Aluminating the Path

Driving Aluminium Circularity in the Solar Photovoltaic Sector

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Report Context

Purpose: Explore end-of-life management options for PV systems, to inform recommendations to the aluminium industry which could maximise:

- aluminium recycling from PV projects at end-of-life, and
- the use of recycled content in new PV projects.

Research Focus: The study investigates end-of-life aluminium management options, material selection drivers, recyclability performance, reuse opportunities, recovery rates, and the potential for incorporating recycled aluminium into new solar PV manufacturing and project installations. 15 stakeholder interviews were conducted as a part of the study with PV manufacturers, PV recyclers, scrap metal traders, extruders, regulatory bodies and academics. The work considers both distributed (rooftop and commercial) and utility scale solar PV.

Geographic Coverage: The work has a global scope with particular attention to regional variations between Europe, Australia, Canada, the United States, India and China, reflecting differing end-of-life management infrastructure, policy and regulatory approaches and recycling capacity development across key markets.

Acronyms

Acronym	Meaning
AFSL	Australian Financial Services Licence
CAR	Corporate Authorised Representative
CBAM	Carbon Border Adjustment Mechanism
CCME	Canadian Council of Ministers of the Environment
CPCB	Central Pollution Control Board
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DOE	U.S. Department of Energy
EEE	Electronic and Electronic Equipment
EoL	End-of-life
EPD	Environmental Product Declaration
EPR	Extended Producer Responsibility
ESG	Environmental, Social and Governance
GHG	Greenhouse Gas
GW	Gigawatt
IAI	International Aluminium Institute
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency

Acronym	Meaning
ISO	International Organization for Standardization
kW	Kilowatt
LCA	Life-Cycle Assessment
LCC	Life-Cycle Costing
LCI	Life-Cycle Inventory
MW	Megawatt
NREL	National Renewable Energy Laboratory
POM	Placed on Market
PV	Photovoltaic
PVDF	Polyvinylidene Fluoride
RRCEA	Resource Recovery and Circular Economy Act
RCRA	Resource Conservation and Recovery Act
SA	Standards Australia
t	Tonne (metric ton)
tCO_2e	Tonnes of carbon dioxide equivalent
TW	Terawatt
WEEE	Waste Electrical and Electronic Equipment

01 Executive Summary

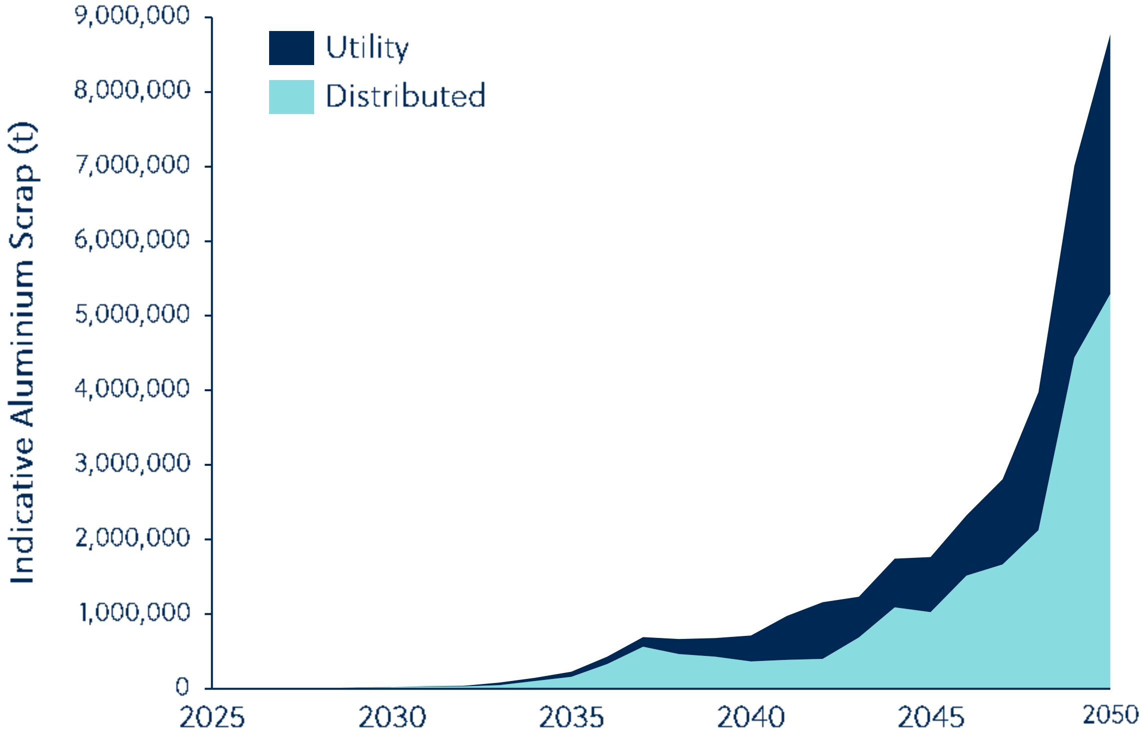
Rising PV deployment is driving aluminium demand but creating an aluminium scrap challenge as PV systems reach their end-of-life

Globally, PV installations are growing rapidly as governments pursue decarbonisation and low-cost electricity. Global installed capacity exceeded 2.2 TW in 2024, with almost 600 GW added in a single year, making solar the largest source of new power generation.[1] However, this rapid expansion creates an emerging challenge: early distributed and utility-scale projects are beginning to reach end-of-life, accelerating rapidly by 2040, while recycling infrastructure remains underdeveloped in most markets.

Over time, as existing PV installations reach end-of-life, aluminium scrap from the PV sector will grow rapidly. Aluminium is integral to both distributed and utility-scale systems, with 6-series aluminium serving as a primary structural material in module frames as well as racking systems for distributed systems. In 2024, an estimated 8 million tonnes of aluminium was used in the manufacture of PV systems, representing 10% of all production.[2] Consequently, scaling and advances in aluminium recycling infrastructure are needed globally to extract, aggregate, process and recycle this aluminium at end-of-life.

Rethink, reuse and recycle provide the primary pathways to prevent and manage the emerging aluminium scrap stream while reducing emissions from a predominantly linear supply chain. Today, recycling in the PV sector is mixed across markets, reflecting the varied requirements for waste management. Europe has demonstrated the effectiveness of strong regulation, achieving over 80% PV recovery rates through mandatory collection and recycling targets under the WEEE Directive.[3] However, this performance remains exceptional globally with most major markets delivering only around 10% recovery.

Chart 1-1: PV aluminium scrap based on a 25-year life[2]



Source: 1. IEA, Electricity analysis and forecast to 2026, (2024), 2. Developed from utility capacity in Global Energy Monitor Wiki Global Solar Power Tracker and all installed capacity in IRENA Electricity Statistics. Assumes a 30-year asset life and aluminium intensity of 21 t/MW for utility and 37t/MW for distributed based upon IEA Task 12. 3. European Environment Agency, Recycling materials from green energy technologies (2025)

Upstream material selection and design decisions create barriers for end-of-life PV aluminium circularity

Decisions made upstream at the manufacturing, project development and installation phase can drive downstream circular outcomes for aluminium.

PV manufacturers are facing a race to the bottom on cost and are considering cheaper alternative materials to aluminium. Module sale prices have fallen 90 per cent since 2010 (US$2.44/W to US$$0.26/W), pushing manufacturers to explore cheaper alternatives like polycarbonate and composites.[1,2] These alternatives present significant end-of-life challenges as they are difficult to recycle. Conversely, aluminium's superior mechanical and circular proprieties are likely to ensure it remains the dominant material selected.

Design decisions around frame connections are influential in the ease of recyclability. Mechanical fasteners support end-of-life recovery, while adhesives and composites often preclude economic separation for recyclers.

Upstream players are driven by material suitability, aesthetic and cost requirements of customers, with limited consideration on end-of-life outcomes. Surface coatings play an equally important role with clear anodised finishes being simpler to recycle, while thick powder and PVDF coatings, chosen for aesthetics or extended durability, hamper scrap quality and increase downstream processing costs.

