protection against moisture, gases and other chemicals, the backside is laminated with a sheet of fluorinated polymers, polyesters, or a combination of both. The most commonly used laminates are

FIGURE 5.1

Schematic of a Crystalline Silicon Solar Panel Wherein Solar Cells Bonded with Ethylene-Vinyl Acetate



SOURCE: Adapted from Huang et al., 2022, p. 3.

polyvinyl fluoride (PVF) or DuPont's Tedlar PVF film (DuPont, 2020), polyvinylidene fluoride (PVDF) and polyethylene terephthalate (PET). Often, PVF and PET are used in the TPT (Tedlar/PET/Tedlar) laminate configuration. It is worth mentioning that the useful encapsulating properties of EVA also become a barrier in recycling because of the difficulty of delamination on its crosslinking and its strong bond with glass, solar cells and backsheets (Chitra, Saini, and Kumar, 2022). Therefore, EVA grades or alternative polymers need to be designed to ensure good encapsulating performance during service and easy recycling. Similarly, for backsheets, better grades of or substitutes for PVF, PVDF and PET are required to facilitate recycling without compromising the chemical protection of the panel.

Depolymerisation of Polyethylene Terephthalate and the Recovery and Purification of Metals

Depolymerisation of PET and the recovery and purification of metals from EoL PV panels are important aspects of waste management and resource recovery.

PET is present as a backsheet constituent and can be either recycled via melt processing or subjected to depolymerisation to recover its constituent monomers (terephthalic acid and ethylene glycol). Various chemical methods are available for PET depolymerisation (e.g. hydrolysis, glycolysis, alcoholysis, aminolysis), resulting in the formation of monomers or derivatives of terephthalic acid for other chemical uses or repolymerisation into PET. Nevertheless, although large-scale depolymerisation requires carefully controlling conditions and is a bit expensive, it allows the reforming of any quality or grade of PET, even better than that of the original PET backsheet. It is important to note that designing backsheets based purely on PET grades or the use of easily processable grades of backsheet is considered a crucial factor for enabling the facile recycling and recovery of polymeric fractions. The recovery of valuable metals (such as aluminium, copper, silicon, silver, lead and tin) from the EoL PV panel is another crucial objective of the circular economy chain (Jung et al., 2016). Recovery includes various mechanical, thermal and chemical operations or a combination of operations following the principles of metallurgy. To make recycling easier and to reduce environmental impacts, it is best to use less costly, lower-toxicity and easily reprocessable metals. Some examples include using less lead, using lead-free solders and (possibly) replacing silver or coated copper-based busbars. Additional innovations and possibilities are expected to emerge in the future.

Silicon Recovery and Purification

Crystalline silicon PV panels contain approximately 5 to 6 per cent silicon by weight that is embedded within a complex matrix composed of such materials as tempered glass (70 to 75 per cent), EVA encapsulants (10 to 15 per cent), metallic contacts (0.05 to 0.10 per cent silver and 1 to 2 per cent aluminium) and polymer backsheets. Recovery and purification require multistage processes that combine mechanical, thermal, chemical and metallurgical treatments. An analysis of the patent landscape from 2009 to 2025 reveals a technological evolution from manual disassembly and simple chemical etching to fully automated integrated systems that achieve more than 95-per-cent material recovery (Fallavollita, 2009; Madhesh et al., 2024; Mahapatra et al., 2025).

Chemical treatment methods dominate the patent literature; 61 per cent of patents employ acid or alkali etching because of the moderate capital costs (which are between US$0.5 million to $2 million for 1,000-tonne-per-year facilities), established infrastructure and 95-to-98-per-cent metal recovery rates. Sequential chemical recovery typically involves ball milling, followed by a sodium hydroxide treatment

to dissolve aluminium back contacts, and then nitric acid leaching to extract silver, achieving more than 95-per-cent recovery (Huang et al., 2022; Liu and Wang, 2022). Processing costs range from US$6 to $10 per kg of silicon, including reagents, labour, energy and waste treatment. These methods achieve 99.0-to-99.5-per-cent silicon purity that is suitable for metallurgical applications but generate 5 to 15 litres of wastewater per kg of silicon, which requires neutralisation and metal precipitation.

Thermal methods offer an alternative pathway, requiring a capital investment of US$1 million to $3 million for a 1,000-tonne-per-year capacity and energy consumption of 1.5 to 3.0 kWh per kg. These processes produce no liquid waste, reducing environmental compliance costs by approximately 40 per cent compared with wet chemical processes (Jung et al., 2020; Yang et al., 2024). There is a two-stage thermal treatment at 220°C to 240°C that separates glass from silicon using diamond wire cutting, followed by an elevated temperature treatment (between 500°C and 600°C) to volatilise EVA completely. Operational challenges include maintaining precise temperature control (at ±10°C) to prevent silicon oxidation.

Advanced halogenation processes achieve the highest purities (between 99.99900 and 99.99999 per cent) through iodide or chloride chemistry. Silicon reacts with silicon tetraiodide vapour at 1,250°C to 1,500°C, forming gaseous silicon diiodide, which deposits in a fluidised bed at 700°C to 1,000°C (Lim et al., 2024). However, these methods require capital investment of US$5 to $15 million for commercial-scale facilities and have processing costs of US$15 to $25 per kg, limiting their application to semiconductor and premium PV markets.

Another method is metallurgical refining through vacuum melting at 1,450°C to 1,550°C, followed by directional solidification to exploit impurity segregation based on partition coefficients. The physical separation of high-purity silicon (the bottom 70 to 80 per cent of an ingot) from impurity-enriched sections achieves 99.999-per-cent purity that is suitable for solar cell applications (Jeyakumar et al., 2024). Zone refining with radio frequency heating at 10-to-50-millimetres-per-hour traverse rates can produce semiconductor-grade silicon (at 99.99999-per-cent purity) after five to ten passes, although the total energy consumption of 8 to 12 kWh per kg limits its economic viability to high-value applications.

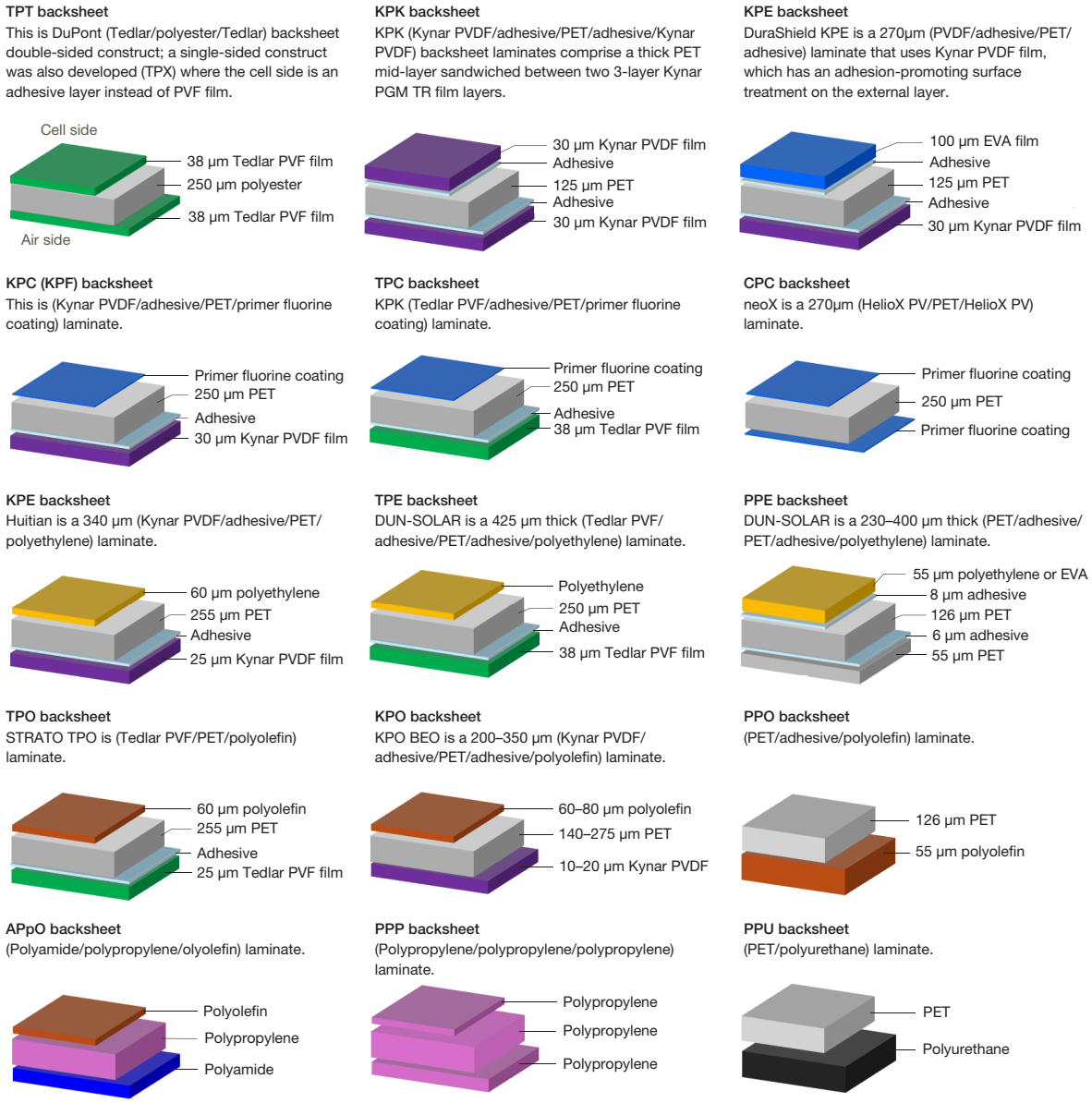
For the Australian context, in which dry mechanical methods are favoured over chemical approaches, integrated multistage purification systems offer promise. Systems that process 2,000 to 5,000 panels daily with automated disassembly, thermal delamination in three-zone conveyor ovens, mechanical crushing, screening, magnetic separation and chemical treatment achieve 95-per-cent material recovery with a silicon purity greater than 99 per cent (Li et al., 2023). These systems align with facilities (such as PV Industries and Sircel in Parkes, New South Wales) that emphasise automated processing with minimal chemical inputs.

Fluoropolymer Backsheet Treatment and Recovery

Polymeric materials in PV modules comprise 3 to 10 per cent of total module weight, translating to approximately 2,500 tonnes of polymer per GW of installed capacity. Backsheet configurations fall into two categories: (1) fluoropolymer-based designs, such as TPT and KPK (Kynar-PET-Kynar), which use PVF or PVDF for superior weatherability, and (2) fluoropolymer-free constructions, such as PPE (PET-PET-EVA) (Czanderna and Pern, 1996; Geretschläger, Wallner, and Fischer, 2016). Figure 5.2 illustrates a structural comparison of commercial fluoropolymer-based PV backsheet configurations. These backsheets exhibit considerable variation in their layered architectures, which increases the complexity of EoL processing and presents significant challenges for the recycling industry.

FIGURE 5.2

Structural Comparison of Commercial Fluoropolymer-Based Photovoltaic Backsheet Configurations



SOURCE: Adapted from Chunduri, 2025.
NOTE: PGM = pigmented; TR = thermally rearranged.

Fluorinated polymer backsheets present significant EoL challenges. During thermal degradation, they release toxic hydrogen fluoride and carbonyl fluoride, produce fluorinated hydrocarbons in pyrolysis oils and increase the potential formation of dioxins (emissions that exceed permissible regulatory limits and pose serious environmental and health hazards) (Aryan, Font-Brucart, and Maga, 2018; Danz et al., 2019). These backsheets also incorporate 6 to 20 per cent titanium dioxide as white pigment, which complicates recovery by contaminating both char fractions and ash during thermal treatment.

Thermal treatment remains the most widely implemented method, with incineration requiring minimum temperatures of 850°C (or 1,100°C for halogenated waste) to combust EVA encapsulants and

polymer backsheets. Energy recovery through combined heat and power systems is possible, although extensive air pollution control systems are required to capture hydrogen fluoride emissions, dioxins and heavy metal particulates (Komoto et al., 2018). Pyrolysis at 550°C in controlled atmospheres decomposes EVA and fluoropolymer backsheets to produce gas, oil and char fractions; however, this approach proves viable only for fluorine-free backsheets because fluorinated polymers generate pyrolysis oils that are heavily contaminated with fluorinated hydrocarbons.

Chemical solvent–based methods represent a gentler approach, employing organic solvents (such as toluene, toluene-xylene mixtures or ethylene glycol) to swell or dissolve EVA at ambient or elevated temperatures (Kang et al., 2012). The crosslinked nature of EVA (with a gel content of 60 to 80 per cent after manufacturing, which increases to 85 to 96 per cent in field-aged modules) limits dissolution in organic solvents. Recent innovations include ionic liquid approaches using organic acids and bases that dissolve PVF and PVDF layers at mild conditions (e.g. 60°C to 70°C for 5 to 10 minutes), substantially decreasing organic solvent consumption while enabling material recovery rather than destruction (Sofi et al., 2024).

Mechanical approaches have emerged as alternatives to thermal and chemical methods. Heated blade technologies employing resistively heated metal wires thermally separate EVA layers through localised heating rather than bulk thermal processing (Yu and Li, 2013). Cryogenic embrittlement using liquid nitrogen makes composite materials brittle for subsequent pulverisation and vibratory separation (Park, 2019). These mechanical methods align with Australian industry preferences for dry processing, although they remain largely at a pilot scale for complete fluoropolymer recovery.

The fundamental incompatibility between fluoropolymer durability and recyclability has led researchers to conclude that fluoropolymers should be avoided in PV module design where possible or clearly labelled to enable separation from other plastic waste streams during EoL processing (Danz et al., 2019). Design-for-recycling approaches favouring PET-based backsheets and reversible encapsulant formulations represent the most promising pathways towards truly circular PV systems.

Silver Recovery from End-of-Life Solar Panels

Each silicon solar cell contains approximately 0.1 grams of silver, and, with global installations exceeding hundreds of GW, the cumulative silver content represents significant economic and environmental recovery potential. Global silver reserves are estimated at 530,000 tonnes, and industrial demand consumes nearly 60 per cent of annual production, of which the solar industry accounts for more than 9 per cent (Tao, 2021). As discussed earlier, silver contributes approximately 25 per cent to the total material recovery revenue despite comprising only 0.006 to 0.060 per cent of panel mass by weight, making the efficient recovery of silver critical to recycling economics.

Panel Disassembly and Pretreatment

Before silver extraction can commence, PV panels must undergo systematic disassembly to access the embedded silicon wafers. Standard panel architecture consists of an aluminium frame, tempered glass cover, two layers of EVA polymer encapsulant, silicon wafers with silver electrodes, copper leads and a polymer backsheet (Gao et al., 2024). Comprehensive recycling solutions facilitate the disassembly of these complex structures through sequential processes beginning with the mechanical removal of the aluminium frames and junction boxes, followed by a thermal treatment at 550°C for 30 minutes. This temperature has been optimised through systematic studies demonstrating that lower temperatures (between 300°C and 400°C) leave backsheets intact, while temperatures exceeding 600°C cause glass embrittlement and fracture.



Innovative dual-purpose thermal delamination has been developed whereby heating the PV module to 300°C to 600°C under nitrogen or air for 1 to 5 hours degrades the EVA polymer and generates an acetic acid fume as a decomposition byproduct. This acid can be captured through water or alkaline scrubbing and subsequently used as the primary reagent for silver dissolution, eliminating the need for externally sourced acids (Gao et al., 2024). Alternative green solvent approaches using a trisodium phosphate solution in hydrothermal processes at 180°C to 200°C separate the front EVA layer with the attached silver grid lines intact, enabling physical recovery without chemical dissolution (Lin et al., 2025). Supercritical dissolution fluids, such as supercritical carbon dioxide or n-butanol under high pressure and temperature, have also been reported to effectively dissolve EVA encapsulant in PV panels, enabling the clean separation of valuable components (e.g. glass, silicon, metals) without high-temperature damage or harmful byproducts and offering a green, efficient and potentially cost-effective alternative to traditional thermal or solvent-based methods for achieving high-purity material recovery, particularly of silicon and silver (Wang, Ma, and Wang, 2024).

Silver Dissolution Methodologies

The patent literature reveals four distinct chemical approaches to silver dissolution: mineral acid leaching, organic acid systems, mixed acid formulations and emerging green solvent technologies. Nitric acid leaching represents the most established method, and, in optimal conditions, it typically employs a 1.5-to-3.0-per-cent nitric acid solution at 50°C to 60°C for 2 to 6 hours to dissolve surface silver electrodes through oxidation to silver nitrate (Su and Liu, 2016). The reaction mechanism depends on acid concentration, proceeding as either $Ag + 2HNO_3 \rightarrow AgNO_3 + NO_2 + H_2O$ or through alternative pathways at different concentrations.

Organic acid systems represent a significant advancement towards environmentally sustainable processing. Acetic acid (50 per cent by weight) mixed with hydrogen peroxide (15 per cent by weight) achieves silver dissolution effectiveness comparable to 35-per-cent-by-weight nitric acid while

exhibiting selectivity for silver over aluminium and copper; aluminium dissolution is reduced from 45.1 ppm (nitric acid) to 13.1 ppm (acetic acid system), and copper is reduced from 65.3 ppm to 18.1 ppm (Gao et al., 2024). The mechanism involves formation of peracetic acid as the active oxidant. Methanesulfonic acid combined with hydrogen peroxide offers another biodegradable alternative, achieving approximately 95-per-cent silver leaching rates with 40 per cent methanesulfonic acid and 10 per cent hydrogen peroxide at 70°C (Zhang and Su, 2017a; Zhang and Su, 2017b). The reaction mechanism depends on acid concentration, proceeding as either $Ag + 2HNO_3 \rightarrow AgNO_3 + NO_2 + H_2O$ or through alternative pathways at different concentrations.

Mixed acid formulations address the simultaneous removal of multiple material layers. Nitric acid–hydrofluoric acid mixtures (nitric acid at 10 to 15 per cent and hydrogen fluoride at 3 to 5 per cent) achieve synergistic dissolution of the aluminium paste layer while simultaneously etching silicon nitride antireflective coatings, releasing silver ions within 60 to 90 minutes at room temperature (Li, Gong, et al., 2025). Deep eutectic solvents using choline chloride dissolved in ethylene glycol combined with oxidisers, such as ferric chloride, represent an emerging paradigm, providing a high chloride ion concentration that complexes with silver chloride to form soluble $[AgCl_2]^-$ species in an environmentally benign medium (Pan et al., 2025).

Silver Purification and Recovery Technologies

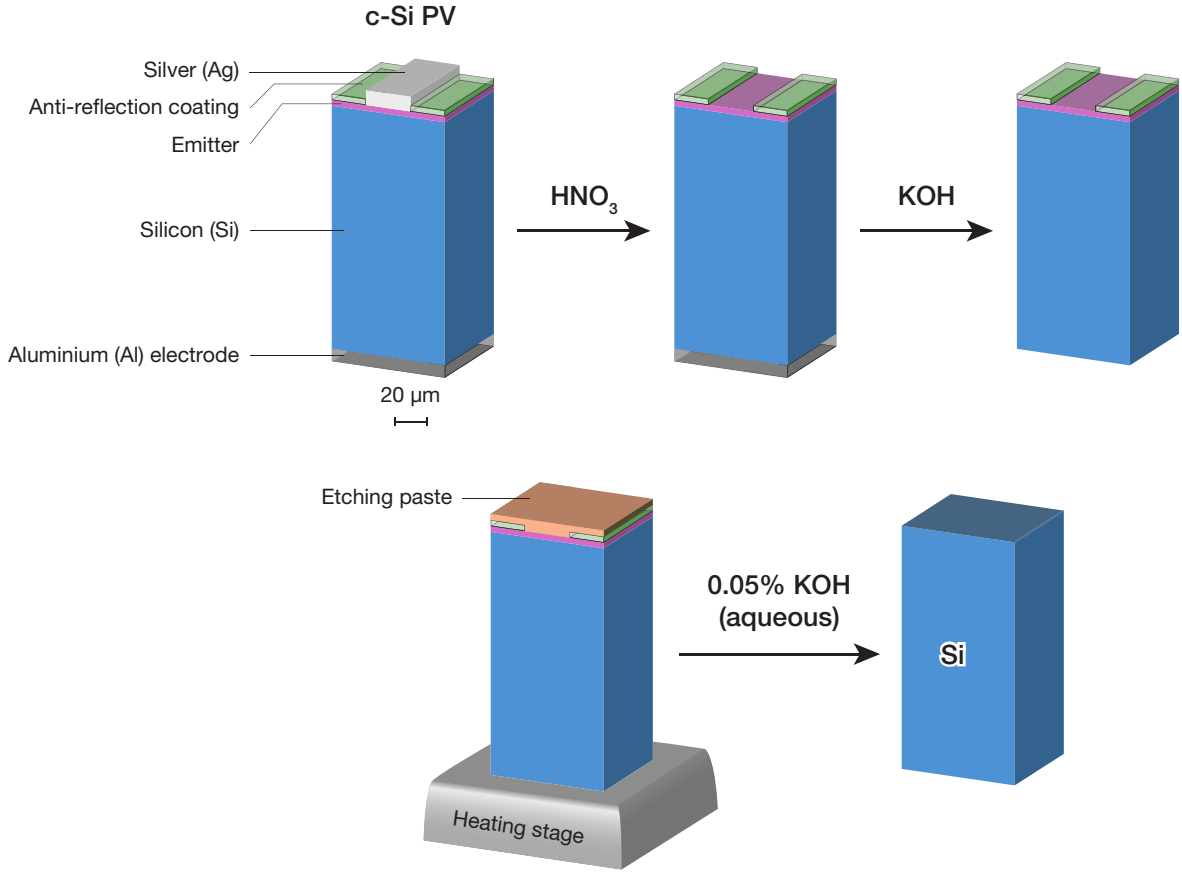
Three principal approaches dominate silver recovery from leachate solutions: chloride precipitation with chemical reduction, electrowinning and emerging laser-assisted nanoparticle synthesis. Chloride precipitation involves adding sodium chloride, hydrochloric acid or hydrochloric-acid–hydrofluoric-acid mixtures to precipitate silver chloride, followed by a reduction to metallic silver using hydrazine hydrate (50 per cent at 50°C to 60°C), zinc powder displacement or ascorbic acid in ammonia solution (Su and Liu, 2016; Wang, Fu, and Xiong, 2015). These methods achieve purities of 99.6 to 99.9 per cent. In another method, silver and aluminium were first extracted through immersion of the silicon wafers in a nitric acid solution (60 per cent) at room temperature for 5 minutes, followed by an immersion of the silicon wafers in a potassium hydroxide (KOH) solution (45 per cent) at 80°C for 8 minutes to extract the aluminium. Figure 5.3 presents a schematic of the processes (Shin, Park, and Park, 2017).

Electrowinning offers direct metal recovery without intermediate precipitation. Three-electrode systems comprising graphite anodes with polypropylene mesh sheaths, silver cathodes and silver/silver chloride reference electrodes achieve silver deposition at a constant voltage of −0.6 volts (V). From acetic acid-based solutions, sequential electrowinning enables recovery of both silver (at 0.7 to 1.2 V) and copper (at 1.2 to 2.0 V). Pulse laser irradiation represents an innovative fourth-generation approach, reducing silver ions directly to nanoparticle aggregates with particle sizes of 1 nanometre to 1 µm and purity exceeding 99 per cent, suitable for conductive ink and electronic paste applications (Jung, Jung, and Heo, 2023).

The evolution of silver recovery technologies demonstrates a clear progression towards improved selectivity, reduced environmental impact and process integration. First-generation approaches achieve 95-to-96-per-cent recovery with 99.6-to-99.9-per-cent purity but generate significant acid waste and toxic nitrogen oxide emissions. Second-generation mixed acid systems reduce the number of process steps while achieving room-temperature processing. Third-generation innovations focus on closed-loop processing in which decomposition byproducts serve as dissolution reagents. Recovery rates consistently exceed 93 to 96 per cent across configurations, and product purities of 99 per cent or higher are achievable through the appropriate purification pathways.

FIGURE 5.3

Schematic Diagram of Recycling Processes to Remove the Silver, Aluminium, Anti-Reflection Coating and Emitter Layer from the Wafer Surface



SOURCE: Adapted from Shin, Park, and Park, 2017, Figure 2.

Automation Potential in Solar Panel Recycling

Automation has emerged as a critical enabler to meet the high throughput, material recovery rates and economic viability necessary to process the anticipated surge in PV waste, projected to reach 60 to 78 million tonnes by 2050. An analysis of 660 relevant patents in PV recycling technologies reveals a comprehensive ecosystem spanning mechanical, thermal, chemical and automated approaches; 131 patents (17.1 per cent) are specifically focused on automation and equipment design (Komoto et al., 2018; Weckend, Wade, and Heath, 2016).

The analysis reveals that cell separation and recovery technologies lead patent activity (60.7 per cent), followed by chemical treatment methods (53.7 per cent) and thermal and pyrolysis processes (42.2 per cent). Automation and equipment design accounts for 17.1 per cent of patents, and the majority of these originate from China (65 per cent), followed by Korea (12 per cent) and Japan (8 per cent). Patent-filing activity has grown exponentially since 2018, reflecting the increasing recognition by industry that manual recycling cannot scale to meet projected waste volumes.

Conventional Automation Systems

Conventional automation represents the most mature and widely adopted approach, including standard mechanical and electromechanical systems performing repetitive tasks through preprogrammed sequences controlled by programmable logic controllers. Typical systems include thermal processing equipment (e.g. furnaces, pyrolysis reactors), crushing and grinding machinery, mechanical separation devices and automated feeding systems. These systems execute fixed-sequence operations and have limited adaptability to process variations, relying on predetermined parameters and timing sequences (Yamazaki and Toda, 2015).

Integrated production lines demonstrate the potential of well-designed conventional automation. Multistage automated systems connecting seven sequential stations—junction box removal, frame removal, tunnel kiln processing, screening, silver extraction, ball milling and material conveying—process 200 to 300 panels daily with minimal manual intervention (Komoto et al., 2022). High-pressure water jet systems combined with mechanical separation offer alternatives to thermal processing, eliminating CO_2 emissions associated with pyrolysis while enabling precise pressure control tailored to different panel constructions (Kimura, 2021).

Sensing and Detection Systems

Sensing and detection systems represent an emerging and rapidly growing technology, employing optical, spectral and imaging technologies to identify, classify and monitor materials throughout recycling processes. These technologies include optical sensors operating across the visible, near-infrared and ultraviolet spectra; X-ray fluorescence for real-time compositional analysis; hyperspectral imaging cameras; and computer vision algorithms (Bell, 2013; Ribeiro Dias and Vinje, 2024). The integration of quality-control checkpoints throughout processing lines enables the real-time verification of separation completeness and material purity, with automated reject-mechanisms diverting nonconforming materials for reprocessing.

Advanced sensor-fusion systems combining camera units and hyperspectral sensors perform material identification by analysing visual characteristics, light transmittance and unique reflective spectral signatures across hundreds of wavelengths. Machine learning–based calibration continuously improves sorting accuracy using feedback loops, directing pneumatic jets or robotic arms for precise separation (Kim and Yoo, 2025). Thickness measurement systems using ultrasonic or infrared probes determine glass plate dimensions before crushing, enabling automated parameter adjustments to fracture only glass layers without penetrating encapsulants (Tsushima et al., 2014).

Artificial Intelligence and Machine Learning

At the time of this writing, no PV recycling facilities have deployed sophisticated artificial intelligence (AI) or machine learning systems in production operations. However, patent literature and efficiencies in adjacent industries show that AI integration represents a credible short-term development pathway for the sector. Some of the potential benefits to integrating AI and machine learning into PV recycling facilities include enhanced recovery rates and material purity, increased operational throughput, elimination of human workers from dangerous tasks and continuous process optimisation through machine learning (Seeniappan et al., 2024).

Patent analysis reveals two primary application areas. First, AI-driven vision systems for automated disassembly—guiding robotic arms to remove aluminium frames and junction boxes with submillimetre accuracy, replacing manual labour at the most delicate stage of the process (Jeyakumar et al., 2024). Second, AI-powered material identification using sensor fusion, combining hyperspectral imaging and spectral



analysis to distinguish among glass, silicon and metals based on chemical signatures, which substantially outperforms conventional optical sorting (Seeniappan et al., 2024).

Beyond these specific patents, reinforcement learning approaches have been proposed for optimising chemical concentrations and reaction times in precious metal recovery and real-time feedback systems for pyrolysis process control. These remain at the conceptual and patent stage and are not yet ready for operational deployment.

For Australian facilities—such as Lotus Energy and PV Industries, which currently emphasise dry mechanical methods—AI integration is most immediately relevant to improving material sorting accuracy and throughput without requiring chemical-intensive processing. As Australian PV waste volumes approach projected levels of approximately 1 million tonnes by 2035, automated systems will become increasingly necessary to achieve the processing scales required for economic viability. The absence of deployed examples should not be read as evidence of limited potential; rather, the sector is at an early stage during which foundational recycling infrastructure is still being established before automation layers are added.

Future development trajectories point towards sensor-rich adaptive systems replacing fixed-sequence processing, digital twin integration enabling virtual process optimisation and predictive maintenance, and cross-facility learning networks in which optimisation strategies propagate across installations.

Material Complexity and Recovery Challenges

To meet the material recovery requirements of a circular solar economy, innovation is needed in both delamination and purification processes. Emerging techniques, such as laser-assisted delamination, fluid-based dissolution of encapsulants and low-temperature thermal processes, can enable the recovery of intact silicon wafers, clean glass sheets and undamaged metal contacts (Lunardi et al., 2018). These

approaches reduce energy consumption and minimise material degradation, making them more suitable for high-value applications.

Advanced Characterisation Techniques for Quality Control

Alongside recovery, quality control is paramount to determine the usability and value of reclaimed materials. Nondestructive analytical techniques—such as X-ray fluorescence, Fourier-transform infrared spectroscopy and scanning electron microscopy—are increasingly used to evaluate composition, structural integrity and contamination in recovered components (Padoan, Altimari, and Pagnanelli, 2019). These tools support real-time decisionmaking about whether recovered materials can be reused, further refined or safely discarded (Wang et al., 2022).

Automation and Artificial Intelligence for Quality Control

Advanced quality control is also being supported by automation and AI (Samimi and Hosseinlaghab, 2025). Machine vision systems integrated with hyperspectral imaging and machine learning algorithms can identify defects and classify materials based on their optical and structural signatures (Khadka et al., 2020). This allows faster, more-accurate sorting and reduces the reliance on manual inspections. Such capabilities are critical to scaling up recycling operations while maintaining consistent quality standards (López-Flores et al., 2024).

To support the broader adoption of EoL PV recycling, standardised protocols for material characterisation, testing and certification are needed. Establishing clear quality benchmarks will enhance market confidence in secondary materials and facilitate the development of reliable supply chains for recycled PV components (López-Flores et al., 2024). Furthermore, integrating LCAs into quality-control frameworks can help quantify environmental benefits, enabling data-driven policy and investment decisions (Atalan and Atalan, 2023).

In conclusion, advancements in material recovery and quality-control technologies are key to realising a sustainable and economically viable solution for PV panel recycling. These innovations will play a central role in enabling circularity in the PV sector and securing the materials needed for future energy transitions.

Analysis of the Pros and Cons of Recovery Methods

Recovery methods involve dismantling modules by mechanical or manual means, separating backsheets and delaminating and recovering prime materials, especially silicon and metals, such as silver, copper and aluminium (Tao and Yu, 2015; Fiandra et al., 2019; Balaji Jadhav et al., 2024; Preet and Smith, 2024; Sanathi, Banerjee, and Bhowmik, 2024; Tierno et al., 2024). There are various pros and cons associated with these different methods.

Recovery of the junction box and the aluminium frame that provides strength to the structure are relatively straightforward, and automated procedures are being developed, including for glass removal (SUNY GROUP, undated).

Backsheet Separation

Access to recoverable primary materials requires the removal of backsheets and EVA casings. It is important to consider the energy intensity of such removal methods and the toxicity and safety of organic solvents and acids (which has potential consequences for health, safety and the environment) and conduct an assessment of the quality of the recovered materials (Tao and Yu, 2015, Preet and Smith, 2024; Sanathi, Banerjee, and Bhowmik, 2024).

Delamination

Delamination (backsheet and EVA separation and/or removal) may occur via mechanical, chemical or thermal procedures. Mechanical delamination has the advantage of requiring minimal energy and no chemicals, but the output quality is lower because it is difficult to completely separate the materials without thermal or chemical assistance, and improvements are required on automated processes to make mechanical procedures more cost-effective (Fiandra et al., 2019).

Thermal delamination processes, during which the module is heated to approximately 500°C to 600°C, might release hydrogen fluoride, fluorinated byproducts (if the backsheet is a fluorinated polymer), lead fumes and benzene and, thus, require investment in infrastructure to trap gases, although variable temperatures and the use of an inert atmosphere (i.e. pyrolysis) could reduce emission toxicity. An advantage of thermal processes is that sufficient time (hours) and temperature (more than 500°C) could lead to the complete removal of the EVA layer before subsequent steps, although the cell could be deformed during the process. A large energy expenditure is required for thermal processes (Fiandra et al., 2019; Preet and Smith, 2024; Sanathi, Banerjee, and Bhowmik, 2024).

Chemical delamination uses acids, organic solvents or both to loosen or dissolve encapsulating polymers. Nitric acid could dissolve or loosen polymers, but toxic nitric oxide and nitrogen dioxide gases are released. EVA dissolves or swells in many solvents, and delamination steps could take place in small cut or milled pieces. The most-effective organic solvents are trichloroethylene, toluene, cyclohexane, o-dichlorobenzene, hexane and a KOH-ethanol solution (all of which are corrosive or toxic), but there are also solvents that are considered greener, such as ethylene glycol acetate, D-limonene or dimethylpropyleneurea. The main concerns are the flammability and toxicity of some of these solvents and the limited options for solvent recovery and recycling. The use of some solvents, such as toluene, requires temperatures above 80°C and comes with energy and safety concerns (Fiandra et al., 2019; Preet and Smith, 2024; Sanathi, Banerjee, and Bhowmik, 2024).

Silicon cannot conveniently be removed from the cell physically because of the thinness of its layer, although it can be dissolved and recrystallised. The traditional method involves using hydrofluoric acid, although this is undesirable for safety and toxicity concerns; strongly basic solutions can also be used (Tierno et al., 2024).

Other Methods

The most recent and up-to-date strategies focus on recovering the metals (especially silver and copper but also aluminium) while minimising silicon losses, in the hope that purified silicon can be reintroduced back into the value chain (Tierno et al., 2024). However, obtaining silicon of sufficient purity is still highly challenging because of the complex leach solutions that are obtained (Tierno et al., 2024).

Copper, silver and aluminium can be recovered with mineral acid (sulfuric acid, nitric acid or both) leaching processes, followed by separation and recovery procedures. Nitric acid is optimal for silver dissolution, followed by precipitation or electrowinning. The variety of metals and metalloids that could dissolve (e.g. silver, aluminium, copper, lead, tin, silicon) complicates the recovery of pure primary materials, so multistep procedures have been developed, such as sequential sodium hydroxide and then nitric acid leaching, leading to high purity silver being obtained. The main cons are the use of strong acids (because of safety concerns) and the expense of multistep procedures involving lamination followed by crushing or milling before leaching and isolation (Fiandra et al., 2019; Balaji Jadhav et al., 2024; Preet and Smith, 2024; Sanathi, Banerjee, and Bhowmik, 2024; Tierno et al., 2024).



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CHAPTER 6

Logistics and Collection Systems for End-of-Life Solar Panels

Raquel Villena Ruiz, Estefanía Artigao Andicoberry, Sergio Martín Martínez, Andrés Honrubia Escribano, Emilio Gómez Lázaro, Carlos Miralles Sánchez, Antony Michael Mora Mora, and Juan Antonio Saura García

> For regional and rural asset owners, the tyranny of distance turns a difficult situation into a genuinely punishing one . . . the decision becomes simple. Pay significantly more for a process that is logistically difficult, or dispose of the panels cheaply. That is a system failure, not a moral one.
>
> **David Carroll**

The accelerating deployment of PV systems worldwide has introduced a significant challenge regarding the sustainable management of EoL PV panels (Li et al., 2025). In Australia, PV waste is projected to exceed 50,000 tonnes annually by 2025 and accumulate to several million tonnes by mid-century, primarily from small-scale residential installations (Deng et al., 2024; Hallam, Thompson, and Deng, 2024). Despite the rapid expansion of PV adoption, the development of infrastructure for collection, assessment, reuse and recycling has lagged (Madden, Florin, and Salim, 2023; Shaw et al., 2024). Although existing recycling technologies can recover between 80 and 95 per cent of PV module materials (Heath



and Drahi, 2024), large-scale commercialisation remains limited because of inconsistent waste flows and economic barriers (Wambach, Libby, and Shaw, 2024).

Consequently, the evidence indicates a need for geographically optimised collection systems supported by policy frameworks that ensure traceability, regulatory compliance and material recovery (Mahmoudi, Huda, and Behnia, 2019; IEA, 2022b). Integrating LCA insights with circular economy principles—emphasising reuse, repair and recycling—will be essential to reduce environmental impacts and enhance resource efficiency across the PV value chain (Tsanakas et al., 2020; Mao et al., 2024). Establishing such sustainable and scalable management systems is fundamental to securing the long-term environmental and economic sustainability of the solar energy sector (Baumgurtel and van der Merwe, 2024).

Photovoltaic Collection and Assessment

Collection and assessment strategies must be tailored to the characteristics of residential, commercial and industrial PV systems. These strategies should consider logistical efficiency, regulatory compliance and the potential for reuse or material recovery. Given the spatial concentration of waste in such states as Queensland and New South Wales, a geographically optimised network of facilities is essential. Reverse logistics models, which leverage existing installer behaviours and infrastructure, are particularly promising. A proposed national regulatory product stewardship scheme for small electrical and electronic equipment and PV systems would further define responsibilities for collection, traceability and recycling (DCCEEW, 2023; Hallam, Thompson, and Deng, 2024).

Facility-Specific Collection and Assessment Approaches

PV collection strategies vary by facility type. Residential systems, which dominate early EoL volumes, benefit from local drop-off points, third-party collection services and emerging extended producer responsibility (EPR) schemes. Municipal programs, such as the Australian Capital Territory government's ACT Circular Economy Strategy and Action Plan, propose regional hubs to improve accessibility (Australian Capital Territory Government, 2023; Deng et al., 2024). Independent recyclers also offer door-to-door services, particularly in suburban and rural areas, often using reverse logistics models. Although not yet fully operational, Australia's proposed expanded e-waste stewardship scheme aims to consolidate such efforts and foster a circular domestic recycling industry (Hallam, Thompson, and Deng, 2024). Similar programs in Europe, such as PV Cycle, have demonstrated the effectiveness of EPR schemes, in which manufacturers are obligated to collect and recycle their own products (Weckend, Wade, and Heath, 2016). In France, for example, the national system managed by Soren has enabled a more-than-13-fold increase in the volume of collected modules between 2015 and 2019, consolidating a specialised recycling network (Komoto et al., 2022).

On the other hand, commercial PV systems, typically installed on warehouses or office buildings, require bulk handling and formalised logistics. These are often managed through partnerships with recyclers that offer tailored services (Hallam, Thompson, and Deng, 2024). Leasing models, though not yet widespread in Australia, could integrate EoL services into contracts, facilitating centralised recovery. Industry partnerships also help ensure compliance with an e-waste stewardship scheme.

Finally, industrial-scale solar farms present unique challenges because of their size and remote locations. Operators often implement internal dismantling and sorting protocols to meet environmental and safety standards. On-site dismantling is common, with panels transported in bulk to regional facilities. Under the e-Stewardship Scheme, industrial stakeholders will be responsible for traceability, documentation and certified recycling (Hallam, Thompson, and Deng, 2024; Mahmoudi, Huda, and Behnia, 2019).