PV manufacturers are concerned about the quality of recycled aluminium and the effects on end PV products. Manufacturers expressed legitimate technical concerns about recycled aluminium use including residual trace elements compromising alloy strength and corrosion resistance, while limited creates liability risk. These concerns are manageable through supply chain transparency, certification standards, and contractual protections.

Table 1-1: Comparison between alternative materials for frames and racking[3]

Material	Material Suitability	Emissions Intensity	Indicative Cost
Aluminium (incumbent)	Advantage	Disadvantage	Disadvantage
Recycled Aluminium	Advantage	Advantage	Disadvantage
Steel	Neutral	Neutral	Neutral
Recycled Steel	Neutral	Advantage	Neutral
Plastic / composites (e.g. PVC, polycarbonates)	Neutral	Neutral	Neutral

Advantage | Neutral | Disadvantage

Source: 1. IEA, Special Report on Solar PV Global Supply Chains (2022) 2. Our World in Data, Solar (photovoltaic) panel prices (2025) 3. See Table 3-1 for references.

Risks across the end-of-life PV aluminium recycling supply chain need mitigating to unlock recycling and reuse

Reuse of decommissioned PV modules offers limited near-term potential. Some aluminium components, particularly distributed racking systems, demonstrate longevity beyond module life and can deliver secondary applications. Scaling reuse requires supply chain standardisation and certification infrastructure that remains nascent globally. Industry stakeholders acknowledge that reuse pathways, though valuable, cannot adequately address the looming volumes of systems approaching genuine end-of-life.

Recycling can be both closed and open loop within the aluminium supply chain, with open loop likely the most viable pathway owing to the geographic concentration of PV manufacture. Regardless of pathway, unlocking aluminium recycling offers significant opportunity for value capture and emissions avoidance, with an estimated reduction of 97%.[1]

Six risks inhibit the commercialisation of the PV recycling supply chain. Combined, these risks mean material contamination from coatings and fasteners reduces scrap value, design variations prevent batch-scale processing, infrastructure maturity varies sharply by market, whole-system recycling economics remain unproven, and collection uncertainty deters investment. Mitigating these risks is critical to unlock significant aluminium recovery. As supply chains scale, automation and economies of scale are expected to drive substantial cost reductions, with studies suggesting breakeven viability at 3,000 tonnes annually.

Table 1-2: Key risks across the supply chain inhibiting recyclers[2]

Risk	Supply Chain Player	Description
1. Panel Supply Risk	Disassembly Collection & PV Recyclers	Panel design and material selection may be inconsistent with recycling technology. Supply may be variable.
2. Technology Risk	Technology Supply & PV Recyclers	Nascent technology for panel recycling means key mitigants such as performance guarantees are yet to be widely available.
3. Policy Uncertainty	PV & Aluminium Recyclers and Investors	Lack of mandatory end-of-life requirements for PV project developers makes landfilling economically more viable.
4. Price Risk	PV & Aluminium Recyclers and Investors	Variable underlying commodity prices (e.g. aluminium, copper, silver) impact the viability of a project.
5. Quality Risk	PV Manufacturers	Contaminants in aluminium can devalue the product stream.
6. Regulatory Risk	PV Manufacturers	Uncertainty around the acceptability of the use of recycled aluminium in end use applications inhibits markets.

Source: 1. Primary Aluminium – Global Average – International Aluminium Institute, Global Aluminium Industry Greenhouse Gas Emissions Intensity Reduction Continues, With Total Emissions Below 2020 Peak (2023), Primary Aluminium – Low Carbon Grid – Aluminium Stewardship Initiative – Issue Brief: Low Carbon Aluminium (2021) , Recycled & Scrap Aluminium – average & Recycled & Scrap Aluminium – Low Carbon Grid – Hydro, Low-carbon and recycled aluminium (n.d.) 2. Developed through stakeholder consultation with supply chain players.

Design for recyclability and enforcement of end-of-life waste management are critical to unlocking aluminium recycling

Policy maturity varies widely, but the opportunity is clear for product stewardship. Governments are taking divergent paths to PV end-of-life management. Europe's mandatory extended producer responsibility (EPR) regimes, supported by Waste Electrical and Electronic Equipment (WEEE) Act and EN 50625 standards, together with instruments such as landfill taxes and bans, have delivered declining landfill rates and aluminium recovery rates above 80 per cent by weight.[1,2] China, despite lacking formal PV EPR legislation, could achieve EPR-like outcomes through the rigorous national standards and permitting mechanisms coming into force.[3] Most other markets (e.g. Australia, Canada, India and the United States) remain fragmented across jurisdictions, with inconsistent rules, unclear producer obligations and thin infrastructure, slowing the build-out of dedicated recycling capacity as volumes rise.

Standards and design integration are lagging globally. PV-specific design-for-disassembly and material specifications exist only in Europe and parts of China. Elsewhere, modules are engineered for 25-year durability but not for end-of-life recovery; alloys, coatings and treatment pathways are rarely chosen with recyclability in mind. Traceability is underdeveloped, with limited use of labelling, product passports or harmonised reporting of module composition. These gaps mean recyclers face variable feedstock quality, higher processing costs and limited ability to demonstrate high-quality secondary aluminium.

Industry and recyclers are united on a path forward which develops markets for recycled product, provides policy certainty and delivers standards alignment.

Source: 1. European Environmental Agency, Diversion of waste from landfill in Europe, (2025); 2. IAI, International Aluminium Publishes Global Recycling Data 3. Ali A., Malik S. A., Shafiullah M., Malik M. Z. & Zahir M. H., Policies and regulations for solar photovoltaic end-of-life waste management: Insights from China and the USA (2023); 4. Refer to Appendix A for detail and references.

Table 1-3: Comparison between regions across policy, recovery and infrastructure[4]

	Australia	Europe	India	China	US	Canada
End-of-life Policy & Standards	Limited	Enforced EPR and design standards	Limited	Incoming EPR-like response	Limited	Limited
Recycling Rate (PV Modules)	Minimal	>80%	Minimal	Nascent	~10%	Limited
Aluminium recovery infrastructure	Export-centric	Developed	Developing	Developing	Developed	Developed
Barriers	Transport distances, low volume	Export drains local processing, varied enforcement	Lack of formalised recovery sector	Informal recovery sector	Lack of market incentive for recovery and state-based variance	Provincial fragmentation
Traceability	Voluntary	Environmental Product Declaration and reporting required	Limited	Voluntary	Voluntary	Environmental Product Declaration pilot

Legend: Advanced | Emerging | Limited

Industry and government are both responsible for enabling the recycling of aluminium in the PV sector

Institution	Risks	Recommendation	Impact	Timing	Complexity
Government	Policy, Technology & Panel Supply Risk	1. Strengthen policy and market signals through enforced product stewardship (e.g. EPR schemes for PV modules). This should be supported through internationally aligned frameworks 2. Support recycling and reuse infrastructure with dedicated grants or low-interest finance 3. Enable reuse pathways with national standards for second-life PV and racking with regulatory assurance for exports			
Standards Bodies (SA, IEC, ISO)	Panel Supply, Quality & Regulatory Risk	4. Embed recyclability into PV standards by setting design-for-disassembly, recyclable coating and testing standards, alongside nationally recognised export-aligned protocols for safe reuse of modules and racking			
PV module and racking system manufacturers	Panel Supply & Quality, Price Risk	5. Standardise use of recyclable-friendly 6-series alloys and coatings 6. Voluntarily redesign frames for ease of disassembly 7. Invest in circular supply chains, piloting procurement of certified recycled content			
Project Developers and Installers	Panel Supply & Quality Risk	8. Preference products with higher recyclability and verified alloy/recycled content 9. Establish end-of-life offtake arrangements with recyclers 10. Work with certified refurbishers to test, grade and document removed modules and racking for reuse			
Disassemblers and PV Recyclers	Panel Supply & Quality, Price Risk	11. Reduce contamination and module damage during disassembly and develop co-located hubs with scrap traders to leverage existing infrastructure while adapting for the multi-material nature of PVs 12. Work with standards bodies, governments and refurbishers to certify recovered materials and PV modules for reuse			
Scrap Metal Traders	Quality & Regulatory Risk	13. Create dedicated streams and invest in sorting to verify alloy composition and improve PV aluminium feedstock quality 14. Build direct relationships with solar PV supplying casthouses and extruders to align specifications and secure offtake			
Casthouses and Extruders	Quality Risk	15. Create grade-specific demand and clear quality specifications for PV-derived aluminium scrap to support closed-loop recycling 16. Offer transparent premiums and public commitments on recycled content to promote clean, traceable aluminium for PV applications			
International Aluminium Institute	Policy,, Panel Supply, Quality & Regulatory Risk	17. Advocate globally for EPR-style product stewardship and harmonised standards on aluminium alloys, coatings and design-for-recyclability for PV frames and racking 18. Convene a cross-value-chain working group under the IEA Photovoltaic Power Systems Programme Task 12 on PV Sustainability, including upstream, downstream, government and standard body players focused on driving high-yield PV aluminium recycling			