Strategic Siting of Collection and Assessment Facilities

The siting of collection and assessment infrastructure is critical to minimising environmental and logistical costs. According to Deng et al. (2024a); Hallam, Thompson, and Deng (2024); and Mahmoudi, Huda, and Behnia (2019), optimal locations should

- be within a 150-kilometre (km) radius of high-density PV waste generation zones
- have access to major transport routes and existing waste infrastructure
- be near metropolitan areas (e.g. Sydney, Melbourne, Brisbane) or regional hubs (e.g. Dubbo, Townsville); recent studies highlight the importance of adapting recycling infrastructure to local conditions, as seen in such countries as Japan, South Korea and Australia, where specific reverse logistics models and regional centres are being developed (Ndalloka et al., 2024; Komoto et al., 2022).

The 150-km service radius is widely recognised as the optimal balance between accessibility and cost-efficiency. For example, an analysis of optimal siting locations in Australia projected that a facility in the Sydney/Penrith region would handle more than 10,000 tonnes of PV waste annually by 2030, serving more than 30 local government areas (Deng et al., 2024).

Centralised Versus Decentralised Infrastructure Models

The choice between centralised and decentralised models depends on regional waste volumes and logistics. Centralised facilities offer economies of scale and streamlined compliance but might incur higher transport costs and emissions. Decentralised models, by contrast, reduce transport burdens and are

better suited to remote regions, such as the Northern Territory, where access and costs are more challenging (Hallam, Thompson, and Deng, 2024).

Additional Logistical Considerations

Other factors influencing site selection include the

- site's proximity to solar farms or urban PV clusters
- availability of land and industrial zoning
- potential for the site to colocate with existing recycling or waste treatment plants
- regional demand for recovered materials (e.g. glass, aluminium, silicon)
- site's proximity to industrial clusters and access to a skilled workforce
- presence of utility-scale PV installations, particularly in Queensland and New South Wales, which are expected to generate more than 40 per cent of Australia's PV waste by 2047 (Mahmoudi, Huda, and Behnia, 2019).

Furthermore, the low valorisation of recovered glass and high transportation costs remain key barriers to an effective circular economy (IEA, 2022b).

Transport: The Carbon Footprint of Supply Chains from China to Australia

The carbon footprint that is associated with the global transport of PV modules is increasingly important to understand, particularly as demand for solar power continues to grow. Although most emissions in the PV life cycle come from manufacturing, maritime freight—both upstream (i.e. raw materials to China) and downstream (i.e. finished modules to Australia)—also contributes. Sea transport is one of the most carbon-efficient freight modes, but long travel distances and large volumes of material result in a measurable climate impact.

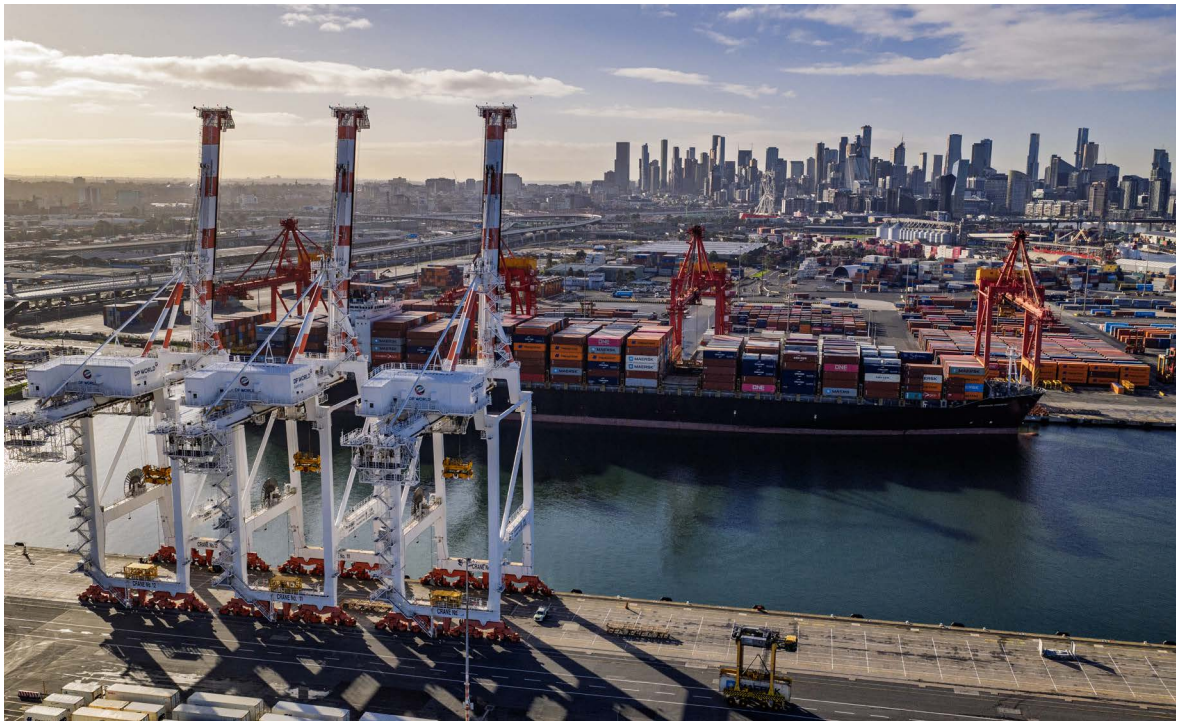
Raw Material Transport to China

China, the world's leading PV module manufacturer, depends on a global network of suppliers for key raw materials. These materials are shipped long distances to Chinese ports primarily using bulk carriers, which are more efficient in CO_2 emissions per tonne-km than container ships (European Commission, 2022). Key raw materials are

- **Quartz and MG Si:** Essential for polysilicon production, these materials are primarily sourced from Australia and India (Fraunhofer Institute for Solar Energy Systems, 2024).
- **Thermal coal:** Though not a direct input in PV modules, thermal coal is vital for powering energy-intensive processes, such as silicon refining. Major suppliers include Indonesia and Australia.
- **Alumina and bauxite:** Crucial for the aluminium used in PV module frames, alumina and bauxite are also largely imported from Australia.
- **Other materials, such as silver, copper, chemicals, and glass:** These materials often come from India and Southeast Asia.

Transport distances vary; the following bulk shipping routes serve as examples:

- India to China: 5,000 to 6,000 km
- Indonesia to China: 3,000 to 4,000 km
- Australia to China: 7,000 to 9,000 km (International Maritime Organization, 2015).



Bulk carriers emit between 3 and 10 grams of CO_2 per tonne-km, depending on the vessel size, fuel type and efficiency (European Commission, 2022). Given that 3 to 5 tonnes of raw material are needed per tonne of finished PV modules, and applying average transport emissions, the upstream maritime footprint is estimated at 15 to 50 kg of CO_2 per tonne of PV modules, or about 3 to 8 kg of CO_2 per kW of installed capacity (Fraunhofer Institute for Solar Energy Systems, 2024).

Transport of Finished Photovoltaic Modules: China to Australia

Once manufactured, PV modules are shipped from Chinese ports (e.g. Shanghai, Ningbo, Shenzhen) to Australia (e.g. Sydney, Melbourne) over distances of 7,000 to 9,000 km (International Maritime Organization, 2015). Modules are typically shipped in 20-foot or 40-foot containers, each holding 20 to 28 tonnes of material (Fraunhofer Institute for Solar Energy Systems, 2024).

Container ships emit 10 to 40 grams of CO_2 per tonne-km, depending on their speed, engine type and fuel used (European Commission, 2022). For a 20-tonne shipment, this translates into 1.4 to 7.2 tonnes of CO_2 per container. On a per-unit basis, the emissions are roughly 3 to 15 kg of CO_2 per kW of installed solar capacity when using a typical module mass of 25 to 30 kg per kW (National Renewable Energy Laboratory, 2021; Dhakal et al., 2022).

Although these emissions are relatively modest compared with the total life-cycle emissions of PV electricity (ranging from 20 to 60 grams of CO_2 per kWh) (National Renewable Energy Laboratory, 2021), they become significant at scale. For instance, Australia's annual PV imports, typically around 1 GW, could result in 30,000 to 100,000 tonnes of CO_2 emissions just from shipping (Taylor et al., 2022).

Total Maritime Carbon Footprint

When considering both upstream and downstream logistics, total emissions from maritime freight in the China-Australia PV supply chain are estimated at 6 to 23 kg of CO_2 per kW of PV capacity transported.

This value depends on several factors, including the

- source and mix of raw materials
- ship type and fuel efficiency
- transport distance and load factors.

Upstream emissions (i.e. raw material transport) contribute 3 to 8 kg of CO_2 per kW, and downstream emissions (i.e. module shipping) contribute 3 to 15 kg of CO_2 per kW, leading to a combined range of 6 to 23 kg of CO_2 per kW (European Commission, 2022; Fraunhofer Institute for Solar Energy Systems, 2024). For national-level deployments, the cumulative emissions are considerable. For example, transporting 1 GW of modules (equivalent to about 30,000 to 40,000 tonnes) would produce 6,000 to 23,000 tonnes of CO_2 from shipping alone.

Strategic Implications for Climate Policy

Although these maritime emissions represent a small portion of PVs' total environmental impact, they are not negligible—especially as global solar deployment accelerates. Therefore, reducing sea freight emissions is increasingly relevant to national decarbonisation efforts. Key strategies for mitigation include

- adopting low-carbon marine fuels, such as green ammonia or biofuels
- optimising packaging and container loads to maximise efficiency
- locating manufacturing closer to demand centres to shorten shipping distances
- investing in cleaner port infrastructure and slow-steaming practices.

As the global solar industry grows, even modest per-unit improvements in logistics efficiency can yield substantial emissions savings. Addressing maritime freight emissions can enhance the sustainability of solar energy and support broader climate goals.

Infrastructure

Existing Facilities and Capabilities: Dedicated Recycling Facilities

Australia's solar recycling sector is emerging, and several companies lead innovation, including

- PV Industries and Lotus Energy, which operate facilities recovering up to 90 per cent of panel materials (Clean Energy Council, 2025)
- ElecSome, which uses mechanical processes to produce recycled glass fines for construction materials (ElecSome, undated-a)
- Solar Recovery Corporation, which claims recovery rates above 99 per cent using proprietary technology (Solar Recovery Corporation, undated).

A previous pioneer in the solar recycling sector was Reclaim PV Recycling, but it ceased operations in 2022 because of financial and logistical constraints (Baumgurtel, 2024).

Australia already has a foundation of recycling infrastructure, supported by more than a decade of public investment through such programs as the Recycling Modernisation Fund and the Clean Energy Finance Corporation, which can be leveraged to scale up PV panel recycling (DCCEEW, 2024b).

Policy and Regulatory Support

Australia's regulatory landscape is evolving. The Product Stewardship Act 2011 provided the framework for voluntary and coregulatory schemes. The Recycling and Waste Reduction Act 2020 repealed

and replaced the Product Stewardship Act and included new measures to advance a circular economy (Australian Government, 2020). The proposed expansion of the National Television and Computer Recycling Scheme to include small electrical and electronic equipment and PV systems would aim for at least 80-per-cent material recovery and including traceability aligned with the National Framework for Recycled Content (DCCEEW, 2023; Hallam, Thompson, and Deng, 2024; Shaw et al., 2024). Design-for-circularity principles, such as modularity, repairability and reduced use of hazardous materials, are gaining traction and should be supported by standards and ecolabels (Shaw et al., 2024). Additionally, such federal initiatives as Solar Sunshot and the Australian Silicon Action Plan support domestic manufacturing and circular supply chains (PricewaterhouseCoopers, 2022).

Opportunities for Supply-Chain Integration

Domestic Integration

Waste distribution forecasts suggest that Queensland, New South Wales, Victoria and South Australia will generate the bulk of PV waste by 2047 (Mahmoudi, Huda, and Behnia, 2019), supporting the case for regional hubs in these states. Additionally, LCA studies show that transport distances significantly affect environmental outcomes; fossil resource impacts vary by up to ±16 per cent, depending on logistics (Mao et al., 2024).

Using electric or low-emission vehicles for transport and locating facilities within 150 km of major waste sources, as detailed in the 'Strategic Siting of Collection and Assessment Facilities' section of this chapter, can reduce environmental burdens. Recent modelling confirms that metropolitan facilities in Brisbane, Melbourne, Sydney, Adelaide and Perth could each access 5,000 to 10,000 tonnes of waste annually, and volumes are expected to double by 2030. Complementary regional sites (e.g. Dubbo, Townsville, Murrumbidgee) would ensure national coverage (Deng et al., 2024).

International Integration

Australia can benefit from international expertise. Some countries, such as France and Japan, have successful EPR models and specialised recycling networks (Komoto et al., 2022). Spain has also implemented EPR through the nonprofit organisation Collective Systems of Extended Producer Responsibility (Sistemas de Colectivos de Responsabilidad Ampliada del Productor, also known as SCRAPs), which manages the collection and recycling of EoL PV panels in line with the national Waste from Electrical and Electronic Equipment (WEEE) regulation and Spanish Royal Decree 110/2015 (European Union, 2012; Ministry of Agriculture, Food and Environment, 2015). These systems ensure traceability, legal compliance and the environmentally sound treatment of PV waste. Additionally, strategic partnerships with the EU, United States and India could facilitate technology transfer and regulatory alignment (Shaw et al., 2024).

Industry Leadership and Innovation

Some companies, such as PV Industries, are developing modular recycling technologies; others, such as ElecSome, are valorising recovered materials for construction. Design innovations, such as lead-free solders and antimony-free glass, can improve recyclability and reduce environmental risks (Shaw et al., 2024). These efforts position Australia as a potential exporter of circular PV solutions. However, the high cost of recycling estimated at $500 to $1,000 per tonne remains a barrier, especially for smaller facilities. Economies of scale and improved material recovery technologies are essential to reduce costs and increase viability (Deng et al., 2024).

Collection Network Requirements

Key Considerations

The existing collection network requires targeted improvements. Some solutions are applicable across the entire system, while others need to be adapted specifically for household or business-to-consumer contexts and for nonprivate household or business-to-business transactions (Deutsche Umwelthilfe, 2021). For business-to-consumer PV modules, the primary challenge lies in establishing a standardised, nationwide collection infrastructure that ensures consumer accessibility and compliance. In the business-to-business sector, one approach would be to reinforce EPR through legal obligations that require manufacturers to provide accessible take-back solutions for modules sold in 2016 or later. For modules sold earlier, enforcement mechanisms should include rigorous inspections and traceability protocols via centralised registries, incentivising proper disposal and preventing illegal dumping or resale abroad.

In this regard, several key factors (illustrated in Figure 6.1) must be addressed to ensure an effective collection network, which is vital for sustainable waste management and resource recovery as the global volume of decommissioned modules increases (EPRI Journal, undated; Solar Energy Industries Association, undated; Curtis, Buchanan, Heath, et al., 2021). These key factors are as follows:

- **Design for disassembly and recyclability.** Modules should be engineered to allow the easy separation of components (such as glass, silicon, metals and plastics) to facilitate efficient recycling processes and maximise material recovery.
- **Standardisation and compatibility.** Developing uniform procedures, interfaces and standards across regions ensures seamless collection and processing. Consistency reduces operational complexity and enhances international collaboration.
- **Logistics optimisation.** Transportation and storage solutions should be cost-effective, environmentally friendly and capable of protecting modules from damage. Implementing efficient reverse logistics—systematic processes for the return, reuse, recycling or disposal of modules—enhances overall supply-chain efficiency by reducing waste, recovering valuable materials and minimising transportation redundancies.
- **Traceability and data management.** Implementing digital tracking systems enables life-cycle monitoring of modules, from installation to EoL, supporting transparency, regulatory compliance and circular economy strategies.
- **Scalability and flexibility.** The collection infrastructure should be adaptable to handle increasing volumes of decommissioned modules globally. Flexible systems can expand efficiently in response to industry growth.
- **Stakeholder coordination.** Effective coordination among manufacturers, recyclers, regulators, waste managers and other stakeholders is essential. International standards and cross-border cooperation facilitate streamlined operations and material recovery.
- **Regulatory compliance and safety.** Collection activities must adhere to international safety standards and environmental regulations to protect workers and ecosystems during handling and transportation.
- **Material recovery focus.** Collection methods should prioritise maximising the recovery of valuable materials (such as silicon, glass, aluminium, copper and rare metals) to support resource efficiency and economic viability. This can be achieved through extensive and accessible collection points—such as municipal waste centres, dedicated drop-off sites and partner facilities—that are equipped with segregation and sorting capabilities to facilitate efficient material recovery.

FIGURE 6.1
Key Considerations for Collection Network Requirements



All in all, early education and initiatives aimed at raising awareness among consumers and stakeholders are required to foster responsible disposal practices and encourage participation in collection programs. By actively involving end users, the effectiveness of PV collection networks can be enhanced. Incorporating these considerations into the design of such networks will promote sustainability, efficiency and resilience in managing PV panel waste on a global scale.

Technology Deployment Needs

Currently, PV module recycling processes use various technologies, such as mechanical, chemical, thermal and optical mechanisms, as well as combinations of these. For example, in Germany, the recycling of silicon-based modules uses processes that are partially adapted from other industries, such as those based on mechanical processes from flat-glass recycling (Wambach, Libby, and Shaw, 2024). Although mechanical dismantling could easily disassemble the aluminium frame and junction box from the PV module, further delamination becomes critical for the remaining tightly adhered components. The efficient removal of EVA is a key step in achieving c-Si PV modules delaminating (Tao et al., 2023).

Delamination technologies can be summarised as physical, thermal and chemical. Ordinary mechanical crushing is an early proposed physical delamination method (Granata et al., 2014). For example, a special device known as a *hot knife* is being used by some companies in Japan for physical delamination (Wang et al., 2022). The companies ImpulsTec (ImpulsTec, undated) and FLAXRES (FLAXRES, undated) are developing alternative processes for breaking up the material composites of PV modules based on physical treatment, such as shock wave fragmentation technology (e.g. electrohydraulic fragmentation) and high-intensity light pulse technology (Wambach, Libby, and Shaw, 2024). Although, in the recycling process of c-Si modules, physical delamination technology requires lower energy consumption than chemical and thermal methods, it cannot effectively remove EVA and liberate different components (Su et al., 2024). Therefore, the combination of other technologies, such as chemical or thermal treatment, must be considered to improve the recycling efficiency.

Thermal delamination mainly uses heating equipment (e.g. tube furnaces, muffle furnaces and box furnaces) to soften and decompose EVA in c-Si modules at high temperatures (up to 650 °C) (Riech et al., 2021), thereby separating such components as glass, solar cells and solder strips from each other. Although thermal delamination technology presents some advantages (such as short time consumption, high delamination efficiency and easy operation), the byproducts (such as waste gas) generated by this technology cannot be ignored (Su et al., 2024).

Chemical delamination technology employs chemical solvents to dissolve EVA, causing EVA to lose its adhesion while having a relatively small impact on the properties of the other components. Different technologies, such as microwave- and ultrasound-assisted dissolution methods, have been proposed to improve the dissolution efficiency of EVA and shorten reaction time (Pang et al., 2021).

In 2018, SUEZ together with Geltz Umwelttechnologie (Geltz Umwelttechnologie, undated; SUEZ, undated) started operating a recycling plant in southern Germany for silicon-based PV modules based on the EU R&D project ElSi (European Commission, 2025). The approach is a combination of mechanical, thermal and electrolytic processes (700°C), with a target to recycle between 90 to 95 per cent of all PV module materials (Gerold and Antrekowitsch, 2024). However, the plant stopped operating in 2021 when SUEZ sold the division of waste management to PreZero (PreZero International, undated).

Regional Capacity Planning

Australia's rapid adoption of PV systems—particularly small-scale rooftop installations—has generated growing concern over the future management of PV panel waste. Effective regional capacity planning is essential to address the geographic, logistical, economic and social challenges that will emerge as increasing volumes of PV systems reach their EoL.

Understanding the Scale and Geographic Distribution of Photovoltaic Waste

The foundation of any effective regional capacity plan lies in a clear understanding of the volume and distribution of PV waste. Australia has experienced rapid growth in solar installations; more than 60 per cent of Australian systems are classified as small-scale (Wambach, Libby, and Shaw, 2024). This percentage implies that a significant share of the waste stream will be widely scattered across urban and suburban residential areas. Additionally, projections indicate a growing accumulation of PV waste in regional and remote areas because of the ageing of large-scale solar farms that were deployed ten to 20 years ago (Martin, 2024).

Collection Infrastructure and Reverse Logistics

A dual infrastructure strategy can be adopted: Large collection and recycling facilities are needed in major urban centres to leverage economies of scale, and they could be complemented by smaller facilities that ensure accessibility in regional and remote areas. To make this infrastructure feasible, reverse logistics can be leveraged to manage transportation flows from users to recyclers and to minimise handling costs. This approach aligns with the one suggested by Wambach, Libby, and Shaw (2024), which highlights regional network hubs supported by transportation corridors and central nodes.

Recycling Infrastructure and Refurbishment Strategies

Although centralised recycling facilities provide cost advantages, it is also essential to expand infrastructure into less populated regions to accommodate the projected increase in waste generation in those areas. This is consistent with the findings from Baumgurtel and van der Merwe (2024), which notes that existing recycling capacity in Australia is insufficient and unevenly distributed.

Another key aspect is the integration of refurbishment and testing centres within the collection network. These centres would evaluate modules' usability and support the creation of a secondary market for used PV panels, promoting reuse and reducing the load on recycling processes (Xia, Yang, and Poon, 2025). Such strategies are crucial in achieving circular economy goals.



Cultural Values and Community Engagement

Beyond physical infrastructure, cultural adaptation and public engagement play a vital role. Recycling strategies must reflect local values and practices, including fair access, job creation and transparent communication with stakeholders (Kenning, 2024). This sociocultural dimension is especially important in remote areas where trust and participation are critical for success.

Policy mechanisms, such as subsidies, tax incentives, and support for domestic manufacturing, are recommended to enhance the adoption and sustainability of recycling systems. These align with broader sustainability programs, such as the EU's Horizon Europe Cluster 5 initiative, which also promote regional inclusion and clean-energy employment (Horizon Europe, 2022).

The successful implementation of these strategies depends on accurate waste forecasting, institutional coordination and consistent regulatory support. Importantly, the integration of refurbishment markets, cultural sensitivity and localised job creation can turn the PV recycling challenge into an opportunity for circular innovation and regional development.

Investment Requirements

It is projected that 70 per cent of the total PV waste generated will be concentrated in metropolitan areas. This projection highlights the need for centralised processing facilities in large cities that are supported by regional microfactories to minimise transportation costs (Gentilini and Salt, 2019; Sustainability Victoria, 2025). The programme Circular Solar in New South Wales allocated $10 million to pilot three projects: an 8,000-tonne-per-year processing plant, a 2,000-tonne-per-year plant and a 100-kW community system that can make use of refurbished modules (New South Wales Environment Protection Authority, 2024). These investments provide one national benchmark for the scale of potential initiatives that Australia could implement.

Logistics

As of this writing, only 17 per cent of a PV panel's weight is recycled (mostly aluminium and glass); meanwhile, more than 70 per cent of the economic value of PV module recycling relies on the recovery of silicon, silver and copper (Baumgurtel and van der Merwe, 2024). New studies show that up to 95 per cent of a 20-kg module can be recovered, with a median value of US$22.6 per panel (Baumgurtel and van der Merwe, 2024). Recent projects have contributed to the development of recycling pilot plants, such as the Sircel facility in Parkes, which has the capacity to process up to 2,000 tonnes annually and achieve recovery rates above 90 per cent (New South Wales Environment Protection Authority, 2024).

Regulatory and Market Needs

Australia is missing a mandatory national scheme, which translates into regulatory fragmentation and uneven costs (Feldman et al., 2024). However, in 2019, Victoria banned landfill disposal, and the Basel Convention amendment restricting exports came into effect in 2025 (Baumgurtel and van der Merwe, 2024). A national EPR framework is key, complemented by subsidies, tariffs and public procurement incentives to drive circularity (New South Wales Environment Protection Authority, 2024).

Developing Markets

The development of secondary markets is also a key step. Contrary to what is generally believed, data indicate that four out of five retired panels still work well, achieving performance levels above 90 per cent of their original capacity (CPVA, 2024). Pilot projects, such as the 100-kW installation in Wagga Wagga, demonstrate in practice that reuse is not only possible but also viable (New South Wales Environment Protection Authority, 2024). The scaling potential is huge: It is estimated that, by 2030, up to 8 GW of capacity could be refurbished and reinstalled, giving this equipment a second life and preventing it from becoming waste prematurely (CPVA, 2024). To guide this effort, the CPVA Certified label serves as a mark of trust, endorsing those projects that incorporate ecodesign and are genuinely committed to the circular economy (CPVA, 2024).

Material Composition and Value Streams

Material Composition

The PV cells (approximately 3 to 5 per cent of the total weight of the module) are the heart of the system, responsible for converting solar energy into electricity through the PV effect. The front glass sheet (approximately 70 to 80 per cent of the total weight) protects these cells from external factors, such as wind, rain and hail, while allowing high levels of light transmission. The encapsulant, usually EVA, represents about 10 per cent of the weight. Its function is to secure and protect the cells, providing electrical insulation (Maysun Solar, 2023).

The backsheet (less than 5 per cent of the total weight, approximately), located on the back of the module, protects against moisture and other external agents, ensuring the mechanical durability of the assembly. It is typically composed of polymers, such as Tedlar (a type of PVF). The aluminium frame (approximately 5 to 10 per cent of the total weight) surrounds the panel, providing structural rigidity, facilitating assembly and improving the panel's resistance to impacts and deformation (Maysun Solar, 2023). Finally, the junction box, located at the rear, contains the electrical terminals that connect the panel to the system and incorporates protection diodes. It accounts for less than 1 per cent of the total weight (Maysun Solar, 2023). Table 6.1 summarises the components of a PV module.

TABLE 6.1
Weight Percentage, Material and Value of Components in a Photovoltaic Module

Component	% of Module Weight	Principal Material	Value
Glass	70–80	Tempered glass	Low value: very abundant and low-cost material
Frame	5–10	Aluminium	Medium value: cost-effective recycling because of a high demand in construction and transportation
Solar cells	3–5	Mono- or polycrystalline silicon	High value: a key element for energy conversion
Encapsulant	≈10	EVA	Low value: protective polymer that is difficult to separate for recycling
Backsheet	<5	Tedlar (PVF) or other polymers	Low value: mechanical and moisture protection
Conductors	<1	Copper, silver	High value: rare, precious metals that are a priority for recovery during recycling

SOURCE: Maysun Solar, 2023.

Value Streams

In this section, we focus on analysing the different material flows in PV recycling, considering their economic value.

The aluminium frame is a very easy element to recover. Although it has a very consolidated market, it can be disassembled manually and is very simple to process. Recycling requires little energy compared with primary aluminium production.

Glass constitutes the largest fraction of the module by weight. Although its unit value is low, it represents a significant flow by volume. If it can be cleanly separated from encapsulants and other components, it can be reused in the manufacture of new flat glass or in industrial applications, thus reducing the need for virgin raw materials (Ardente, Latunussa, and Blengini, 2019; Fan, 2021).

Silicon, the heart of the cells, is more complex. Its recovery requires processes that eliminate metals, contacts and dopants, but if the necessary purity is achieved, it can be reintroduced into the production of new wafers or used in other high-tech industries (Ardente, Latunussa, and Blengini, 2019; Fan, 2021).

Precious and conductive metals, such as silver and copper, represent a minimal percentage by weight but have great economic value. Silver, in particular, is crucial for the viability of recycling processes. Finally, polymers (the EVA and backsheet) do not provide direct economic value; rather, they pose an environmental challenge because they currently allow only limited energy recovery while more-sustainable reuse alternatives are being researched (Ardente, Latunussa, and Blengini, 2019; Fan, 2021).

As of this writing, industry efforts are progressing the recycling of EoL PV modules using two main methods: thermomechanical methods and chemical methods. Although chemical methods stand out for the quality of their materials, thermomechanical processes are simpler and less energy-intensive, facilitating their application in environments with limited technology. However, the materials obtained through thermomechanical methods are generally of lower quality, which can limit their applications. These methods generally have a lower environmental impact because of their low energy consumption and greater efficiency. In contrast, chemical processes, although they are more environmentally demanding, can be economically viable if the demand for high-purity materials is considered (Saura, Jordaan, and Espinosa, 2025).



Conclusion

This chapter demonstrates that the collection, transport and processing of PV modules are key elements in determining whether a circular PV economy can be achieved cost-effectively. In addition to cost benefits, the reduction of the carbon footprint of the linear supply chain—estimated at 6 to 23 kg of CO_2 per kW of transported capacity—provides an additional rationale for building domestic circular infrastructure that progressively reduces import dependence. The reduction of import dependence can be addressed through such initiatives as developing jurisdiction-specific solutions and expanding the development of secondary markets. The geographic distribution of PV waste across Australia necessitates jurisdiction-specific infrastructure models; dispersed waste profiles, as in Queensland, favour modular and mobile facilities, whereas concentrated settlement patterns, as in Victoria, support regional fixed-site networks.

The development of secondary markets for reused panels, supported by certification frameworks (such as the CPVA Certified label), offers a complementary pathway that can extend panel life cycles, reduce pressure on recycling capacity and generate economic value that substantially exceeds material recovery alone. As waste volumes accelerate towards projected peaks in the early 2030s, the findings suggest that near-term prioritisation of coordinated investment in geographically optimised infrastructure, standardised traceability systems and workforce development could help build logistics infrastructure commensurate with the scale of the potential circular economy.

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CHAPTER 7

Applications and Value of Recovered Materials from Solar Panels

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> PV module recycling and upcycling has become an emerging market, grabbing the attention of academia and industry, worldwide.
>
> ***Waste Management Review***

Previous chapters have examined various policy, circular economy, supply chain and manufacturing challenges that contribute to the growing amounts of EoL PV waste expected in the coming decades across Australia. This accumulation of PV waste represents an opportunity to recover significant amounts of embedded high-value materials. Given that c-Si modules dominate more than 90 per cent of the global PV market (Bošnjaković, 2024), the application of their recovered materials has strategic potential in various manufacturing processes because of their electrical, thermal and catalytic properties. This chapter examines the existing and emerging applications of four key recovered materials (silicon, silver, copper and aluminium) from c-Si EoL PV modules, highlighting their technological potential and contribution to circular energy transitions.

Applications for Recovered Silicon

Silicon is the foundational semiconductor in crystalline solar cells and represents about 3 to 5 per cent of a PV module's mass. Recovering silicon from EoL panels is technologically challenging but important because producing new silicon wafers is extremely energy-intensive (wafer production accounts for approximately 50 per cent of the total energy in module manufacturing). High-purity silicon is considered a critical material for the PV industry. In this section, we survey how the recovered silicon can be repurposed.



Direct Reuse in New Solar Cells (with Limitations)

Although silicon wafers can be recovered via chemical etching to remove metal electrodes, anti-reflection coatings, emitter layers and p–n junctions, the purity requirements for direct reuse in new solar cells are exceptionally high, demanding purity levels higher than 99.99999 per cent (Raji et al., 2024; Saha et al., 2025). Recovered silicon typically achieves a purity of more than 99.9 per cent, which is insufficient for direct use in new solar cell ingots without additional treatments to achieve a comparable efficiency to virgin silicon feedstock (Saha et al., 2025). Furthermore, the existing volume of solar waste and low recycling rates do not align with the substantial demand for silicon that is needed for ingot production, and the efficiency of second-life solar cells with recycled silicon is generally poor compared with virgin silicon solar cells (Saha et al., 2025). Despite these challenges, methods have been developed to nondestructively recover silicon wafers with characteristics that are nearly equal to commercial virgin wafers, including a thickness of 250 µm, resistivity of 1.6 ohm-centimetres, minority-carrier lifetime of 2.17 microseconds and an ultralow reflectivity of 12 per cent (compared with 25 per cent for commercial wafers). This makes recovered silicon wafers potentially promising for use in new PV modules (Raji et al., 2024).

Conversion into Silica Nanoparticles

Converting recovered high-purity silicon into nanomaterials, such as silica nanoparticles (SNPs), is considered a superior solution to address the demand-supply gap for SNPs (Saha et al., 2025). SNPs are recognised for demonstrating an array of desirable properties, such as the capacity for simple surface modification, optical transparency and excellent chemical and thermal stability. These nanoparticles are further recognised for their biocompatibility, high surface area and versatile functionalisation. These attributes enable a variety of potential applications. In the medical and biomedical fields, they are used for drug delivery, for optical imaging and diagnostics, and as antibacterial agents (Jeelani et al., 2020; Saha et al., 2025). Their application also extends to the agricultural sector, an area in which they can

increase seed viability, enhance a plant's resistance to stress and serve as carriers for pesticides (Jeelani et al., 2020). Industrially, these nanoparticles find utility in environmental remediation (e.g. water purification, removal of heavy metals and dyes, enhanced oil recovery), as components in anticorrosion coatings and in the production of electronic devices, sensors, adsorbents and catalysts (Jeelani et al., 2020; Saha et al., 2025). For example, hydrophobic SNPs, which can be synthesised from recovered silicon from EoL PVs, have demonstrated a high protection efficiency of 99.5 per cent and a 200-fold reduction in corrosion rates when applied as anticorrosion coatings on aluminium substrates (Saha et al., 2025).

Nanostructured Silicon for Lithium-Ion Batteries

Silicon has long been considered a transformative anode material for LIBs because of its extraordinarily high theoretical capacity (Nitta and Yushin, 2014), which is approximately 3,600 milliampere-hours per gram^{-1} for $Li_{15}Si_4$ and nearly ten times that of graphite, which is 372 milliampere-hours per gram^{-1} (Jin et al., 2017; Mishra, Monika, and Patial, 2025). However, there are two intertwined challenges involved in implementing silicon-based anodes in devices. First, silicon-based anodes are subject to massive volumetric expansion during lithiation (from 300 to 400 per cent). However, nanosizing the particles helps mitigate this issue, enhancing battery stability and extending cycle life (Eshraghi et al., 2020; Sim et al., 2023; Qiu et al., 2025). Upcycling recovered silicon to create nanostructured ultra-pure silicon for use as an active material in the negative electrodes of 3b generation LIBs is considered a high-value-added application for recovered silicon (Eshraghi et al., 2020; Saha et al., 2025).

Second, the electrochemical performance of silicon-based anodes is sensitive to the chemical purity of the silicon (Li et al., 2023). Undesirable contaminants, including such metals as iron, copper and nickel—often remnants from refining processes—promote electrolyte decomposition, causing uneven solid electrolyte interphase formation, elevated internal resistance and accelerated capacity fade (Sun et al., 2024). Hence, battery-grade silicon (commonly exceeding 99.9-per-cent purity) is critical.

Silicon recovery from EoL PV cells often involves hydrometallurgical strategies. Although conventional approaches traditionally use aggressive multireagent acid mixtures, more-streamlined single-reagent methods, such as those employing phosphoric acid, have emerged (Eshraghi et al., 2020; Sim et al., 2023; Raji et al., 2024). These simplified methods can effectively remove impurities and antireflection coatings, achieving high silicon purity and impressive recovery yields while minimising the generation of complex, separate waste streams (Sim et al., 2023). Following purification, the recovered silicon is typically nanosized through such methods as ball milling to create porous structures that can better accommodate volume changes during charge and discharge (Eshraghi et al., 2020; Qiu et al., 2025). When incorporated into LIB anodes, this recovered and nanostructured silicon has demonstrated competitive performance, comparable to or even exceeding commercially sourced silicon. This innovative approach transforms PV panel waste into high-performance, inexpensive electrode material, significantly contributing to circular economy initiatives.

Applications for Recovered Silver

Silver is one of the most valuable constituents of c-Si PV panels despite making up less than 0.1 per cent of a module's weight. Silver is used in the metal contacts (busbars and fingers) printed on solar cells. Because each panel contains a few grams of silver, the volumes will add up significantly as millions of panels reach EoL; by 2050, the cumulative recoverable silver from PV waste is forecast to be thousands of tonnes. Recovering silver is, therefore, a high priority for economic reasons (i.e. it can help make recycling profitable) and to reduce dependence on primary silver mining. In this section, we outline how reclaimed silver could be used in industry.

In 2019, the PV sector accounted for 10 per cent of global annual silver production, and continued expansion of solar cell manufacturing at a TW scale could strain global silver reserves (Vinayagamoorthi et al., 2024). Therefore, the efficient recovery and recycling of silver from EoL PV panels is not merely an environmental imperative but also crucial for long-term resource availability and economic sustainability (Vinayagamoorthi et al., 2024).

Advanced recycling methods are being developed to extract this valuable resource. Mechanical methods are often the first step, involving the removal of the aluminium frame and junction box (Raji et al., 2024; Vinayagamoorthi et al., 2024; Saha et al., 2025). Subsequent PV module dismantling stages typically involve sophisticated approaches, such as hydrometallurgical processes in which solar cell wafers are dissolved in acid solutions (e.g. nitric acid) to create leachates containing such metals as copper, aluminium and silver (Eshraghi et al., 2020; Tokoro et al., 2020; Han et al., 2023). Another emerging technique is the electrical dismantling method, which uses pulsed power technology to selectively separate copper wires with silver from the cell sheet, potentially producing particles reusable as raw materials for copper smelting (Tokoro et al., 2020). Chemical etching methods are also employed to remove silver electrodes, antireflection coatings and other layers from silicon wafers, aiming for a clean separation of materials (Raji et al., 2024).

Recovered silver can achieve high levels of purity, sometimes exceeding 98 per cent. For instance, one method successfully recovered silver in the form of chlorargyrite (AgCl) with 98.1-per-cent content, meeting the second-class standard of China's nonferrous metal industry standard (Han et al., 2023).

The recovered, high-quality silver can then be reused in various industrial applications, helping to conserve virgin mineral resources and generate economic returns. Although scientific literature does not specify unique applications for PV-recovered silver that are distinct from newly mined silver, its successful recovery means that it is available for general uses of silver, which span numerous high-demand sectors. Silver's excellent electrical conductivity makes it indispensable in the electronics industry for components, electrical contacts and conductive inks (Rao R. et al., 2015; Syed, 2016; Bouafia et al., 2021). Moreover, historically, silver has been extensively used in photographic and radiographic films because of its light-sensitive properties, and recovered silver can also reenter this sector; however, it should be noted that this sector is already active in silver recovery (Masebinu and Muzenda, 2014; Canda, Ardelean, and Hepuţ, 2018). Silver is also a versatile catalyst in various chemical processes, and its recovered form can contribute to catalytic applications (Wen, Yin, and Dai, 2014; Bhosale and Bhanage, 2015; Sharma et al., 2021). Furthermore, because of its antimicrobial properties, silver has uses in dental materials, in medicines and as a disinfectant, including in wastewater treatment processes (Syed, 2016; Sim et al., 2018). Finally, the aesthetic appeal and malleability of silver ensure its continued demand in jewellery and silverware manufacturing (Syed, 2016; Mišta-Jakubowska et al., 2019).

By effectively recycling silver from EoL PV panels, the industry significantly contributes to circular economy principles. Silver recycling transforms what was once considered waste into a valuable resource, mitigating environmental impact, conserving finite resources and generating economic benefits. The reintroduction of recovered silver into the manufacturing supply chain supports a more sustainable energy future, aligning with the broader goals of resource efficiency and responsible waste management (Han et al., 2023; Franzoni, Leggerini, and Bannò, 2024).

Applications for Recovered Copper

Copper is another important metal in PV panels, primarily found in the wiring, cables and cell interconnections (busbars). Although copper is more abundant (and less expensive per kg) than silver, it is used in larger quantities in PV systems; for example, a typical 60-cell c-Si module contains several tens of grams



of copper (in ribbons and the junction box wires), and additional copper is present in system cabling. Moreover, copper is highly recyclable, and scrap markets are well-established globally (Sah, Chitra, and Kumar, 2023).

Copper's intrinsic properties, including its excellent electrical and thermal conductivity, malleability and resistance to corrosion, render it indispensable across numerous industrial sectors (Kahar et al., 2023; Sah, Chitra, and Kumar, 2023). The PV industry contributes significantly to global copper demand; projections indicate that EoL PV panels could yield approximately 420,000 tonnes of copper by 2050, representing a substantial economic value. Recovering this metal is vital for achieving economic benefits and environmental protection and for ensuring the long-term sustainability of the copper supply chain—not only for making new PV panels but for many other sectors, too (Sah, Chitra, and Kumar, 2023; Shafiq et al., 2024).

Various advanced methods are used to recover copper from EoL PV panels, ranging from initial mechanical separation to sophisticated hydrometallurgical and chemical processes (Shafiq et al., 2024). Typically, the aluminium frames and copper ribbons are mechanically removed as a first step (Raji et al., 2024; Vinayagamoorthi et al., 2024; Saha et al., 2025). Subsequent stages often involve chemical methods, such as acid leaching, in which strong acids (e.g. nitric acid) are used to dissolve and extract copper along with other metals (Han et al., 2023; Shafiq et al., 2024). These processes can yield highly pure copper; for instance, one method successfully recovered copper oxalate (moolooite) with 98.7-per-cent content (Han et al., 2023), while another method demonstrated the recovery of reddish-brown copper powder with 97.27-per-cent purity and a 90-per-cent recovery rate from connecting wires (Sah, Chitra, and Kumar, 2023). Additionally, novel electrical dismantling methods, utilising pulsed-power technology, have shown promise in selectively separating copper and silver wires from cell sheets, achieving 95.6-per-cent recovery of the total copper in the sample (Tokoro et al., 2020).

Copper is an indispensable metal with diverse applications across numerous sectors, ranging from fundamental industrial uses to applications in advanced biomedical and electronic technologies (Kundu

et al., 2023). Copper is crucial for major industrial machinery, telecommunications, the internal wiring of electronic devices, copper windings in electric motors and generators, household electrical appliances (such as refrigerators, washing machines and air conditioners), and printed circuit boards for computers and smartphones and in switches and relays (Kundu et al., 2023; Sah, Chitra, and Kumar, 2023).

Beyond traditional uses, copper plays a significant role in printed electronics as a low-cost, highly conductive material for flexible transparent heaters, transparent conductive electrodes, thin-film transistors, flexible circuits, antennas and radio frequency identification tags (Zeng, He, et al., 2022). In the biomedical field, copper-containing materials are being developed for their beneficial biological effects, including protecting the cardiovascular system, promoting bone fracture healing and exhibiting antibacterial properties (Wang et al., 2021).

Beyond the potential for reintroducing recovered copper into traditional markets for electronic device manufacturing and general electrical, telecommunications and biological applications (provided that high purity levels are achievable), innovative upcycling applications are emerging. In one notable example, copper that was recovered from EoL PV panels was transformed into high-value copper oxide nanoparticles through green synthesis methods, demonstrating significant antibacterial properties and suggesting potential applications in medicine (Shafiq et al., 2024).

In the Australian context, recovered copper from EoL PV systems is best positioned as a secondary feedstock for established domestic metals and manufacturing markets rather than as a niche or technology-specific material stream. Although Australia holds one of the world's largest copper resource bases, refined copper production remains relatively limited and is closely tied to large, polymetallic operations, such as those at Mount Isa, Olympic Dam and the Cannington mine, where copper is coproduced with lead, zinc, silver, uranium and gold (Britt and Czarnota, 2024). This structure creates a natural role for recycled copper as a supplementary input into existing scrap handling, refining and fabrication pathways.

In PV-specific recycling systems, copper is typically recovered early through mechanical preprocessing, alongside aluminium frames and junction box wiring, allowing it to be directly routed into Australia's mature secondary copper markets without requiring PV-dedicated upgrading or purification steps (Suyanto et al., 2023). As a result, PV-derived copper can be readily reintroduced into domestic manufacturing streams that serve electrical infrastructure, energy systems and industrial fabrication, supporting the continuity of supply across high-volume, copper-intensive sectors.

From a system perspective, the practical value of copper recovery lies in its role as a bulk, high-throughput material stream that improves overall process efficiency and landfill diversion performance in PV recycling facilities rather than as a high-margin product. Techno-economic modelling indicates that, although higher-value materials (such as SoG-Si) dominate revenue, copper contributes materially to total recovered mass and stabilises operational performance by providing a consistent, market-ready output fraction (Suyanto et al., 2023).

Looking forward, global PV technology roadmaps indicate a growing interest in copper-based metallisation and interconnection schemes as partial substitutes for silver, driven by long-term supply and cost considerations (Hallam et al., 2023). In Australia, this trend strengthens the application potential of recovered PV copper as a domestic input to future PV component manufacturing and refurbishment pathways, linking PV waste valorisation directly to clean-energy supply-chain resilience.



Applications for Recovered Aluminium

Aluminium in PV panels is primarily in the frame that surrounds the module and sometimes in the module backsheet as a thin aluminium layer (although most backsheets are plastic). The frame, typically made of anodised aluminium (often an alloy, such as 6063), holds the glass and cell laminate together and provides structural support. Aluminium frames account for roughly 10 to 20 per cent of a panel's weight.

Aluminium is one of the most recyclable materials in the world; it can be remelted repeatedly with minimal quality loss and with huge energy savings compared with primary production. In this section, we briefly look at how aluminium from EoL PV modules is recovered and its subsequent potential applications.

Aluminium recovered from waste PV panels serves various valuable applications and can contribute to a circular economy and resource conservation. Primarily, the aluminium frames are mechanically removed during the recycling process (Raji et al., 2024; Saha et al., 2025). These removed aluminium strips are then classified as *extrusion scraps*, which already possess an established market for further use (Vinayagamoorthi et al., 2024).

Beyond direct mechanical recovery, chemical methods are employed to extract aluminium from other parts of the solar cell, such as the silicon wafer, often achieving high purity. For instance, a single-reagent approach using phosphoric acid can efficiently leach aluminium from PV cells, with minimal precipitate formation (Sim et al., 2023). Another hydrometallurgical process that uses nitric acid can extract aluminium from silicon wafers (Han et al., 2023). The resulting aluminium, once recovered, can be converted into specific compounds for industrial use. For example, aluminium phosphate (berlinite) that is isolated from recovered aluminium can be used in high-temperature kiln refractories, as a curing agent for refractories, as a flux for special glass and in the manufacturing of ceramics and organic synthesis catalysts (Han et al., 2023).

Furthermore, if high purity is achieved, recovered aluminium could be channelled into broader markets for new aluminium products. General applications of aluminium include its critical role in the automotive industry for light-weight design; it is used in engine blocks, power train parts, space

frames, sheet structures, closures, hang-on parts and other structural components (Hirsch, 2014). In civil engineering, pure aluminium alloys are also proposed for structural applications in seismic engineering, such as shear panels and torsional links, because of their low-yield strength and high ductility (De Matteis, Brando, and Mazzolani, 2012). Other potential applications for processed aluminium waste include its use in the production of hydrogen as a renewable-energy source and as a material for refractories, composites, ceramics, reductants, catalysts and absorption agents (Modalavalasa and Ayyagari, 2024). The conversion of aluminium waste into mesoporous alumina supports for catalysts also represents a promising avenue for valorisation (Osman et al., 2017).

In the Australian context, recovered aluminium from EoL PV systems is best positioned as a secondary feedstock for established domestic metals manufacturing and metallurgical value chains rather than as a PV-specific material stream. As the world's leading producer of bauxite and a major producer of alumina, Australia's aluminium industry is anchored in a globally significant upstream base, while primary aluminium smelting and downstream fabrication remain closely integrated with export-oriented supply networks. Within this structure, PV-derived aluminium can be readily absorbed into existing secondary smelting, alloying and fabrication markets that serve high-volume domestic sectors (such as construction, transport and packaging) in which aluminium's lightweight structural performance, corrosion resistance in coastal environments and extrudability into complex profiles underpin widespread use in window and door frames, roofing and façade systems, vehicle body panels and chassis components, and beverage cans and packaging foils (Lennon et al., 2022; Britt and Czarnota, 2024).

A key application pathway lies in aluminium–silicon alloy systems, which underpin a wide variety of casting and engineering products. The co-recovery of aluminium and silicon from PV modules strengthens the potential for closed-loop alloying, in which secondary aluminium streams are upgraded through controlled silicon additions to meet specification requirements for structural and functional alloys rather than being downcycled into low-grade scrap (Jennings et al., 2024). This pathway aligns PV aluminium recovery directly with domestic manufacturing demand in the building, automotive and engineered-



product sectors, including emerging electric-vehicle platforms that increasingly rely on aluminium alloys to offset battery mass and improve system efficiency.

Beyond fabrication and alloying, aluminium also supports metallurgical applications within Australia's broader resources and advanced-materials sector. In aluminothermic (thermite) reduction, aluminium functions as both a metal fuel and chemical reductant, enabling the extraction of high-value and critical metals from oxide feedstocks and the production of ferroalloys and specialty metals for advanced manufacturing and energy technologies (Makhambetov et al., 2025). In this context, secondary aluminium recovered from PV systems represents a supplementary reductant feedstock, linking PV waste valorisation to domestic critical-mineral upgrading and ferroalloy production pathways.

At the system level, Australian TEAs of PV recycling show that aluminium is typically recovered early in mechanical preprocessing and routed into mature domestic scrap and secondary metals markets, where it contributes substantially to recovered mass and process throughput, even when overall system revenue is dominated by higher-value outputs, such as SoG-Si. This positions aluminium as a high-volume, market-ready stream that improves landfill diversion, supports a continuous feedstock supply for manufacturers and strengthens the environmental performance of PV recycling systems (Suyanto et al., 2023).

Beyond these application pathways, the role of secondary aluminium recovered from PV systems also carries a system-level decarbonisation significance. Primary aluminium production is among the most energy-intensive and emissions-intensive routes in the metals sector because of the combined impacts of bauxite refining, alumina calcination and electrolytic smelting (Lennon et al., 2022). In contrast, secondary aluminium requires only a small fraction of this energy input, positioning PV-derived aluminium as a lower-carbon alternative feedstock for both fabrication and metallurgical use. In this sense, PV aluminium recovery not only strengthens domestic manufacturing and critical mineral upgrading pathways but also contributes to Australia's broader objectives in industrial emissions reduction and low-carbon materials supply.

Conclusion

The increasing volume of EoL PV panels presents both a significant challenge and a strategic opportunity for Australia. Some of the most-valuable elements embedded in these panels—including silver, aluminium, copper, silicon, indium and gallium—are critical and, in many cases, scarce. Their recovery and reuse through efficient recycling processes can greatly enhance the sustainability of Australia's energy systems, particularly in energy storage, conversion and advanced manufacturing technologies (Komoto et al., 2018).

Silver, because of its superior electrical conductivity, can be recycled and reused in the production of high-tech batteries, fuel cells and electronics (Kang et al., 2012). Aluminium and copper, often recovered from PV frames and wiring, can be redirected into renewable-energy infrastructure, such as wind turbines, power electronics and electric-vehicle components (Latunussa et al., 2016). Recovered silicon, once purified, offers promising applications in next-generation solar cells, LIBs and thermoelectric devices (Eshraghi et al., 2020).

Emerging recovery processes, including hydrometallurgical treatments and bioleaching, are gaining strong attention for their selectivity, efficiency and reduced environmental footprint. These methods allow the targeted recovery of critical and precious metals while minimising chemical waste and energy use (Dias et al., 2016). Integrating such processes within Australia's domestic recycling and manufacturing sectors offers strategic advantages: It strengthens sovereign capability, reduces dependence on imported critical minerals and supports local innovation and job creation (Department of Industry, Science and Resources, 2023).



In the Australian context, the strategic value of recovered PV metals lies not only in their generic reusability but also in their direct alignment with established domestic manufacturing and resource-processing value chains. Recovered aluminium can be reintroduced into construction, transport and packaging sectors as both fabrication feedstock and alloying input and, in part, as a metallurgical reductant for ferroalloy and critical-metal upgrading pathways, linking PV waste valorisation to advanced materials processing. Secondary copper can supplement electrical infrastructure, power transmission and electronics manufacturing, reinforcing mature domestic scrap and refining markets. High-purity recovered silicon aligns with Australia's emerging ambitions in solar manufacturing, battery materials and semiconductor-adjacent processing, while silver recovery supports electronics, electrical interconnection technologies and advanced energy systems in which long-term supply constraints are increasingly recognised. Together, these application pathways position PV recycling as a strategic industrial input stream that connects solar waste management with domestic manufacturing resilience, materials sovereignty and low-carbon industrial development.

Achieving this vision requires coordinated policy support, investment in R&D and active collaboration among government, research institutions and industry. With one of the world's highest solar adoption rates and strong expertise in advanced materials, Australia is well positioned to lead globally in the development of a circular economy for PV materials, closing the loop on solar technology while driving a more resilient and sustainable clean-energy future (Masson and Kaizuka, 2020).

Chapter 7 References

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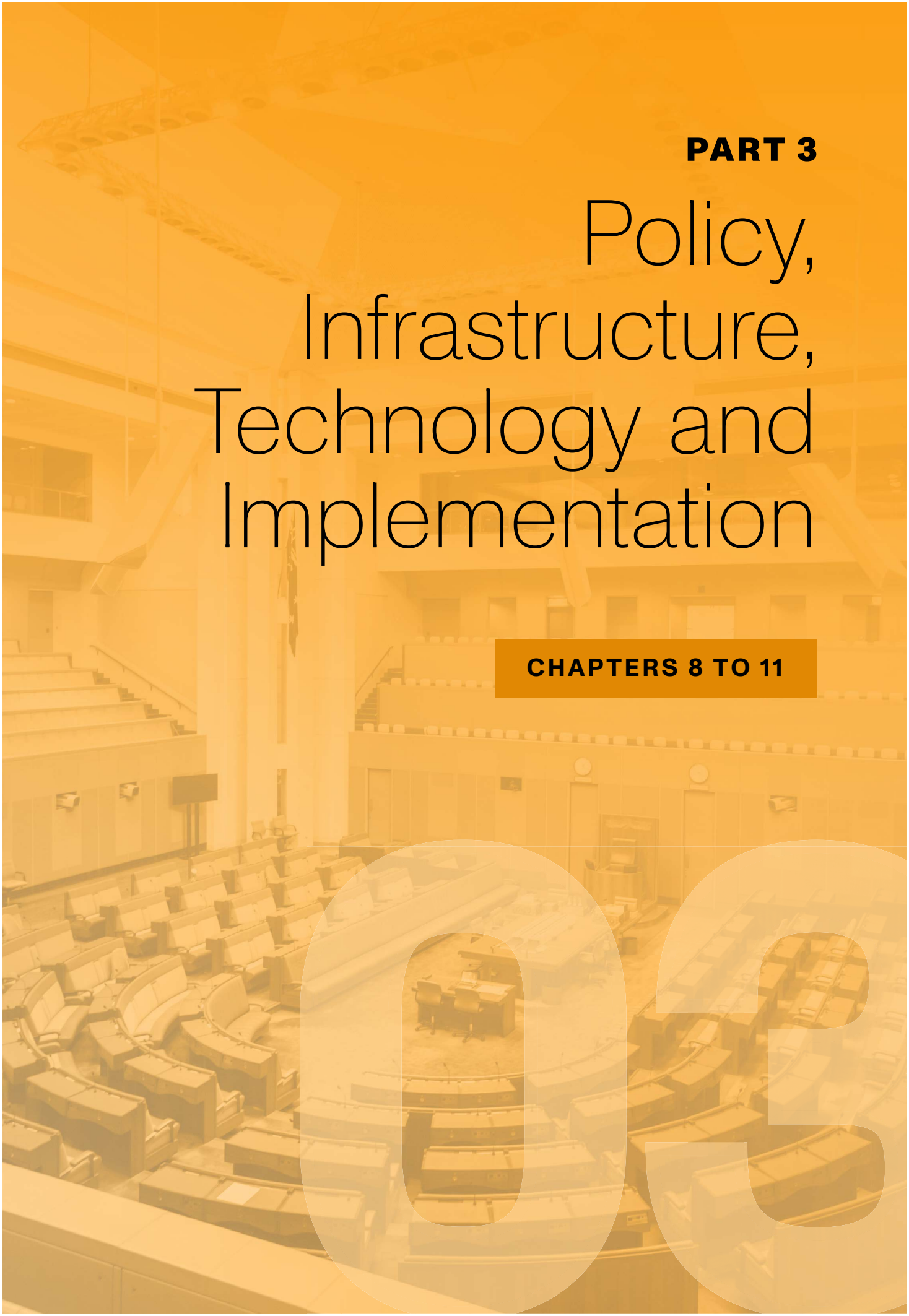
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PART 3

Policy, Infrastructure, Technology and Implementation

CHAPTERS 8 TO 11

03

CHAPTER 8

Holistic Approaches: Social, Environmental and Business Considerations for a Photovoltaic Circular Economy

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> We need to build consumer confidence in these [waste avoidance] services as the 'new normal' and support 'buying to last' consumption patterns.
>
> **Sustainability Victoria**

In the previous chapters, we established the circular economy foundation and technical requirements necessary for the development of a circular PV system. In this chapter, we will complement that work by discussing social, environmental and commercial requirements. These requirements can support the adoption rate in the transition to a circular PV system because the combination of these considerations provides a holistic and more accurate starting point for implementing circular economy strategies.

Social Considerations

Understanding the specific context in which PV systems are deployed will provide guidelines for how and which circular-economic strategies can be adopted. Context-tailored solutions respond to different elements, such as social conditions, environmental needs, regulations and commercial readiness. A recent study by Zhang et al. (2023) identified the main socioeconomic incentives driving PV panel uptake across different regions in Australia. The study showed that such factors as population density, housing types and personal characteristics (including education levels, gender, age and marital status) affect solar development. Additionally, the study highlighted New South Wales, Queensland and Western Australia as states with major solar deployment.

Circular PV systems will need to be tailored to state-based contexts because customers in different states have different access to and information about circular solutions and infrastructure. There are different needs regarding solutions for New South Wales as opposed to those for the Northern Territory. For example, in Northern Australia, a region that represents 53 per cent of Australia's surface and 5.3 per cent



of Australia's population, solar farms have strong potential but face challenges related to the large distances between population centres, poor infrastructure and high transportation costs (Mathur, Gregory, and Imran, 2022).

Australia is a large country with large distances between its major cities and rural towns. These distances can prove logistically challenging for a nationwide PV recycling system. As identified in the 'Waste Diversion Potential' section in Chapter 2, solutions to this problem include developing recycling infrastructure that can assist with the large volumes of waste that are expected in the country in the near future. The TEAs for material requirements and recovery of PV panels support commercially viable recycling operations in Australia. And, although different parts of the country have different electricity tariffs, landfill levies and logistics, there is nevertheless a clear business case for PV recycling. The question of whether centralised or decentralised models will work best will rely on local contexts, such as an area's access to solar farms, its availability of land for industrial zoning, its proximity to recycling and waste-treatment centres, and social considerations (e.g. the availability of job training and access to a labour force with relevant skills).

Regional recycling facilities across Australia could serve as job attractors if the right combination of logistical infrastructure and workforce training are colocated. Such approaches will require policy directives by state and territory governments to ensure their practical implementation, and these directives will also need to account for other economic considerations, such as job creation in regional and remote areas. The latter can help reduce regional urban migration, which puts pressure on housing and amenities and creates other problems in Australian cities.

In sum, regional hubs have varying geographic, logistical, political, economic and social challenges. In this chapter, we consider a variety of social dimensions that should be addressed when developing a circular PV system, including

- energy incentives that address socioeconomic factors
- social behaviours in the postproduction stages of the PV life cycle
- sociotechnical imaginaries related to solar power
- methods for building social awareness.

Energy Incentives That Address Socioeconomic Factors

The literature suggests that social behaviour change can affect sustainability transitions alongside technological and regulatory changes. This requires both awareness-building initiatives (such as education programs) and policy environments that acknowledge people's lived realities and create incentives to make sustainable practices feasible and attractive.

Social behaviours need to first be understood so that solutions that account for the drivers that affect energy use can be designed to support them. For example, even though Australia's National Construction Code requires a minimum 7-star rating (out of 10) for energy efficiency in new construction (National Construction Code, 2022), the existing stock of older buildings that are energy inefficient needs to be considered because climate change affects the users of these buildings. Because of climate change, Australia has more days of extreme weather than it did decades ago, and this extreme weather affects the comfort of users in energy-inefficient buildings. The Nationwide House Energy Rating Scheme, which provides energy ratings for homes, includes coverage of new and existing homes to provide an assessment of their energy needs (Nationwide House Energy Rating Scheme, undated).

These energy-need assessments assist in making occupants comfortable in their homes. The Nationwide House Energy Rating Scheme assessment includes major fixed appliances, thermal performance and on-site solar generation and storage. Although these programs have supported overall improvements in energy efficiency to help meet net-zero targets, vulnerable populations (such as the elderly, children and low-income households) are still significantly affected by energy-inefficient homes. Vulnerable populations might not have the disposable income needed to be thermally comfortable, such as by using a heater on cold days or an air conditioner on hot days. Often these populations are less able to adopt simpler energy-efficiency measures—such as installing insulation or drought proofing to keep indoor spaces comfortable—because of costs or rental housing constraints. With rising temperatures in such places as Melbourne, more energy is being used to heat homes in winter and cool homes in summer. The use of PV panels in homes supports less reliance on grid connections to make homes more comfortable.

The problem is even more acute with renters and people living in social housing. In addition, there is a housing affordability crisis (Australian Institute of Health and Welfare, 2025), particularly among the younger cohort and single older women. Renters are often loath to make demands on their landlords for fear of not securing ongoing leases.

Social Behaviours in the Postproduction Stages of the Photovoltaic Life Cycle

To analyse the potential for developing a circular PV system, it is important to understand circular consumption and supply-chain management dynamics (Farooque et al., 2019). To analyse the PV sector in Australia, the PV life cycle can be divided into three postproduction stages: purchase, usage and EoL management.

The purchase stage is key because it determines the rest of the PV life cycle. Wholesalers, which serve as the entry point of imported PV panels to Australia, decide the quality and quantity of PV panels that enter the country. Nevertheless, the end customers (retailers, installers and residential and commercial consumers) also influence the quantity of PV installations that occur and the quality of the PV systems that are installed.

The second and third stages for circular PV systems relate to the usage and EoL management logistics of the purchased panels. These stages are also influenced by socioeconomic and policy factors (Walzberg, Carpenter, and Heath, 2021; Madrigal, Iyer-Raniga, and Yang, 2023). As highlighted by Walzberg, Carpenter, and Heath (2021, p. 913) in their study of how social factors influence PV recycling programs, 'Social behaviours could play a critical role in developing secondary PV markets and managing EOL PV, because psychological and behavioural traits often undermine the viability of technical solutions'.

A comprehensive study on the barriers to and enablers for PV EoL management in Western Australia reviewed attitudes and behaviours from sellers, recyclers and local government representatives. The authors highlighted costs and lack of regulation, communication and interest as common barriers to recycling EoL PVs and increased customer awareness and behavioural change as two of the main enablers (Shrestha and Zaman, 2024).

The circular economy positions waste avoidance at the top of the priority list. In a circular system, waste is eliminated, as is the case in nature. To transition to a circular economy, responsible consumption practices are also critical. Even if Australians understand the behaviours involved in living sustainably (such as buying local, avoiding waste and using public transport), they still need to understand the impact of the *rebound effects*, the behavioural responses to increases in efficiency that reduce or negate sustainability benefits (Dransfield, Finegan, and Power, 2026). Specifically, there is little purpose in ensuring that every house has access to renewable energy through PV panels if that energy is ultimately wasted. From a built-environment perspective, communities will not only need to think sustainably but also act sustainably. Government incentives could go a long way to support such behaviour, as was the case with solar feed-in tariffs (FITs) to support renewable energy in Australia in 2008 (Henderson, undated). More advice is needed for consumers on options for energy-efficient appliances and products, from induction stovetops to electric vehicles.

Sociotechnical Imaginaries Related to Solar Power

Australia's solar energy transition exemplifies the global tensions between rapid decarbonisation imperatives and the complex social realities of energy system transformation. Multiple contested visions of solar technology compete to define Australia's renewable-energy future, each carrying distinct implications for economic structure, social relations, government policy and environmental outcomes. This section outlines the main sociotechnical imaginaries that relate to solar technology in contemporary Australian society. Science and technology scholars Sheila Jasanoff and Sang-Hyun Kim introduced the term *sociotechnical imaginaries* in 2009; they describe the social theory roots of the concept and define it as 'collectively imagined forms of social life and social order reflected in the design and fulfillment of nation-specific scientific and/or technological projects' (Jasanoff and Kim, 2015, p. 120). Sociotechnical imaginaries are shared visions and beliefs that societies (and groups within them) cultivate regarding what technologies should be prioritised and why they are important. In other words, sociotechnical imaginaries are collective, institutionalised ways of imagining the relationship between technology and social and economic progress (Longhurst and Chilvers, 2019).

Institutionally endorsed technology development pathways and social beliefs about how we should develop technology combine to formulate what are known as *sociotechnical imaginaries* (Rudek, 2022). In sociotechnical imaginaries related to solar power, public concerns about solar development projects extend beyond simple support or opposition to encompass complex negotiations over landscape values, community benefits and procedural justice. As Scovell et al. (2024) demonstrated through an analysis of local solar-farm acceptance, communities evaluate projects through multiple lenses, including perceived impacts on visual amenity, dust and noise during construction and effects on property values. These concerns intersect with broader narratives about energy transitions; public acceptance is influenced by beliefs about the role of renewables in replacing fossil fuels and ensuring energy security.

In the following sections, we present a collection of five sociotechnical imaginaries that relate to the solar sector in Australia. They are presented here not as a full and comprehensive list but rather a selection of dominant narratives that are often cited in academic literature and reflected in public discourse (Miller, 2020). Importantly, in the context of this mainly technical publication, these imaginaries demonstrate how assessments of the efficacy of solar technologies might be useful beyond their purely technical value. In



sum, the need to address social concerns related to solar developments (and the underlying sociopolitical forces that shape people's beliefs and concerns about those developments) is crucial for shaping the role of solar technologies in a successful energy transition.

Sociotechnical Imaginary 1: Renewable-Energy Superpower

This sociotechnical imaginary frames Australia as a global energy exporter of hydrogen and solar-derived commodities (Beasy, 2022; Beasy, Lodewyckx, and Gale, 2024). This is the dominant vision in Australia, and government and industry widely promote it. The focus is often on utility-scale projects, export infrastructure and national leadership coupled with strategic vision. Policy frameworks emphasise technological innovation, economies of scale and integration with global value chains (Curran, 2019). The Australian Renewable Energy Agency's funding priorities reflect this vision, supporting grid-scale projects and emerging technologies, such as concentrated solar thermal systems (Owens, 2024).

Sociotechnical Imaginary 2: Energy Sovereignty, Democracy and Community Ownership

This imaginary, particularly popular in regional settings, describes an Australia with geographically distributed solar energy generation. The emphasis is on incorporating community control and ownership of solar technology, often supported by participatory governance. Importantly, this imaginary prioritises local energy security through microgrids and stand-alone power systems that do not feed into the grid but empower local communities (Mey and Hicks, 2015; Gui and MacGill, 2018; Hill and Connelly, 2018; Mey and Hicks, 2019).

Sociotechnical Imaginary 3: Techno-Economic and Market-Based Vision

This sociotechnical imaginary envisions solar power and Australia's energy transition as primarily a technical problem, a market-based problem, or both. Energy-transition challenges are presented with solutions that are primarily couched in terms of scale and requisite amounts of public or private investment (Sovacool et al., 2020; Beasy, 2022; Virens, 2024).

Sociotechnical Imaginary 4: Environmental Justice and Extractive Industry

In this imaginary, rafts of injustices that continue to affect indigenous communities are foregrounded. It warns that large-scale utility solar-farm projects in remote areas can reproduce colonial injustices via power disparities and relationships based on the extraction of resources from one party at the cost of the other (O'Neill, Thorburn, and Hunt, 2019; Thorburn et al., 2019). This imaginary calls for substantive benefit-sharing, indigenous self-determination and the avoidance of colonial patterns (Riley, 2021).

Sociotechnical Imaginary 5: Extractive Circularity

This imaginary treats renewable-energy technology as future mineral feedstock and export commodities, integrating circular economy principles with renewable-energy expansion to manage material flows sustainably. It focuses on strategic extraction enabling long-term circularity, as existing PV panels and wind turbines become tomorrow's material reserves (Völker, Kovacic, and Strand, 2020). By emphasising design for recyclability and the development of cross-sector material pathways, this vision promises to decouple renewable-energy growth from perpetual virgin extraction, positioning temporary mining intensification as a necessary investment in future circular systems (European Commission, undated-b).

Competing Imaginaries

The struggle between these sociotechnical imaginaries shapes material outcomes through planning processes, investment decisions and regulatory frameworks. Policy settings largely favour the renewable superpower vision through mechanisms supporting large-scale generation certificates and streamlined approvals for major projects. However, growing social movements and an increasing recognition of social licence requirements maintain pressure on pursuing viable alternative approaches.



Methods for Building Social Awareness

Presenting technical information to the public in a manner that people can readily understand has a positive influence on the adoption of circular strategies. Moreover, including insights from analyses of communities where solar-energy development projects are proposed can enable the design of communication strategies that help affected communities better understand how the renewable-energy transition relates to them. That understanding can help increase communities' acceptance of innovative renewable-energy technologies. In this section, we discuss different methods for building social awareness about and public acceptance of a PV circular economy.

Bringing Solutions Closer to Urban Centres

An example of a shift in the way technical solutions are presented is framing PV material recovery as *urban mining*. The process of manufacturing PV panels uses materials obtained from mining activities that have negative, sometimes irreversible, impacts on the environment and social security (Xavier, Ottoni, and Abreu, 2023; Aska et al., 2025). Framing PV material recovery as urban mining offers an alternative to traditional extractive mining; while extractive mining continues the status quo of the linear economy, urban mining both symbolises and employs principles from circular economics, industrial ecology and industrial metabolism (Xavier, Ottoni, and Abreu, 2023). Urban mining can also be adopted as an approach to secure resource availability (Zeng, Xiao, et al., 2022), especially when there are supply risks for resources in high demand, such as copper (IEA, 2025).

As discussed in Chapters 5 and 7, materials in PV panels represent valuable sources of critical materials, such as silicon, copper and silver. Widespread recovery of these critical materials is most promising in urban areas where many PV panels are reaching their EoL. Mapping of these urban mines is one of the priorities of urban mining efforts (Xavier, Ottoni, and Abreu, 2023).

In Australia, industry is starting to look at an urban-mining concept for PV panels. The Smart Energy Council has highlighted urban mining as the solution to material scarcity and inefficient material recovery systems (Smart Energy Council, 2025a). PV recycling companies, such as Lotus Recycling and Ecocycle, are already using the term *urban mining* to describe their services and practices (Lotus Recycling, undated; Ecocycle, 2024).

Building Consumer Awareness

To successfully transition to a circular economy, consumer awareness is one of the main challenges to address (Kirchherr et al., 2018), and it requires a cultural shift (Chenavaz and Dimitrov, 2024). The recovery of the materials embedded in EoL PV panels is a practice that needs to be understood beyond the lens of waste management.

According to Sustainable Governance Indicators, Australia is ranked 22nd in the world for environmental sustainability (Sustainable Governance Indicators, undated). The Australian government is deeply committed to sustainability as evidenced in its net-zero targets and support of renewable-energy generation (DCCEEW, 2025b). Public sentiment about environmental issues in Australia goes through cycles of peaks and troughs. Positive public sentiments about environmental issues rose between 2005 and 2008; in 2024, these sentiments fell by 0.4 per cent (IBISWorld, 2025). It is not uncommon for sustainability scholars to find links between sustainable behaviours and sustainability outcomes, including outcomes for the circular economy. For instance, a Sustainability Victoria report found that the majority of Victorians believe that living sustainably is important (Sustainability Victoria, 2023). Behaviours that relate to sustainable living are also related to acting on pro-environmental behaviours. These include such behaviours as using products that contain recycled content. Approximately two-thirds of the people surveyed in the Sustainability Victoria report indicated that using renewable energy through PVs also supports new jobs and investment

opportunities (Sustainability Victoria, 2023). School children also influence at-home sustainability behaviours by, for example, encouraging adults to check energy-efficiency ratings before buying new appliances.

Given that many Australians perceive they are already experiencing the impacts of climate change, their attitudes towards sustainability have also changed. Social licence (e.g. trust, support and approval from local communities) is critical to achieve in addition to government support underpinning policy and regulations.

Mainstreaming the Circular Economy

To mainstream the circular economy, it is critical to not only build social licence but also find ways in which social licence can be catalysed to support societal transitions. Although economic incentives and regulatory considerations have a place in the circular PV economy, not everything can be regulated. For instance, PV panels might be subjected to EPR, but, to ensure that EPR is implemented, different parts of the PV supply chain must work well together—both upstream and downstream. Various actors need to work together to ensure that there are no disconnects across the value chain. Such coordination requires other forms of societal engagement beyond regulation alone—for example, through network governance (Cramer, 2020). Instead of the traditional, unicentric form of governance, *network governance* refers to the alignment and engagement of stakeholders to support the implementation of a circular economy.

Traditional governance models engage with various stakeholders through centralised or federal approaches, as in the case of Australia, which relies on a traditional government-led model to support the implementation of a circular economy. However, this is not the case with network governance models, in which nongovernmental actors (such as business firms, public organisations and private organisations) work together as interdependent stakeholders in the transition to a circular economy (Iyer-Raniga and Cramer, 2026).

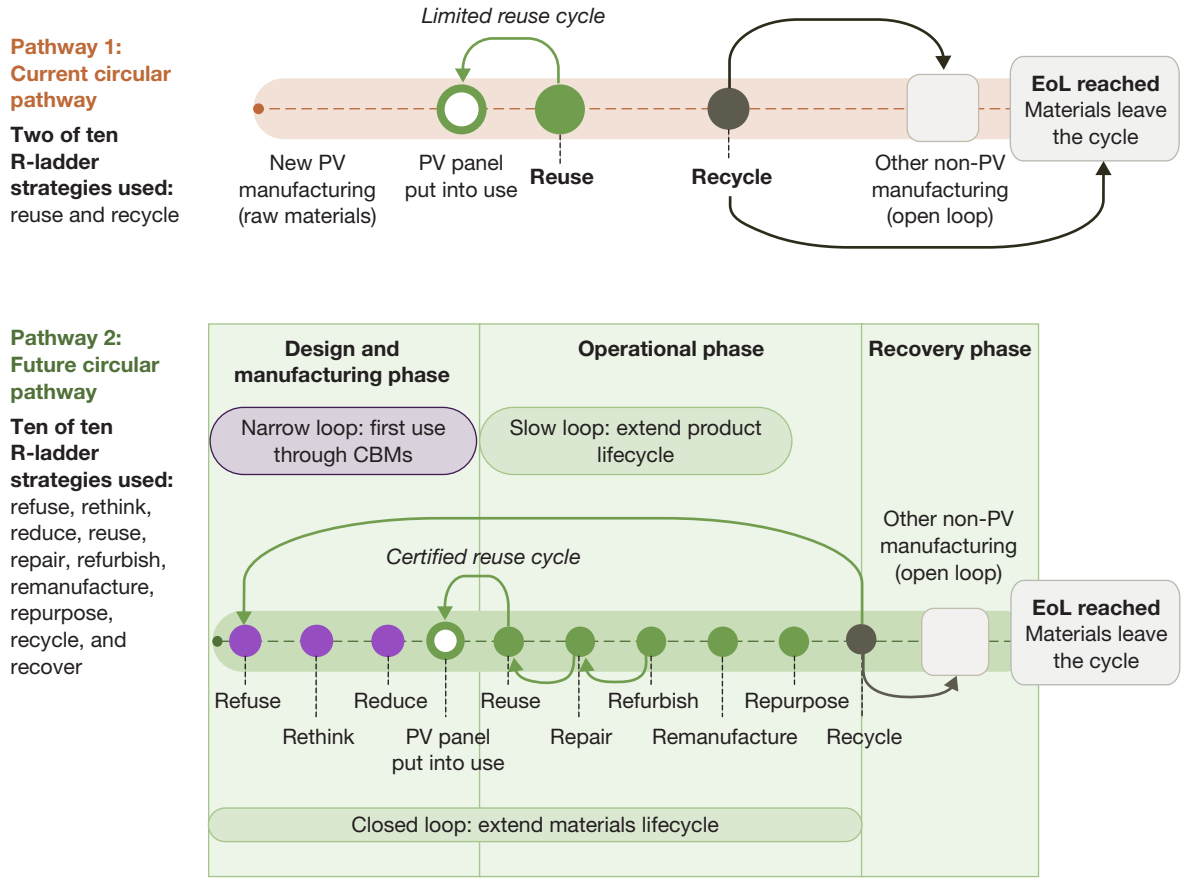
Future Thinking: An Example of a Circular Photovoltaic System Enabled by a Shift in Social Behaviours

Chapter 3 presented examples of a circular economy being developed for PVs. These examples and other efforts to develop a circular PV system—such as SOLARCYCLE'S new panels manufactured with recovered glass (SOLARCYCLE, 2024) and Queensland's Reuse Pilot (Smart Energy Council, 2025b)—focus on a handful of circular strategies. Nevertheless, exploring how to integrate several circular strategies into Australia's PV system can provide a more feasible pathway to circularity—if efforts include social considerations. We assessed several studies on how to integrate circularity through the use of R-ladder strategies in PV systems (Heath et al., 2022; Rabaia et al., 2024; Madrigal, Iyer-Raniga, and Yang, 2023; Tsanakas et al., 2020; Walzberg, Carpenter, and Heath, 2021), and we conclude that PV circular systems will be possible when they account for the social factors involved and are supported by policy frameworks that enable reduce, reuse, repair, recycling and even product-as-a-service systems. With a system that provides reassurance through such features as PV passports, warranties, certificates in new PV modules and enhanced communication between recyclers and manufacturers, PV installers and PV recycling and reuse services will be better equipped to navigate the interrelationship between social needs and technical innovations. Setting up these service providers for success could aid in creating a circular PV system.

Figure 8.1 depicts an example of how R-ladder strategies can be applied to the PV life cycle, starting with the reduce strategy and ending with the recycling strategy to avoid landfilling (which, in turn, could lead to open-loop or closed-loop destinations). The reduce strategy could be applied to reduce the amount of materials embedded in a PV module (Heath et al., 2022); however, the sustainability benefits will be greater if such reductions are accompanied by a decrease in energy demand and, therefore, in the number of PV panels purchased. With fewer new PV panels, there will be an increased interest in maintaining, rethinking, repairing, reusing and recycling existing panels. Refusing PV panels that do not comply with

FIGURE 8.1

View of a Photovoltaic Life Cycle Within a Circular System



SOURCES: Adapted from Majewski and Dias, 2023; Heath and Drahi, 2024; and Madrigal, Iyer-Raniga, and Jing, 2023.

NOTE: Pathway 1, while preferable to linear pathways, uses only two of the ten R-ladder strategies, and recycled materials are not used in PV remanufacturing. Pathway 2, which uses all ten R-ladder strategies, increases the life-cycle period of both the panel and its materials (retaining more value before EoL processing).

circularity standards will help to increase the usage of and decommissioning processes for PVs. Additionally, PV module quality is essential for PV efficiency reliability because 'material circularity alone (at 70% closed-loop recycling) cannot compensate for poor lifetime and efficiency' (Mirletz et al., 2024, p. 8). Hence, the purchase of new high-quality PV panels that have digital passports and are designed for circularity will add reliability to the circular system. On this note, PV modules that have longer life cycles can represent a reduction in PV panel replacements, which allows the market to develop and scale up solutions for circular PV systems (Mirletz et al., 2024).

With an incentivised market for PV reuse and recycling, the life cycle of PV panels can be extended, and the need to use raw materials in manufacturing can be decreased.

Environmental Considerations

The transition to a circular economy in the PV sector requires a strategic shift in the way materials, energy and processes are managed throughout the life cycle of PV systems. Beyond economic and technical considerations, the environmental implications of EoL PV management are crucial to achieving national

sustainability goals and international climate targets. The circular management of PV waste—including reuse, refurbishment and high-value recycling—can significantly reduce environmental impacts compared with landfilling or low-efficiency recovery processes (Jensen and Remmen, 2017).

A holistic approach includes the following environmental considerations:

- **carbon footprint reduction**—examines how material recovery and domestic processing can reduce emissions across supply chains
- **resource conservation**—highlights the importance of preserving critical raw materials and enabling the closed-loop use of high-purity materials
- **hazardous material management**—addresses the need to mitigate risks associated with the handling and disposal of potentially toxic substances
- **long-term sustainability metrics**—provides a framework for monitoring and evaluating the environmental performance of PV systems over time, including circularity and resource efficiency indicators.