High Impact/Short Term (next 5 years)/High Complexity

Moderate Impact/Moderate Term (next 10 years)/Moderate Complexity

Low Impact/Long Term (15 years +)/Low Complexity

02 The challenge of end-of-life PV waste for the aluminium sector

The global PV sector faces a growing challenge: rising demand for aluminium in PV modules, frames, and structures as PV installations grow exponentially, while end-of-life PV systems generate increasing volumes of scrap aluminium.

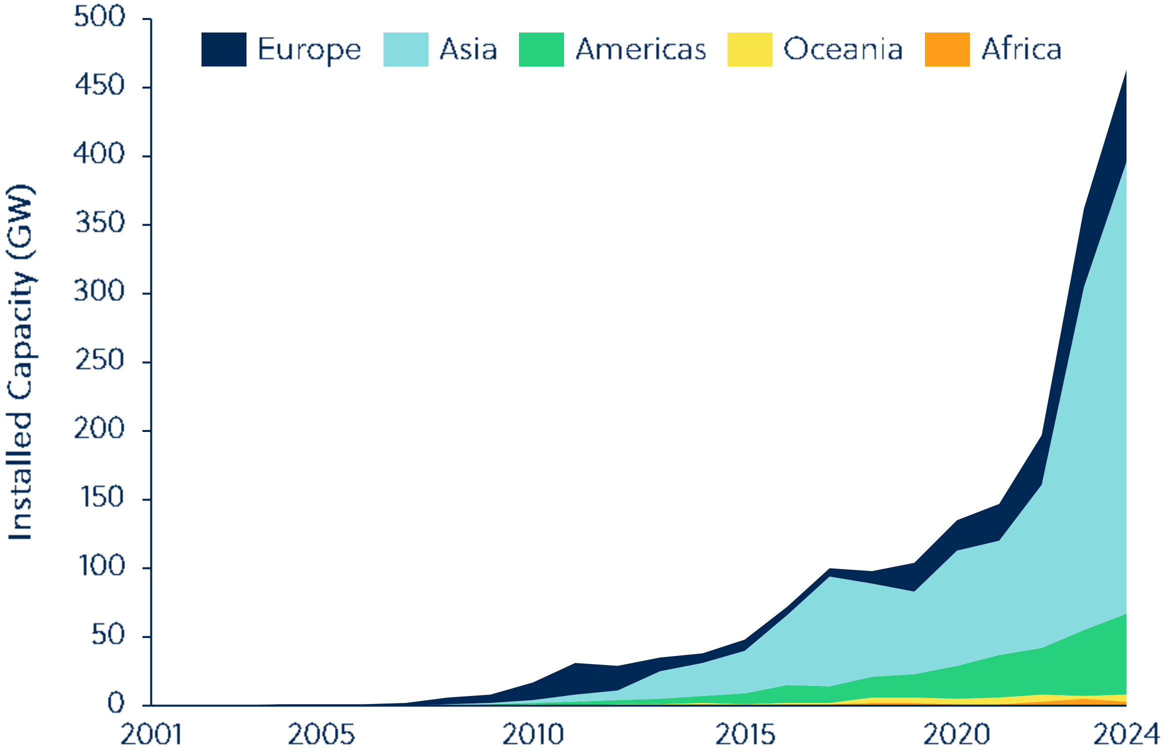
Globally, PV installations are growing rapidly as governments pursue decarbonisation and low-cost electricity

Global PV deployment is accelerating as governments respond to decarbonisation goals and electricity from solar PV has become the cheapest. Cumulative installed PV capacity passed roughly 2.2 TW in 2024, with almost 600 GW added in 2024, making solar the largest source of new power generation globally.[1]

Growth is highly concentrated in China but increasingly diversified across regions. China accounted for about 329 GW of new capacity in 2024, while the United States, India, Brazil and Germany each delivered multi-gigawatt markets that signal a broadening investment base for PV.[2] Industry and policy stakeholders expect solar capacity to exceed 7 TW by 2030, positioning PV to deliver the majority of new renewable capacity required under global clean energy targets.[3]

This rapid build-out is reshaping demand for upstream materials and components, particularly aluminium used in module frames and racking structures. Ensuring secure supply of aluminium while managing embodied emission impacts is an emerging concern for financiers, governments and project sponsors as solar becomes a central pillar of the power system transition.

Chart 2-1: Global installed PV capacity over time[4]



Sources: 1.) IEA, Electricity analysis and forecast to 2026, (2024;) 2. IEA, Solar PV (2025); 3. SolarPower Europe, Global Market Outlook for Solar Power 2025-2029 (2025) 4. Developed from utility capacity in Global Energy Monitor Wiki Global Solar Power Tracker and all installed capacity in IRENA Electricity Statistics.

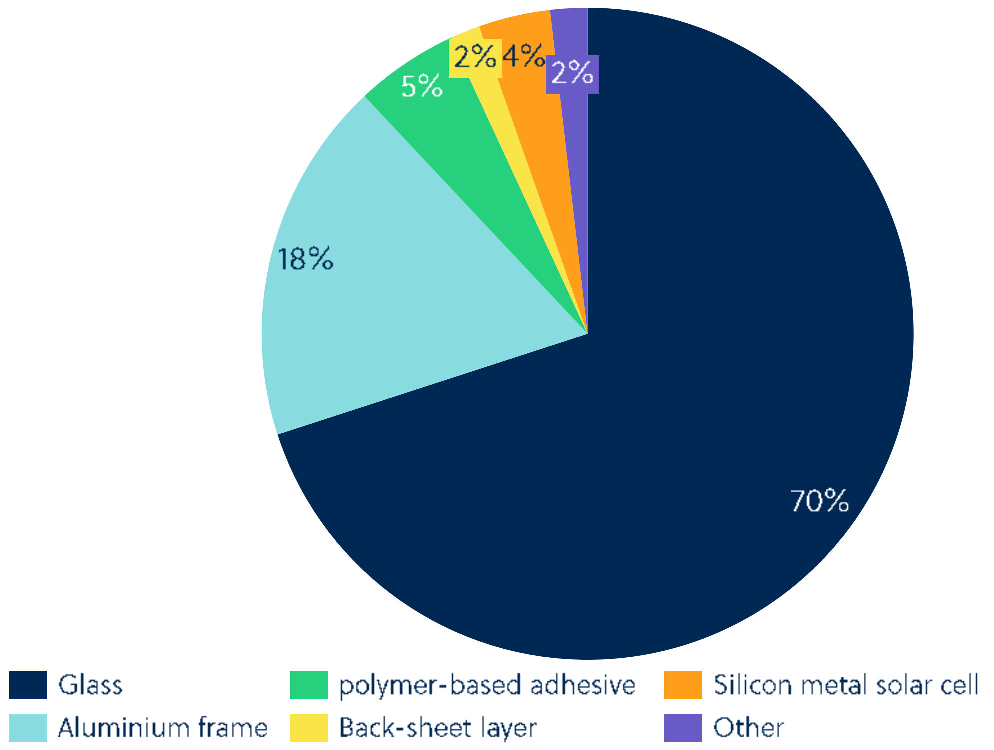
PV waste is becoming a challenge as utility projects begin to be decommissioned, and distributed installations reach end-of-life

The rapid global expansion of solar PV deployment from 2010 onwards has created a structural waste and scrap metal management challenge as the earliest installations approach end-of-life. PV waste currently stems primarily from damaged panels during installation or early-stage replacements, but this trajectory is about to shift. Global cumulative PV waste is projected to reach 1.7 million tonnes by the early 2030s, accelerating to 60–78 million tonnes by the 2050s under standard deployment assumptions.[1] This scale will quickly overwhelm existing recycling infrastructure if current capacity trends continue. Recyclers identified this could accelerate quicker, with utility scale projects considering early panel retirements as they balance performance efficiency with cost of replacement.