Together, these considerations form a foundation for designing environmentally sound EoL PV panel collection, dismantling and processing systems that support both Australian and global climate ambitions.

Carbon Footprint Reduction

Both PV modules and inverters have life-cycle carbon footprints, especially through upstream activities, such as raw material extraction, manufacturing and long-distance transport.

The embedded carbon emissions in PV modules are associated primarily with the production of high-purity silicon, aluminium frames and silver-based conductors. In the case of PV inverters, the main contributors to carbon emissions include aluminium housings, copper wiring, power electronics and energy-intensive semiconductors. The inverters also typically have shorter lifetimes than the modules (10 to 15 years versus 25 to 30 years, respectively), requiring replacement and contributing to cumulative carbon impacts.

Addressing these embedded emissions is crucial for achieving Australia's climate goals. Included in Australia's Net Zero Plan are the commitments to reduce GHG emissions by 43 per cent below 2005 levels by 2030 and reach a net-zero emissions and 82-per-cent renewable electricity target by 2050 (DCCEEW, 2025c).

EoL PV strategies that prioritise reuse, refurbishment and high-efficiency recycling can play a pivotal role in mitigating the carbon footprint of PV systems. Recycling PV materials (such as aluminium, silicon, silver and copper) not only conserves valuable resources but also significantly reduces the emissions associated with virgin material production. For instance, recycling aluminium saves up to 95 per cent of the energy required for primary extraction (International Aluminium, 2024). Life-cycle analyses indicate that recycling can reduce GHG emissions associated with PV systems by 20 to 30 per cent, depending on the recycling process and technology type (Chowdhury et al., 2020).

Most PV modules and inverters installed in Australia are imported, primarily from East and Southeast Asia (Florin, Salim, and Madden, 2023), and long shipping distances add significantly to transport-related emissions (Vaqueiro Contreras et al., 2023). To address this, the Australian government launched the Solar Sunshot Program in March 2024, investing $1 billion to strengthen local PV manufacturing and component supply chains (Australian Renewable Energy Agency, 2025). By reducing Australia's dependence on imported modules and fostering local production, Solar Sunshot is expected to lower embodied emissions across the PV life cycle.

Ecodesign strategies also offer substantial mitigation potential. For modules, such innovations as detachable frames and adhesive-free backsheets reduce dismantling energy and promote recyclability (Fraunhofer Institute for Solar Energy Systems, undated; Bilbao et al., 2021). For inverters, modular



designs with replaceable parts can extend PV system lifetimes and reduce the need for full-unit replacements (Santos, 2022). Incorporating low-carbon aluminium or recycled copper into casings and windings can further decrease upstream emissions (Béjat et al., 2025).

Currently, Australia lacks dedicated carbon-footprint standards for PV components, although some initiatives (such as Climate Active) enable organisations to certify carbon-neutral operations and products (Climate Active, undated). Additionally, Australia's National Waste Policy Action Plan and the Circular Economy Framework aim to double the national circularity rate by 2035, which could lead to an estimated 14-per-cent reduction in national GHG emissions (DCCEEW, 2024a).

Finally, integrating LCAs and environmental product declarations into procurement, design and EoL decisionmaking can help quantify and reduce emissions across both module and inverter life cycles.

Moreover, as we explain in more detail in the 'Long-Term Sustainability Metrics' section later in this chapter, future product stewardship schemes should consider climate metrics in their design, particularly for inverters, whose higher turnover rate offers more-frequent opportunities for carbon savings through reuse or remanufacturing.

Resource Conservation

PV modules and inverters contain a variety of base and functional materials, including aluminium, copper, silicon, silver, rare earths and engineered polymers. Many of these are either resource-intensive to extract or subject to global supply constraints. Recovering these materials at EoL can reduce the demand for virgin mining, support local manufacturing inputs and avoid environmental degradation.

PV inverters are often overlooked in resource planning, yet they contain copper coils, aluminium housings, power electronics, circuit boards and increasingly rare elements, such as tantalum and neodymium in capacitors or transformers. Unlike PV modules, inverters typically require replacement every 10 to 15 years, meaning more-frequent turnover and higher per-decade material consumption.

If disassembled and recovered properly, inverter components can provide high-quality secondary materials, such as recycled copper and aluminium, which significantly reduce upstream carbon and energy use compared with virgin alternatives. Modular inverter designs with easily replaceable components also support conservation by reducing the need to discard the full unit when faults occur (Santos, 2022).

Hazardous Material Management

As Australia prepares for increasing volumes of EoL PV systems, robust strategies for managing hazardous materials are essential to protect workers, communities and ecosystems. Both PV modules and inverters may contain substances classified as hazardous under various chemical and environmental standards. Without dedicated handling protocols, these materials can pose long-term risks during dismantling, storage, transport and disposal.

Hazardous Substances in Photovoltaic Modules

Although modern PV modules are designed for safety during use, several EoL risks persist because of these modules' material composition. Notable hazardous constituents include

- lead: found in solder joints and junction boxes, especially in modules manufactured before 2015
- cadmium: used in some thin-film technologies (e.g. cadmium telluride), although these are rare in the Australian market
- antimony: present in glass; can hinder recycling, depending on the final use of the cullets
- fluorinated polymers: found in backsheets (e.g. PVF, PVDF); persistent and difficult to recycle.

Scoping Study: Solar Panel End-of-Life Management in Australia highlights the presence of lead and antimony as key concerns in Australia's PV waste stream and calls for dedicated dismantling and treatment protocols to minimise exposure and contamination risks (Deng et al., 2024). The presence of these hazardous materials has implications for regulatory frameworks and industry preparedness for a circular economy amid fragmentation across regulations in different states of Australia.



Hazards in Photovoltaic Inverters

PV inverters contain a variety of electrical and electronic components that also raise safety concerns, including

- electrolytic capacitors: often contain flammable or corrosive electrolytes
- lead-based solder: common in circuit boards and older electronics
- printed circuit boards: might contain brominated flame retardants and heavy metals (e.g. lead, mercury)
- lithium-ion or lead-acid batteries: in hybrid or off-grid inverter systems, with associated fire and chemical risks.

The improper disposal or untrained dismantling of these components could lead to short circuits, fire hazards and environmental contamination. Unlike PV modules, which are often treated as e-waste or construction debris, inverters clearly fall under electrical and electronic waste regulations, although Australia lacks harmonised national handling protocols specific to PV inverters.

In Australia, PV modules and inverters are not explicitly classified as hazardous waste at the national level. Under the Recycling and Waste Reduction Act 2020, PV systems are classified as a 'listed class of products', but this does not equate to a hazardous classification under the National Environment Protection (Movement of Controlled Waste between States and Territories) Measure (Australian Government, 2020). Therefore, PV modules are not subject to mandatory reporting requirements for hazardous waste handling and transport.

However, the following are important state-level exceptions:

- Victoria has implemented more-stringent rules. Since December 2019, Victorian landfills ban the disposal of all e-waste, including PV modules, inverters and batteries. Victoria is the only state with mandatory disposal restrictions for these components (Komoto et al., 2022; Office of Circular Economy, Department of Environment and Science, 2023).
- Western Australia introduced an e-waste landfill ban effective 1 July 2024. However, the initial phase of the ban does not include PV panels and other PVs, meaning PV modules and inverters remain outside the regulated categories. Households are encouraged—but not legally obliged—to dispose of regulated e-waste at drop-off points rather than kerbside bins (Department of Justice, 2024).
- The Australian Standard AS/NZS 5377:2022, which governs e-waste handling, has not yet been updated to include PV modules or inverters, although a revision process is underway. This leaves a regulatory gap in other states and territories, where PV systems may still be landfilled legally (Standards Australia, 2022).

For PV inverters, the situation is similar. They follow general e-waste disposal rules. Although some are refurbished, most are either recycled in Victoria or stockpiled or landfilled elsewhere. There is no nationwide mandate for recycling PV inverters, and significant barriers remain in terms of collection, storage and treatment infrastructure.

Hazard mitigation can be addressed through upstream design and downstream infrastructure measures. Priority actions include

- promoting lead-free solder and halogen-free printed circuit boards in inverters and modules
- avoiding fluorinated polymers in backsheets through material substitution
- building or upgrading dedicated dismantling lines and hazardous waste facilities under such programs as the Recycling Modernisation Fund
- including worker training and safety standards in national PV waste guidelines.

Long-Term Sustainability Metrics

Key metrics under consideration include the carbon footprint per kWh generated, material recovery rates, energy payback time, embodied energy and recyclability scores. The European Product Environmental Footprint Category Rules for PV modules provide a model framework, recently adapted by the European Commission's Joint Research Centre to offer harmonised carbon footprint methodologies specifically for PVs, covering silicon content, energy sources in manufacturing and recyclability assumptions (Ardente et al., 2025).

As of this writing, Australia lacks binding sustainability disclosure requirements for PV products. However, voluntary standards are emerging. For example, the NSF/ANSI 457-2019 standard, although U.S.-centric, is referenced by Australian suppliers for sustainability certifications of inverters and modules (NSF Joint Committee, 2019). This standard covers life-cycle GHG emissions, recycled content and EoL take-back programs.

Australia's sustainability ambitions are formalised under the National Waste Policy and the Renewable Energy Target. However, reporting on actual sustainability performance remains limited. For instance, although the National Waste Policy Action Plan sets an 80-per-cent resource recovery rate by 2030, existing PV recycling rates remain well below 20 per cent, largely because of inadequate tracking systems and the absence of performance-based metrics in procurement and subsidy schemes (Taylor et al., 2025).

Promising developments include the Recyclability Index for PV (Viegand Maagøe, 2025), which Australia could adapt or integrate into future product stewardship schemes. This index evaluates ten criteria, including dismantling ease, hazardous content and material separability. Australia's proposed PV Product Stewardship Scheme could use these indicators to define minimum recyclability thresholds or ecodesign incentives.

Australia's Circular Economy Framework targets a doubling of resource productivity by 2035, encouraging closed-loop supply chains (DCCEEW, 2024a). To support this, material-flow tracking and EoL data collection for inverters should be included alongside module tracking under new regulatory systems.

Commercial Considerations: Business-Model Development

The transition to a circular economy in the PV sector is crucial for managing the imminent wave of EoL waste. CBMs are evaluated for feasibility and viability to bridge the gap between complex recycling technology (a hard-tech innovation) and the enablement of scalable market solutions.

Typically, CBMs derive from the following five strategic archetypes:

- **Product-as-a-service** allows the installer or manufacturer to retain ownership of the modules, internalising EoL responsibility and incentivising design for disassembly.
- **Product life extension** focuses on maximising the use period of a PV system through repair, refurbishment and certification for a secondary market.
- **Sharing platforms** aim to optimise asset utilisation, such as through peer-to-peer (P2P) energy trading.
- **Circular supplies** dictate the replacement of virgin inputs (such as high-purity silicon) with secondary raw materials recovered from EoL panels.
- **Resource recovery**, e.g. ROSI (Beyer, 2022), involves converting unrepairable modules into valuable secondary materials via high-value recycling of components, such as aluminium, copper and silicon.

Implementing feasible and viable CBMs is essential for ensuring the long-term sustainability and resource security of the entire PV ecosystem.

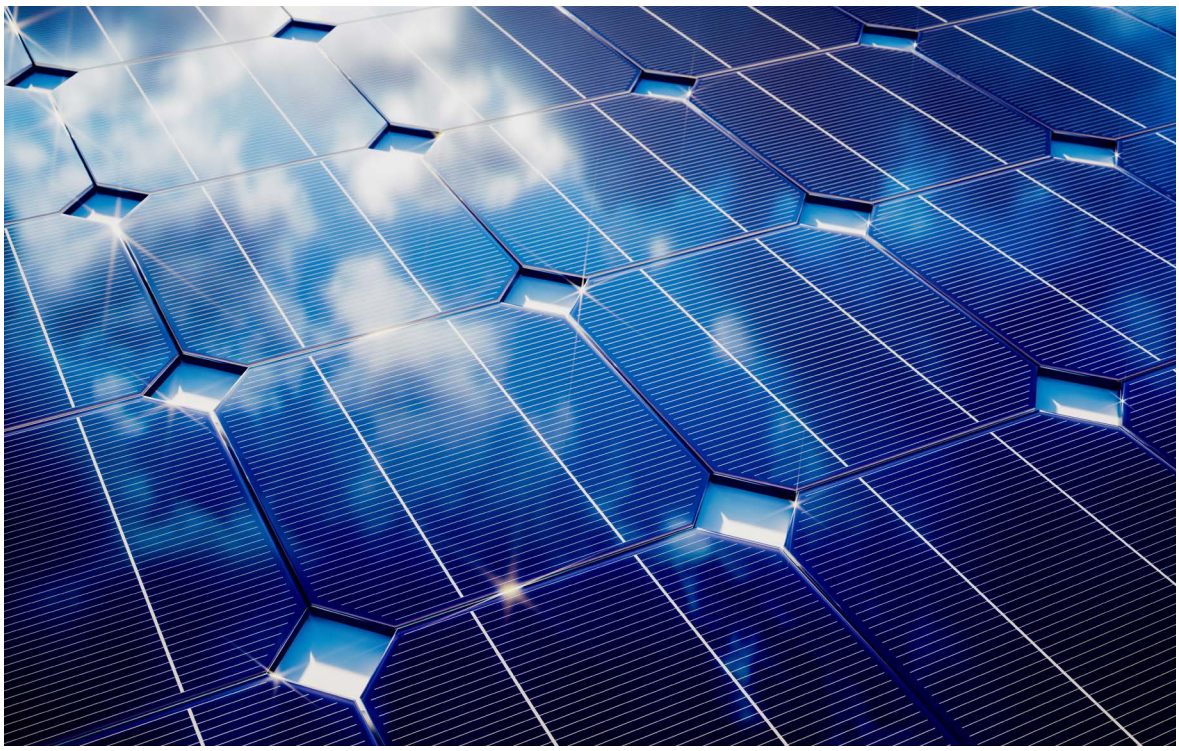
Circular Business Models: Five Archetypes

In this section, we consider five archetypes for CBMs that can address the ecosystem of PV panels, including their feasibility and viability.

Product-as-a-Service

This CBM is manifested primarily through power purchase agreements (PPAs) and solar lease structures. Product-as-a-service is a highly effective CBM that has achieved significant global scale, particularly in the United States, and is seeing strong adoption in Australia. Globally, large residential installers, such as Sunrun and Tesla Solar in the United States, pioneered the solar lease and residential PPA, allowing millions of homeowners to install PV panels with zero upfront costs. The key circular mechanism here is the retention of asset ownership by the third-party provider, who then assumes responsibility for all maintenance, performance monitoring and, crucially, EoL management, thereby internalising the incentives for product life extension and eventual resource recovery (Stahel, 2010; Tukker, 2015).

In the Australian context, although outright purchase remains common, the PPA model has gained significant traction, especially in the commercial and industrial sectors, and this model is increasingly being adapted for residential use. Australian companies, such as Horan & Bird Solar and Australian Solar Quotes, offer residential PPAs in which the customer purchases the solar energy generated at a predetermined rate (in cents per kWh) that is typically lower than the utility rate, and the provider owns and maintains the system for the long term, sometimes 10 to 25 years. This provides an immediate cash flow benefit and predictable pricing, acting as a crucial energy hedge against rising utility costs.



A notable and innovative Australian CBM is the true solar-as-a-service model pioneered by such companies as Plico Energy in Western Australia. This model extends the product-as-a-service concept to include a complete solar and battery storage system delivered on a fixed weekly subscription fee. Plico takes on the complexity of system selection and maintenance, and their financial backing is often structured to ensure the long-term viability and customer support that can be lacking in simpler financing models. The subscription structure embodies the CBM philosophy: The customer pays for a service (energy independence and reliable power) rather than owning a depreciating product, ensuring that the provider is responsible for asset monitoring, repairs and, ultimately, the circular pathway of both the modules and the battery-storage component.

This strategic shift from one-time sales to long-term service contracts in Australia directly supports circularity by creating a guaranteed, centrally managed EoL stream, which is essential for making downstream resource recovery (i.e. recycling) business models financially viable at the required scale.

Product Life Extension

This PV system CBM focuses on maximising the operational lifespan of the PV product through reuse, refurbishment and remanufacturing; compellingly, research has demonstrated that simply extending a PV system's life from 30 to 40 years is more favourable for environmental impact reduction than basic recycling alone (Singh et al., 2021; Paç and Gok, 2024). This CBM is crucial because a significant number of panels are currently decommissioned early. This is often due to minor system faults, roof repairs or upgrades, despite a PV system being fully functional. Globally, this model is championed by companies, such as FabTech Solar Solutions in the United States, that specialise in refurbishing and reselling vast quantities of panels that were damaged during initial installation or decommissioned prematurely, thereby democratising access to cheaper solar energy and drastically reducing waste volume.

In Australia, the concept is actively being commercialised through such initiatives as Second Life Solar; this initiative was developed from a successful pilot that proved that a high percentage (89 per cent) of collected EoL panels are still fully serviceable and can be certified for redeployment (New South Wales Climate and Energy Action, 2024). A 2023 Australian survey of installers revealed that almost 30 per cent of decommissioned PV systems are less than 10 years old and have been prematurely decommissioned because of faulty PV panels and broken inverters (Florin, Salim, and Madden, 2023). These initiatives not only create a secondary marketplace for used panels but also perform the necessary testing and certification to reassure communities about the investment and performance of second-life assets, although the lack of a consistent national reuse framework remains a key hurdle. By prioritising reuse and refurbishment, these initiatives establish a critical circular pathway that both delays the need for energy-intensive recycling and transforms potential waste into a valuable resource, benefiting both cost-conscious consumers and national resource conservation goals.

Sharing Platform

Also known as *P2P energy trading platforms*, these CBMs are designed to optimise distributed energy asset utilisation, allowing producers to sell their surplus power directly to local consumers instead of selling it back to the grid at low FITs (Zhang et al., 2016; IRENA, 2020). This system maximises the value of such assets as rooftop PV systems and home batteries. The P2P energy trading model enhances PV circularity by directly optimising asset utilisation and strengthening the product life extension CBM. By enabling PV owners to sell surplus energy at higher rates than traditional tariffs, P2P platforms increase the financial return and longevity of the PV panels, creating a compelling incentive for continued maintenance and delayed decommissioning (Zhang et al., 2016; IRENA, 2020). This successful maximisation of the asset's service life is achieved despite the technological challenge of integrating diverse decentralised assets and the logistical complexity of managing variable energy flows across local networks.

This CBM is being successfully trialled and deployed both in Australia and globally. In Australia, the most prominent example is Powerledger, an Australian company that develops blockchain-based software for tracking, tracing and trading renewable energy (Powerledger, undated). Their platform facilitates P2P trading in local communities, allowing neighbours and businesses to buy and sell energy from each other. This technology has been used in various Australian trials, such as the RENeW Nexus Trial in Fremantle, Western Australia. Another example is Localvolts, which operates as an independent, authorised electricity retailer and P2P marketplace across Australia's national grid, allowing everyday consumers to participate.

Globally, P2P platforms are advancing quickly. Piclo in the United Kingdom operates an independent marketplace that matches consumers with nearby renewable generators. In a different application, the SOLshare project in rural Bangladesh uses a P2P approach to build solar minigrids, enabling energy trading among households and providing access to electricity in underserved areas (SOLshare, 2022). The Quartierstrom project in Switzerland demonstrated a local electricity market in which residents successfully traded solar power within their neighbourhood (Ableitner et al., 2019). These systems are shifting the energy market from a centralised to a decentralised model, increasing the efficiency and value of renewable-energy assets.

Circular Supplies

This PV system CBM focuses on replacing virgin inputs with secondary raw materials recovered from EoL panels (IRENA, 2020). Globally, such companies as First Solar have established integrated recycling programs to use recovered semiconductor material and glass to manufacture new thin-film panels, achieving up to 90-per-cent recovery and closing the loop directly. In Australia, this model is demonstrated through specialised processes that enable high-purity nano-silicon to be recovered from EoL panels for use in next-generation LIB anodes, creating a valuable new circular supply chain for critical minerals (Rahman et al., 2021; Manohar et al., 2025). This approach transforms the EoL PV asset from waste into a valuable resource input, fundamentally altering the economics of PV manufacturing towards true circularity.

Resource Recovery

This CBM involves converting unrepairable modules into valuable secondary materials via high-value recycling; it has established commercial examples both in Australia and internationally. ROSI's entire business model is based on selling these high-value secondary materials back to the solar and semiconductor manufacturing industries, thereby drastically reducing reliance on virgin materials and setting a high benchmark for circularity with low landfill waste (Rahman et al., 2021).

In Australia, the resource recovery model is being commercialised by such companies as PV Industries and ElecSome. PV Industries offers a comprehensive end-to-end service, collecting EoL panels; performing initial disassembly to separate materials, such as aluminium and glass; and using advanced processes for the recovery of valuable materials, including silver, copper and silicon (PV Industries, undated). Similarly, ElecSome is pioneering an upcycling approach, using recovered PV panel glass fines to create a nano-engineered concrete aggregate known as SolarCrete (ElecSome, undated-b). These Australian companies are demonstrating innovative pathways to reintegrate materials into the construction and manufacturing industries. Both are actively developing the required infrastructure and processing technology to maximise diversion from landfills and secure valuable material supplies, although achieving the massive scale required for financial viability remains a key challenge.



Key Barriers to Scaling Circular Photovoltaic Business Models

The successful deployment of CBMs for PV systems is currently limited by acute challenges across technological, operational and economic domains. Technologically, the PV industry suffers from a lack of standardisation in panel construction, making high-purity resource recovery complex and expensive because existing low-recovery methods fail to efficiently reclaim high-value materials, such as silicon and silver (Curtis, Buchanan, Smith, et al., 2021). Operationally, the most significant impediment is the failure of the reverse supply chain: PV waste is highly dispersed across many locations, and high transport costs across Australia's vast distances severely erode the economic viability of recycling. Economically, the cost of advanced recycling is drastically undercut by cheap landfilling (Curtis, Buchanan, Smith, et al., 2021), while cheap imports of new PV modules undermine the market for product life extension (i.e. refurbishment) (Strupeit and Bocken, 2021). This adverse economic equation, driven by the lack of a mandatory EPR scheme, means that recyclers are challenged in achieving the scale or securing the funding necessary for long-term sustainability (Salim et al., 2019).

Recycling Business Models

In Australia, such companies as PV Industries use a business model in which system owners pay for recycling services, and recovered materials are sold into secondary markets. Customers can either drop panels off at designated collection centres, where PV Industries arranges pickup, or can opt for direct collection for an additional fee. Once received, the modules are transported to PV Industries' recycling facilities, where the aluminium frames, junction boxes and cables are removed and typically sold. The glass, silicon wafers and backsheets are then separated using mechanical processes and can be sold for reuse in manufacturing (PV Industries, undated).

Similarly, ElecSome also charges for collection or drop-off, transportation and recycling services. Additional revenue is generated through the sale of its product, SolarCrete, which upcycles recovered glass fines into a nano-engineered concrete aggregate. Other recovered materials are directed into diversified applications: Silicon wafers are mined for reuse as PV- or battery-grade silicon, electric conductors

are reused in electrical appliances, silver and copper are reused and distributed as raw materials for other industries, aluminium is repurposed for cans or other PV panel frames, and plastics and polymers enter established sustainable recycling channels (ElecSome, undated-a).

In some cases, local councils participate in the system by collecting EoL PV panels and paying a gate fee to recyclers, typically on a per-kg basis, similar to how these councils pay to recycle e-waste. For example, the recycler Sircel operates under this model, which helps offset its logistics costs.

Despite these initiatives, the Australian PV recycling model faces economic barriers. One of the primary challenges is scale. For the recycling methods used in Australia, the cost to break even can only be achieved at more than 2,500 tonnes per year. Another limitation lies in technology. Existing recycling companies can manage the delamination of modules, but the commodities are then sent to material recovery facilities that lack specialisation in PV laminates, thus compromising value and output yield. Additionally, there is a risk of not finding suitable markets for mixed outputs (e.g. glass, silicon wafers, backsheets). At the same time, processes capable of recovering all the valuable materials from PV panels with high yield and purity, resulting in higher revenue, have high capital investment. These processes are only feasible for larger facilities handling more than 5,000 tonnes per year (Deng et al., 2024).

U.S.-based SOLARCYCLE presents a more economically scalable model. The company addresses both the need for sufficient panel volume and consistent revenue from secondary materials by forming long-term partnerships. Such developers as Ørsted and EDF Power Solutions North America have partnered with SOLARCYCLE to recycle panels that were damaged or broken during construction and operation of their projects. Additionally, such manufacturers as Qcells and Canadian Solar refer their customers to SOLARCYCLE for recycling services, and Canadian Solar offers upfront recycling services at the time of purchase (SOLARCYCLE, undated). Agreements are also in place on the supply side, including with manufacturers Runergy Alabama and Heliene. These agreements secure SOLARCYCLE as a major supplier of 'ultra-low carbon glass' for its PV modules made from recycled materials sourced from retired PV panels (SOLARCYCLE, 2024).

Addressing the challenge of technology limitations, ROSI, a French technology start-up company, has developed dedicated material recovery techniques to deeply separate the materials laminated in EoL PV panels. Beyond extracting high-value materials, ROSI has developed a patented process for reintegrating them into various industries, from solar to semiconductors. The company's main revenue will come from reselling these materials (Deng et al., 2024).

Commercialisation and Deployment of Recycling Strategies for Photovoltaics

The deployment of PV recycling strategies depends on successful models for translating scientific breakthroughs and proof-of-concept demonstrations into scalable solutions. Commercialising these technologies requires strategies commonly used for hard-tech innovations—solutions developed from physical technologies (as opposed to digital) that require specialised infrastructure for the R&D activities necessary to reach scalability. This section briefly describes common steps to translate PV circularity technologies from laboratory inventions (with technology readiness levels [TRLs] between 2 and 4) to market solutions (with TRLs between 6 and 9). For a more detailed account, see Modestino et al. (2025).

From Basic to Translational Research

Early stage PV recycling solutions typically advance through a demonstration of fundamental principles and the development of proof-of-concept prototypes at universities, national laboratories or research institutions, supported by government agencies through various research programs. This translational research approach requires that innovators identify key techno-economic drivers and metrics that will

define success. It is often helpful to build early TEA models with reasonable assumptions to guide research activities towards high-impact goals. Customer discovery activities also play a key role in guiding the research focus and identifying product-market fit. The goal of translational research is to demonstrate the technical feasibility of concepts and enhance their techno-economic viability. Early experimental results can be used to refine TEA models and inform customer discovery iteratively.

Venture Formation

Once early proof-of-concept prototypes have been demonstrated that address product viability with suitable raw materials and real-world conditions, innovators often consider commercialisation pathways via start-up formation. Start-ups can leverage these early prototypes for multiple purposes: validating techno-economics, showcasing development progress or commercialising the company's first products. Start-ups also engage in pilot developments during which technologies are tested at more-realistic scales to bridge translational research breakthroughs and commercial adoption. Pilots play a key role in generating high-quality data to inform future scale-up activities. As scale-up progresses beyond pilots, start-ups could engage in first-of-a-kind commercial demonstrations, but these require substantial capital investment, making relationships with large customers, government agencies, investors and financial actors crucial at this stage.

Strategic Partnerships

After a successful venture launch and pilot completion, innovators are better positioned to communicate the technology's value to stakeholders across the PV ecosystem. These dissemination efforts—through industry conferences, technical reports or collaborative case studies—help build credibility and attract attention from potential partners. The focus often shifts to converting pilot success into commercial agreements with early adopters, whether they are solar asset owners facing decommissioning challenges, module manufacturers interested in circular supply chains or materials companies seeking secondary feedstocks. Strategic partnerships with established players in the PV or recycling industries can provide critical advantages: access to steady streams of EoL modules, integration with existing logistics networks, connections to buyers of recovered materials or manufacturing expertise to scale processes. Successful ventures often leverage larger partners' existing capabilities to complement their technology and accelerate market penetration.

Exit Strategies

PV recycling ventures face distinct scaling challenges compared with other technology sectors. Building the infrastructure for collection, processing and material recovery requires significant capital, while profitability depends on such factors as waste stream volumes, material commodity prices and competition from virgin material suppliers. For many ventures, the path to impact might not involve building a standalone billion-dollar company. Instead, acquisition or licensing arrangements with established industry players—such as PV manufacturers, waste management companies and materials processors—can accelerate deployment. The viability of different exit strategies depends on finding organisations whose strategic interests align with circular PV systems, whether driven by sustainability commitments, regulatory pressures or economic opportunities in secondary material markets. Success requires maintaining focus on establishing viable pathways for PV circularity at scale.

Conclusion

An understanding of the social, environmental and market considerations brings a leverage factor in the development of a circular economy for the PV sector because the identification of specific factors in areas



(such as social needs and market readiness) offers a higher success rate for the application of circular strategies. Such elements as energy demand, purchase standards and social behaviours have a strong impact on the overall life cycle of PV panels and the potential environmental and economic benefits of EoL PV panels. This chapter highlighted the importance of context in successful circular transitions. A circular PV system requires both the coordination of all the considerations within the supply chain from the manufacturing stage on and a perspective that understands the stakeholders as part of a bigger social and environmental system. Such coordination and perspective influence the understanding of market readiness and new business models to develop socio-techno-economic solutions.

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CHAPTER 9

A Techno-Economic Perspective on End-of-Life Photovoltaic Recycling

Venkatakrishnan Balasubramanian, James Bond, and Ylias Sabri

> [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.
>
> **Rong Deng, Verity Tan, Chence Niu, and Renate Egan**

Australia is entering a phase of rapidly rising PV waste as ageing PV panels reach their EoL. The lack of a coordinated recycling infrastructure presents risks for landfilling capacity, resource recovery and circular economy targets.

In this chapter, we present a national TEA to determine the financial and operational viability of a PV recycling infrastructure. The assessment is structured in two parts:

- **a baseline TEA** for a 2,500-tonne-per-year commercial-scale recycling facility across five states (Victoria, New South Wales, South Australia, Western Australia, Queensland)
- **detailed scenario modelling** for Queensland and Victoria, testing the following three infrastructure configurations:
  - Scenario A—centralised hub

- Scenario B—decentralised fixed facilities
- Scenario C—mobile screening with fixed recycling.

The capacity expansions modelled in the following scenarios represent staged, annual planning–level increases in processing capability rather than an instantaneous physical expansion within a single year. We expect real-world deployment to occur through modular equipment installation, phased commissioning and operational ramp-up.

Each scenario is evaluated in terms of capital expenditures (CAPEX), operating costs, transport exposure and long-range net present value (NPV) performance (between 2025 and 2055). Additionally, we identify the infrastructure pathway most suitable for each state and outline the policy settings required to support a national deployment strategy.

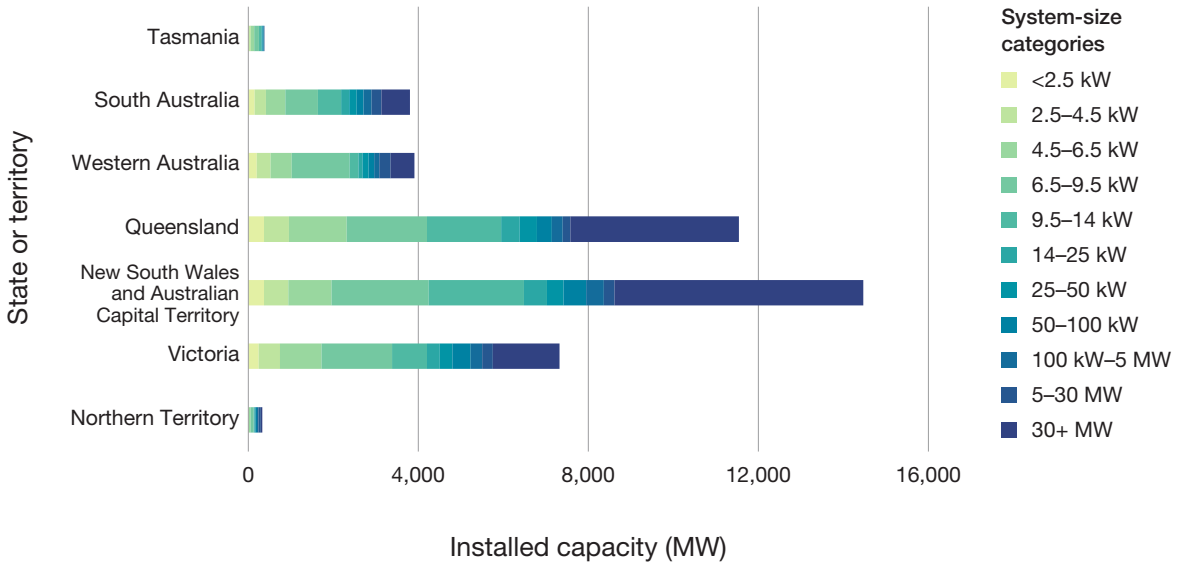
National Installation Trends and Waste Projection Basis

Australia's rapid uptake of rooftop and utility-scale solar has created a significant pipeline of EoL PV modules. APVI installation data show strong growth in every jurisdiction; New South Wales, Australian Capital Territory and Queensland lead in small and medium systems, and Queensland maintains long-term, high-density residential and commercial adoption (Figure 9.1). These trends form the basis for the waste projections shown in Figures 9.4 and 9.5 later in this chapter.

We estimated EoL volumes by applying a 12-year average module life to historical installations. This assumption aligns with observed failure patterns, accelerated replacement behaviour and commercial system turnover. Victoria and Queensland show a sharp rise in waste from 2030, reflecting the surge in installations from 2018. These dynamics define the future scale and timing of recycling demand.

A key modelling boundary must be acknowledged. The TEA assumes that all projected EoL panels enter formal screening prior to reuse or recycling. In practice, literature indicates that only around 10 per cent

FIGURE 9.1
National Installation Data



SOURCE: Features data from APVI, undated-b.
NOTE: System-size categories range from less than 2.5 kW (residential) to 30 MW or more (utility-scale).



do so (Xu et al., 2025), and most material flows through informal or untracked pathways. The full-inflow assumption allows alternative scenarios to be evaluated against realistic, state-specific waste trajectories while maintaining national analytical consistency. However, the full-inflow assumption represents a deviation from real-world behaviour. The baseline TEA, therefore, represents an upper-bound performance profile rather than existing operational conditions. A more comprehensive national TEA that incorporates participation rates, stewardship compliance and collection variability is needed for future planning. The resulting waste projection dataset underpins both components of the TEA: the baseline assessment of a 2,500-tonne facility across five states and the detailed scenario modelling for Victoria and Queensland.

We present our key assumptions in Appendix A and the methodology we used for this TEA in Appendix B.

Baseline Techno-Economic Assessment for a 2,500-Tonne per Year Photovoltaic Recycling Facility

The baseline TEA evaluates the financial and operational performance of a 2,500-tonne-per-year PV recycling facility across Victoria, New South Wales, South Australia, Western Australia and Queensland. This reference facility underpins all scenario modelling and enables the consistent comparison of capital costs, operating conditions and long-term financial outcomes.

A 2,500-tonne capacity design was selected as a practical commercial scale for early deployment. It provides sufficient scale to reduce processing costs while remaining practical to locate in metropolitan and major regional centres. With 350 operating days per year, the facility processes approximately 7.1 tonnes per day, allowing for routine maintenance and operational contingencies.

We estimated capital costs using the six-tenths scaling method, anchored to a 10,000-tonne facility reported by Mahmoudi, Huda, and Behnia (2020) and normalised using the Chemical Engineering Plant Cost Index (CEPCI), which increased from 596.2 in 2020 to 798.8 in 2025. On this basis, the fixed capital cost for a 2,500-tonne facility is $7.53 million, and the working capital is set at 15 per cent of CAPEX, which comes to $1.13 million. These values provide an inflation-adjusted foundation for long-term financial modelling.

Operating expenditures (OPEX) cover seven categories: raw materials, utilities, labour, maintenance, waste disposal, transport and general overhead. State-level inputs reflect updated market data and differences in electricity tariffs, waste levy structures, labour rates and logistics. Raw-material requirements are held constant at $535 per tonne, while utility costs vary markedly from $107 per tonne in Western Australia to $234 per tonne in South Australia. Figure 9.2 illustrates an OPEX breakdown, and details are in Appendix C.

Waste disposal charges remain a major cost component. Composite landfill fees, including levies and gate charges, range from roughly $146 per tonne in South Australia and Western Australia to more than $200 per tonne in Victoria. Labour demand is stable at five to six full-time equivalent staff per site, with modest state-level variations. Transport costs reflect local collection distances, reaching $160 per tonne in Victoria and South Australia but only $60 per tonne in Queensland.

When aggregated, total OPEX ranges from approximately $1,302 per tonne in Western Australia to $1,519 per tonne in Victoria, driven mainly by electricity, landfill costs and transport burdens.

We undertook cash-flow modelling over a 30-year operating life using an 8-per-cent discount rate and consistent tax, depreciation and revenue assumptions. Results are positive across all jurisdictions. NPVs range from $14.17 million in Victoria to $16.50 million in Queensland. Western Australia ($16.45 million), New South Wales ($16.00 million) and South Australia ($15.13 million) perform similarly. Full financial summaries are in Appendix C, and Figure 9.3 shows the comparative cash-flow growth.