End-of-life management is particularly complex given the multi-material nature of PV modules. Glass and aluminium frames make up nearly 90% of mass,[2] while polymers, silicon, and traces of precious metals require specialised recycling treatment. Despite high theoretical recovery rates, practical recycling capacity and infrastructure consistently lag behind deployment, with global recovery rates falling far short of policy targets.

Some countries and industry leaders are responding with new regulations and investments to accelerate collection, disassembly, and recycling. Developing recovery systems now is critical to capturing the full resource value of PV waste and preventing valuable material leakage to landfill, unlocking both economic and environmental benefits for communities and supply chains.

Chart 2-2: PV module waste and scrap by material type[3]



Sources: 1. IRENA, End-of-life Management: Solar Photovoltaic Panels (2016) 2. IRENA, Renewable Energy Benefits: Leveraging Local Capacity for Solar PV, (2017) 3. Latunussa, C., Mancini, L., Blengini, G., Ardente, F., Pennington, D., Analysis of Material Recovery from Silicon Photovoltaic Panels (2016)

Aluminium is used in a range of components in the PV sector, requiring specific alloys matched to performance demands

Aluminium is integral to solar PV installations, serving as a primary material across module frames, racking systems, and racking. Distributed rooftop systems require 23–31 t/MW, with aluminium optimised for lightweight frames and racking where structural constraints favour lower-mass materials.[1] Utility-scale installations are less aluminium-intensive at 11–27 t/MW,[2] with steel typically preferred for large-span tracker and support systems where weight considerations are secondary to cost.

Aluminium demand from the PV sector has been accelerating historically. In 2024, approximately 460 GW of newly installed PV capacity globally embedded an estimated 8 million tonnes of aluminium.[1] This represents 10% of global primary aluminium production in a single year.[1] As deployment trajectories steepen, this share could grow materially.

Component-specific alloys are essential, preferencing 6-series aluminium. Distributed systems employ 6063-T5/T6 series aluminium for module frames, leveraging superior extrudability and corrosion resistance, with 6063, 6061, and 6005 alloys used for racking applications where stiffness and malleability are prioritised. Utility-scale systems employ 6063-T6 and 6061-T6 alloys for frames to ensure structural stability and weldability, while ground-mounted tracker systems specify 6061-T6 to deliver high tensile and yield strength with fatigue resistance. Material selection for auxiliary components (e.g. inverters and cable supports) remains cost-driven, with limited substitution opportunities constraining wider aluminium penetration.

Table 2-1: Aluminium material intensity by PV scale[1]

Installation Type	Component	Aluminium Type	Key Properties
Distributed	Frame	6063-T5/T6	Light weight, ease of extrudability, corrosion resistant
	Racking (rooftop)	6063-T5/T6 6061-T6 6005-T5	Light weight, stiffness, malleability
	Other (e.g. Inverters)	6063 6062	High thermal conductivity, extrudability, corrosion resistant
Utility	Frame	6063-T6 6061-T6	Structural stability/strength, corrosion resistant, good weldability
	Racking (ground-mounted tracker)	6061-T6	High tensile and yield strength, fatigue resistant, corrosion resistant*
	Other (e.g. Inverters)	6063 6062	High thermal conductivity, extrudability, corrosion resistant

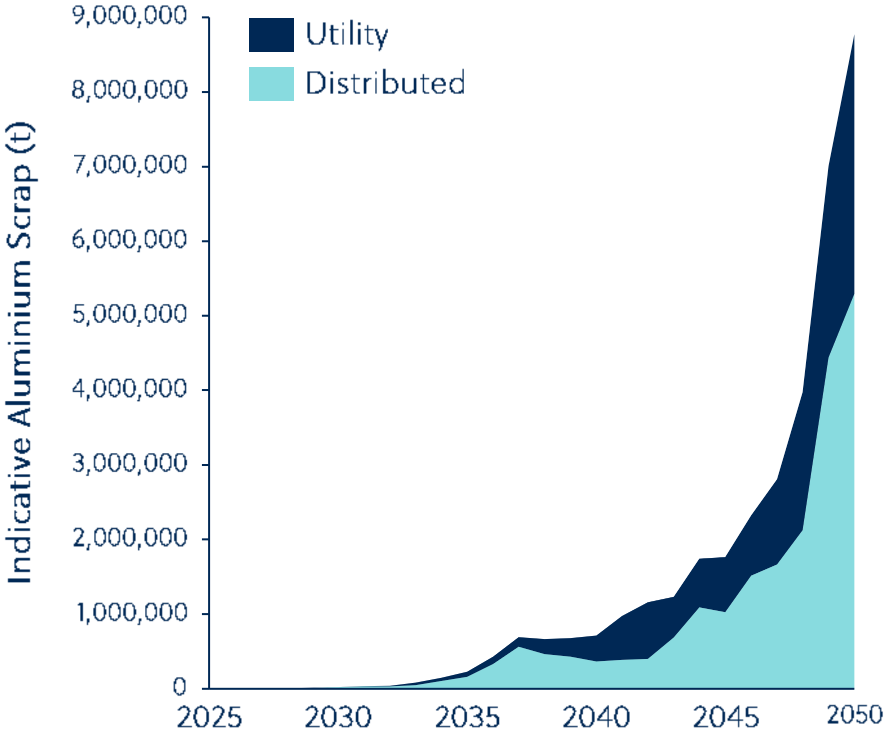
Source: 1. Developed assuming a 2.2 m² utility scale module and a 1.7 m² distributed scale module. Ranges for material intensity by component developed from IEA Photovoltaic Power Systems Programme, Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems (2020) 2. Estimated based upon low aluminium intensities for utility and distributed installations and benchmarked against total primary aluminium production from International Aluminium Institute, Primary Aluminium Production (2025)
Note: *Steel is predominantly used for racking, with aluminium components used for more intricate roles.

Over time, as existing PV installations reach end-of-life, aluminium scrap from the PV sector will grow rapidly

As the installed base of solar PV systems matures, decommissioned modules will unlock a significant secondary aluminium supply stream. Assuming a 25-year operating life for both distributed and utility scale solar PV as shown in chart 2-3, aluminium scrap from distributed systems will emerge first, followed by utility-scale contributions later in the decade as newer utility projects approach end-of-life. This cascading timeline reflects deployment patterns and ownership structures: distributed rooftop systems, typically owner-operated and smaller in scale, reach decommissioning thresholds more rapidly and with less coordinated planning than utility assets as they comprised the majority of initial installations. However, this timeline could vary by market and region, with stakeholders identifying that while panels have a useful life of 25 to 30 years, utility scale operators are likely to repower sites earlier (e.g. after 15 years). This is because they face a balance between the capital cost of replacement and declining efficiency of older modules.[1] Consequently, the decision to reuse versus recycle these panels will determine the aluminium scrap availability.

Realising the aluminium recovery opportunity faces significant structural challenges. In some markets, approximately 30% of decommissioned panels in current waste streams are removed before nominal end-of-life due to degradation or early failure, often ending up in landfill for lack of collection infrastructure.[2] Where recovery does occur, it is from scrap metal for aluminium and other components. Furthermore, economies of scale for recycling remain constrained until significant volumes of PV waste is available. This timing mismatch creates a critical gap: distributed waste will accumulate sooner but be more fragmented, requiring collection networks and processing capacity before market-driven recycling economics fully materialise.