FIGURE 9.2

Operational Expenditure Breakdown for Baseline Techno-Economic Assessment

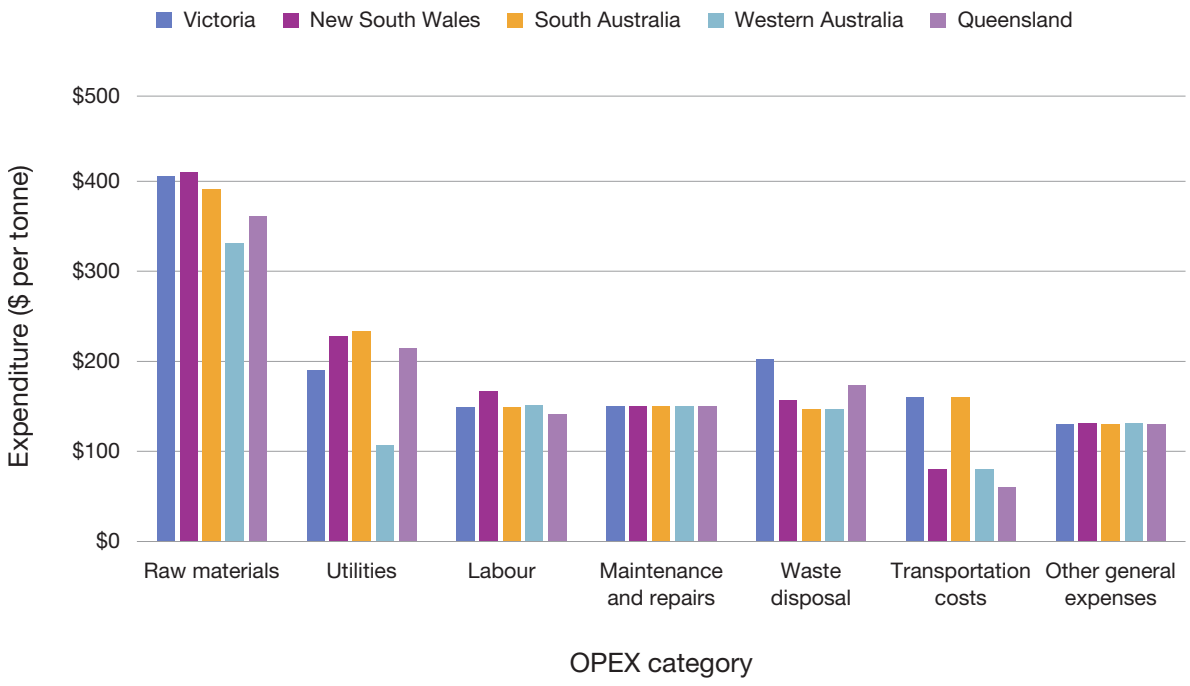
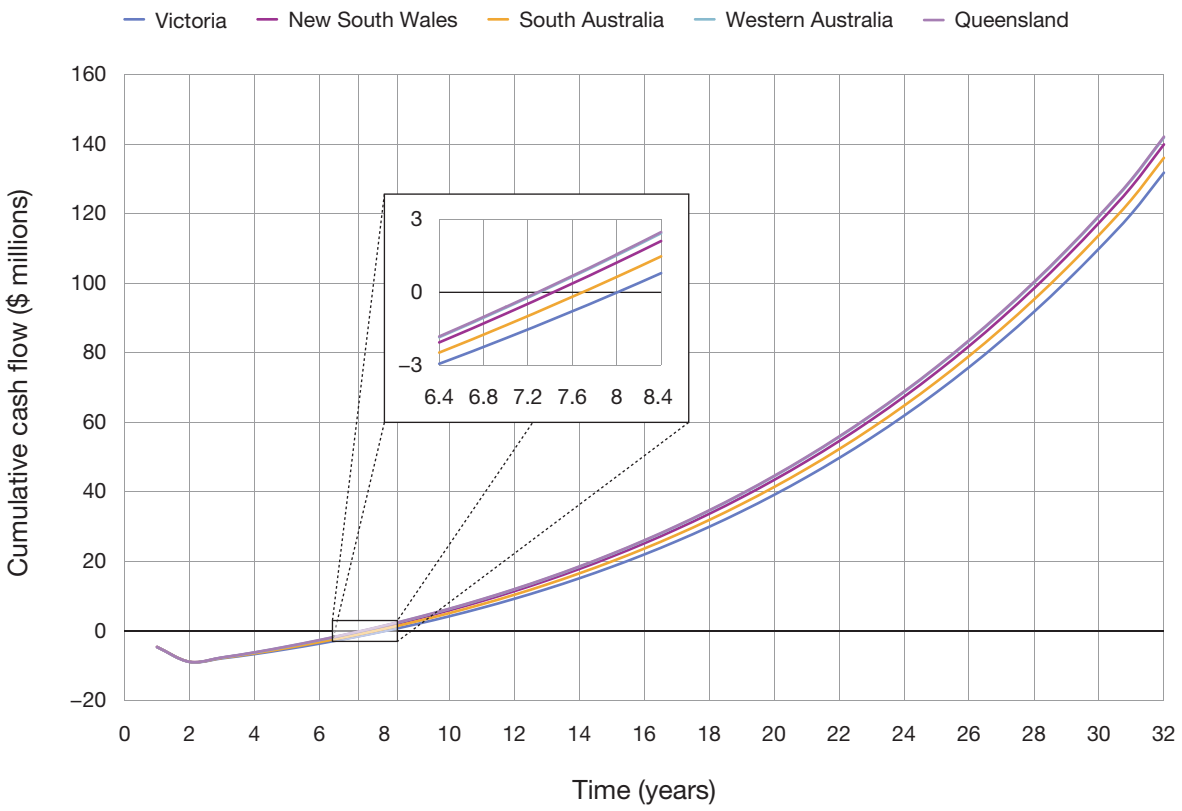


FIGURE 9.3

Comparative Cash-Flow Growth Profiles for Solar Panel Recycling Facilities in Australia



SOURCE: Authors' techno-economic assessment, drawing on data from APVI, undated-b.
NOTE: The payback profiles for Western Australia and Queensland are nearly identical, resulting in overlapping projection lines.

Payback periods fall between 7.2 and 8.0 years. Queensland and Western Australia achieve the fastest returns, at approximately 7.2 years, followed by New South Wales (7.5 years) and South Australia (7.7 years). Victoria shows the longest payback period, at around 8 years, reflecting its higher OPEX.

Overall, the modelling confirms that a 2,500-tonne facility is financially viable in all assessed states, even under conservative operating assumptions. Variations in NPV and payback periods are explained primarily by electricity costs, composite landfill charges and transport requirements.

Key Insights from the Baseline Techno-Economic Assessment

We arrived at the following insights from our TEA:

- The 2,500-tonne facility is financially viable in all five states, confirming its commercial feasibility under existing cost structures.
- State-level differences in OPEX are driven chiefly by electricity tariffs, composite landfill charges and labour cost differentials.
- Silver is the dominant contributor to recovered-material revenue despite its minimal mass share, making its recovery efficiency critical for profitability.
- Glass and aluminium contribute essential mass recovery but limited economic return, reinforcing the role of policy (not commodity value) in driving recycling outcomes.
- Transport costs are significant, ranging from around 4 per cent of total OPEX in Queensland to around 11 per cent in Victoria and South Australia.

- Operating resilience is strong; there are positive long-term NPVs across all jurisdictions despite escalating waste disposal and energy costs.
- Differences in overall feasibility primarily reflect regulatory settings, particularly landfill regimes and energy pricing.

The baseline assessment demonstrates that policy alignment and consistent stewardship mechanisms will be central to maintaining sector viability as volumes accelerate.

Case Study Focus: Victoria and Queensland

The national assessment confirms that a 2,500-tonne-per-year PV recycling facility is viable across all five states. Building on this foundation, the analysis focuses on Victoria and Queensland to examine how differences in waste generation patterns, geography and regulatory settings influence long-term infrastructure performance. These states offer contrasting solar adoption profiles and spatial characteristics, making them ideal for testing alternative deployment pathways.

We developed waste projections using installation data from APVI's annual National Survey Reports combined with a 12-year module life. This method ties EoL volumes directly to historical installation patterns rather than generic decay curves. The rapid uptake of rooftop solar in Queensland and Victoria since 2010 drives a sharp rise in waste from 2030 onward. Together, these profiles provide a clear picture of future recycling demand in two structurally different markets.

Three infrastructure configurations were evaluated:

- **Scenario A** involves a fully centralised hub combining collection, screening and recycling in a single, large facility.
- **Scenario B** involves a decentralised network of regional recycling sites supported by independent screening and collection operations.
- **Scenario C** involves mobile screening units that are deployed to accumulation points and feed sorted recyclable fractions into fixed recycling facilities.

All scenarios were assessed using consistent financial parameters, throughput assumptions and material recovery rates. For Victoria, we applied a 50–50-per-cent reuse and recycling split, while for Queensland, we used a 55–45-per-cent distribution to reflect market conditions. Figures 9.4 and 9.5 present the corresponding waste projections for each state.

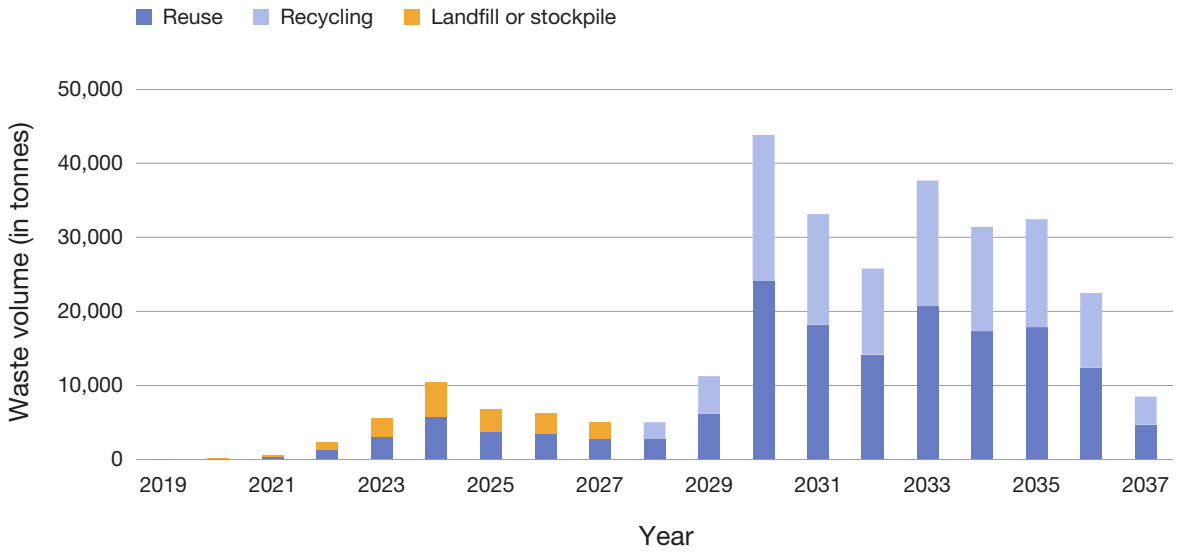
The purpose of the case study is to identify which scenario delivers the strongest long-term performance in each state. The assessment examines CAPEX, operating conditions, NPV outcomes, transport demands and scalability. By integrating state-specific waste projections with the three infrastructure models, our analysis highlights the configurations best suited to deliver a resilient and economically efficient EoL PV recovery system.

Scenario-Based Techno-Economic Assessment Results for Queensland

We provide detailed waste-projection calculations, input tables and staging data for all Queensland scenarios in Appendix D. The following analysis evaluates three infrastructure configurations: a fully centralised hub (Scenario A), a decentralised network of regional fixed facilities (Scenario B) and a mobile screening model linked to fixed recycling sites (Scenario C). We scaled all systems from the 2,500-tonne-per-year reference facility using the six-tenths rule and assessed the period from 2025 to 2055. Queensland's waste profile remains modest until 2030 and then increases sharply as large cohorts of PV systems reach their assumed 12-year EoL.

FIGURE 9.4

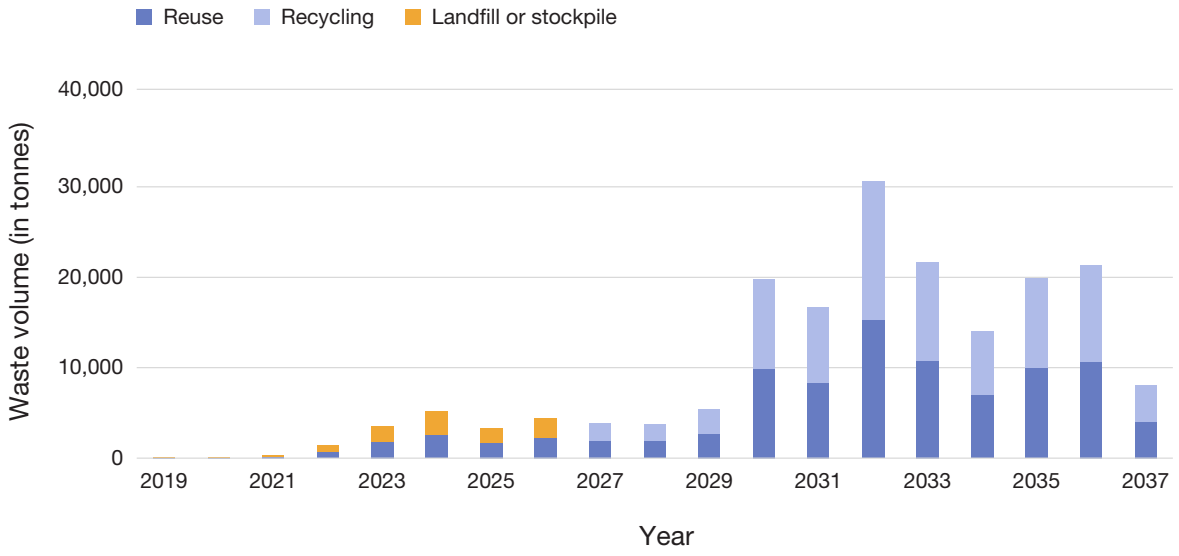
Waste Projections for Queensland Based on a 55–45% Reuse-Recycling Split



SOURCE: Features information from APVI, undated-b.

FIGURE 9.5

Waste Projections for Victoria Based on a 50–50% Reuse-Recycling Split



SOURCE: Features information from APVI, undated-b.

Scenario A: Centralised Recycling Hub

Scenario A assumes a single centralised hub starting at 10,000-tonnes per year and expanding to 25,000 tonnes per year through two scale-up stages. CAPEX in Scenario A is the highest of all scenarios, requiring $17.29 million initially, followed by $8.51 million and then $12.90 million in subsequent stages. Despite strong economies of scale and reduced intersite transport, the scenario performs poorly financially. NPV remains negative overall (–$11.42 million from 2025 to 2031, $2.61 million from 2032 to 2041 and –$2.22 million from 2042 to 2055), yielding a total NPV of –$11.03 million. Queensland's dispersed geography, long transport corridors and delayed waste volumes make a single-hub model economically unsuitable.



Scenario B: Decentralised Regional Network

Scenario B deploys regional facilities scaling from 2,500 to a total capacity of 7,500 tonnes per year. CAPEX rises modestly with staged expansion, reaching $18.77 million in total—less than one-half the requirements of Scenario A. Financial performance strengthens once post-2030 volumes emerge, moving from an early NPV of –$5.88 million (from 2025 to 2031) to $1.35 million (from 2032 to 2041) to $9.25 million (from 2042 to 2055), for a total NPV of $4.72 million. The model aligns well with Queensland's distributed waste generation and delivers the best overall performance.

Scenario C: Mobile Screening with Fixed Recycling Sites

Scenario C uses mobile screening units deployed to regional accumulation points with recyclable fractions sent to fixed plants. CAPEX mirrors Scenario B at $18.77 million, but OPEX is higher due to mobile operations. NPV improves across the three periods (–$5.64 million from 2025 to 2031, –$0.09 million from 2032 to 2041 and $5.98 million from 2042 to 2055), resulting in a marginally positive total NPV of $0.25 million. The model provides strong geographic reach but remains less cost-stable than the decentralised fixed-site network.

Scenario-Based Techno-Economic Assessment Results for Victoria

We include all detailed waste-projection tables, capacity staging data and financial inputs in Appendix D. Although Scenario B remains the preferred configuration in both states, Victoria's compact geography and concentrated waste generation allow the decentralised model to operate through a smaller network of closely connected regional facilities, whereas Queensland requires a more geographically distributed network to accommodate longer transport distances and dispersed waste generation.

Scenario A: Centralised Recycling Hub

Scenario A consolidates all activities into a single large facility, scaling from 5,000 to 10,000 to 15,000 tonnes per year. CAPEX is substantial, rising from a cumulative $11.41 million to $19.92 million to $28.43 million. Despite scale efficiencies, the model suffers from underutilisation in its early years. NPV starts at −$14.10 million (from 2025 to 2031) and improves to $3.15 million (from 2032 to 2041) but then falls to −$2.95 million (from 2042 to 2055). The overall NPV of −$13.90 million shows that a single-site hub is not commercially viable at projected Victorian waste volumes.

Scenario B: Decentralised Fixed Sites

Scenario B uses regional facilities, with total installed capacity scaled in modular 2,500-tonne-per-year increments to 7,500 tonnes per year. Cumulative CAPEX is $18.77 million, around two-thirds of the cost of centralisation. Victoria's urban density reduces transport burdens significantly, allowing the network to operate efficiently. Financial performance improves steadily: NPV is −$7.62 million from 2025 to 2031, $1.78 million from 2032 to 2041 and $12.20 million from 2042 to 2055, producing a total NPV of $6.36 million. Scenario B is the strongest performer, achieving both flexibility and capital efficiency.

Scenario C: Mobile Screening with Fixed Recycling

Scenario C mirrors Scenario B's staged capacity but substitutes mobile screening for part of the logistics chain. The model provides targeted reach in remote or low-volume zones but offers limited benefit in a compact state. Additionally, the higher operational variability reduces this scenario's financial stability. NPV results are −$7.41 million from 2025 to 2031, −$0.11 million from 2032 to 2041 and $7.54 million from 2042 to 2055, for a total NPV of $0.02 million. Although viable in specific regional contexts, this scenario does not outperform fixed-site decentralisation.

Comparative Assessment, Policy Implications and Final Recommendations

Cross-State Comparative Assessment

The comparative assessment shows that infrastructure suitability is determined primarily by each state's geography, waste-flow density and logistics rather than by the underlying recycling technology. Although the same techno-economic assumptions were applied across jurisdictions, the performance of Scenarios A, B and C diverges sharply once spatial context is introduced.

Queensland's large landmass, dispersed population and long transport corridors make logistics the dominant cost driver. Under these conditions, the centralised hub (Scenario A) performs poorly despite its scale efficiency because high CAPEX and extensive haulage suppress financial returns at every horizon. The mobile screening model (Scenario C) offers some value in remote or sparsely populated areas, but its operating variability limits systemwide competitiveness. The decentralised fixed-site network (Scenario B) consistently delivers the strongest results, achieving positive long-term NPVs and aligning well with Queensland's distributed waste generation profile.

Victoria exhibits the opposite pattern. Waste is concentrated in the Melbourne metropolitan area and inner regional corridors, enabling short transport distances and stable throughput. Here, centralisation cannot justify its substantial capital burden, and mobile screening adds little benefit in a compact state with minimal long-haul collection. The decentralised fixed-site network (Scenario B) again emerges as the most effective configuration, offering balanced capital needs, strong transport efficiency and clear scalability as waste inflows rise. A consolidated comparison of all scenarios is provided in Table D.5 in Appendix D.



Across both states, Scenario B demonstrates the clearest economic advantage: moderate CAPEX, manageable transport exposure and a scale path aligned to rising waste inflows. Scenarios A and C remain strategically limited to specific geographies or niche operating conditions.

Policy Implications for Infrastructure Planning

The scenario outcomes point to several structural priorities that can guide national planning for EoL PV infrastructure. The system's design needs to be grounded in the spatial characteristics of each state rather than built around a uniform national template. Queensland's dispersed waste distribution clearly favours modular decentralised facilities that reduce transport exposure, while Victoria's compact settlement pattern supports a network of regionally located fixed sites.

Effective capital planning also requires a measured expansion pathway. Large, centralised assets do not achieve economic viability during early and mid-horizon periods, primarily because of the low initial throughput and high capital lock-in. Infrastructure that scales in step with verified waste inflows avoids these early deficits and enables more-flexible long-term investment.

Our analysis also reinforces the centrality of logistics. Transport distances alone can erode the viability of technically sound configurations, especially in geographically extensive states. National guidance should, therefore, prioritise efficient collection radii, coordinated aggregation points and integrated haulage planning.

Flexible deployment models could be enabled by the regulatory environment. Decentralised networks rely on predictable stewardship funding and consistent licensing processes, while mobile screening requires dedicated compliance pathways for temporary operations and management of reuse-grade modules.



Taken together, the analysis shows that implementation of the decentralised regional hub model should be adapted to local geographic and waste generation characteristics. In Queensland, this involves a more geographically distributed network of regional facilities to accommodate dispersed waste generation and long transport distances, whereas in Victoria the same model can be implemented through a smaller number of closely connected regional hubs. Mobile screening remains best suited to remote areas where fixed infrastructure is impractical.

Final Recommendations for a National Deployment Strategy

The combined findings from the national baseline assessment and the Queensland-Victoria modelling scenarios support a distributed regional hub network as the most robust foundation for Australia's PV waste infrastructure. Decentralised fixed-site facilities consistently deliver the strongest balance of capital efficiency, operational reliability and transport optimisation, while centralised facilities become viable only at very high and sustained throughput levels.

Staged capacity development should underpin all major investments, ensuring that infrastructure grows in line with material inflows and avoiding the premature capital burden associated with large, centralised builds.

National policy support also could help stabilise stewardship funding, harmonise licensing requirements and coordinate logistics planning across jurisdictions. These measures will reduce interstate disparities and strengthen investor confidence.

State-specific deployment pathways remain essential. While the decentralised regional hub model remains the preferred configuration in both states, its implementation differs according to geography and waste distribution. Queensland requires a more geographically distributed network of regional facilities to accommodate its spatial footprint and dispersed waste profile, whereas Victoria can implement the same model through a smaller number of interconnected regional hubs. In both contexts, mobile screening should be deployed selectively in remote corridors rather than adopted as a default model.

Conclusion

The integrated TEA demonstrates that Australia's emerging EoL PV panel challenge will require infrastructure systems that are adaptive to the physical, logistical and regulatory characteristics of each state. Although the modelling confirms that a 2,500-tonne-per-year recycling facility is technically and financially viable across multiple states, the implementation of the preferred long-term configuration differs significantly between Queensland and Victoria. Across both case studies, the decentralised regional hub model (Scenario B) consistently provides the strongest balance of capital efficiency, transport optimisation, operational resilience and long-term financial performance.

A central finding of this study is that the modelling assumes that all projected waste flows enter the formal screening and sorting stream before reuse or recycling decisions are made. The scenarios, therefore, represent an upper-bound view of system performance rather than a reflection of existing material flows. This discrepancy reinforces the need for a more comprehensive sectorwide assessment that captures consumer behaviour, installer practices, informal stockpiling, secondary markets and the maturity of emerging stewardship mechanisms.

Despite this limitation, the analysis provides clear directional insights. Highly centralised facilities may require very high and sustained throughput to approach commercial viability, and their performance remains strongly dependent on geography, logistics and capital intensity. Mobile screening configurations remain strategically important for remote corridors but do not outperform fixed-site networks in densely settled regions. The evidence from both Queensland and Victoria points to a distributed, staged-expansion model as the most robust national pathway, capable of scaling with rising waste flows while avoiding premature capital lock-in.

Taken together, **these results establish a practical blueprint for Australia's PV waste infrastructure roadmap: a regionally adaptive, modular network of recycling and screening assets that evolves with the country's accelerating solar transition**, supported by stronger stewardship incentives and coordinated logistics planning. A more detailed and behaviour-inclusive TEA that incorporates actual screening participation rates and on-the-ground disposal patterns is essential for refining these pathways and informing the next generation of policy and investment decisions.

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CHAPTER 10

Policy Framework: Gaps, Opportunities and Recommendations

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> Product stewardship schemes make sure everyone in the supply chain is responsible for the waste they create.
>
> **Australian Department of Climate Change, Energy, the Environment and Water**

In this chapter, we explore the existing regulation of the PV industry and the gaps in the policy and regulatory landscape that need to be addressed to accelerate the delivery of a circular economy and the opportunities for doing so.

The Role of Regulation

As detailed in preceding chapters, developing a sustainable PV circular economy can generate a variety of social, economic and environmental benefits. However, as with other industrial sectors, policy interventions are needed to incentivise PV waste recycling. Such interventions are generally seen as a mechanism for correcting market failures (Ledyard, 2018). A market failure occurs when the market is distorted by factors that lead to the inefficient allocation of resources within the free market (Deardorff, 2000). In the case of PV waste, the dominant market failure is the lack of sufficient market signals to drive investment and development in PV recycling and second-life PV facilities. The regulation of mandatory PV recycling has several theoretical bases: addressing market failures, supporting circular economy goals and resource efficiency, enforcing the polluter-pays principle and enabling coordinated action.

More specifically, for PV waste, two different market failures appear to be operating. The first failure relates to the negative externalities that can result from the waste.[1] EoL PV panels, particularly

[1] Pigouvian theory suggests that regulation is needed to impose an appropriate tax that effectively prices in these externalities, thereby correcting the faulty market signal. One mechanism is to mandate recycling and waste recovery (see Pigou, 2002).



first-generation panels, which contained lead and cadmium among other neurotoxins, represent hazardous waste (Sustainability Victoria, 2025). If the panels are not properly disposed of, there can be negative environmental impacts (because the chemicals can leach into soil and waterways) and negative health impacts (if people are exposed to those toxins) (U.S. Environmental Protection Agency, 2025). The cost of these health and environmental impacts to the broader public is not internalised by manufacturers or consumers, leading to suboptimal investment in recycling or other measures to mitigate these impacts. The biggest market failure in the EoL management of PV systems remains the overbearing cost of recycling compared with the cost of sending EoL panels to a landfill.

There are initiatives to increase regulation to promote recycling in Australia, coordinated under the National Waste Policy and accompanying National Waste Policy Action Plan (Department of the Environment, Water, Heritage and the Arts, 2009; DCCEEW, 2024c). The Action Plan highlights three areas of government policy to address this market failure:

- government legislation, regulation, policies, standards and guidelines
- investment in infrastructure, procurement and funding support
- market development and support through innovation, barrier reduction and demand generation.

Similarly, the *Wired for Change* discussion paper signalled the Australian government's intention to develop regulations that promote the recycling and safe disposal of small electrical products and PV waste (DCCEEW, 2023). The paper proposed mandatory recycling of large-scale PV systems under the Recycling and Waste Reduction Act 2020.

A second cause of market failures is asymmetry in the information environment. Consumers typically lack information about the environmental and health impacts related to the improper disposal of hazardous waste, such as dumping or landfilling, and information about the available options and pathways for recycling, reuse, or both (The Recycling Partnership, 2023). As a result, there is no demand signal

within the marketplace from consumers for more-sustainable management of PV waste. Meanwhile, in the absence of a regulatory mandate, PV manufacturers, importers, retailers and installers lack incentives to invest in transparent, traceable and verifiable EoL management processes, such as product stewardship schemes and digital product passports (DPPs) that store data about a product's materials, supply chain, usage and EoL options (Weckend, Wade, and Heath, 2016).

In addition to these core market failures, there are also several other justifications for developing a robust regulatory framework for a PV circular economy. Without regulation, PV manufacturers are incentivised to design products that are the least cost as opposed to pursuing ecodesigns that are more durable, easier to repair or disassemble, and recyclable (Lifset et al., 2023). EPR programs are often the preferred regulatory approach of governments that have chosen to mandate PV recycling because they embody the polluter-pays principle, which ensures that the PV manufacturer that causes the potential environmental harm is responsible for rectifying it (OECD, 2024). Mandating EPR levels the playing field by ensuring that those who would otherwise be bad actors in the marketplace are compelled to take positive steps to minimise their harm, while good actors that internalise their waste costs are not competitively disadvantaged.

This concept of a *level playing field* is particularly important, given that the management of EoL PVs involves a complex value chain and numerous actors, including manufacturers, installers, waste operators, recyclers, transporters, collection facilities, consumers, and local, state and national governments (Weckend, Wade, and Heath, 2016). In the absence of clear rules and mandated responsibilities, no single actor has sufficient incentive to undertake the R&D required, bear the cost or lead the coordination. By providing institutional clarity and legal certainty, regulation creates an impetus for coordinated action, reduces transaction costs and imposes clear responsibilities and legal liability on identified parties.

Finally, PV technologies are increasingly part of a competitive global marketplace for material resources. Many nations have made efforts to decouple their economic growth from unsustainable resource use and support the development of a circular economy. Such efforts are evident in the EU's Circular Economy Action Plan (Directorate-General for Environment, 2020) and Australia's National Waste Policy Action Plan, which commits the Commonwealth and state governments to a circular economy by 2030 (DCCEEW, 2024c). Solar panels contain critical minerals, such as silver, indium and germanium (Clean Energy Council, 2025), many of which face heavily constrained global supply chains that are increasingly dominated by China under long-term supply contracts with mineral-producing nations (Shokri, 2025). This has led to concerns about the long-term security of supply (Cohen, Shirley, and Svensson, 2023). Circular economy mandates will, over time, enable the imposition of recycled content provisions in all new PV panels and enable the recovery of critical minerals and other commodities from waste panels. This will reduce reliance on virgin materials by providing an alternative source of supply while preventing critical minerals from ending up in a landfill.

For these reasons, PV recycling regulation is an emerging critical waste-management issue. Initially the waste stream is likely to be dominated by older, pre-2015 panels, which are more likely to contain hazardous substances and might, in some respects, be closer to conventional e-waste than newer PV products. This suggests that early recycling arrangements might need to place a greater emphasis on safe handling, testing, hazardous-materials management and integration with existing electronic or hazardous-waste infrastructure. As a result, the industry might need to adapt its processing models concurrently with capacity building. There could be advantages to early investment despite changes in module components, given the establishment of collection networks, technical capabilities and market experience. However, facilities must maintain flexibility for the larger, later waste stream of newer modules. This points to the value of a staged and flexible approach to capacity development and PV recycling systems.

This critical waste-management issue has arisen as the volume of EoL PV panels begins to accrue through a combination of the retirement of ageing installations and the early retirement of other systems as consumers upgrade the size of their system or install batteries (Ley, 2021). In many jurisdictions, because of both voluntary industry approaches failing and the presence of market failures, this PV waste goes to landfill (Xia, Yang, and Poon, 2025).

Examples of Global Best Practices in Circular Economy Policies

Given that Australia is in the early stages of developing a PV circular economy, it is helpful to learn from other models and frameworks. Three national case studies from the EU, Japan and South Korea and a subnational case study focused on U.S. state programs provide insights into the opportunities and challenges within Australia.

The European Union's Circular Economy Framework

The EU has a deep regulatory framework for PV panel EoL management. The Waste from Electrical and Electronic Equipment (WEEE) Directive mandates the recovery and recycling of PVs installed or generated in EU member states. The WEEE Directive was the first regulatory approach to both separate PV regulations from other e-waste and mandate recovery and recycling targets. The directive was initially passed in 2003 and recast in 2012 to implement recovery and recycling requirements for PV panels that scaled from 2012 to 2019. As of 2019, the WEEE Directive requires recovering 85 per cent of EoL PV panels by weight and recycling or preparing 80 per cent for reuse (EU, 2012). The EU also specifically excludes PV panels from being classified as hazardous waste under the Restriction of Hazardous Substances directive, lowering the costs of EoL PV waste management (European Commission, undated-c). Individual EU member states implement the WEEE and Restriction of Hazardous Substances directives through transposition laws, such as the Electrical and Electronic Equipment Act (Elektrogesetz) in Germany and Decree No. 2014-928 in France. Transposition laws can vary from the WEEE Directive, but they all include the same recovery and recycling targets for PV panels.

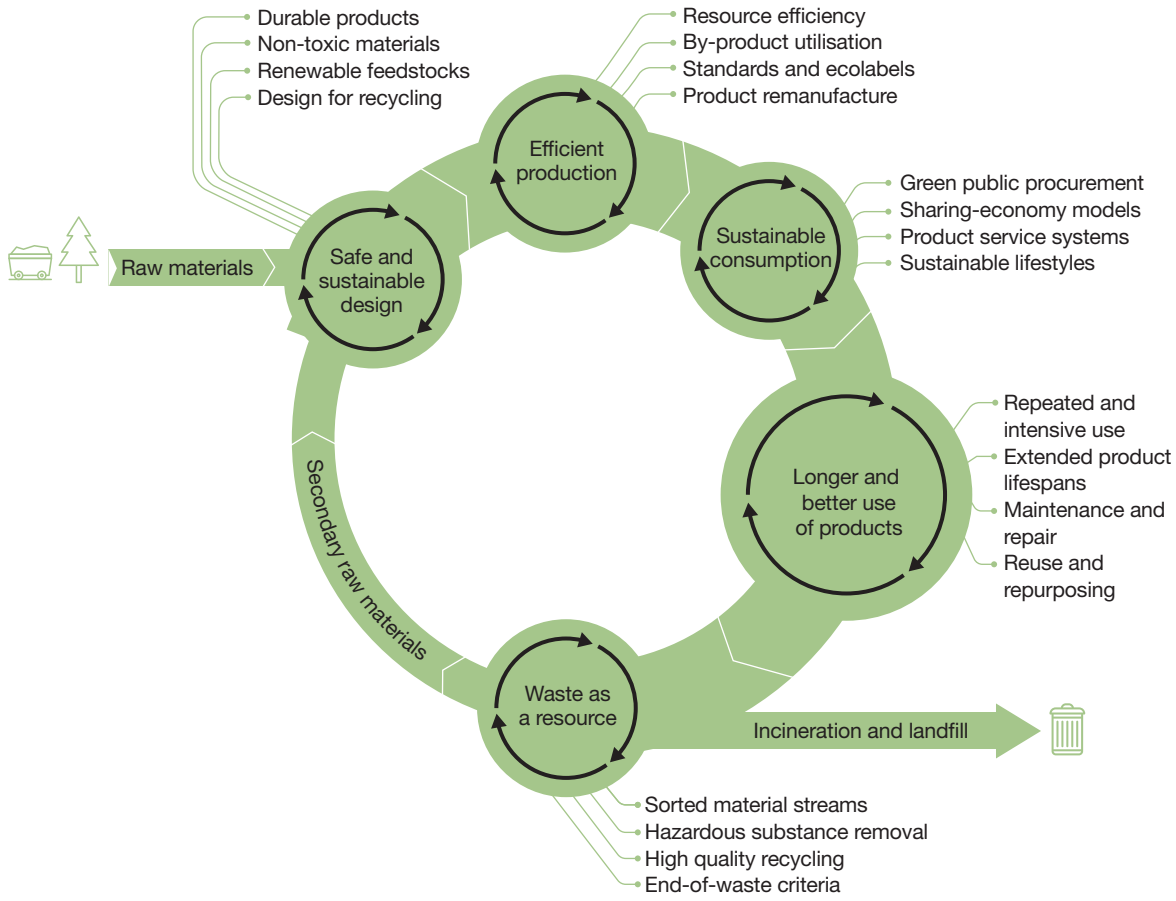
A core aspect of the EU approach to a circular economy is the polluter-pays principle (European Commission, undated-a). The polluter-pays principle requires that the cost of waste disposal falls to the holders of the waste or the producers of the product that created the waste (EU, 2008). The WEEE Directive follows this principle via EPR, requiring that 'each producer should be responsible for financing the management of the waste from his own products' (EU, 2012). The EPR obligation extends to funding and organising the collection, treatment, recovery and disposal of PV waste. This obligation can be carried out by individual producers or by joining a collective in which multiple producers pay an organisation to handle their PV waste management. The EU mandated recycling targets in the WEEE without PV panel recycling being independently commercially viable (BIO Intelligence Service, 2011); it instead imposes the extra cost of waste management on producers of PV panels. A variety of incentive programs across EU member states—such as tax credits, direct subsidies and guaranteed purchase agreements through FIT systems—offset these costs to producers.

The European Union's Recyclability Index and Design Standards

In addition to its circular economy framework, the EU has promoted several initiatives that incentivise circularity principles in PV product design (Figure 10.1). For example, one of the most significant developments under the EU's circular economy framework is the ongoing development of the EU PV Recyclability Index. Ordered by the European Commission through the Climate, Infrastructure and

FIGURE 10.1

European Environment Agency's Circular Economy Concept



SOURCE: Adapted from European Environment Agency, 2024 (CC BY 4.0).

Environment Agency (European Commission, 2023), the index is designed to quantify the recyclability potential of PV modules and inverters at the design stage, providing an evidence-based tool for policy-makers and consumers (Polverini et al., 2025). Unlike traditional EPR systems, which often rely solely on weight-based recovery targets, the EU PV Recyclability Index aims to shift the regulatory focus towards recyclability quality and design incentives.

The index uses a multicriteria scoring system built around ten parameters that are grouped into the following three domains:[2]

- **service-related**—(1) identification of technology type, (2) presence of hazardous substances, (3) dismantling instructions and (4) disclosure of material composition
- **dismantling-related**—(5) number of disassembly steps, (6) required tools and (7) removability of fasteners, frame or encapsulant
- **material-related**—(8) concentration of substances of concern (e.g. fluorine, antimony), (9) intrinsic recyclability of materials and (10) homogeneity of material combinations.

[2] A similar approach was proposed by Mahmoudi, Huda, and Behnia (2021). Their approach breaks the material flow of EoL PV panels down into the product (e.g. PV modules), component (e.g. frame, PV cells, cables, transformers), material (e.g. glass, metal) and substance levels (e.g. the raw critical minerals). Therefore, it is possible that a recyclability index could be mapped to the use of components at these different levels in the Australian economy and mapped to the three domains used in the EU.

Each parameter is scored on a 1 to 5 scale, and the final recyclability index is a weighted aggregation of these scores, calibrated separately for PV modules and inverters. For example, high-impact components, such as silver-bearing solar cells or gold-bearing printed circuit boards, receive higher weightings because of the embodied critical minerals. A pilot validation of the index was conducted at the National Renewable Energy Centre of Spain on eight PV module models and eight inverter models to refine the scoring system and ensure practical applicability (Viegand Maagøe, 2025). The study found a high degree of reproducibility and consistency in evaluating the recyclability of PV modules against an index designed to evaluate according to service, dismantling and material parameters (Viegand Maagøe, 2025).

EU voluntary certification schemes provide complementary market-based incentives for sustainable PV design. For example, third-party ecolabelling programs, such as the voluntary Electronic Product Environmental Assessment Tool (EPEAT), play a key role in promoting sustainability in the PV industry. Managed by the nonprofit Global Electronics Council, this tool is the leading Type 1 ecolabel for PV modules and other electronics (NSF Joint Committee, 2019). A Type 1 ecolabel, as defined by the international standard ISO 14024, refers to eco-labelling schemes that use clearly defined criteria for products (International Organization for Standardization, 2019).

The EPEAT categorises products into bronze, silver or gold tiers based on adherence to required and optional sustainability criteria. Required elements include declaring recycled content, conducting an LCA, reporting on energy efficiency and water use and providing product take-back services and processing requirements. Optional criteria include meeting a minimum percentage of recycled content, publicly disclosing LCA results, documenting the quality of wastewater discharges and achieving material recovery targets. Modules attaining higher levels of optional compliance are awarded silver (50 per cent or higher) or gold (75 per cent or higher) status (NSF Joint Committee, 2019). The EPEAT's newly released criteria for PV modules include a benchmark for embodied carbon, setting a threshold of 400 CO_2-equivalent kg per kW peak or less to qualify products as ultra-low carbon (Global Electronics Council, 2023).

The EU's Ecodesign for Sustainable Products Regulation, which entered into force on 18 July 2024, will introduce a DPP. Although, as of this writing, PV modules are not included in the mandatory DPP framework, the European Solar Photovoltaic Industry Alliance, an initiative launched by the European Commission, has recommended the implementation of a mandatory DPP for PV modules. The proposed components include product information, material inventory, a carbon footprint and circularity calculator, traceability, value-chain process management and circular economy tools (European Solar PV Industry Alliance, 2024). Taking inspiration from the battery DPP, PV manufacturers could also be mandated to use a predefined percentage of secondary minerals while manufacturing (Michael, 2023).

In parallel with regulations, innovations in PV module manufacturing must be increasingly guided by emerging standards emphasising recyclability. The IEA Photovoltaic Power Systems' Task 12 guidelines on PV module design for recycling provide general design for recycling principles alongside specific recommendations for c-Si PV modules. These guidelines encourage manufacturers to select materials that ensure durability and support efficient EoL processing. Key considerations include the backsheet design, the minimisation or reversibility of encapsulants, and the selection of metal components (Bilbao et al., 2021). One example of this alignment is First Solar, the only PV manufacturer with global in-house PV recycling capabilities. Since establishing the first global PV panel recycling programme in 2005, the company has consistently invested in advancing its recycling technologies. It currently operates recycling facilities in the United States (Ohio), Malaysia, Vietnam and Germany. First Solar offers collection and recycling services for its cadmium telluride panels worldwide. Its modules are designed for high-value recycling, enabling the recovery of more than 90 per cent of materials for reuse in the production of new PV panels, glass, rubber and aluminium products (Deng et al., 2024).



Japanese Recycling Model

Japan regulates EoL PV panels through a combination of its general regulatory framework for waste management, the Waste Management Act (Government of Japan, 2001), and specific producer obligations in the Renewable Energy Act (National Diet of Japan, 2011). Neither act focuses specifically on PV panels. Instead, Japan released guidelines for how its existing waste management laws apply to PV panels (Ministry of the Environment, 2024). The first edition was published in 2016 (Ministry of the Environment, 2016), and the most recent third edition was published in 2024. The guidelines discuss the waste classification of PV panels and how the Waste Management Act applies to the concept of EPR. The guidelines classify PV panels as industrial waste unless an elution test shows high contents of hazardous materials. The Waste Management Act requires EPR; the producers of industrial waste must manage their EoL, whether in-house or through a processing contract.

The Waste Management Act requires producers of PV panels to manage and fund their collection, transportation and disposal, whether via reuse, recycling or landfilling. The cost to the producer of EoL care is mitigated by incentives in the Renewable Energy Act, which introduced the FIT system in 2012. The FIT system incentivises renewable-energy development through fixed price guaranteed purchase agreements, usually for 20-year terms (Sadayuki and Nobuaki, 2026). The feed-in premium system was introduced in 2022, adding a premium to the fixed price and gradually replacing the FIT system. Producers must create a reserve to fund EoL management, but since 2020 this has been created by directly withholding funds from the FIT or feed-in-premium purchase agreement for extra security. Japan requires that producers of PV panels fund EoL management but does not require recycling or reuse specifically.

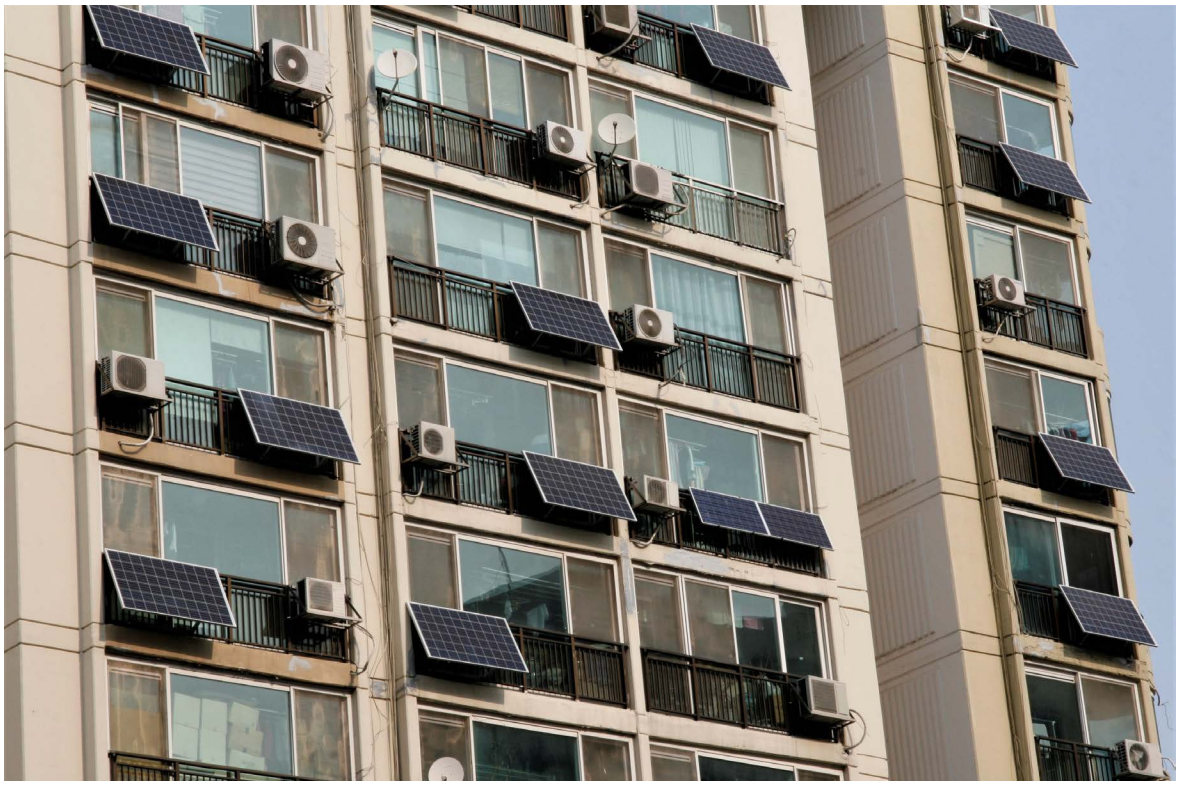
South Korean Initiatives

Because of its continued growth in solar power generation, South Korea recently implemented EPR to regulate PV EoL management (Photovoltaic Power Systems Programme, undated). South Korea regulates PV EoL management and mandates recycling of PV panels through the Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles (EEEV Act) (Ministry of Climate, Energy and Environment, 2023) and the associated Enforcement Decree (Ministry of Climate, Energy and Environment, 2022). The EEEV Act implemented EPR on PV panels at the start of 2023, requiring producers to reuse or recycle a specified annual percentage—at least 80 per cent—of EoL PV panels by weight.

Producers that do not meet the mandatory recycling target are fined based on the difference between their recycling rate and the target. The preexisting online waste-disposal verification system, Allbaro, ensures compliance by tracking the 'flow of waste management from discharge to transport and treatment of waste' online in real time (Korea Environment Corporation, undated). The growth of PV panel waste lags behind the growth of solar power generation, separated by the lifespan of the PV panel: 25 to 30 years (IEA, 2022a). Solar power generation in South Korea started growing quickly in 2005 (IEA, undated), so the volume of EoL PV panels will grow rapidly. In 2023, South Korea's Ministry of Trade, Industry and Energy forecasted the growth of discarded PV panel waste volume: 1,223 tonnes in 2025, 2,645 tonnes in 2027, 6,796 tonnes in 2029 and 9,632 tonnes in 2032 (Ministry of Trade, Industry and Energy, 2023).

U.S. State Programs

The United States does not regulate EoL PV panels through any universal federal laws or regulations, instead leaving PV-specific policies up to the jurisdiction where the PV installation is located. The Bureau of Land Management (BLM) has a decommissioning policy for utility-scale solar projects



located on federal lands managed by the BLM. In December 2024, solar projects on BLM-managed federal land made up 6.3 per cent of U.S. solar-power generation capacity.[3] The EoL management of most PV panels is left up to the states.

Most states—35 and the District of Columbia—do not regulate EoL PVs separately from other e-waste. The regulatory framework of BLM and the states that regulate EoL PVs involves requiring solar facility developers to submit decommission plans that meet certain requirements, often during the permitting process prior to construction (Curtis, Buchanan, Heath, et al., 2021). Decommissioning plan requirements across these jurisdictions can include land restoration of the site, proof of financial assurance to fund decommissioning and/or specific decommissioning activities, such as recycling (Curtis, Buchanan, Heath, et al., 2021). Two states—California and Hawaii—have also passed regulations classifying EoL PV panels as universal waste, even if leaching tests show that they meet the toxicity characteristics of hazardous waste (California Code of Regulations, Title 22, Social Security; Section 66273.7.1, Applicability—PV Modules). This classification provides a simplified set of hazardous waste management standards for PV panels and other common electronic and chemical waste, streamlining recycling processes (Department of Toxic Substances Control, 2020).

Solar facility developers are required to provide financial assurance to fund decommissioning efforts in BLM-managed lands in Louisiana, Minnesota, Montana, New Hampshire, North Dakota, Vermont, California, Hawaii and Washington (Curtis, Smith, et al., 2021). Bonds, funds or other financial assurance must be set aside prior to construction and must cover estimates of all decommissioning costs. These financial assurance requirements are an alternative to EPR seen in other regulatory frameworks, such as in the EU, Japan and Korea. Financial assurance requirements in the United States typically apply only to utility-scale solar power generation projects and impose the responsibility of decommissioning costs on solar facility site developers rather than PV panel producers (Curtis, Smith, et al., 2021). This focus on sites rather than panels reflects the geographic variation in policies across the United States.

Specific decommissioning activities vary by state, and only three states—Washington, Maine and North Carolina—require recycling; the rest leave disposal methods up to the solar-facility owner. In general, market conditions favour landfilling; as of 2020, landfilling fees were US$1 to $5 per module, while recycling costs were US$15 to $45 per module (Huang et al., 2022). Washington state regulations echo the form of the WEEE in the EU. Washington is the only state with a mandated reuse and recycling rate—85 per cent by weight (Washington State Legislature, 2017). Washington is also the only state that imposes EPR through its PV Module Stewardship and Takeback Program. PV panel manufacturers must finance a take-back and recycling system to meet the 85-per-cent target (Washington State Legislature, 2017). Maine and North Carolina mandate the recycling of PV panels and any components that are recyclable, without setting a target (North Carolina General Statutes, Chapter 130A, Section 130A-309.240; Maine Revised Statutes, Title 35-A, Section 3491). The decommissioning plan requirements of three other states—Montana, New Hampshire and North Dakota—incentivise recycling or reuse by offsetting the salvage value from the decommissioning cost estimate, reducing the required financial assurance (Administrative Rules of Montana, Title 17, Section 17.86.105; New Hampshire Administrative Code, Site Evaluation Committee, Section Site 301.08; North Dakota Administrative Code, Title 69, Section 69-09-10-06).

[3] In December 2024, there were 64 projects on BLM-managed land, making up 13.9 GW of solar-power capacity (BLM, undated). In December 2024, the total installed solar-power capacity in the United States was 219.8 GW (Kaiser, 2024).

Policy Effectiveness Comparison

The global policy landscape for EoL PV management is still nascent and varies drastically within and among countries. Therefore, a policy that works one place can fail in another, depending on policy design, implementation and enabling conditions. For example, the mandatory take-back and recycling system in Germany has been successful in achieving recycling targets despite logistical challenges, whereas the mandatory take-back and recycling system in Washington has not yet begun because producers have yet to buy in. Economics and logistics favour landfilling EoL PV panels, so regulatory policies often include reuse or recycling mandates to achieve environmental goals. However, regulatory policies that mandate reuse or recycling also encourage illegal dumping.

EPR frameworks exist in the EU via the WEEE Directive, in Japan through the Waste Management Act, in South Korea through the EEEV Act and in Washington through Senate Bill 5939. Similarly, South Korea implemented EPR at the start of 2023, so the effectiveness of the policy is still largely to be determined. Japan does not mandate recycling, so its only measure of policy effectiveness is compliance by producers. Japan assures compliance by building an EoL fund directly by withholding a percentage of solar power generators' PPAs. Washington planned to implement the first EPR policy in the United States on 1 July 2025 but pushed the implementation timeline back to 1 July 2031 because producers threatened to leave the state (Department of Ecology, undated); this delay demonstrates regulatory accommodation and the increasing risks of regulatory capture. Other states in the United States that regulate EoL PV panels regulate utility-scale solar power generation installations, but Washington is the only state in the United States that imposes take-back and recycling responsibilities on PV panel producers. This gives PV panel producers an incentive to manufacture and sell panels elsewhere in the United States. The EU WEEE Directive was adopted by each member state, avoiding similar problems.

The WEEE Directive is in effect in each EU member state through each country's transposition. For example, Germany's transposition of the WEEE Directive, the Elektrogesetz regulation, requires producers to register in the Stiftung Elektro-Altgeräte-Register and to fund and manage a take-back and recycling system that meets the collection (85 per cent) and recycling (80 per cent) rate quotas. Germany is the EU member state with the highest solar-power generation capacity (Masson et al., 2025), and the first to install large numbers of PV panels (Held, 2024). This makes Germany the EU country with the largest number of EoL PV panels—it represented 56 per cent of EoL PV panels collected in the EU in 2018 (Masson and Kaizuka, 2021). Germany and other EU countries with high PV capacity consistently meet the WEEE Directive quota of recycling 80 per cent of collected EoL PVs but fall well under the collection quota (Komoto et al., 2022). This is largely due to the lag in PV waste after PV panels are installed.

Workshops in 2021 and 2022 evaluated Germany's take-back and recycling programme and showed that there are also logistical challenges in the collection system. The collection of private household PV panels requires consumer buy-in by bringing their EoL PV panels to collection sites. However, one study notes that 'it is roughly estimated that a maximum of 10% of end users order a collection via registered manufacturers and authorised agents' (Held, 2024, p. 33). There is little transparency on how the remaining household PV panels are disposed of, including resale or illegal disposal routes. PV panels that do make it to collection sites are not sorted there, imposing avoidable transportation costs as panels are brought to the wrong recycling site first. Another collection issue is the breakage of PV panels from improper handling and storage along the way from the consumer to the collection site to the recycling site.

Regulation in the Australian Context

Experience with Voluntary Approaches

Australia's approach to regulation has been shaped by experience with voluntary schemes to support PV recycling, which have thus far proven to be inadequate. Voluntary industry-based recycling schemes, such as those trialled in France (French Environmental Code, Legislative Part, Book V, Article L541-10) and Victoria, Australia (Victoria State Government, 2020), typically attracted the most–environmentally conscious, reputation-aware, and well-resourced companies within the sector. These tended to be companies that were least likely to be the cause of improper disposal in the first place. Unfortunately, these schemes failed to attract the low-cost and poorest-quality manufacturers of PV panels (i.e. those who manufacture panels that are most likely to reach EoL early because of product defects) and the firms least likely to still be operating within the sector at EoL (Parliament of Australia, 2024).

A further challenge with voluntary schemes is that they are largely unenforceable; monitoring and compliance functions are inadequate, and there is a limited ability to impose penalties or corrective actions. This is not a problem when scheme participants act within the scheme's guidelines; however, when the guidelines are breached and the actions that can be taken are highly limited, it can undermine trust and confidence in the voluntary industry scheme and will limit its effectiveness at scale (Environment and Communications References Committee, 2025, p. 188). Voluntary approaches can create a path dependence and lock-in of weak industry standards. Such standards are insufficient to drive long-term certainty to support investment and innovation in the infrastructure needed to support the collection and processing of PV recycling for secondary materials markets (Australian Council of Recycling, 2024, p. 11).

Finally, voluntary industry recycling schemes could not garner broad uptake because of the associated higher costs involved. In an operating environment in which PV companies are facing declining



profit margins, these costs are recouped from customers as the price of PV panels rapidly descends the cost curve. In an increasingly price-sensitive environment, in which consumers are struggling globally with cost-of-living pressures, any comparatively higher costs imposed on a product are likely to affect consumer purchasing behaviour. As a result of the failure of voluntary schemes, many jurisdictions are now investigating regulating mandatory participation in PV recycling (Circular Economy Ministerial Advisory Group, 2024, p. 38).

The Regulatory Landscape

Australia's regulatory foundation for a PV circular economy is the National Waste Policy (Australian Government, 2018).[4] This policy provides a framework for Australia to transition towards a circular economy, outlining targets, such as achieving 80-per-cent average resource recovery by 2030, that address specific industries and waste streams. The associated National Waste Policy Action Plan 2024 sets specific commitments for both government and industry (DCCEEW, 2024c). The broad objectives of the National Waste Policy are supported through the Recycling and Waste Reduction Act 2020 (Australian Government, 2020), which replaced the Product Stewardship Act 2011. This act established a national ban on the export of certain waste materials, including unprocessed plastic, glass, paper and tyres. At the same time, the act promoted measures to enhance domestic recycling capacity and strengthened product stewardship schemes, which required industries to manage the environmental impacts of products across their life cycle—from production to use to disposal. Other regulatory interventions include mandatory product stewardship schemes (e.g. for packaging and electronics), alignment with such international conventions as the Basel Convention (Basel Convention, 1989), and funding initiatives under the Recycling Modernisation Fund (DCCEEW, 2025a). Together, these measures establish a multilevel governance approach aimed at reducing landfill dependence and embedding circular economy principles across Australian supply chains.

The Commonwealth regulations are often implemented through the actions of state and territory governments, which have direct responsibility for waste management. Although states are actively coordinating to maintain consistency with Commonwealth guidance on waste management and product stewardship, specific regulations vary among Australian states and territories. For example, one common mechanism for moving towards a more circular economy for PVs is banning the disposal of PV waste (specifically, panels and inverters) in landfills. Such bans create demand for other disposal pathways, particularly recycling. Although all states and territories are taking steps to enhance consumer education, waste collection and recycling, as of this writing, not all states ban the disposal of PV panels in landfills (Table 10.1). Some states have specific provisions for e-waste, which can include PV systems; some have pilot programs in place; and some are in the consultation phase of new waste management policies that would include PV waste (Gentilini and Salt, 2019; Deng et al., 2024).

Future Policy Priorities for Australia's Circular Economy

Given the state of Australia's policy landscape, the future development of a circular economy for PVs will be contingent on the creation of two enabling conditions: (1) building a competitive marketplace for PVs that addresses market failures (as discussed in 'The Role of Regulation' section), and (2) advancing innovation to tackle the remaining technological barriers that impede cost-effective circularity and scaling. Specific dimensions of each of these areas are discussed in the following sections.

[4] An action plan for the implementation of the National Waste Policy was released in 2019 (Australian Government, 2019).

TABLE 10.1
Summary of State and Territory Regulations Regarding the Disposal of Solar Photovoltaic Waste in Landfills

State or Territory	Regulatory Summary
Australian Capital Territory	In August 2023, the Australian Capital Territory government released the ACT Circular Economy Strategy and Action Plan 2023–2030, which identifies PV panels as a 'priority waste stream' and discusses 'opportunities to design out waste for solar PV systems' (Australian Capital Territory Government, 2023). The plan has also imposed restrictions on disposing of e-waste in landfills. Incentives exist to collect and recycle PV panels, but small systems without batteries are permitted to be deposited in landfills (Australian Capital Territory Government, undated).
New South Wales	Under the Waste Avoidance and Resource Recovery Act 2001 (New South Wales Government, 2001), PV panels are classified as e-waste and must be disposed of in accordance with the Environment Protection Authority (New South Wales Environment Protection Authority, 2021). The guidelines require that PV panels be recycled or reused wherever possible.
Queensland	The Queensland E-Products Action Plan (Office of Circular Economy, Department of Environment and Science, 2023) outlines a ten-year strategy to address e-waste. Meanwhile, the Environmental Legislation Amendment Regulation 2025 (Queensland Government, 2025) removes PV panels from the regulated waste framework, enabling them to be managed as general waste similar to other e-waste. The Queensland Government has also launched a $2.5 million PV panel recycling pilot programme and invested $3 million into Queensland Renewable Energy Industry Association Grants to support industry efforts on PV recycling (de Brenni and Lindard, 2024).
Northern Territory	Under the Northern Territory Government's Circular Economy Strategy 2022–2027 (Department of Environment, Parks and Water Security, 2022), the territory is identifying 'opportunities to increase the recovery of priority and problematic wastes', including PV panels. In addition, the Circular Economy Northern Territory grant programme provides grants for projects that 'improve recycling outcomes and address critical gaps around waste management and resource recovery' in the territory (Department of Environment, Parks and Water Security, undated). At the time of this writing, however, the territory does not have specific regulations or a landfill ban for PV panel disposal.
Western Australia	Western Australia is implementing Phase 1 of the Waste Avoidance and Resource Recovery (E-Waste) Regulations 2024, which came into force on 1 July 2024 (Department of Water and Environmental Regulation, 2023). A landfill ban on PV waste is anticipated for future phases.
South Australia	Under the South Australia Environment Protection (Waste to Resource) Policy 2010 (Government of South Australia, 2021), the state has imposed restrictions on disposing of e-waste in landfills. Although this does not currently apply to PV waste, the inclusion of small PV systems on the South Australian list of prohibited landfill wastes is under consideration as part of the review of the state's waste policy (Mussared, 2024).
Victoria	Since 2019, it has been illegal to put e-waste, including PV panels, in household rubbish or landfill in Victoria (Victoria State Government, 2024).
Tasmania	Solar PV panel disposal is governed by Tasmania's general environmental and waste management laws, which lack specific PV waste management regulations.

Building a Competitive Market

Product Stewardship Schemes

One of the key policy interventions for incentivising the development of a circular economy for PVs is the implementation of robust product stewardship schemes. Landfill bans divert PV waste away from landfills, but product stewardship schemes create the framework for the subsequent management of waste. For example, in Victoria, 73 per cent of PV panel waste was recovered, but only 18 per cent was sent to a PV panel recycler (Randell, 2021). Although the Commonwealth government identified PV panels as a priority product for stewardship in 2016, the lack of a national product-stewardship–scheme mandate has resulted in a policy vacuum. This vacuum has placed the nascent domestic PV recycling industry in a precarious state, lacking the regulatory certainty needed for investment, and the inaction has reinforced

a market failure in the form of a substantial cost difference between the cost of sustainable stewardship of PV waste and disposal in a landfill. For example, the current cost of recycling each PV panel in Australia is estimated to be around $15.00, roughly three times the cost of sending it to landfill, at $4.50 (Randell, 2021). This is not entirely unique to Australia; the United States is experiencing a similar disparity. In the United States, recycling costs US$15 to $45 per PV panel, compared with a landfill cost of US$1 to $5 per panel (Curtis, Buchanan, Heath, et al., 2021; Huang et al., 2022). However, the Australian context presents added difficulties, including the long distances involved in shipping panels overseas for recycling and the high costs associated with transporting EoL panels from rural and remote communities to recycling facilities. Moreover, Australian consumers are forced to contend with a relatively high turnover of foreign PV manufacturers and importers because of the lack of a domestic PV manufacturing industry (Quinn, 2023). This price gap creates a strong economic incentive for landfilling, making it impossible for legitimate recyclers to compete and threatening the viability of the entire sector. This policy failure is occurring at the worst possible moment, as a perfect storm of market forces—including the collapse of offshore reuse markets, rapid price deflation of new panels and an increase in battery incentives and deployment—is dramatically accelerating the rate of decommissioning. Some states have taken leadership by banning panels from landfills (Table 10.1), but this has created a fragmented and inefficient regulatory landscape.

To address this policy and market failure, Australia is currently in the process of establishing a national product stewardship scheme for PV systems, including PV modules, inverters and associated storage components. Although the Product Stewardship Act 2011 provides the legislative basis for such schemes, PV products are not yet subject to mandatory regulation. Since 2016, PV systems have been listed on the Minister's Product Stewardship Priority List,[5] yet no enforceable obligations currently apply (Chhillar et al., 2024). In 2020, DCCEEW launched a call for partnerships to codesign the PV product stewardship scheme. The proposed model introduces clear roles and responsibilities, funding mechanisms and supporting infrastructure. Importers and manufacturers will be required to pay fees to a central scheme administrator, who will use these funds to deliver key outcomes, including for collection, transport, processing, recycling, disposal, education, compliance, reporting and governance. This financial model will help make PV recycling more commercially viable by supporting a network of government-appointed operators for service delivery within defined areas. Free public access to drop-off and collection services will further encourage participation and help scale the recycling system (DCCEEW, 2023). Although industry proposals were received, no formal agreements were pursued at that stage (DCCEEW, 2024d). Despite the absence of a national framework, various pilot initiatives have emerged at the state and local levels. For instance, the Queensland government funded a PV panel recycling pilot, establishing 15 collection and processing sites across the state (Table 10.1).

To be effective, a product stewardship scheme for PVs cannot be a narrow, EoL disposal programme. A holistic, whole-of-life-cycle accountability approach could elevate responsibility to the top of the critical mineral supply chain and again at the point of import and sale. The complex nature of the PV supply chain—in which global manufacturers may use multiple distributors and have no direct control over the final sale—requires a clear point of accountability. However, several critical policy gaps hinder the development of an effective stewardship framework for PV systems in Australia:

- **Lack of legal obligation.** Importers and retailers are not currently required to finance or participate in EoL recovery activities (Jensen and Remmen, 2017; Madden, Florin, and Salim, 2023).
- **Absence of material-specific recovery targets.** Critical materials, such as silver, silicon and copper, are not prioritised within any mandated recovery pathways (Madden, Florin, and Salim, 2023).

[5] The Minister's Priority List identifies the Minister's current priorities for product stewardship action. The Priority List was initiated under the Product Stewardship Act of 2011 and continued under the Recycling and Waste Reduction Act 2020.



- **Limited integration of ecodesign principles.** Existing procurement, labelling and incentive systems do not reward recyclability or low-impact design (Chowdhury et al., 2020).
- **Fragmented oversight and enforcement.** In the absence of national regulation, responsibility for PV waste management falls to local governments and consumers, resulting in inconsistent handling practices (Florin et al., 2020; Deng et al., 2024).

There are relevant model frameworks currently in use in Australia that can help support a national, rigorous product stewardship for PV systems. For example, stakeholders broadly support a co-regulatory approach, modelled on the National Television and Computer Recycling Scheme, with industry-driven delivery under government-defined minimum requirements. Such a model would assign operations responsibility to industry actors under mandatory government-defined requirements, including minimum recovery thresholds, design-for-recyclability incentives and carbon footprint reporting—all of which are aligned with Australia's net-zero and circular economy goals (Ardente et al., 2025). The development of this scheme represents a unique opportunity to transition from fragmented, voluntary initiatives towards a cohesive national framework that supports infrastructure investment, innovation and long-term sustainability in the PV sector.

In addition, the New South Wales Product Lifecycle Responsibility Act 2025 provides another model blueprint for product stewardship. It clearly defines the legally liable brand owner as either the entity that owns the product name under which it is supplied or, crucially, the first importer (New South Wales Government, 2025). This model correctly shifts the burden from consumers and local councils to the entities that profit from placing the products on the Australian market, ensuring accountability regardless of the complexity of the distribution channel. Adopting a harmonised, national framework would simplify industry compliance and make Australia a more stable and attractive destination for investment in the circular economy.



While stakeholders wait for a national product stewardship scheme to be finalised, there are interim measures that could be pursued. For example, the Australian government could quickly launch a national pilot programme, modelled on the proven success of Queensland's Solar Panel Stewardship pilot programme. This pilot could act as a kind of life-support system for Australia's local recycling industry, designed to provide a steady stream of EoL PV waste feedstock to prevent market collapse. It would also provide the critical, real-world data on logistics and costs needed to derisk and design a permanent, equitable and financially sustainable national scheme. Alternatively, in the absence of policy action at the Commonwealth level, states could work in parallel to draft harmonised, state-based mandatory stewardship legislation modelled on the New South Wales Product Lifecycle Responsibility Act 2025. Such a state-based legislative backstop could act to derisk private investment by providing an alternative pathway to market. These interventions would work in concert with other circular economy actions, such as a national ban on landfilling PV panels and targeted coinvestment from such vehicles as the National Reconstruction Fund to develop advanced, commercial-scale material recovery facilities in Australia.

Industry Standards

In addition to regulatory requirements, industry standards represent an important mechanism for implementing common best practices for products, processes and services to ensure the quality, safety and interoperability of PV technologies. Industry standards provide a framework for consistency, reduce risks and complexity and offer a benchmark for performance and reliability across various sectors. Moreover, when integrated into regulatory frameworks, compliance with standards can determine whether manufacturers have access to the Australian market. For example, in the EU, producers of PV panels must enrol in the relevant national WEEE register (WEEE Forum, undated), report on the quantity of PV panels and inverters put on the market, and comply with collection, recovery and recycling targets.

The existing industry standards for PV arrays in Australia have primarily concentrated on installation and safety requirements, as suggested by AS/NZS 5033:2021 (Standards Australia, 2021). This focus, although essential for the initial deployment of PV technology, has largely overlooked the comprehensive life-cycle management of these systems. These standards could be extended to include design-specific standards.

The life cycle of PV technology encompasses not only its installation and operational phases but also EoL management, including disposal and recycling. The closest applicable standard available for disposal and recycling of PV technology is AS 5377:2022, *Management of Electrical and Electronic Equipment for Re-Use or Recycling* (Standards Australia, 2022).

The two major areas that, as of this writing, lack sufficient standardisation relate to

- **Reuse or recycling of PV panels:** The absence of clear guidelines and standards for the reuse and recycling of PV panels presents a challenge. Without established protocols, the processes for collecting, refurbishing and recycling these panels can vary widely, leading to inefficiencies and potential environmental impacts.
- **PV panel assembly:** The lack of standardised assembly procedures for PV panels further complicates the recycling process. Different manufacturers might use varying materials, technologies and assembly techniques, resulting in a heterogeneous market. This variability not only complicates recycling efforts but also affects the overall sustainability of PV technology.

The absence of uniform regulations for PV waste collection, hazardous materials management and recycling approvals can lead to fragmented and inefficient systems. This fragmentation hinders the effective reuse and recovery of valuable materials from EoL PV panels, which ultimately increases waste and reduces the overall sustainability of the industry (Sica et al., 2018; Gentilini and Salt, 2019).

The variability in the assembly processes of PV panels also means that the equipment, techniques and labour required for recycling different types of PV panels can differ significantly. This inconsistency can lead to inefficient recycling plants that struggle to streamline their operations. As a result, the potential to create sustainable recycling solutions will be diminished because of the operating costs associated with complex recycling plants (Gentilini and Salt, 2019).

Material Classification Issues

As described previously, there is a lack of industry standards in the PV sector, both for recycling practices and panel assembly methods. The heterogeneity of the PV panel market is accentuated by the variation in types of PV modules. Silicon-based PV modules are most common, but there are a variety of more-specialised, thin-film PV modules that use diverse materials, including cadmium, indium and gallium. The recycling process depends on the materials in the PV panel, so the recycling technology is different for each type of PV module. Tracking the recovery and transport routes of PV panels requires transparency about the materials in the panel. PV panels are not always labelled with the type of PV module used (Held, 2024), which can complicate efforts to properly sort PV panels for efficient recycling or disposal. Information reported on imported PV panels is also not sufficient to identify the materials in a PV panel.

Issues with PV module sorting affected the efficiency of Germany's take-back and recycling programme (Held, 2024). Local waste-management authorities at collection points are responsible for sorting silicon-based and non–silicon based panels to be recycled in different facilities. A combination of insufficient training and a lack of labels displaying the PV module type led to improperly sorted modules being diverted to the wrong treatment or recycling facility. This led to an avoidable increase in logistics costs because treatment and recycling facilities also needed to sort module types before transporting improperly diverted modules (again) to the correct facility.

International customs information on the trade of goods is also insufficient to separate PV panels by the materials used in the PV module. Harmonised System (HS) codes are an international standard to identify traded commodities, but the most-detailed, six-digit HS codes for PV commodities only separate modules and panels.[6] More information can be presented with the HS code; for example, the United States requires ten digits, adding four levels of detail to the HS codes. Reporting further information requires compliance by the export panel manufacturer. Chinese manufacturers produce and export low-cost PV panels but do not always report what materials they use (Tanaka, 2024). This opacity could lead to the same EoL sorting inefficiencies that affected Germany's recycling efforts (Held, 2024). Resolving material classification issues requires compliance by countries and manufacturers globally.

Export and Import Controls

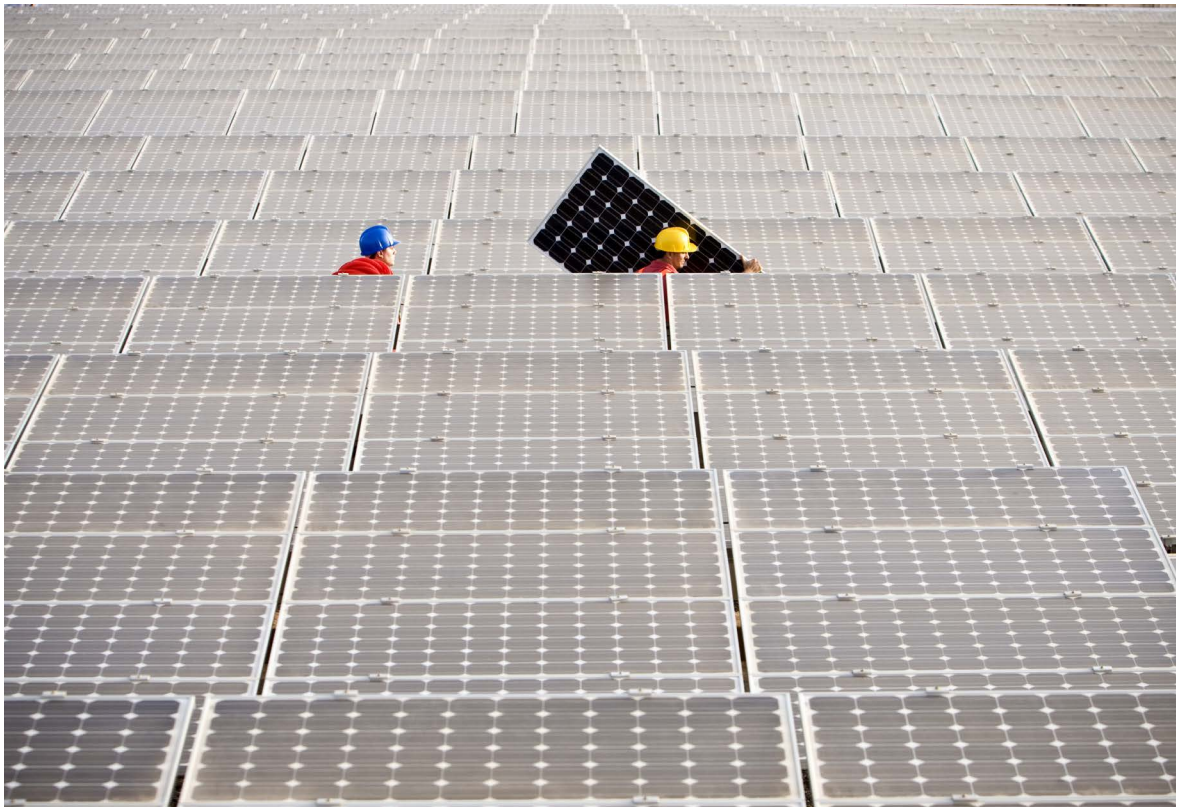
Chinese-manufactured PV products—cells, modules and wafers—dominate the global market, making up more than 80 per cent of global production in 2021 (Abdelilah et al., 2022). PV manufacturers in China have lower production costs than those in other markets, such as the United States, the EU and Korea (Abdelilah et al., 2022). Some countries have implemented tariffs or duties to increase the competitiveness of their domestic PV industries. The EU implemented an import tariff on Chinese PV panels in 2013 but revoked the policy in 2018 and has since avoided similar policies because of their impact on EU solar deployment targets (Blenkinsop, 2024). Unlike the EU, the United States has maintained prior export control policies and implemented a series of further duty and tariff policies. These policies include layered antidumping and countervailing duty (AD/CVD), Section 201, and Section 301 tariffs implemented from 2012 to 2025 (Office of the United States Trade Representative, undated; Daily, 2012; International Trade Administration, 2014; Office of the United States Trade Representative, 2024; International Trade Administration, 2025). U.S. AD/CVD tariffs extend to solar cell imports from China, Taiwan, Cambodia, Thailand, Vietnam and Myanmar after a U.S. Department of Commerce investigation determined that Chinese-headquartered manufacturers shifted final assembly to these countries to circumvent the AD/CVD tariffs on PV cells and modules (International Trade Administration, 2023).

In response to such barriers to the U.S. market, Chinese exports of PV cells and modules have historically deflected to other markets with high PV demand and fewer trade barriers (Lin and Liu, 2025). Australia has a large and growing PV market (Egan and Koschier, 2024), and there are PV panels on one in three Australian households (Bowen et al., 2024). Australia also has a free-trade agreement with China (Department of Foreign Affairs and Trade, undated), which could position Australia as an ideal market for Chinese PV exports to divert to in response to tighter U.S. import controls.

Reuse and Repair Markets

In addition to PV system recycling, a product stewardship scheme also seeks to encourage repair and reuse. Creating a second life for PV systems that returns them to service can extend their life, enhance access to low-cost PV systems, reduce the need for the acquisition of new equipment and delay their conversion to waste (Franco and Groesser, 2021). However, DCCEEW's review of international approaches to e-stewardship notes that barriers exist in these markets as well. It notes concerns about cross-border flows of second-hand information technology and PV waste and issues related to product redundancy and refurbishment costs (DCCEEW, 2023). That said, one example of emerging support for reuse is found in France, where Soren—the country's sole nonprofit Producer Responsibility Organisation for the PV industry—plays a central role in coordinating the decommissioning of PV panels (Deng et al., 2024). Soren manages France's obligations under the WEEE Directive 2012/19/EU, which includes provisions encouraging the preparation of equipment for reuse (EU, 2012). In line with these objectives, Soren

[6] HS 854142 covers PV modules not assembled into PV panels; HS 854143 covers PV modules assembled into PV panels.



has partnered with Envie 2E Aquitaine, a social enterprise specialising in recycling and reuse, to explore and develop a viable market stream for second-hand PV panels. Together, they opened the first PV panel reuse and processing facility in Europe on 27 September 2022. The facility is expected to receive approximately 4,000 tonnes of PV panels annually, and Envie 2E Aquitaine estimates that around 5 per cent of these panels can be resold, following all necessary operational testing, to individuals, businesses and communities (Envie, 2022). This collaboration, driven by policy, is expected to boost the development of the reuse market in France by establishing dedicated infrastructure for the processing, refurbishment and resale of second-hand PV panels.

Job Creation Potential

The job creation potential of recycling efforts is often greater than the estimated direct labour required for landfill operations. In the Australian context, one study estimated that direct full-time jobs created per 10,000 tonnes of waste is 9.2 for recycling and 2.8 for landfill (Access Economics, 2009).[7] The employment created for general waste recycling spans truck and forklift drivers, recycling and rubbish collectors, earth-moving plant operators, factory process workers, and general and production managers (Access Economics, 2009). In the case of PV waste recycling, the jobs created would also likely include a subset of a more specialised STEM workforce. More recently, Green Industries South Australia commissioned a study that revealed that, by 2030, a circular economy could create an additional 25,700 jobs and reduce GHG emissions by 27 per cent in South Australia alone (Green Industries SA, 2017). The

[7] This estimate from 2009 (9.2 jobs in recycling per 10,000 tonnes of waste) has been reused in multiple government documents and policies, including CSIRO's *Circular Economy Roadmap for Plastics, Glass, Paper and Tyres* report (Schandl et al., 2021). A more recent estimate does not appear to be readily available.



workforce generated via a circular economy of PV systems will allow Australia to realise the ambitions to create a sovereign PV panel manufacturing capability.

Investment Requirements Versus Returns

The investments required to establish a circular economy for PV waste in Australia can vary, depending on the desired returns. R&D, education and training are vital investments across varying lines of effort that support PV EoL management. The dependency on labour costs and material benefits for establishing sustainable recycling efforts means that all subsequent consideration and planning of the PV recycling business in Australia should also centre on these two factors (Huang and Deng, 2023).

One study that modelled the profitability of a PV recycling industry in Australia estimated that—based on European PV CYCLE financial reports from 2011 to 2013—the profit would be between $0.036 and $0.12 per watt in 2032 (Kang, White, and Thomson, 2015). A more recent assessment found that the largest cost is the fixed cost of establishing the facility; a facility processing 10,000 tonnes or less of PV waste material annually would likely not be profitable, but a 20,000-tonnes-per-year facility is profitable in all but the most pessimistic scenario (Mahmoudi, Huda, and Behnia, 2020). The costs included the processing fees, the expense of collection services, labour costs and assets, and the investment for building collection centres.

However, it might be inaccurate to directly transfer the costs in the European market to the Australian market. Because Australia has a large land area and a small population, fewer recycling centres and collection points might be needed, but the logistics costs could be higher. These estimates are also heavily dependent on future policy in Australia related to the fluctuating costs of processing the panels and the value of key materials, such as polysilicon. The high dependency on benefits from material sales makes profitability extremely susceptible to market fluctuation. To alleviate this dependency, and because of

the unprofitability of recycling processes, the introduction of gate fees or government subsidies will be a necessary step for the PV recycling industry to get started and to reduce financial risk and instability (Liu, Zhang, and Wang, 2020).

To realise the social and environmental benefits that circular economy efforts provide, investors will need to have a longer-term outlook on their investments (Gentilini and Salt, 2019). Given the increasing levels of waste and inevitable resource scarcity, CBMs provide the opportunity for investors to future-proof their investments in the long term as they await their returns. These longer-term green investments could be bundled up and sold as green investment products in the stock market.[8]

International Competitiveness Analysis

To build resilience in PV supply chains, the Australian government plans to invest $1 billion in domestic PV manufacturing (Edmonstone, 2024). The goal of Australia's Solar Sunshot programme is to contribute to Australia's economic security and resilience (Edmonstone, 2024). However, although Australia is a global leader in specific aspects of PV recycling research, this does not seem to translate to patents or commercial activities. Challenges for commercial activities include strong cost competition from China, limited access to intellectual property, lack of internal know-how and trade secrets, the significant capital and R&D investment required and environmental, social and governance considerations. A report published by CSIRO found that Australia's research into PV recycling is second in the world for recycling silicon from PVs (after China) and suggested that the establishment of midstream activities—such as the production of metallurgical silicon and polysilicon—poses a great potential investment for Australia (Delaval et al., 2024).

Geopolitical Considerations

To mitigate the risks associated with an overreliance on China for energy security and PV supply chains, Australia is investing in domestic PV manufacturing (Bowen et al., 2024). The complex supply chains associated with PV panel material could be simplified if Australia approached PV manufacturing with a circular economy in mind, ensuring that the critical resources from EoL PV waste can be reused and recycled in-country. Australia imports more than 70 per cent of its PV panels from China, Malaysia and Singapore (Johnston, 2018). The Republic of Korea and Hong Kong are other major suppliers (Johnston, 2018). Manufacturers of panels used in Australia are mostly based in Asia, meaning that the Australian sales and installation industry must "work within the Asia-Pacific region to establish [the] goals, design priorities and collaborations required for better product and process design" (Gentilini and Salt, 2019, p. 21).