Chart 2-3: Indicative PV aluminium scrap based on a 25-year life[3]



Source: 1. Chen, K., Zuo, J., Chang, R., Qian, X., Carbone, A. & Zhang, W., The rational decommissioning of solar photovoltaic (PV) technologies: evidence from Australia (2026) 2. Salim, H., Florin, N. Madden, B., Managing end-of-life solar photovoltaic in Australia: Key findings from installer surveys (2023), 3. IEA, Electricity analysis and forecast to 2026, (2024), 2. Developed from utility capacity in Global Energy Monitor Wiki Global Solar Power Tracker and all installed capacity in IRENA Electricity Statistics. Assumes a 30-year asset life and aluminium intensity of 11 t/MW for utility and 23t/MW for distributed based upon IEA Task 12.

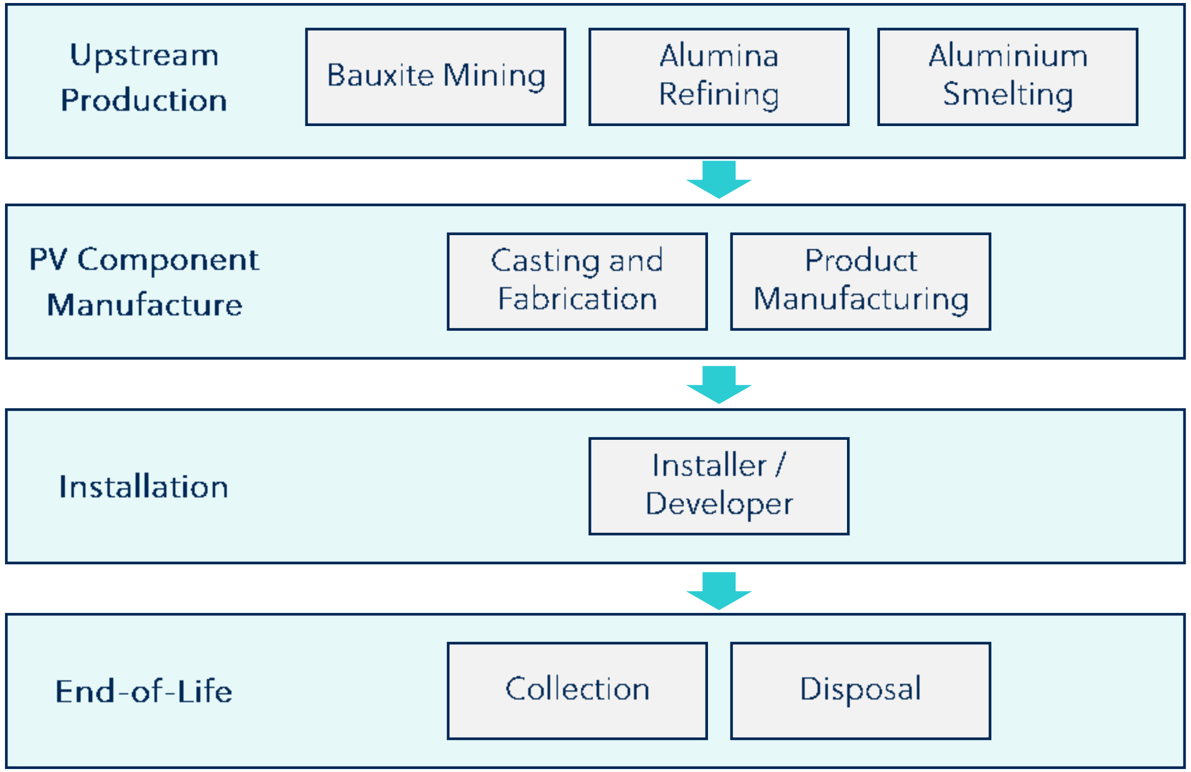
At present, the aluminium supply chain supporting the PV sector is predominantly linear creating a waste and emissions challenge

Today, most PV installations rely on primary aluminium sourced through a conventional linear supply chain. This process begins with bauxite mining, followed by alumina refining, smelting, and fabrication into frames and racking components. While some module recycling and reuse occurs at end-of-life, particularly in regions like Europe, the global market is still dominated by primary aluminium inputs.

A linear supply chain amplifies both waste and emissions risks as PV deployment accelerates. Although end-of-life PV volumes are currently small, they will increase sharply in coming decades, creating a waste challenge. At the same time, continued reliance on primary aluminium, which had an average emissions intensity of 14.8 tCO_2e per tonne aluminium in 2023,[1] means rising demand will drive higher overall embodied emissions unless alternatives are adopted.

Enhancing circularity in PV aluminium offers a major opportunity for emissions reduction and value capture. Recovering aluminium from end-of-life PV systems can displace primary production, reducing carbon intensity and resource depletion. In addition to environmental benefits, recycling unlocks economic value from scrap aluminium and other materials, supporting a more sustainable and resilient supply chain.

Figure 2-1: Primary aluminium life cycle



Source: 1. International Aluminium Institute, Global Aluminium Industry Greenhouse Gas Emissions Intensity Reduction Continues, With Total Emissions Below 2020 Peak (2023)

Rethink, reuse and recycle emerge as the key potential pathways to prevent and manage the aluminium scrap challenge

The 10Rs framework clusters circular economy strategies into three hierarchies: narrowing material flow (Refuse, Rethink, Reduce), slowing material circulation (Reuse, Repair, Refurbish, Remanufacture, Repurpose), and closing loops (Recycle, Recover). Applied to PV aluminium, this hierarchy prioritises upstream design intervention before addressing end-of-life recovery. For the sector to maximise resource efficiency, all three levels must be deployed simultaneously and strategically.

Rethink, Reuse, and Recycle emerge as the three primary pathways for aluminium circularity because they address distinct phases of material stewardship with compounding value. Rethinking design-for-disassembly prevents waste upstream and enables aluminium recovery. Reuse extends product life, deferring aluminium entry into scrap and waste streams and eliminating energy-intensive reprocessing. Recycle serves as the essential backstop, reliably recovering over 95% of aluminium in frames while displacing primary production and saving embodied carbon.[2] Together, these three pathways maximise material value, minimise emissions, and ensure long-term aluminium supply security.

Stakeholder engagement reveals a critical gap: industry lacks the physical recycling and institutional infrastructure to deploy all three pathways simultaneously. The challenges faced for each of these pathways are explored in Chapters 2-4. Chapter 5 outlines key recommendations to drive circular outcomes for key players across the value chain and from Government.

Table 2-3: The 10 R's framework of circularity[1]

Item	Description
Refuse	Avoid unnecessary or unsustainable materials and designs; refuse virgin aluminium where high-quality recycled alternatives are available.
Rethink	Rethink PV module and racking design for modularity, longevity and circularity; optimise aluminium use and connections for disassembly and reuse.
Reduce	Minimise aluminium mass and energy use in production by using lightweight profiles and high-strength recycled alloys while maintaining performance.
Reuse	Extend component life by reusing aluminium frames and racking in new PV installations or other structural applications.
Repair	Repair damaged modules and mounting systems in situ, preserving aluminium components wherever possible to avoid premature scrapping.
Refurbish	Restore used PV modules and mounting assemblies to working condition for resale or redeployment, retaining existing aluminium frames for future cycles.
Remanufacture	Recover aluminium frames and racking, then remanufacture them (after inspection and possible re-coating) into new PV systems that meet current standards.
Repurpose	Repurpose recovered aluminium profiles from PV systems into alternative uses such as construction, fencing or industrial framing.
Recycle	**At end-of-life, collect and process aluminium frames and racking through secondary smelters so the aluminium re-enters production with significantly lower energy and emissions than primary aluminium.**
Recover	Where recycling is not feasible, recover aluminium from mixed or contaminated waste streams using advanced separation, avoiding landfill wherever possible.

Source: 1. Malooly, L. and Daphne, T., R-strategies for a Circular Economy (2023) 2. IEA Photovoltaic Power Systems Programme, Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries (2022)

Today, recovery from PV waste is mixed across markets, reflecting the varied requirements for waste management

Global PV recycling performance demonstrates a stark regulatory divide. Europe leads with mandatory collection and recycling targets established through the Waste Electrical and Electronic Equipment (WEEE) Directive, achieving recovery rates exceeding 80% in practice.[1] However, this performance is exceptional globally. The United States operates without PV-specific recycling mandates, with most end-of-life modules routed to landfill or general e-waste streams, with some metal recovery by scrap metal traders. Canada, India, and Australia do not report recycling rates, reflecting nascent infrastructure and limited policy commitment.[2] China similarly does not report a recycling rate however faces a distinct challenge: with 329 GW of solar capacity added in 2024 alone,[3] recycling occurs predominantly through informal channels without standardised measurement or regulatory oversight, obscuring true recovery.

Stakeholders report significant material leakage to landfill across all regions outside Europe. This is driven by the absence of mandatory take-back schemes, collection infrastructure, and design standards that facilitate disassembly. Most markets are only beginning to experience end-of-life pressures as installations deployed during the 2015–2020 growth phase approach service expiry.

This fragmented landscape creates both risk and opportunity. Without coordinated policy frameworks and investment in collection and processing capacity, valuable aluminium and other materials will be lost before circular economy models can mature.

Table 2-4: PV recovery varies significantly by market, with largely poor performance in major markets today

Country	PV Recycling Rate
Europe[1]	>80%
US[4]	~10%
Canada[2]	Limited PV-specific recycling
China[5]	Nascent
India[2]	Minimal formal recycling
Australia[2]	Minimal

High   Low

Source: 1. European Environment Agency, Recycling materials from green energy technologies (2025) 2. IEA Photovoltaic Power Systems Programme, Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries 3. IEA, Solar PV (2025) 4. NREL, Solar Photovoltaic Module Recycling: A Survey of U.S. Policies and Initiatives (2021) 5 (2022) 5. Wang, C., Tian, P., Zuo, J., Zhong, H., Liu, X., Liu, H., Ma, L., Wang, P., Feng, K., Li, J., Facilitating circularity of end-of-life photovoltaic in China with environmental benefits and costs informed by a high-resolution waste map (2025)

03 The role of upstream material selection decisions in aluminium recycling from end-of-life PV

Material selection drivers across PV manufacturing and installation create both barriers and opportunities for recycled aluminium adoption, with current design choices locking in recyclability outcomes in the future.

Decisions made at the manufacturing, project development and installation phase can drive circular outcomes for aluminium

Manufacturers and project developers face four critical choices that will determine how readily modules and racking can be recycled or reused at the end of service life.[1] These decisions are explored throughout chapter 3.

The first decision concerns the base material selected for components such as frames and racking. While aluminium is not the only option for frames and racking, its durability, corrosion resistance and high recovery rates make it a strong circular choice, provided design practices support disassembly and sortation. However, high cost could see other materials such as polycarbonates preferenced.

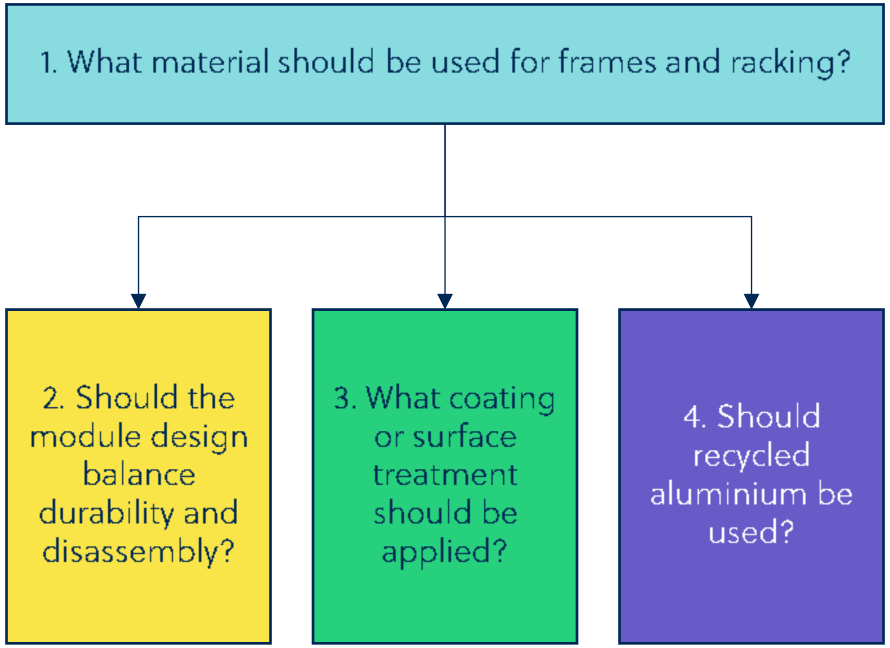
The second decision involves balancing durability against disassembly. Designs which use mechanical fasteners and reversible adhesives improve end-of-life recovery economics relative to permanently bonded laminates or composite structures. However, these shifts in design require changes to manufacturing supply chain processes, adding to upfront costs.

The third decision is the type of coatings and/or surface treatments applied. Coating choices directly influence the future scrap value that recyclers can realise and their willingness to invest in collection and processing capacity.

The fourth decision concerns the use of recycled aluminium content. Using recycled billet in new frames or racking components creates direct closed-loop pathways, reduces embodied carbon and signals market demand which justifies investment in recovery infrastructure, but faces proof of quality, performance and provenance concerns.

These four upstream decisions are interrelated and collectively determine how successfully aluminium can be circulated within PV supply chain.

Figure 3-1: The four key decisions guiding aluminium recycling outcomes



Source: 1. Decision framework developed from stakeholder consultation with PV equipment manufacturers, project developers and installers.

PV manufacturers are facing a race to the bottom on cost and are considering cheaper alternative materials to aluminium

The global PV market operates under intense cost pressure. Module prices have fallen 90 per cent since 2010, driven by manufacturing scale in China and competition across all suppliers.[1] Within this environment, manufacturers face continuous pressure to reduce component costs, including frames and racking.

Faced with this pressure, some manufacturers are exploring alternative frame materials. Manufacturer stakeholders identified they were actively exploring the use of polycarbonate alternatives which offer lower unit cost (see Table 3-1 on page 23). However, these alternatives present significant drawbacks for end-of-life circularity. Polycarbonate alternatives suffer from lower stiffness, require thicker sections to maintain structural integrity, have poor thermal stability and offer very limited recycling pathways outside incineration. Embodied carbon of polycarbonate rivals primary aluminium, but unlike aluminium, recovered polymeric material cannot re-enter manufacturing supply chains economically.[2]

Switching frame materials at scale would create substantial supply chain disruption. Global aluminium extrusion capacity for PV is distributed across China, Europe and India, with established quality standards and compatibility with existing racking and fastening systems. Transitioning to large-scale alternatives would require new tooling, certification testing, and changes to balance-of-system components, imposing substantial capital costs and implementation delays on manufacturers already operating on thin margins.[2,3] As such, while alternatives present a threat to aluminium long-term, in the medium-term it is likely to remain the dominant material.

The strategic opportunity lies in positioning aluminium, particularly when sourced with recycled content, as the circular material of choice. While near-term cost premiums exist for design-for-disassembly and standardised alloys, establishing market guardrails which ensure the full lifecycle costs are considered could incentivise circular supply chains, particularly for aluminium. Stakeholder engagement highlights growing corporate and government commitment to recycled content procurement, creating a market signal that can justify manufacturers' investment in circular design practices.

Current frame and racking designs still prioritise durability over disassembly, embedding aluminium in systems that are difficult and costly to separate at end-of-life. Permanent attachment methods such as adhesive bonding, welding and crimped fasteners, combined with silicone-sealed glass–EVA laminates and corroded bolted connections in utility-scale racking, make non-destructive recovery of frames and profiles economically marginal for recyclers.[4,5] Addressing this requires concurrent innovation in reversible attachment systems and material interface standards so that circular outcomes can be achieved without compromising durability expectations.