Advancing Innovation

Advances in developing a sustainable marketplace for a PV circular economy must be coupled with technological innovations that address barriers to the cost-effective recycling of PV systems. As of this writing, Australia lacks a dedicated entity specialising in PV panel recycling and material recovery. Existing recycling companies can manage the delamination of modules, but the commodities are then sent to material recovery facilities that lack specialisation in PV laminates, potentially compromising value and output yields (Deng et al., 2024). Research into improving recycling processes and recovering materials at a higher purity is also critical so that these materials are suitable to be reused. For example, the University of New South Wales achieved 99-per-cent solar-cell separation (Martin, 2023), while Deakin University has developed a highly valuable, chemical-free nanosilicon extraction process (Deakin University, 2023). Commer-

[8] In 2025, the global Sustainable Bond Issuance was valued at US$1 trillion (ESG News, 2025).

cialising, scaling and receiving government support beyond R&D are becoming more essential because of growing PV recycling demand. Institutional support will not only boost recyclers' profits, but government subsidies could also encourage consumer participation (Deng et al., 2024). Some specific areas of innovation for PV recycling are discussed in the following sections.

Recycling Research for Special Photovoltaic Technologies and Systems

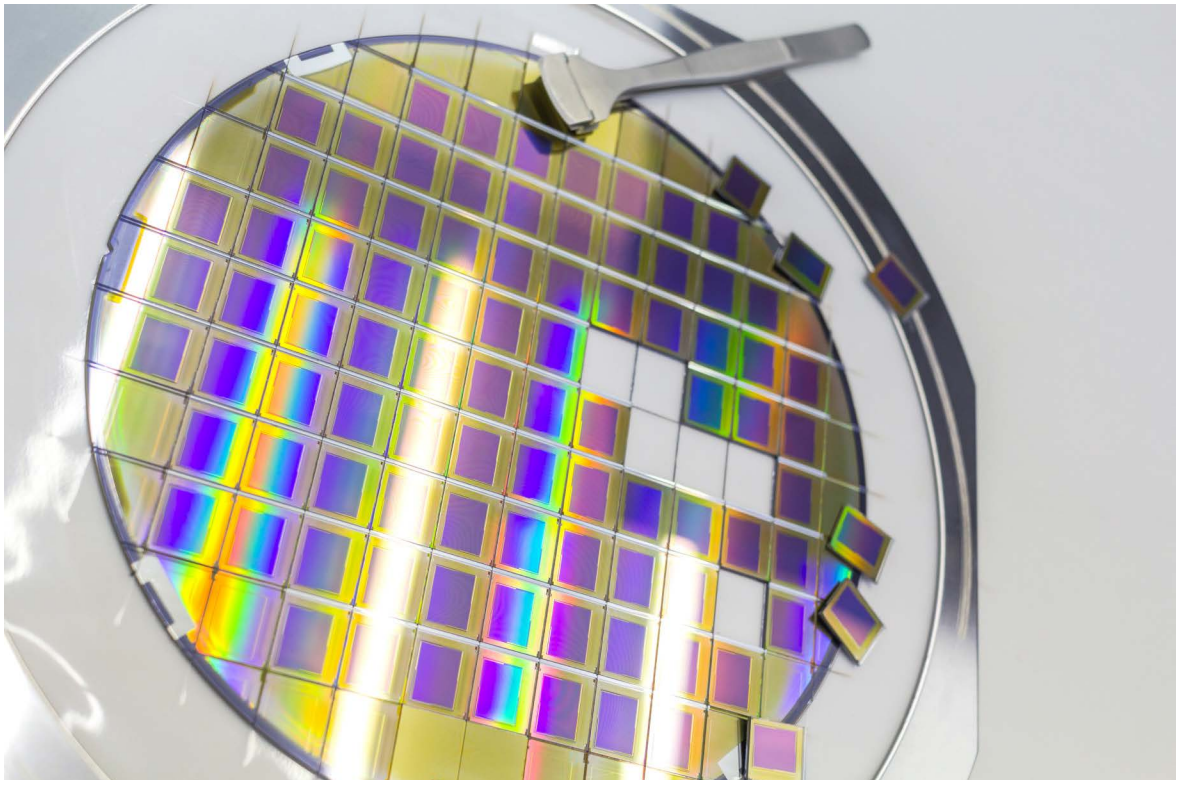
Recycling PV modules is crucial for achieving sustainable development throughout the full life cycle of green energy. PV modules contain valuable materials, such as aluminium, silicon, silver, copper, glass and polymers. Efficient EoL recycling reduces environmental pollution, decreases reliance on raw materials and promotes resource and economic circulation (Chowdhury et al., 2020).

Compared with conventional PV modules, special PV technologies—such as building-integrated PVs (BIPVs), agrivoltaics, indoor PVs for powering the Internet of Things and low-light electronics, road- and infrastructure-integrated PVs, floating PVs and lightweight portable systems—are more complex in their material composition, offering greater recycling potential. For example, BIPV modules contain not only standard PV materials but also architectural glass, insulation, sealants and coatings. Their dual-glass structures often use high-transparency, impact-resistant glass combined with polyvinyl butyral or EVA encapsulants to improve durability and safety. Many BIPV products also include multifunctional coatings, such as low-emissivity or coloured films, which improve energy efficiency and aesthetics (Kuhn et al., 2021). Flexible PV systems frequently use high-performance polymers, such as ethylene tetrafluoroethylene for lightweight, weather-resistant encapsulation (Maoz et al., 2025). Floating PV systems, on the other hand, rely on extensive anticorrosion coatings to withstand prolonged exposure to water and humidity (Sahu, Yadav, and Sudhakar, 2016).

Despite their higher theoretical recycling value, special PV modules receive limited attention in existing recycling practices that mainly extract silicon, aluminium and glass, following conventional PV recycling methods (Chowdhury et al., 2020). Multifunctional coatings, sealants, insulation layers and special coatings are rarely recovered, despite containing complex chemical materials, including indium, tin, titanium and composite oxides. Most are treated as waste and end up in landfills or incineration. This gap arises from both the technological challenges of separating complex multilayer materials and the absence of industry standards and policies addressing emerging PV designs (Bilbao et al., 2021).

As the market penetration of special PV systems expands, developing advanced recycling technology and value assessment models has become a critical industry priority. Future research should focus on efficient separation and recovery methods for multilayer, chemically bonded and functionally integrated modules. Policy and standardisation efforts are also important. Future research should include life-cycle cost-benefit analyses to inform evidence-based regulation and investment. Optimising recycling processes and strengthening policy frameworks will enhance resource recovery and improve the overall sustainability of special PV components.

Australia's unique context offers both challenges and opportunities for advanced PV recycling. The country's vast solar capacity, diverse climatic conditions and growing adoption of innovative PV applications create a strong need for tailored domestic recycling solutions. Australia's geographic isolation and limited domestic manufacturing base also make resource recovery particularly valuable because it could reduce dependencies on imported materials and support local circular economy initiatives. Leveraging Australia's strong research capabilities and collaborative industry networks can position the nation as a leader in developing specialised recycling technologies for next-generation PV systems.



Process Optimisation

Process optimisation within the context of the circular economy involves systematically analysing and increasing the efficiency of operations and resources throughout the product's entire life cycle. This entails maximising resource utilisation, minimising waste and improving overall efficiency and quality. For PV systems, this might extend beyond manufacturing to include sustainable design for longevity, efficient operation and EoL management, including reuse, repair and material recovery.

At the manufacturing stage, even small gains in yield can have outsized impacts on waste. For instance, a 10-per-cent boost in module production yield can reduce life-cycle waste by up to 15 per cent, while a 10-per-cent drop in yield could raise it by 86 per cent (Ovaitt et al., 2022). Advances (i.e. reduction) in wafer thickness and kerf loss can reduce polysilicon use by 25 to 30 per cent per module string, thus trimming cost, feedstock demand and the recycling and circularity burdens (Fischer, Woodhouse, and Baliozian, 2024). Further gains might be achieved through judicious business-model integration and the efficient layout of manufacturing facilities and processes (Zúñiga et al., 2020).

Downstream optimisation and circular activities, such as reuse and repair, might be underprioritised today. Panels are not reaching their expected 25- to 30-year lifespan before they are decommissioned; the average operational lifetime in Australia is estimated at 15 to 20 years (Tan et al., 2022). A reduction from 30 to 15 years, halving the commissioned lifetime, translates to doubling PV waste and highlights the serious need for a better understanding and mitigation of the lifetime shortfall. Policies supporting quality control, certification and the development of secondary markets for second-hand panels could further help reduce the waste of valuable, functional assets and would redirect material and capital towards more economic and environmental pathways (Salim et al., 2023).

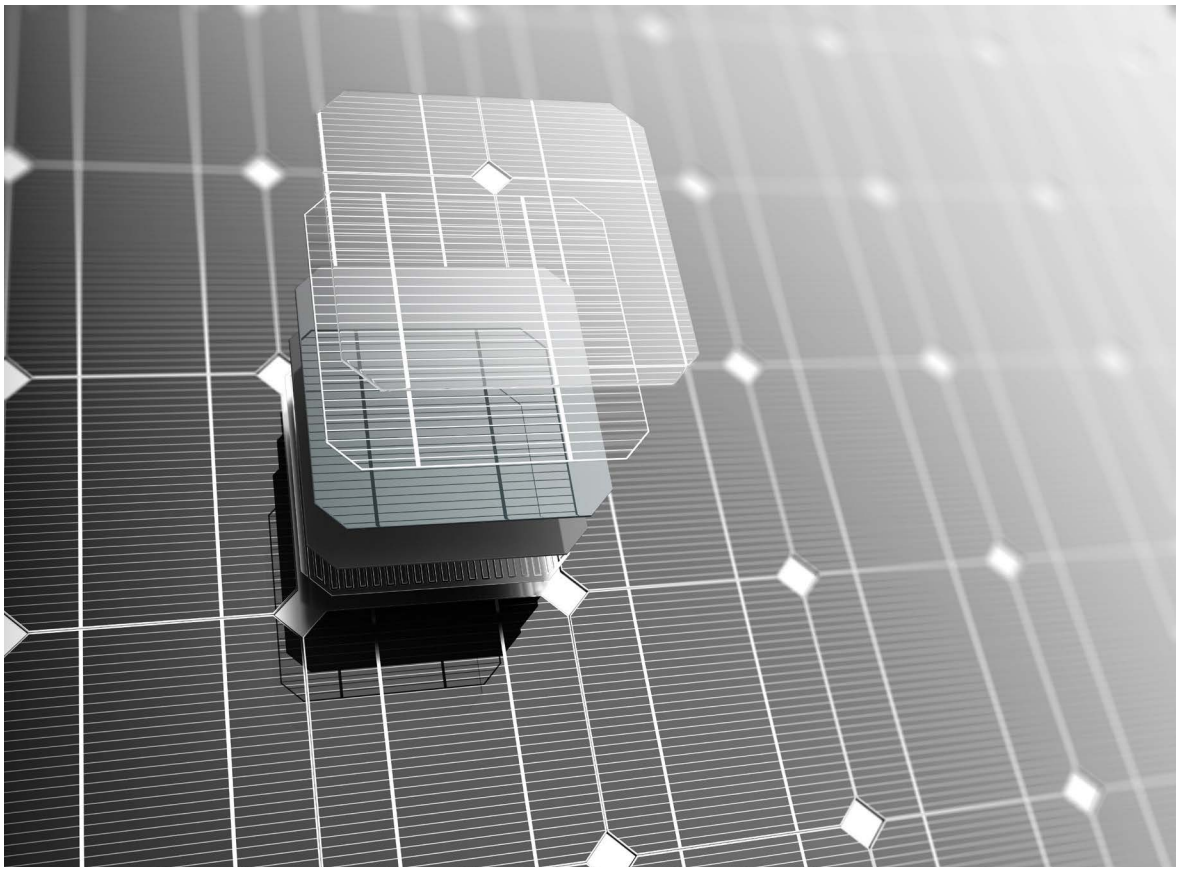
Bridging logistical deficiencies could also contribute to a circular economy for PV. The expansive spatial distribution of small-scale rooftop PV installations across Australia, along with its many remote

communities, presents a formidable logistical challenge for efficient panel installation and collection at decommissioning (Australian Energy Council, 2023). Careful waste and recycling logistics planning can help site optimal collection facilities to minimise the overall logistical burden of installation and collection activities. A poorly planned or onerous logistical burden would increase costs and degrade the benefit-and-cost calculus that installers and recyclers face when deciding whether to invest in new facilities and infrastructure. Suggestions for facility siting have been put forward and should include contingency and scenario planning for potential changes from technology improvements that might alter panel throughput (Deng et al., 2024).

Material Recovery

The 'Material Recovery Breakthroughs' section in Chapter 5 outlines methods for recovering materials from c-Si panels (including silver, silicon, glass, aluminium and copper) alongside the challenges of achieving economic viability. For instance, thermal recycling becomes viable only when silicon wafer values exceed US$350 per tonne, and cost-effective mechanical recycling would require technological innovation and facility optimisation to achieve an approximately 30-per-cent reduction in processing costs (Deng et al., 2019; Heath et al., 2020; Heath et al., 2022).

In Australia, recyclers are generally able to recover aluminium frames, copper cables and glass, but the recovery of other materials, particularly silver, silicon and copper from within the cells, remains technically challenging and occurs at varying degrees of success, depending on the process. Among these materials, silver recovery presents the most significant economic opportunity. As outlined in the 'Material Recovery Breakthroughs' section in Chapter 5, a 25-per-cent increase in extraction efficiency could



raise revenue by more than US$5 per m^2 of panel (Fortier et al., 2019; Preet and Smith, 2024). However, as mentioned previously, silver, silicon and copper remain among the most-difficult materials to extract from solar cells, posing both technical and cost-related challenges.

Several Australian companies are actively researching less hazardous methods to recover high-purity silver, although these efforts remain in the R&D phase. For example, in 2024, one company successfully extracted silver from waste solar cells, although the process is still under development. Separately, another company is collaborating with universities to develop recovery methods for high-purity silicon and silver, achieving purity levels of 98 per cent for silicon and 99.9 per cent for silver (Agraffeil et al., 2025, p. 71).

With the support of new funding, a third company, in partnership with the University of Newcastle, is developing an environmentally friendly beneficiation process to recover high-purity silver and silicon from wafer material. Initial results have shown silver recovery rates above 90 per cent, and early testing suggests similar outcomes for high-purity silicon. There is also potential to separately recover other materials, such as copper (Agraffeil et al., 2025).

Although the commercialisation of silver recovery processes is expected to progress in Australia, challenges remain in scaling these technologies efficiently. Another major barrier to scaling PV recycling in Australia is the lack of secondary markets for recovered materials beyond aluminium frames and copper cables. Without a domestic solar-panel manufacturing supply chain, it is difficult to find consistent demand for recycled glass, silicon and other materials. Although one Australian company has demonstrated some success, selling 6 tonnes of recovered glass for use in a construction project, such examples remain limited (Agraffeil et al., 2025, p. 74). Scaling the recycling industry would likely depend on establishing reliable, high-value markets for recovered materials.

The recovery and reuse of materials from EoL PV modules necessitate robust standards and certified reference materials to ensure quality, safety and performance. Recovered materials (including silicon, silver, aluminium and polymers) must meet well-defined purity and performance benchmarks to be reintegrated into new PV modules or other industrial applications. The lack of globally harmonised standards for recycled PV materials poses significant challenges, leading to inconsistencies in material quality and performance. Certified reference materials for secondary raw materials are essential for precise quality control, enabling manufacturers to verify material properties and ensure compliance with regulatory requirements. Establishing standardised certification protocols, such as the international standard for environmental management systems (ISO 14001), will enhance resource efficiency, reduce environmental impacts and foster industry confidence in the use of recycled components (Klüppel, 1998; Curtis, Buchanan, Heath, et al., 2021; Urbina, 2022).

Automation and Scaling

The transition from laboratory-scale PV recycling to commercially viable operations hinges on automation technologies that can address fundamental economic and safety barriers. Existing processes face a critical challenge: Labour represents 64 to 72 per cent of total operating costs, creating an unsustainable business model that automation must address (Rubino et al., 2020; Lim et al., 2022; Trivedi, Meshram, and Gupta, 2023). Beyond economics, safety concerns drive the need for automation that eliminates human involvement in dangerous conditions, particularly when handling hazardous chemicals that pose workplace safety and health concerns (Xu et al., 2018; Sim et al., 2025).

Electrochemical processing offers significant advantages for automation because of its continuous operation capabilities and proven industrial scalability. Slurry electrolysis that uses single-step processing demonstrates commercial feasibility by eliminating the manual sorting and handling steps that challenge mechanical approaches (Deng, Zhuo, and Shen, 2022; Fathima et al., 2022). The technology's effectiveness is demonstrated through its metal recovery capabilities, achieving greater than

98-per-cent copper recovery efficiency at 1.5 to 3 kWh per kg of copper, showcasing the potential for high-efficiency recovery of valuable metals from PV modules (Fathima et al., 2022). This approach is technologically ready for industrial implementation, and the energy consumption is comparable to industrial electrowinning. Technical challenges persist in electrolyte management, particularly in addressing corrosive systems and optimising reaction kinetics through electrocatalyst integration (Fathima et al., 2022). Additionally, the transition to commercial scale faces systemic barriers, including the lack of integrated processing facilities and low volumes of EoL modules (Sim et al., 2025).

Mechanical automation has achieved significant breakthroughs in addressing processing bottlenecks, particularly in frame removal—the main throughput and economic constraint caused by required manual labour (Rubino et al., 2020). Manual frame removal takes approximately 5 minutes per module (Rubino et al., 2020), but commercial automated solutions have dramatically improved these timelines. An automated frame separator made by the Japanese company NPC processes modules in 40 seconds (Deng, Zhuo, and Shen, 2022; Trivedi, Meshram, and Gupta, 2023), enabling the processing of 40 tonnes per day at full capacity. Similarly, Veolia in France, which operates the world's first dedicated c-Si PV recycling facility (established in 2018), uses fully automated processes with grinders, eddy current separators and optical sorters to achieve more than 95-per-cent recovery in 1.5 minutes per module, demonstrating that comprehensive automation can deliver both speed and efficiency while enabling upscaling to commercial scale with a target capacity of 4,000 tonnes per year (Deng, Zhuo, and Shen, 2022).

Advanced physical methods, such as high-voltage fragmentation, demonstrate superior crushing selectivity and material purity compared with conventional mechanical approaches (Song et al., 2023; Sim et al., 2025), but they face significant scalability barriers. These systems require specialised equipment exceeding 100 kV with complex parameters for pulse frequency and rising time, making large-scale manufacturing difficult. Although promising for selective material separation, these advanced techniques remain limited to small-scale demonstrations and require the development of high-cost, customised equipment for commercial viability.

The economics of PV recycling require substantial throughput for viability. The European Full Recovery End-of-Life Photovoltaic project, an automated multistep recovery process that achieves more than 95-per-cent material recovery, requires approximately 7,000 tonnes per year for profitability (Dias et al., 2021; Dias et al., 2022). The advanced PhotoLife process, which includes polymer separation and silver-silicon recycling, needs 30,000 tonnes per year for economic feasibility (Rubino et al., 2020). However, the primary obstacle remains translating laboratory processes to pilot scale (Tan, Jia, and Ramakrishna, 2022; Trivedi, Meshram, and Gupta, 2023; Preet and Smith, 2024). The existing processing costs of $600 to $1,000 per tonne must decrease to $400 to $500 per tonne to achieve economic viability (Deng et al., 2019). Reductions in valuable materials used in newer modules might pose additional economic challenges for these targeted recycling processes (Deng, Zhuo, and Shen, 2022; Dias et al., 2022).

Automation serves as the critical enabler for transforming PV recycling from a cost centre to a profitable operation. Without automation, high labour and compliance costs render local recycling uncompetitive, even after accounting for transport costs from Europe or Asia. The convergence of labour-cost reductions, safety improvements and throughput scaling creates compelling economic drivers for automation adoption, which promises to narrow the cost differential. Success will depend on integrating multiple automated technologies while leveraging existing industrial infrastructure to minimise both deployment risks and CAPEX.

Australia's competitiveness in PV recycling will depend on how effectively automation is leveraged to overcome structural disadvantages in labour costs and scale. Industrial expertise, renewable-energy inte-



gration and a strong culture of safety all position Australia well to adopt advanced electrochemical and mechanical technologies to automate PV module recycling. The Australian market is also supported by low industrial electricity prices and proximity to raw materials, which could help drive down costs once a sufficient level of investment support is reached. However, achieving cost parity in the global market would require coordinated policy support to reduce capital risk, stimulate domestic equipment supply chains and ensure that throughput growth aligns with the scaling potential of automated systems.

Conclusion

Profitable PV recycling emerges only when regulation, scale and market coordination converge. In the EU, these conditions are created through harmonised EPR mandates, ecodesign incentives and collective producer schemes under the WEEE Directive. Europe's success lies not in the inherent commercial viability of PV recycling but in the predictable policy environment that enables investment and economies of scale.

By contrast, Australia's smaller market, geographic dispersion and reliance on imports present structural challenges to achieving similar scale efficiencies. However, there are also opportunities for Australia to design a leaner, innovation-driven model leveraging automation, advanced material recovery and regional collection networks to offset scale limitations. To realise this potential, Australia should adopt a nationally harmonised product stewardship scheme building on learnings from the EU, including the integration of recyclability metrics, such as the EU PV Recyclability Index, and providing transitional financial support to derisk early investments. This would enable Australia to transform its growing PV waste stream into a profitable, competitive and sovereign circular economy.



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CHAPTER 11

Implementation Roadmap: Pathways to a Circular Solar Economy

Benjamin L. Preston and Darren Johannesen

> A national approach to recycling solar panels is currently being developed, with the involvement of federal and state governments, industry and business so that capacity can better meet demand.
>
> **Australian Clean Energy Council**

Although Australia was an early adopter of PV technology, a global PV market now exists. The challenge of managing large volumes of EoL PV panels is an international one, yet one in which Australia can leverage its position to be a global leader. International collaboration can enhance Australia's access to solutions, emerging innovations and governance models that can reduce waste, recover valuable materials and build resilience into the PV supply chain (Draper, 2021; Kandpal et al., 2024). As demonstrated by the preceding chapters in this report, Australia is well positioned to take a global leadership role in developing a PV circular economy.

Nevertheless, additional work will be required before a functioning, economically efficient circular economy can be implemented. This work spans logistical infrastructure development, regulatory reform, technological innovation and the maturation of manufacturing and product standards. Australia faces multiple structural challenges, and the work will need to address logistical and cultural barriers that have, to date, prevented Australia capitalising on its high PV adoption rates to become a global leader. Building and scaling a circular economy will necessitate the proper sequencing of a broad variety of activities. Therefore, it is best to envision the development of a PV circular economy as a transition process that will unfold over several years.

In this chapter, we illustrate how that sequencing could be implemented between 2026 and mid-century through a circular economy implementation roadmap—a plan for what actions need to be undertaken, when and by whom. The roadmap centres on six types of activities (Table 11.1), which together form the foundation for a coordinated national strategy. Each activity will be led by specific actors with the appropriate authority, expertise and resources.

Building a circular economy would likely necessitate action from all levels of government, the private sector and individual Australian households. This collective effort must be designed to complement other major national priorities—such as climate adaptation, disaster resilience and the preservation of sovereignty—so that it strengthens rather than competes with them.

TABLE 11.1

A Typology of Activities and Actors That Are Essential for the Future Implementation of a Solar Photovoltaic Circular Economy in Australia

Activity	Definition	Examples	Actors
R&D	Activities aimed at generating new knowledge and developing innovative products, services and processes	• Materials separation and purification processes • TEAs of circular economy processes • Policy analysis for regulatory interventions	• University-based researchers • CSIRO • Solar PV industry researchers • Research funders
Policy and regulatory reform	Evaluating, updating and improving policies and regulations to achieve a PV circular economy	• Updates of waste regulations • Product stewardship schemes • EPR regulations • Liability indemnification for panel reuse • Financial incentives for early stage recycling facilities	• Commonwealth departments • State agencies • Courts • Solar PV industry
Market scaling	Efforts to expand the size of the circular economy by increasing the volume of EoL waste managed and growing the market for reused assets and recycled materials	• Enhanced recycling capacity and efficiency • Market development and certification for recovered materials • Development of domestic PV module manufacturing	• Solar PV industry • Waste management firms • Banks and investors
Logistics	Facilitating the efficient movement of products and materials to enable their recycling back into the production cycle	• Establishment of EoL panel collection and storage facilities • Development of transportation networks for EoL panels and recycled materials	• Solar PV industry • Waste management firms • Logistics and transport firms
Applications	Developing downstream applications for the materials recovered from the PV recycling process	• Development of new potential applications for recovered materials • Design of materials processing standards that support emerging applications • Enhancement of domestic manufacturing capabilities for PVs that leverage remanufacturing processes	• PV industry • Manufacturers • Material processors
Engagement	Engaging with individuals, groups or organisations that influence or are affected by the evolution of the PV circular economy	• Establishment of trade associations for PV reuse and recycling • Launch of public awareness campaigns on the appropriate disposal of panels • Communication between industry and policymakers on industry needs	• All stakeholders



Planning Horizons for Implementing a Solar Photovoltaic Circular Economy

To advance a PV circular economy, the various activities identified in Table 11.1 need to be integrated and implemented over time. Although some of the building blocks for a circular economy are already in place—recycling infrastructure, a growing regulatory regime and technical knowledge—many elements need to be scaled up, costs need to come down, and infrastructure and logistics need to be developed. Hence, in planning the future, stakeholders should consider a 25-year horizon. This is consistent with Australia's Net Zero Plan to decarbonise the economy by 2050 (Riedy et al., 2022; Lempert et al., 2019; DCCEEW, 2025c). However, careful planning is needed to prioritise actions over the next 25 years.

One mechanism for structuring that planning is the Three Horizons framework (see, e.g., Curry and Hodgson, 2008; Lempert et al., 2019; Riedy et al., 2022). The horizons represent different periods of decisionmaking and social, economic and technological advancement. The first horizon (Horizon I) corresponds with the short-term future, grounded in the existing state of conditions based on present-day values and trends. We anticipate this phase persisting until 2030 as planning, policy and innovation ramp up. The second horizon (Horizon II) represents a medium-term transition phase, describing the key actions needed to shift from the existing state to a desired future state. This phase is associated with the scaling up of a PV circular economy, inclusive of human capital, investment, infrastructure and logistics. Accordingly, we anticipate this phase persisting for a decade (from 2030 to 2040). The third horizon (Horizon III) represents the long-term, sustainable future beyond 2040. Over this time horizon, there is significant uncertainty about how the PV circular economy will evolve and what surprises, shocks and stressors the industry might face. Nevertheless, thinking in the long term can be beneficial for setting short-term priorities. In this chapter, we use this Three Horizons framework and these time horizons to organise the actions and associated time needed to facilitate the development of a robust, PV circular economy by mid-century.

Research and Development

Given the remaining technical challenges associated with developing an industrial-scale PV circular economy and the need to scale up reuse, recycling and recovery efforts to improve its economic feasibility, ongoing R&D will be needed (Michas et al., 2019; Heath et al., 2020; Curtis, Buchanan, Smith, et al., 2021; Mirletz et al., 2022; Firoozi, Firoozi, and Maghami, 2025; Xia, Yang, and Poon, 2025). Over the short term, R&D should be oriented towards

- addressing high-priority technical hurdles for which solutions are needed to scale up recycling and recovery efforts
- undertaking engineering and workflow studies to increase the efficiency of reuse and recycling infrastructure
- evaluating the potential costs, benefits and trade-offs of circular economy development and maturation.

As the circular economy begins to expand, R&D efforts can shift to improving its efficiency by continuing to improve cost-effectiveness and the integration of PVs and other technology supply chains, such as critical minerals and battery storage. In addition, as the flow of EoL panels grows, R&D efforts can focus on developing a robust second life for those panels through recovery, refurbishment and remanufacturing. Over the long term, R&D efforts can shift towards enabling greater supply-chain situational awareness across the PV industry and keeping up with inevitable changes in the design and material composition of PV panels. For example, reducing the critical-mineral intensity of PV panels also reduces the financial incentives for material recovery. As a consequence, ongoing innovation will be needed in panel design to reduce barriers to reuse and recycling.

Table 11.2 summarises R&D priorities over the three time horizons.

Policy and Regulatory Reform

Public policy and the regulatory regime regarding the fate of EoL PV panels will play a critical role in enabling the development of a healthy circular economy. The long-standing paradigm of take-use-dispose patterns of consumption is indicative of a market failure; once a PV panel reaches its EoL, there

TABLE 11.2
Solar Photovoltaic Research and Development Priorities over Three Time Horizons

Horizon I: Build Foundations (2025–2030)	Horizon II: Scale Rapidly (2031–2040)	Horizon III: Sustain and Lead (2041–2045)
• Automating diagnostic tools for panel function assessments • Streamlining and automating processes for panel disassembly • Improving the encapsulate and back-film removal process • Enhancing the solar-cell metal recovery and purification process • Evaluating potential avoided emissions of the circular economy	• Designing optimisation for efficient recycling and reduced material intensity • Identifying reliable applications for recovered materials • Investigating opportunities for coprocessing facilities and processes for PVs and other clean-energy technologies • Developing processes for the refurbishment and remanufacturing of EoL panels • Developing environmental, social and governance criteria relevant to tracking private-sector PV circular economy initiatives	• Developing supply-chain intelligence systems for circular economy tracking • Supporting ongoing process improvements in material processing and recovery as technologies evolve

are no viable pathways for monetising the embodied energy and materials or assigning a value to their environmental impacts when disposed. As a result, it can be cheaper to remove a panel from use and dispose of it than extend its life or recover the materials for subsequent applications. Policy can be used to correct this failure, internalising the full life cycle and embodied value of PVs to incentivise reuse and recycling (Equilibrium, 2019; Majewski et al., 2021; Majewski and Dias, 2023; Nunes et al., 2023; Chhillar et al., 2024; Xia, Yang, and Poon, 2025; Nyffenegger et al., 2026).

Over the next five years, for example, policy initiatives should focus on developing the foundations for an eventual PV circular economy. This includes identifying existing policies that could inhibit the development of such an economy, including the absence of a mandate for recycling and reuse and inconsistencies across Australian states and territories regarding the EoL management of PVs. Policymakers can also assist in designing market incentives that encourage the development of needed infrastructure that supports a PV circular economy—specifically facilities with the capacity to disassemble and recycle PV panels. Australia can also monitor policy innovation in other regions and nations to align its own policy and regulatory landscape with that of other PV producers and trading partners.

Over the medium term, Australia's policy landscape would benefit from establishing clear lines of responsibility to different actors concerning their role in developing a circular PV economy. For example, the use of EPR regulations can incentivise manufacturers to take back EoL panels and send them onward into the circular economy. Public policy can also play an important role in advancing workforce development programs that assess skill shortages in the industry and identify pathways for filling those gaps through training and education.

Meanwhile, indemnifying manufacturers for liabilities associated with the reuse of EoL panels can help overcome a barrier to the successful development of firms specialising in second-life assets. The implementation of common standards across Australia and in cooperation with trading partners and overseas manufacturers can assist in reducing the cost of recycling and material recovery from EoL panels.

Table 11.3 summarises policy and regulatory reform priorities over the three time horizons.

TABLE 11.3

Solar Photovoltaic Policy and Regulatory Reform Priorities over Three Time Horizons

Horizon I: Build Foundations (2025–2030)	Horizon II: Scale Rapidly (2031–2040)	Horizon III: Sustain and Lead (2041–2045)
• Identifying policy barriers to the circular economy • Reforming waste management regulations to divert PV panels from landfills • Designing policy incentives (such as national product stewardship schemes) to accelerate the development of the circular economy infrastructure • Aligning Australia's circular economy policies, regulations and standards with those of trade partners	• Implementing policy incentives for the reuse, recycling and remanufacture of EoL PV panels at the state and national level • Collecting waste levies associated with EoL PV modules to deter landfill disposal • Developing design and manufacturing standards to ease EoL recycling • Implementing EPR regulations for EoL PVs • Developing liability indemnification standards for PV reuse and remanufacture • Developing environmental, social and governance criteria relevant to tracking private-sector PV circular economy initiatives • Education of consumers to prioritise procurement of PV modules that meet circularity criteria (e.g. recycled content, recyclability, take-back commitments), creating demand for circular products	• Easing financial incentives as the market for a circular economy matures • Evaluating policy effectiveness to enable the ongoing reform and optimisation of the policy regime

Market Scaling

As the volume of EoL PV panels grows exponentially over time, there will be a need for markets and business models for supply-chain components that can keep pace with that growth (Tsanakas et al., 2020; Franco and Groesser, 2021; Madden, Florin, and Salim, 2023; Salim et al., 2023; Mirletz et al., 2024; Nyffenegger et al., 2025; Nyffenegger et al., 2026). Although policy reforms can create enabling conditions, there will need to be an efficient, scalable and adaptable marketplace led by the private sector that links the supply of EoL panels and associated materials to demand for their uptake and use in downstream applications.

By 2030, Australia's solar industry can facilitate this market development by reducing barriers to the reuse and recycling of EoL PV panels. First and foremost, industry can take a leadership role in raising consumer and commercial awareness of the benefits of developing a circular economy and presenting ideas for how to engage with that economy. Community acceptance of circular economy principles and, more importantly, the facilities and infrastructure that underpin that economy will be critical (Chen et al., 2025; Derin Güre et al., 2025). In addition, industry can support the development of a digital marketplace to facilitate trade in used assets by linking those in the market for discounted used panels to suppliers. This marketplace can be complemented by enhancing the use of leasing business models that can—in conjunction with product stewardship schemes and EPR standards—support the centralised collection of EoL panels.

There is also a short-term need to start building the support industries and workflows needed for a circular economy (such as panel testing, certification and insurance), recognising that business enterprises will need time to mature and reach economies of scale. The decade between 2031 and 2040 should focus on the rapid expansion of the circular economy marketplace. This could include the widespread deployment of facilities and infrastructure that test and evaluate panels for reuse and recertification, the high-throughput disassembly of EoL PV panels, the integration of EoL PV supply chains with other waste streams (e.g. battery waste) and the development of sustainable enterprises to refurbish and remanufacture EoL panels. Beyond 2040, Australia would benefit from a competitive and efficient marketplace for panel reuse or for panel recycling and material recovery (or for both).

Table 11.4 summarises market-scaling priorities over the three time horizons.

TABLE 11.4
Solar Photovoltaic Policy Market-Scaling Priorities over Three Time Horizons

Horizon I: Build Foundations (2025–2030)	Horizon II: Scale Rapidly (2031–2040)	Horizon III: Sustain and Lead (2041–2045)
• Creating digital marketplaces that specialise in the trading of used or refurbished PV modules • Enhancing the use of leasing or pay-per-use business models that keep PV panel ownership and responsibility with producers that have the capacity to manage recycling and reuse • Identifying applications for PV recycled materials that can accommodate large material volumes • Launching consumer awareness campaigns to maximise the flow of EoL PV panels through the circular economy	• Developing insurance products that address liabilities associated with new panels and, in particular, panel reuse • Implementing warranty programs for second-life panels to reduce risk for consumers	• Establishing retail enterprises based on the reuse of EoL panels that cater to both individual households and commercial businesses

Logistics

A functioning circular economy supply chain for PVs will necessitate significant logistical infrastructure and processes, which will have to be developed and managed efficiently to ensure financial viability (Islam et al., 2020; Molano et al., 2022; Jayarathna, Agdas, and Dawes, 2023; Iakovou et al., 2024; Zhou and Li, 2025). The removal, sorting, reuse and recycling of EoL panels will necessitate transportation, storage capacity and a variety of facilities dedicated to serving different parts of the supply chain (e.g. testing, refurbishment, disassembly). Australia's existing industrial capacity (e.g. waste management and recycling facilities, industrial processing, road freight, high-tech manufacturing) provides a solid foundation for supporting these logistical needs.

Nevertheless, the volume of projected EoL PV waste indicates that this foundation will need to expand markedly. A short-term priority is building an understanding of the geographic distribution of potential PV waste streams to prioritise investments in circular economy logistics. For example, much of Australia's existing solar capacity lies in the continent's southeast, which is also likely to be a hotspot for future PV development. As a result, the southeast will also be a hotspot for EoL PV waste. Building capacity in this region for collection, storage, reuse and recycling can minimise the need to transport waste over long distances to other facilities or regional markets. This regional capacity can be aided by the development of public-private partnerships that can efficiently move EoL PV waste along the circular economy value chain.

As the volume of PV waste expands after 2030, investments can be made in specialty enterprises that focus on testing, refurbishing and certifying used PV panels and enhancing the capacity of recycling facilities to process growing PV waste flows. Over the long term, Australia's PV economy can concentrate on advancing efficient supply-chain solutions that enable the rapid processing and material extraction of high volumes of PV waste while also developing a national network of PV repair, refurbishment and remanufacturing providers that is commensurate with the scale of PV deployment.

Table 11.5 summarises logistics priorities over the three time horizons.

TABLE 11.5
Solar Photovoltaic Policy Logistic Priorities over Three Time Horizons

Horizon I: Build Foundations (2025–2030)	Horizon II: Scale Rapidly (2031–2040)	Horizon III: Sustain and Lead (2041–2045)
• Mapping supply chains based on projected deployment and identifying resource hubs that can be used to site future collection and recycling facilities • Establishing community and industry public-private partnerships to designate drop-off locations for collection • Developing transportation protocols and guidance for the safe storage and bulk movement of EoL panels • Creating a digital ID system to monitor the movement of a panel throughout its life cycle • Establishing municipal programs and facilities to temporarily hold used and EoL PV modules before resale, testing or recycling	• Expanding distribution networks for the movement of products and materials from recycling facilities to downstream retailers • Investigating opportunities for coprocessing facilities and processes for PVs and other clean-energy technologies • Developing processes for the refurbishment and remanufacturing of EoL panels • Developing facilities to assess and certify (or recertify) the performance, safety and longevity of used panels • Expanding the domestic capacity for manufacturing new PV modules using recovered materials • Implementing low-carbon transportation schemes for new, used and EoL PV modules and recovered materials	• Establishing advanced recycling plants capable of high-throughput, high-yield recovery of materials, such as silicon, silver, copper and glass • Establishing repair and remanufacturing workshops capable of replacing components, updating inverters or resealing damaged panels

Applications

Developing a thriving domestic market for the reuse and/or refurbishment of PV panels can help extend their life. Nevertheless, all panels will eventually be retired. As a result, building a sustainable circular economy for PVs will be contingent on developing cost-effective downstream applications for the materials recovered from the PV recycling process (Chowdhury et al., 2020; Sandanayake et al., 2022; Akhter et al., 2024; Bulińska, Sujak, and Pyzalski, 2025). Glass and aluminium, for example, which make up the bulk of a PV panel by weight, have numerous applications in construction materials, packaging and other consumer products. In principle, they can be remanufactured into new PV panels and other finished goods, provided those manufacturing capabilities exist within Australia. Similarly, while copper, silver and silicon are present in PV panels in much lower amounts, their recovery and purification can allow those materials to be used in a variety of electronics manufacturing processes.

Over the short term, efforts should focus on improving an understanding of the application opportunities for the reuse, remanufacture and recovery of PV panels and embodied materials. These efforts can include enhancing opportunities for scaling up secondary markets for used and EoL PV panels, enhancing existing industrial and commercial applications for recovered materials and exploring new applications that have yet to be fully integrated into supply chains.

By 2040, the PV industry can make significant gains in developing standardised processes and supply chains for the trade-in and reuse of recovered materials in diverse applications. These processes include optimising material recovery and purification for specific applications, developing robust remanufacturing capacity to efficiently use recovered materials and exploring overseas markets for PV reuse and material delivery. Once mature, Australia's PV circular economy can focus on continuous improvement to reach 100-per-cent circularity and maintain adaptability to the inevitable changes that will occur in PV technologies.

Table 11.6 summarises application development priorities over the three time horizons.

TABLE 11.6
Solar Photovoltaic Application Development Priorities over Three Time Horizons

Horizon I: Build Foundations (2025–2030)	Horizon II: Scale Rapidly (2031–2040)	Horizon III: Sustain and Lead (2041–2045)
• Mapping PV components and materials to downstream applications • Developing sustainable, cost-effective and scalable secondary markets for used PV panels • Developing new potential applications for recovered materials that can be integrated into the evolving supply chain • Developing standardised protocols for material characterisation, testing and certification	• Developing procurement contracts and systems to facilitate the trade-in of recovered materials • Designing materials processing and purification standards to optimise their use for specific downstream applications • Enhancing domestic manufacturing capabilities for PVs that can engage in remanufacturing processes with recovered materials, such as new PV panels, batteries or building products • Exploring opportunities for the export of secondary market panels and/or recovered materials to diversify supply chains	• Increasing circular economy efficiency by pushing the industry towards 100-per-cent circularity through continuous process improvement • Adapting circular economy supply chains to accommodate changes in PV technology, panel design and panel composition



Engagement

A robust circular economy of PVs will necessitate actions by a broad variety of stakeholders, including researchers, government regulators, manufacturers, installers, recyclers, and individual households and businesses that are increasingly seeking cost-effective mechanisms for deploying PVs. Coordination and knowledge-sharing among these different actors will be needed to overcome social, economic, technical and policy barriers and enable the efficient scaling of the circular economy (Rosenzweig et al., 2017; Soliman and Taylor, 2022; Pillan, Costa, and Caiola, 2023; Chen et al., 2025; Derin Güre et al., 2025).

An important priority over the next few years will be building awareness among consumers, producers and regulators regarding the PV circular economy, the opportunity for its development and the role of different actors in making it a reality. This priority involves efforts from the bottom up to build relationships among councils, households and community-based organisations. In addition, efforts need to begin now to work with insurers to address financial and policy challenges, such as the insurance and liability aspects of reuse. Similarly, Australia's R&D enterprise can collaborate with research institutions internationally to share knowledge on addressing the technical aspects of PV design, recycling, logistics and applications.

Over the medium term, engagement is needed on multiple fronts to help build a viable market for a circular economy. This includes an active role by federal and state regulators and standards bodies that are critical for ensuring a stable policy foundation and consistency across the industry. Relatedly, Australia can engage with other nations to develop common standards for PV design to integrate circular economy principles into global supply chains. Domestically, recyclers and material recovery firms can collaborate with the construction industry, electronics manufacturers and other sectors in the development of applications for recycled materials.

Finally, given the potential scale of an Australian circular economy industry around PVs, outreach to institutions, such as universities and technical and further education (TAFE) programs, will also be needed to develop the workforce needed to drive the industry forward. As the circular economy matures, engagement efforts can transition to the ongoing monitoring and evaluation of the marketplace with the goal of continuous process improvement and international outreach to help build capacity for circular economy approaches overseas and to maintain consistency in technologies and methods.

Table 11.7 summarises engagement priorities over the three time horizons.

Cross-Cutting Issues

Capacity Building Across Government, Industry and Consumers

Developing a circular economy for PVs in Australia will depend on enhancing the capacity of government, industry and communities to plan, regulate, invest in and manage EoL PV waste. As an emerging industry, this transformation requires coordination across federal, state and local governments.

Institutionally, capacity building involves strengthening the ability of regulators, local governments and businesses to plan, implement and monitor circular economy initiatives. This includes developing frameworks for EPR, certifying recycled materials and enforcing quality standards for reused components. At the industrial level, Australia lacks the facilities, supply chains and processing capacity needed to manage the projected volumes of EoL PVs. The private sector will need support to scale up recycling and remanufacturing infrastructure, improve process efficiency and attract investment. The Australian government's $1 billion Sunshot initiative offers a major opportunity to integrate circular economy

TABLE 11.7
Solar Photovoltaic Stakeholder-Engagement Priorities over Three Time Horizons

Horizon I: Build Foundations (2025–2030)	Horizon II: Scale Rapidly (2031–2040)	Horizon III: Sustain and Lead (2041–2045)
• Educating homeowners and Australian businesses about the benefits of a circular economy and the options available for secondary markets, the appropriate disposal of EoL PV panels, or both • Eliciting participation from community-based organisations and local councils to build awareness of circular economy benefits and the changing policy and industrial landscape • Engaging insurance providers to address liability issues related to PV reuse, recycling, logistics and applications to reduce potential barriers to a circular economy • Building international R&D consortia to rapidly advance knowledge on materials recovery, separation and purification methods	• Coordinating with regulators (such as the Clean Energy Regulator, the Australian Energy Market Operator and state waste-management and environmental protection agencies) to develop low-impact material recovery processes • Working with PV retailers, installers, remanufacturers and digital technology firms to develop and test approaches for enhancing supply situational awareness, including the tracking and collection of EoL panels • Developing the circular economy workforce by integrating PV technology and circular economy principles and processes into university and TAFE programs • Engaging international PV manufacturers and importers to inform future design specifications to enable more-efficient disassembly and recycling • Engaging domestic recyclers and materials processors to scale up recovery capabilities and invest in advanced processing technologies • Encouraging standards bodies (e.g. Standards Australia) to develop product specifications for PV panels and recycling and remanufacturing processes	• Convening industry stakeholders to facilitate ongoing evaluations of the circular economy, inclusive of macroeconomic benefits, material volumes and costs, market evaluation costs, and environmental impacts • Expanding knowledge and technology transfers to other nations with significant solar capacity to develop a global PV circular economy • Pursuing partnerships to integrate domestic and international PV circular economy supply chains to achieve economies of scale and accelerate technology and infrastructure deployments



principles into the design and operation of new facilities (Australian Renewable Energy Agency, 2025). Embedding recycling, refurbishment and material recovery capabilities in this investment would ensure a sustainable domestic solar industry.

Workforce development across the value chain is central to this effort and should be treated as a national and state priority. Building a skilled workforce for PV circularity will require collaboration among vocational-education-and-training providers, universities, industry and state and federal governments. Training programs can equip workers with collection, diagnostics and advanced recycling and remanufacturing capabilities.

Finally, capacity building that supports innovation, knowledge-sharing and entrepreneurship at the local-to-regional scale (such as at centres of excellence) could help pilot CBMs, such as panel refurbishment, material recovery and service-based energy solutions. Such initiatives will support domestic PV manufacturing and recycling efforts.

International Partnerships

As indicated in the previous discussion and Tables 11.2 through 11.7, developing or enhancing international partnerships is a key step for advancing each component of Australia's PV circular economy. Australia can leverage its position to be a global leader in the international solar economy. One of the most immediate avenues for international cooperation is through technology R&D. Such countries as Germany, Japan and South Korea are advancing state-of-the-art PV recycling and materials recovery technologies (Komoto et al., 2018; Padhamnath et al., 2025). By collaborating with these innovation leaders, Australia can advance the recovery of critical minerals (such as silver) from used PV modules and improve design standards to enhance recyclability. International cooperation can also inform policy

and regulatory reforms (see Table 11.3). For example, the EU's experience with EPR standards can help develop comparable standards that work within the Australian context.

Australia can engage in bilateral and multilateral forums to align its product stewardship schemes with global best practices and ensure consistency with its domestic policies (Salim et al., 2021; Majewski and Dias, 2023; Chhillar et al., 2024). On the trade, supply-chain and logistics front, Australia's role as a major exporter of critical minerals positions it to influence circular material flows with international manufacturers (Sinclair and Coe, 2024). Finally, international engagement can support capacity building and finance. Multilateral institutions, such as IRENA and the United Nations Environment Programme, are working with governments to scale circular economy processes and infrastructure and develop circularity metrics (Xijie, Rim, and An, 2023; Ravikumar et al., 2024). Australia can contribute to and benefit from these platforms, especially in the Indo-Pacific region (Emami et al., 2025), by sharing data, codeveloping standards and investing in CBMs that extend PV system life and minimise environmental impacts from EoL assets.

Conclusion

There is a long road to establishing a circular economy for PVs in Australia, and it requires deliberate public action to catalyse private investment and regional innovation while also striking a balance with government support for other priorities. The scenario modelling for Queensland and Victoria in Chapter 9 suggests that, despite differing industrial, economic and geographic contexts, both states converge on a single viable model: a decentralised network of regional facilities that brings collection, testing, refurbishing and recycling close to the source of solar deployment. This model is adaptable to local conditions, drawing on Victoria's urban density and Queensland's existing distributed waste management.

Achieving this outcome will depend on (1) targeted public investment to derisk early infrastructure and logistics development, (2) harmonised regulatory frameworks across states to ensure that regional facilities can be set up across Australia and (3) support for workforce and technology capacity building. Beyond enabling investments, it will take time for Australia's market to mature with sufficient competition, innovation and scale. Without a structured and strategic public commitment, the transition to a circular solar economy will remain difficult. With the sustained implementation of the roadmap outlined in this chapter, Australia can become a global leader in building a solar industry that not only supports the clean-energy transition but also a circular economy that fosters material, workforce and regional development opportunities.

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APPENDIX A

Modelling Assumptions Used for the Techno-Economic Assessments

This appendix documents the key assumptions underpinning the TEA presented in Chapter 9 and identifies the structural limitations that readers should consider when interpreting the results.

Modelling Assumptions and Limitations

The TEA presented in Chapter 9 is built on a clearly defined set of technical, financial and operational assumptions that are intended to ensure comparability across states and consistency across the three infrastructure scenarios. These assumptions are grounded in industry practice, published literature and stakeholder feedback; however, several structural limitations must be acknowledged to contextualise the results appropriately.

Assumed Waste Inflow to Formal Testing and Screening

The modelling assumes that the entire EoL PV waste stream projected for each year enters a formal screening-and-testing pathway before being allocated to reuse or recycling. This assumption enables a comprehensive evaluation of systemwide infrastructure needs, including capital scaling, logistics demand and processing capacity across the three scenarios.

In practice, the market functions very differently. Industry consultations indicate that **only about 10 per cent of discarded panels enter structured testing or screening**, and the remainder are handled through unregistered disposal channels, informal reuse markets, scrap metal recovery or direct landfill (Deng et al., 2024). This disparity between analytical inflow and real-world throughput is one of the most significant limitations of sector modelling and underscores the need for stronger stewardship mechanisms and improved data capture before long-term investments are finalised.

Uniform Recovery Efficiency Across States and Scenarios

The TEA applies a fixed material recovery rate of 96 per cent of incoming mass, reflecting an upper-bound performance based on c-Si processing technologies (Theocharis et al., 2022). Although this assumption aids comparability, it does not capture operational variability among facility types, differences in feedstock contamination or technology-specific constraints, particularly in mobile or decentralised systems. The reference recycling model reported by Mahmoudi et al. (2020) assumes a recovered-material purity of 99 per cent. The present analysis does not vary material purity independently across states or scenarios and therefore assumes a consistent recovered-material quality when applying material selling prices.

Consistent Financial Parameters Across Jurisdictions

Discount rates, depreciation schedules, labour structures and working capital ratios are held constant across all states and scenarios. Although this ensures a harmonised analytical framework, it naturally masks some location-specific differences, including financing conditions, labour market constraints and regulatory compliance burdens.

Simplified Screening, Transport and Collection Behaviour

Screening costs are applied per panel and differ only by scenario configuration rather than local market conditions. Transport distances and collection radii are generalised to reflect typical geographic patterns but do not model detailed routing, congestion or seasonal variability. Queensland's sprawling settlement patterns and Victoria's dense metropolitan structure mean that real-world logistics will differ more significantly than the simplified model suggests.

Economic Inputs Based on Existing Prices and Composite Disposal Charges

Raw material prices, electricity tariffs and composite waste disposal costs are treated as static within each phase of financial analysis. Although appropriate for a high-level TEA, this approach does not capture future volatility, including evolving landfill levies, potential carbon pricing mechanisms or commodity price cycles for aluminium, copper, glass and silver.

Implications of These Limitations

These modelling assumptions ensure methodological consistency but inevitably narrow the representation of real-world behaviours (Tables A.1 and A.2). The most consequential limitation remains the assumption of a full waste inflow to formal screening, which overstates short-term processing demand and inflates CAPEX in early years. This reinforces the need for a more granular, behaviour-linked TEA incorporating variable participation rates, compliance trajectories under stewardship schemes and alternative pathways for reuse and informal disposal.

TABLE A.1
Baseline Techno-Economic Assessment Assumptions for a 2,500-Tonne-per-Year Recycling Facility

Parameter	Baseline Value	Explanation
Nominal facility capacity	2,500 tonnes per year	Reference facility used for all scaling
Operating days	350 days per year	Allows for maintenance and public holidays
Nominal throughput per day	7.1 tonnes per day	2,500 tonnes divided by 350 days
Base CAPEX	$7.53 million	Includes main process units, buildings, utilities and installation
Working capital	$1.13 million	Set as 15 per cent of base CAPEX (0.15 × 7.53 million)
Financial discount rate	8 per cent	Used in all NPV calculations for scenarios
Project life	30 years	2025 to 2055 horizon
Corporate tax rate	30 per cent	Australian company tax rate
Depreciation method	Straight line	Applied over the economic life of major assets
Gate fee and stewardship income	State specific, expressed per tonne	Calibrated to match the baseline NPV for each state
Labour requirement	About 5 to 6 full-time equivalents	Facility manager, two operators, maintenance technician, forklift operator and administrative support
Base labour cost	About $0.35 million per year	Varies slightly between states but same structure
Waste disposal streams	Contaminated glass, fly ash, liquid waste, sludge	Quantities and unit costs differ by state
Typical waste disposal cost	Queensland: about $0.43 million per year Victoria: about $0.51 million per year	Reflects higher levy and treatment cost in Victoria
Transport assumption	100,000 panels per year by road in 20-to-24-tonne loads	Gives approximately $150,000 per year for Queensland and $400,000 per year for Victoria baseline plants
Annual regulatory and compliance cost	About 1 per cent of CAPEX per year	Covers licence renewals, monitoring and reporting
R&D allowance	5 per cent of CAPEX	Represents optimisation and process improvement spend; a one-time cost

TABLE A.2

Scenario Scaling Assumptions for Queensland and Victoria

Parameter	Assumption or Basis	Queensland	Victoria
Baseline reference facility	2,500 tonnes per year recycling facility	Same	Same
Scenario scaling method	Six-tenths rule for CAPEX scaling. Formula: $CAPEX_2 = CAPEX_1 \times (Capacity_2 / Capacity_1)^{0.6}$	Same	Same
Working capital	Set as 15 per cent of CAPEX for all facility sizes	Same	Same
Scenario A facility size	One large central facility Queensland: 10,000 → 15,000 → 25,000 tonnes per year; Victoria: 5,000 → 10,000 → 15,000 tonnes per year	Same	Same
Scenarios B and C facility size	2,500 → 5,000 → 7,500 tonnes per year total installed recycling capacity	Same	Same
Screening rate assumption	Applied per panel; screening cost depends on scenario, not state Baseline fraction: 55-per-cent reuse and 45-per-cent recycle	Scenario A: low cost per panel because of hub model Scenario B: medium cost per panel Scenario C: highest cost per panel because of mobile operations	Same logic
Reuse and recycle fractions	Reuse: 55 per cent of tested panels Recycle: 45 per cent	Same	Reuse: 50 per cent Recycle: 50 per cent
Operational days	350 operating days for all cases	Same	Same
Transport intensity logic	Determined by facility configuration: centralised is the lowest per tonne; decentralised has more regional movements; and mobile has intermittent movement	Longer distances because of Queensland's geography	Higher density and shorter hauls in Victoria
Collection model	Panels transported to either central hub (Scenario A), regional depots (Scenario B) or mobile testing points (Scenario C)	Sparse network produces higher distance per tonne	Dense network reduces distance per tonne but results in higher congestion delays
Regulatory framework	Annual environmental compliance, reporting and safety obligations treated as recurrent; one-off setup as percentage of CAPEX	Same structure but state specific requirements (Queensland Department of Environment, Tourism, Science and Innovation)	Same structure but more-frequent inspections (Environment Protection Authority Victoria)
R&D allocation rule	5 per cent of CAPEX	Same	Same
Discount rate	8 per cent for TEA scenario modelling	Same	Same
Material recovery logic	Mass balance recovery fixed at 96 per cent of incoming mass; recovery composition based on c-Si modules	Same	Same
Electricity and utility scaling	Proportional to throughput; linear scaling with minor efficiency gains at higher capacities	Slightly lower electricity cost per kWh than Victoria	Higher grid tariffs than Queensland
Labour scaling logic	Staffing increases stepwise: centralised facility uses economies of scale; decentralised facility uses replicated staffing across regional sites	Larger distances between depots increase staffing for logistics	Higher industrial labour rates than Queensland
Waste disposal logic	Disposal quantities scale directly with throughput; unit-handling rates are state-specific based on levy and treatment class	Lower waste levy than Victoria	Higher waste levy and treatment charges

Appendix A References

Deng, Rong, Verity Tan, Chence Niu, and Renate Egan, *Scoping Study: Solar Panel End-of-Life Management in Australia*, Australian Centre for Advanced Photovoltaics, March 2024.

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APPENDIX B

Methodology Used for the Techno-Economic Assessment

This appendix details the quantitative methods used to estimate costs and financial performance in the TEA. The TEA is based on standard chemical engineering cost-estimation practices combined with discounted cash-flow analysis. Three linked elements are used in all states and scenarios: a CAPEX estimation, an OPEX estimation and an annual cash-flow calculation.

Capital Expenditure Estimation

Capital costs are estimated using a two-step approach. First, the capital cost of a reference recycling facility reported in the literature (Mahmoudi, Huda, and Behnia, 2020) is escalated to the target analysis year using the Chemical Engineering Plant Cost Index (CEPCI). Second, the escalated capital cost is adjusted to the required facility capacity using the six-tenths scaling rule.

When normalising for the CEPCI, we used a reference facility with a known capital cost in year A and a target year B in the following equation:

$$\text{CAPEX in year B} = \text{CAPEX in year A} \times \frac{\text{CEPCI in year B}}{\text{CEPCI in year A}}.$$

When calculating capacity scaling for a base facility with capacity Q_1 and cost CAPEX_1, a facility with capacity Q_2 has

$$\text{CAPEX}_2 = \text{CAPEX}_1 \left(\frac{Q_2}{Q_1} \right)^{0.6}.$$

The total fixed capital investment for each scenario is the sum of all staged expansions, while working capital is set as a fixed fraction of base capital:

$$\text{Working capital} = f_{\text{WC}} \times \text{CAPEX}_{\text{base}},$$

where f_{WC} is 15 per cent.

Operating Expenditure Estimation

Annual OPEX are built up from seven cost categories: raw materials, utilities, labour, maintenance and repairs, waste disposal, transport and general overheads. For any year t with throughput Q_t in tonnes per year,

$$\text{OPEX}_t = \sum_i \left(C_{i,\text{var}} \times Q_t \right) + \text{FOPEX},$$

where $C_{i,\text{var}}$ is the variable cost per tonne for category i, and FOPEX is the annual fixed operating cost.

The unit operating cost in that year is

$$\text{OPEX per tonne}_t = \frac{\text{OPEX}_t}{Q_t}.$$

Waste disposal costs use composite charges that combine levies, gate fees and treatment costs for each state rather than headline levy values alone.

Discounted Cash-Flow and Financial Indicators

Annual cash flow is calculated after tax and after all operating and financing charges. The baseline methodology for calculation was adopted from Balasubramanian et al. (2021). For year t,

$$\text{Revenue}_t = \sum_j \left(Q_{j,t} \times P_{j,t} \right),$$

where $Q_{j,t}$ is the quantity of recovered material j, and $P_{j,t}$ is its selling price. Thus,

$$\text{Operating profit}_t = \text{Revenue}_t - \text{OPEX}_t \quad \text{Net cash flow}_t = \text{Operating profit}_t - \text{Tax}_t - \text{Capital spending}_t.$$

NPV at discount rate r over a project life of n years is

$$\text{NPV} = \sum_{t=0}^{n} \frac{\text{Net cash flow}_t}{(1+r)^t}.$$

The payback period is determined as the first year in which the cumulative undiscounted cash flow becomes positive and remains positive for the remainder of the project life.

These expressions are applied consistently across the baseline assessment and all Queensland and Victoria scenarios; only the facility capacity, number of stages, state-specific prices and throughput profiles vary between cases.

Appendix B References

Balasubramanian, Venkatakrishnan, Nawshad Haque, Suresh Bhargava, Srinivasan Madapusi, and Rajarathinam Parthasarathy, 'Techno-Economic Evaluation Methodology for Hydrogen Energy Systems', in Abul Kalam Azad and Mohammad Masud Kamal Khan, eds., *Bioenergy Resources and Technologies*, Elsevier Science, 2021.

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APPENDIX C

Operating Expenditure Breakdown Used in the Techno-Economic Assessment

This appendix provides a breakdown of the OPEX calculations we used in the TEA. Table C.1 provides details about the seven OPEX cost categories as they relate to different Australian states, Table C.2 summarises the baseline parameters used in the TEA, and Table C.3 lists our waste levy assumptions.

TABLE C.1
OPEX Breakdown for Baseline Techno-Economic Assessment

OPEX Categories	OPEX for Victoria ($)	OPEX for New South Wales ($)	OPEX for South Australia ($)	OPEX for Western Australia ($)	OPEX for Queensland ($)
Raw materials	536	536	536	536	536
Utilities	190	228	234	107	215
Labour	149	167	149	151	141
Maintenance and repairs	151	151	151	151	151
Waste disposal	203	156	146	146	173
Transportation costs	160	80	160	80	60
Other general expenses	131	131	131	131	131
Total ($ per tonne)	1,519	1,449	1,507	1,302	1,406

TABLE C.2
Baseline Techno-Economic Assessment Summary

Parameters	Victoria	New South Wales	South Australia	Western Australia	Queensland
Fixed capital ($ millions)	7.53	7.53	7.53	7.53	7.53
Working capital ($ millions)	1.13	1.13	1.13	1.13	1.13
Operating life (years)	30	30	30	30	30
Production capacity (tonnes per year)	2,500	2,500	2,500	2,500	2,500
Fixed operating costs ($ millions)	0.69	0.75	0.70	0.71	0.80
Variable other operating costs ($ per tonne)	362.83	236.35	306.43	226.43	233.40
Raw material cost ($ per tonne)	535.59	535.59	535.59	535.59	535.59
Utilities cost ($ per tonne)	189.63	227.66	234.00	107.22	214.98
NPV ($ millions)	14.17	16.00	15.13	16.45	16.50
Payback period (years)	8.00	7.50	7.70	7.20	7.20

TABLE C.3
Waste Levy Assumption

State	Waste Levy ($ per tonne)	Source	Estimated Gate Fee ($ per tonne)	Source	Composite Disposal Cost ($ per tonne)
South Australia	156 (metro); 78 (nonmetro)	DCCEEW, 2024e	~200	Resource Hub Consulting, 2025	~356
New South Wales	180.20 (metro); 103.80 (regional)	New South Wales Environment Protection Authority, 2026	~200	Assumption	~374
Victoria	169.79 (metro, 2025–2026); 84.78 (rural municipal); 149.33 (rural industrial)	Environment Protection Authority Victoria, 2025	~200	Assumption	~370
Queensland	125 (metro); 97 (regional)	Queensland Government, 2025	~200	Assumption	~315–325
Western Australia	85 (2024–2025); 88 (2025–2026); 90 (2026–2027); 93 (2027–2028)	Government of Western Australia, 2025	~200	Assumption	~285–293

Appendix C References

DCCEEW—*See* Department of Climate Change, Energy, the Environment and Water.

Department of Climate Change, Energy, the Environment and Water, 'States, Territories and Local Government', webpage, Commonwealth of Australia, last updated 18 December 2024e. As of 19 May 2026: https://www.dcceew.gov.au/environment/protection/waste/publications/national-waste-resource-recovery-reporting/states-territories-local-government-2024

Environment Protection Authority Victoria, 'Waste Levy', webpage, last updated 28 May 2025. As of 19 May 2026: https://www.epa.vic.gov.au/waste-levy

Government of Western Australia, 'Waste Levy Rate Schedule', webpage, last updated 24 September 2025. As of 24 June 2026: https://www.wa.gov.au/service/environment/environment-information-services/waste-levy-rate-schedule

New South Wales Environment Protection Authority, 'Waste Levy Areas and Levy Rates', webpage, last updated 16 March 2026. As of 19 May 2026: https://www.epa.nsw.gov.au/Your-environment/Waste/waste-levy/levy-regulated-area-and-levy-rates

Queensland Government, 'Levy Rates', webpage, last updated 28 May 2025. As of 19 May 2026: https://www.qld.gov.au/environment/waste-reduction-recycling/disposal-levy/about/levy-rates

Resource Hub Consulting, 'SA Waste Levy', fact sheet, July 2025.

APPENDIX D

Calculations Used in the Techno-Economic Assessment Scenarios

This appendix presents the underlying data supporting the waste projections and capital expenditure calculations in the TEA in Chapter 9. Tables D.1 and D.2 provide state-level EoL PV waste projections for Queensland and Victoria, Tables D.3 and D.4 detail the capital expenditure estimates for each state, and Table D.5 presents the cross-state financial and operational comparisons across the three scenarios.

TABLE D.1

Waste Projection Calculated from Australian PV Institute Installation Data—Queensland

Projected Waste Year	Installed Year	Installed Capacity (# of Panels)	Installed Panels (Tonnes)	Reuse (# of Panels)	Recycle (# of Panels)	Reuse (Tonnes)	Recycle (Tonnes)	Reuse Panel Waste Year
2019	2007	701	18	386	315	10	8	2031
2020	2008	4,116	103	2,264	1,852	57	46	2032
2021	2009	24,436	611	13,440	10,996	336	275	2033
2022	2010	92,431	2,311	50,837	41,594	1,271	1,040	2034
2023	2011	225,346	5,634	123,940	101,406	3,099	2,535	2035
2024	2012	418,712	10,468	230,292	188,420	5,757	4,711	2036
2025	2013	269,397	6,735	148,168	121,229	3,704	3,031	2037
2026	2014	247,523	6,188	136,138	111,385	3,403	2,785	2038
2027	2015	200,096	5,002	110,053	90,043	2,751	2,251	2039
2028	2016	201,717	5,043	110,944	90,773	2,774	2,269	2040
2029	2017	449,364	11,234	247,150	202,214	6,179	5,055	2041
2030	2018	1,753,800	43,845	964,590	789,210	24,115	19,730	2042
2031	2019	1,325,055	33,126	728,780	596,275	18,220	14,907	2043
2032	2020	1,030,702	25,768	566,886	463,816	14,172	11,595	2044
2033	2021	1,506,138	37,653	828,376	677,762	20,709	16,944	2045
2034	2022	1,257,004	31,425	691,352	565,652	17,284	14,141	2046
2035	2023	1,298,317	32,458	714,074	584,243	17,852	14,606	2047
2036	2024	900,211	22,505	495,116	405,095	12,378	10,127	2048
2037	2025	339,766	8,494	186,871	152,895	4,672	3,822	2049

TABLE D.2

Waste Projection Calculated from Australian PV Institute Installation Data—Victoria

Projected Waste Year	Installed Year	Installed Capacity (# of Panels)	Installed Panels (Tonnes)	Reuse (# of Panels)	Recycle (# of Panels)	Reuse (Tonnes)	Recycle (Tonnes)	Reuse Panel Waste Year
2019	2007	1,108	28	554	554	14	14	2031
2020	2008	2,727	68	1,364	1,364	34	34	2032
2021	2009	10,506	263	5,253	5,253	131	131	2033
2022	2010	59,281	1,482	29,641	29,641	741	741	2034
2023	2011	140,811	3,520	70,406	70,406	1,760	1,760	2035
2024	2012	208,201	5,205	104,101	104,101	2,603	2,603	2036
2025	2013	132,662	3,317	66,331	66,331	1,658	1,658	2037
2026	2014	177,009	4,425	88,505	88,505	2,213	2,213	2038
2027	2015	154,240	3,856	77,120	77,120	1,928	1,928	2039
2028	2016	148,071	3,702	74,036	74,036	1,851	1,851	2040
2029	2017	214,465	5,362	107,233	107,233	2,681	2,681	2041
2030	2018	789,387	19,735	394,694	394,694	9,867	9,867	2042
2031	2019	665,512	16,638	332,756	332,756	8,319	8,319	2043
2032	2020	1,224,890	30,622	612,445	612,445	15,311	15,311	2044
2033	2021	866,543	21,664	433,272	433,272	10,832	10,832	2045
2034	2022	561,523	14,038	280,762	280,762	7,019	7,019	2046
2035	2023	795,640	19,891	397,820	397,820	9,946	9,946	2047
2036	2024	850,174	21,254	425,087	425,087	10,627	10,627	2048
2037	2025	320,890	8,022	160,445	160,445	4,011	4,011	2049

TABLE D.3
Estimated Capital Expenditures for Queensland

Stage	Added Capacity (Tonnes per Year)	Cumulative Capacity (Tonnes per Year)	Incremental CAPEX ($ millions)	Cumulative CAPEX ($ millions)
Scenario A. Centralised recycling hub				
Base facility	10,000	10,000	17.29	17.29
Stage 2	5,000	15,000	8.51	25.80
Stage 3	10,000	25,000	12.90	38.70
Scenario B. Decentralised fixed facilities (regional plants)				
Base facility	2,500	2,500	7.53	7.53
Stage 2	2,500	5,000	5.62	13.15
Stage 3	2,500	7,500	5.62	18.77
Scenario C. Mobile screening plus regional plants				
Base facility	2,500	2,500	7.53	7.53
Stage 2	2,500	5,000	5.62	13.15
Stage 3	2,500	7,500	5.62	18.77

TABLE D.4
Estimated Capital Expenditures for Victoria

Stage	Added Capacity (Tonnes per Year)	Cumulative Capacity (Tonnes per Year)	Incremental CAPEX ($ millions)	Cumulative CAPEX ($ millions)
Scenario A. Centralised recycling hub				
Base facility	5,000	5,000	11.41	11.41
Stage 2	5,000	10,000	8.51	19.92
Stage 3	5,000	15,000	8.51	28.43
Scenario B. Decentralised fixed facilities (regional plants)				
Base facility	2,500	2,500	7.53	7.53
Stage 2	2,500	5,000	5.62	13.15
Stage 3	2,500	7,500	5.62	18.77
Scenario C. Mobile screening plus regional recycling				
Base facility	2,500	2,500	7.53	7.53
Stage 2	2,500	5,000	5.62	13.15
Stage 3	2,500	7,500	5.62	18.77

TABLE D.5

Cross-State Comparison of Scenarios

Parameter	Queensland Scenario A	Queensland Scenario B	Queensland Scenario C	Victoria Scenario A	Victoria Scenario B	Victoria Scenario C
Initial installed capacity (tonnes per year)	10,000	2,500	2,500	5,000	2,500	2,500
Final installed capacity (after all stages; tonnes per year)	25,000	7,500	7,500	15,000	7,500	7,500
Initial investment (base facility; $ millions)	17.29	7.53	7.53	11.41	7.53	7.53
Stage 2 investment ($ millions)	8.51 (5,000 tonnes per year)	5.62 (2,500 tonnes per year)	5.62 (2,500 tonnes per year)	8.51 (5,000 tonnes per year)	5.62 (2,500 tonnes per year)	5.62 (2,500 tonnes per year)
Stage 3 investment ($ millions)	12.90 (10,000 tonnes per year)	5.62 (2,500 tonnes per year)	5.62 (2,500 tonnes per year)	8.51 (5,000 tonnes per year)	5.62 (2,500 tonnes per year)	5.62 (2,500 tonnes per year)
Cumulative capital investment ($ millions)	38.70	18.77	18.77	28.43	18.77	18.77
NPV 2025–2031 ($ millions)	–11.42	–5.88	–5.64	–14.10	–7.62	–7.41
NPV 2032–2041 ($ millions)	2.61	1.35	–0.09	3.15	1.78	–0.11
NPV 2042–2055 ($ millions)	–2.22	9.25	5.98	–2.95	12.20	7.54
Total NPV (2025–2055; $ millions)	–11.03	4.72	0.25	–13.90	6.36	0.02
Operational efficiency	Strong economies of scale	Moderate	Moderate	Strong economies of scale	Moderate	Moderate
Transport burden	Lowest	Medium	Highest	Lowest	Medium	Highest
Flexibility and reach	Low	Medium	High	Low	Medium	High
Scalability risk	High CAPEX lock-in	Manageable	High OPEX variability	High CAPEX lock-in	Manageable	High OPEX variability
Commercial strength	Suboptimal in all phases	Strongest performer	Marginally viable	Suboptimal in all phases	Strongest performer	Near break-even by late period
Best fit by state	High volume metro or regional	Regional clusters with steady flow	Remote or dispersed zones	High volume; Melbourne corridor	Regional clusters	Remote or dispersed zones

NOTE: All monetary values are in Australian dollars.

APPENDIX E

Photovoltaic Module Capacity to Mass Conversion Table for Recycling Applications

This appendix presents the capacity-to-mass conversion methodology used to translate installed PV system capacity data into module mass and projected waste tonnage. These calculations form an intermediate step between the installation data obtained from APVI and the waste generation forecasts used as inputs to the TEA. This appendix is included to provide transparency regarding the assumptions, conversion factors, and formulas (Table E.1) applied in deriving the waste projections used throughout Chapter 9.

Definitions

- W = watt
- kW = kilowatt
- MW = megawatt
- 1,000,000 W = 1,000 kW = 1 MW
- P = module rated power in W
- M = module weight in kg
- C = system capacity in MW

Summary for 100 Tonnes

- **Mass:** 100 tonnes
- **Number of panels:** 4,000 panels
- **Total capacity:** 1,600 kW (1.6 MW)
- **Capacity per tonne:** 16.0 kW

Key Assumptions

Residential PV panels typically weigh between 18 and 25 kg per unit, while commercial and utility-scale panels generally range between 22 and 30 kg per unit, depending on design and technology.

Our calculations assume the following:

- average PV panel weight (M) = 25 kg
- average module rated power (P) = 400 W (0.4 kW).

TABLE E.1

Formulas Used in the Techno-Economic Assessment

Parameter	Formula	Units
Module power in kW	P / 1000	kW
Panels per MW	1,000,000 / P	panels per MW
Panels for capacity	C × 1,000,000 / P	panels
Total mass in kg	C × 1,000,000 × M / P	kg
Total mass in tonnes	C × 1000 × M / P	tonnes
Panels per tonne	1000 / M	panels per tonne
Capacity per tonne	P / M	kW per tonne
MW per tonne	P / M / 1000	MW per tonne

Abbreviations

AD/CVD	antidumping and countervailing duty
AI	artificial intelligence
APVI	Australian PV Institute
BAPV	building-attached photovoltaic
BIPV	building-integrated photovoltaic
BLM	Bureau of Land Management
CAPEX	capital expenditures
CBM	circular business model
CEPCI	Chemical Engineering Plant Cost Index
CO_2	carbon dioxide
CPVA	Circular PV Alliance
c-Si	crystalline silicon
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DPP	digital product passport
EEEV Act	Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles
EoL	end of life
EPEAT	Electronic Product Environmental Assessment Tool
EPR	extended producer responsibility
EU	European Union
EVA	ethylene-vinyl acetate
e-waste	electronic waste
FIT	feed-in tariff
FOPEX	fixed operating cost
GHG	greenhouse gas
GW	gigawatt
HS	Harmonised System
ICIRN	International Clean Innovation Researcher Networks
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kg	kilogram
km	kilometre
kt	kilotonne
KOH	potassium hydroxide
KPK	Kynar-PET-Kynar
kW	kilowatt
kWh	kilowatt-hour
LCA	life-cycle assessment

LIB	lithium-ion battery
MG Si	metallurgical-grade silicon
MSA	methanesulfonic acid
MW	megawatt
NPV	net present value
OECD	Organisation for Economic Co-operation and Development
OPEX	operating expenditures
P2P	peer-to-peer
PET	polyethylene terephthalate
PPA	power purchase agreement
PV	photovoltaic
PVDF	polyvinylidene fluoride
PVF	polyvinyl fluoride
R&D	research and development
RMIT	Royal Melbourne Institute of Technology
SCRAPs	Sistemas de Colectivos de Responsabilidad Ampliada del Productor
SNP	silica nanoparticle
SoG-Si	solar-grade silicon
TAFE	technical and further education
TEA	techno-economic assessment
TPT	Tedlar/PET/Tedlar
TRL	technology readiness levels
TW	terawatt
UNSW	University of New South Wales
V	volt
WEEE	Waste from Electrical and Electronic Equipment
Wp	Watt-peak

Glossary

cadmium telluride	A crystalline compound formed from cadmium and tellurium and used as a semiconductor material in thin-film solar cells
circular economy	An economic model that seeks to minimise waste and maximise the use of energy and materials by keeping products, materials and resources in use for as long as possible through such strategies as product life extension, reuse and recycling
copper-indium-gallium-selenide solar cells	A thin-film solar cell technology that uses copper, indium, gallium and selenium as the semiconductor material
crystalline silicon (c-Si)	The dominant semiconductor material used in solar cells, comprising both monocrystalline and polycrystalline silicon technologies
decommissioning	The process of removing and disassembling PV systems at the end of their operational life
degradation	The gradual decline in the performance and efficiency of PV panels over time caused by environmental factors, material ageing and operational stress
delamination	The separation of layered materials in a PV panel, typically occurring between the encapsulant and the cell or glass, often caused by moisture ingress or thermal cycling
encapsulant	A protective material, typically ethylene-vinyl acetate (or EVA), that surrounds and protects solar cells within a module from environmental damage
end-of-life (EoL)	The stage in a product life cycle at which it can no longer perform its intended function and is retired from service and ready for disposal, recycling or reuse
ethylene-vinyl acetate (EVA)	A polymer commonly used as an encapsulant in PV panels to protect the PV cells from moisture and mechanical stress
extended producer responsibility (EPR)	A policy approach that makes producers responsible for the entire life cycle of their products, including take-back, recycling and final disposal
gigawatt (GW)	Unit of power equal to one billion watts
hydrometallurgy	A method of metal extraction and recovery using aqueous chemistry, often employed in recycling processes to recover valuable materials from EoL PV panels
inverter	A device that converts direct-current (DC) electricity generated by PV panels into alternating current (AC) electricity suitable for use in homes and businesses or for feeding into the electrical grid
kilowatt (kW)	Unit of power equal to one thousand watts
life cycle	The series of stages through which a product passes from its creation, through its use phase, to its EoL management
material recovery	The process of extracting valuable materials from waste products for reuse in manufacturing new products

megawatt (MW)	Unit of power equal to one million watts
module	A complete PV panel assembly consisting of interconnected solar cells, encapsulated and mounted in a protective frame
net zero	The balance between the amount of greenhouse gas emissions produced and the amount removed from the atmosphere, achieved when emissions are reduced as much as possible and remaining emissions are offset
photovoltaic (PV)	The conversion of light into electricity using semiconducting materials that exhibit the PV effect
product stewardship	An approach to managing the environmental impacts of products throughout their life cycle, involving shared responsibility among stakeholders
pyrometallurgy	A method of extracting and refining metals using high-temperature processes, sometimes used in PV panel recycling
recycling	The process of converting waste materials into new products to prevent the waste of potentially useful materials and reduce consumption of fresh raw materials
refurbishment	The process of restoring used equipment to good working condition, often involving cleaning, testing, repair and replacement of worn components
renewable energy	Energy derived from natural sources that are replenished at a higher rate than they are consumed, such as solar, wind, hydro and geothermal power
resource efficiency	The practice of using natural resources in a sustainable manner, minimising waste and environmental impact while maximising economic and social benefits
reverse logistics	The process of planning, implementing and controlling the efficient flow of products and materials from the end user back through the supply chain for the purpose of recovery, recycling or disposal
silicon wafer	A thin slice of semiconductor material, typically silicon, used as the substrate for solar cells
solar cell	The basic unit of a PV module that converts sunlight directly into electricity through the PV effect
supply chain	The network of organisations, activities, information and resources involved in producing and delivering a product from supplier to end user
sustainability	Meeting the needs of the present without compromising the ability of future generations to meet their own needs, encompassing environmental, economic and social dimensions
thin film	A second-generation solar-cell technology that deposits one or more thin layers of PV material on a substrate, requiring less material than crystalline silicon cells
urban mining	The process of reclaiming raw materials from discarded products, buildings and waste streams
waste management	The collection, transport, treatment and disposal of waste, including the monitoring and regulation of these processes

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