Source: 1. IEA, Special Report on Solar PV Global Supply Chains (2022) 2. Tummalieh, A., Beinert, A., Reichel, C., Mittag, M. & Neuhaus, H., Holistic design improvement of the PV module frame: Mechanical, optoelectrical, cost, and life cycle analysis (2021), 3. National Renewable Energy Laboratory, IEC 61215: What it is and isn't (2012) 4. IEA Photovoltaics Power Systems Programme, PV Module Design for Recycling Guidelines (2021) 5. Al Zaabi, B. & Ghosh, A., Managing photovoltaic waste: Sustainable solutions and global challenges (2024)

These materials have varied benefits and costs across their lifecycle

Table 3-1: Comparison between alternative materials for frames and racking

Material	Material Advantages	Material Disadvantages	Emissions Intensity ($t\ CO_2e$/ t material)	Indicative Cost (USD/t material)	Conclusion
Primary Aluminium *(incumbent for frames and distributed racking)*	Easily extrudable, light weight, anodised layer supports corrosion resistance[1,2]	High embodied carbon, price volatility, galvanic compatibility with some alloys[1,2]	12-17[3]	\$2,000-\$2,800[5]	Property advantages justify cost, emissions intensity may become problematic over time
Recycled Aluminium		Quality specifications can be limited in availability, higher cost[1,2]	0.5-2[4]	Recycled aluminium trades at a discount to primary but can be more expensive if additional processing steps required[1]	Same mechanical properties as aluminium, lower emissions intensity
Primary Steel *(incumbent for utility racking)*	High strength, low cost, high stiffness, mature supply chain, lower emissions[1,2]	Heavier, needs galvanising/coating, steel extrusion can be more costly and impose design rigidity[1,2]	1.4-3[6]	\$400-\$1,000[7]	Promising where weight and design rigidity aren't an issue
Recycled Steel			0.2-0.9[6]		
Plastic/composites (e.g. PVC, polycarbonates)	Low weight, ease of extrusion, corrosion resistant, good for bespoke applications[1,8]	Much lower stiffness, greater thermal expansion, lower outdoor durability (UV and heat), limited recyclability[1,8]	3-6[9,10]	\$600-1,800[11]	Durability, stiffness and end-of-life management challenges make plastics less suitable.

Advantage | Neutral | Disadvantage

Source: 1. Informed by stakeholder consultation 2. Solar Energy System, Comparison of steel and aluminium structure for solar PV mounting (2023) 3. Global Aluminium Industry Greenhouse Gas Emissions Intensity Reduction Continues, With Total Emissions Below 2020 Peak (2023), 4. Hydro, Low-carbon and recycled aluminium (n.d.) 5. Trading Economics, Aluminium (accessed 3/12/2025) 6. World Wildlife Fund, Mined the gap: Australia's place in the emerging green iron value chain (2025) 7. Trading Economics, Steel (accessed 3/12/2025) 8. UNQ, Pros and Cons of Polycarbonate Sheets: Strategies for Overcoming Challenges (2025) 9. Energy Transition Commission, Sectoral Focus: Plastics (2019) 10. Climatiq, Factor – Polycarbonate Slab (2023) 11. Trading Economics, Polyvinyl (accessed 3/12/2025)

Upstream players are driven by material suitability, aesthetic and cost, with limited consideration on end-of-life outcomes

Environmental durability is the primary technical driver behind coating use. Clear anodised coatings provide electrochemical protection against corrosion and are standard for distributed installations in moderate climates.[1] For coastal and high-UV environments, manufacturers apply thicker anodised finishes or multi-layer systems combining anodising with thin polyester or polyurethane topcoats for added durability.[2] For utility-scale systems in coastal regions, some manufacturers specify heavier powder coatings (e.g. polyester or PVDF fluoropolymers) chosen for superior UV resistance and aesthetic uniformity.[3,4]

Aesthetic and market differentiation drive coating decisions in competitive segments. Coloured powder coatings (polyester, epoxy, PVDF) are widely used in residential markets where visual uniformity and "black frame" aesthetics command premium positioning.[5,6] PVDF (polyvinylidene fluoride) coatings, while substantially more expensive, are increasingly specified for utility-scale projects as a durability differentiator.[4]

Cost optimisation remains a critical factor, particularly in price-sensitive markets. Anodised coatings are the most economical option for corrosion protection, whereas powder coatings and PVDF add material and processing costs that manufacturers seek to minimise.[4] Consequently, the presence of these coatings drives the discount recyclers receive on the London Metals Exchange price.

Stakeholder engagement revealed that recycling implications of coating choice are rarely weighed during material selection. Manufacturers and project developers prioritise durability and aesthetics, with end-of-life recovery economics treated as a downstream concern.

Table 3-2: Coating motivations and implications

Coating	Driver	Recyclability
Clear anodised	Cost minimisation and corrosion protection	High
Thick anodised with polyester topcoat	Marine durability and extended service life	Moderate
PVDF fluoropolymer	Maximum UV protection	Low
Black powder coat	Aesthetic Appeal	Low

Source: 1. Growel, Anodizing applications in the solar industry: technical insights for high-efficiency solar systems (2025) 2. The Construction Specifier, Selecting aluminium finishes for coastal areas (2013) 3. Sinoextrude, PVDF coating vs powder coating for architectural cladding (2025) 4. High Performance Coatings, Understanding AAMA 2605 Standards for High Performance Coatings (n.d.) 5. Aluvoltec, Aluvoltec Solar Panel Frames: Premium Aluminium Frames (2025) 6. PV knowhow, Why Solar Panel Frame Material Matters (2024)

PV manufacturers are concerned about the quality of recycled aluminium content and the effects on final PV product

Through our stakeholder consultation, PV manufacturers perceived technical and commercial concerns about sourcing aluminium extrusions with recycled content. These concerns are rooted in product liability, warranty obligations and the technical requirements of frames and racking. These concerns represent legitimate barriers that must be addressed through supply chain transparency and quality assurance mechanisms and proof of performance compliance. This perception was supported by discussion with aluminium recycling value chain players.

Technical performance concerns center on material purity and mechanical properties. Recycled aluminium content may contain residual trace elements (e.g. iron, silicon, copper or zinc) that affect alloy strength, ductility and corrosion resistance if contamination levels exceed specification limits. For 6-series extrusions used in PV frames, ISO 12020-2 standards and companion alloy standards mandate maximum impurity levels; violations can compromise frame integrity under different environmental conditions.[1,2] Stakeholder discussions reveal that manufacturers lack confidence in the quality of currently available recycled billet streams because recyclers often blend materials from multiple sources and provide limited material or batch-level documentation.

Warranty and liability exposure compounds this concern. If a PV system fails due to frame corrosion or mechanical failure, manufacturers face potential warranty claims and reputational damage. Sourcing recycled material from an unknown supply chain, with no documented provenance or third-party testing, presents unquantifiable liability risk that manufacturers are reluctant to assume without long-term contractual protection and insurance arrangements.

Chart 3-3: Pathways to overcoming manufacturer concerns

Barrier	Current State	Solution Pathway
Material purity uncertainty	Limited ; mixed-source batches	certification and testing standards
Lack of supply volume certainty	Recyclers lack demand signals	Long-term offtake contracts to stimulate market
Unproven performance equivalence	Manufacturers assume recycled content is below primary aluminium in quality	Third-party testing; benchmark data publication
Cost premium	Recycled content may incur a premium to meet quality requirements	Blended procurement; low-carbon premium
Warranty liability exposure	Single sourcing failure leading to reputational damage	Contractual protections and product insurance

Source: 1. iTeh Standards, EN 12020 – 2:2022 Aluminium and aluminium alloys (2022), MDPI, Structure and Properties of Aluminium Alloys (2021)

04 The opportunities and challenges for PV scrap aluminium reuse and recycling

Problematic alloy composition, coatings, and system design challenges could undermine circularity and expose the PV industry to higher costs and environmental impacts.

Solar PV modules which are decommissioned before end-of-life can be reused, but would only delay the PV aluminium scrap issue

Solar PV modules decommissioned before true end-of-life represent a reuse opportunity. Many panels removed for repowering, site redevelopment or inverter upgrades still operate at greater than 80% per cent of their original capacity and can deliver productive service in lower-duty applications or new markets.[1] Capturing this value can defer recycling costs, reduce material demand and provide affordable generation capacity for communities and regions where new modules remain cost-prohibitive.

Scaling reuse faces several barriers which must be overcome. Technically, second-life modules require verification of electrical safety, insulation resistance and performance, but there is no globally harmonised testing protocol; retesting to local IEC/UL/AS standards adds time and cost and creates liability concerns for refurbishers.[1] Regulatory uncertainty, particularly around the Basel Convention and national import rules, means second-hand modules risk being classified as waste at borders, deterring cross-border trade.[1] Infrastructure gaps, including limited refurbishment hubs and aggregation facilities, further raise logistics and handling costs, especially where modules are removed from dispersed sites.

Targeted interventions can unlock the reuse opportunity, however this only delays rather than prevents the PV waste issue. Harmonised second-life testing standards, streamlined import/export rules for certified modules and investment in regional refurbishment hubs would improve economics and confidence for both domestic and export reuse pathways. However, this would not prevent the need for recycling of aluminium when end-of-life is reached.

Case Study 4-1: Opportunities for component reuse

Module Frames

Module frames present the clearest reuse opportunity. Frames are mechanically durable and can retain structural integrity for 50+ years under proper maintenance.[2] However, reuse markets remain nascent globally due to:

(1) variability in frame designs and adhesive systems limiting standardised testing protocols,

(2) lack of certified refurbishment infrastructure in most markets, and

(3) regulatory uncertainty regarding liability and performance warranties for reused components.

Stakeholders report willingness to develop reuse infrastructure, but only if certification standards and take-back mechanisms are clarified.

Distributed Racking Systems

Distributed racking systems demonstrate the highest reuse feasibility. These components are engineered for decades of outdoor service and require only mechanical inspection and corrosion treatment for redeployment. Distributed racking can be retained through multiple installations, reducing aluminium demand per repowered site by 25–40%.
However, module standardisation challenges persist:

(1) modern modules are thinner (30–35mm) than legacy panels (50mm), requiring new clamps and hardware incompatibility resolution.

(2) Additionally, module length and width have evolved with cell architecture changes, meaning rail spacing may not accommodate new modules.

Source: 1. Institute of Sustainable Futures, Enabling a Responsible Second-Hand Market for Photovoltaic Systems in Australia (2023) 2. Based upon stakeholder consultation.

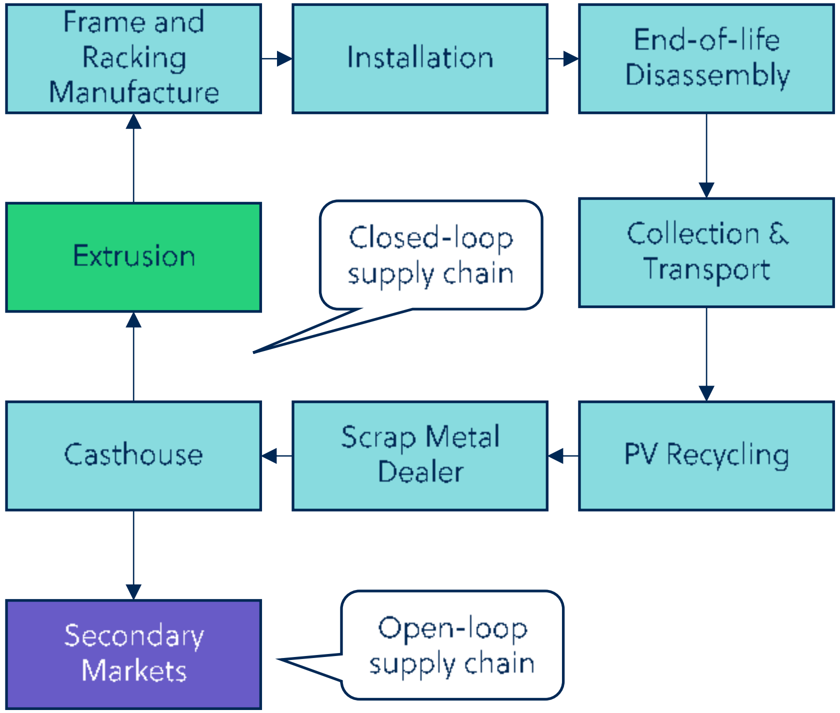
Recycling can be both closed and open loop within the aluminium supply chain, with open loop likely the most viable pathway

Recycling end-of-life PV aluminium can follow both closed-loop and open-loop pathways, but open-loop flows are likely to dominate in the medium term. Closed-loop recycling keeps aluminium within PV value chains, returning recovered frames and racking to new module or racking production after end-of-life. This requires high alloy purity, of scrap streams and close geographic alignment between where PV is manufactured and where systems are decommissioned. These conditions are currently met only in a limited number of manufacturing hubs in Europe and parts of Asia.

For most markets, open-loop recycling is the more practical pathway. PV frames and racking can be processed into furnace-ready scrap and sold into established secondary aluminium markets such as automotives, construction and general engineering. Stakeholder interviews highlighted that recyclers in North America are already optimising logistics and processing for these alternative commodity markets, reflecting both limited local PV manufacturing and the capital intensity of dedicated closed-loop facilities. In Europe, increasing use of measures such as the carbon border adjustment mechanism and chain-of-custody certification is tightening quality expectations for recycled inputs, but industry participants still see greater near-term scale in open-loop flows.

Regional supply chain structures will shape how PV aluminium is recycled. PV manufacturing centres with co-located extrusion capacity and robust systems are best placed to pilot closed-loop models. However, open-loop opportunities for recycled aluminium content, such as in the construction sector, present an equally compelling pathway. Conversely, markets dependent on PV imports are more likely to use PV scrap in secondary markets. For investors and policymakers, the priority is to ensure that recovered aluminium consistently reaches high-value secondary uses, while building the standards, data systems and commercial partnerships needed to support higher-purity, closed-loop opportunities as they become viable.

Figure 4-1: Closed and open loop aluminium recycling supply chains



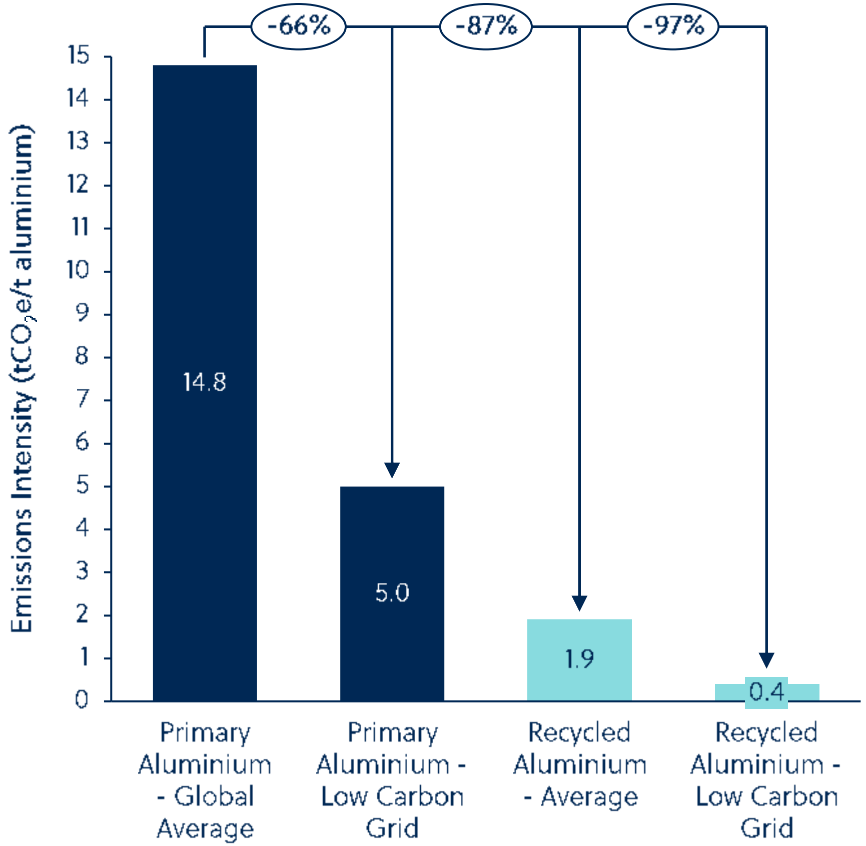
The benefits of aluminium recycling are significant for value capture, emissions avoidance and material circularity

The environmental benefits support the case for aluminium recycling. Primary aluminium production has an emissions intensity average of 14.8 tCO_2e per tonne, driven by the electrolysis-intensive Bayer process.[1] Recycled aluminium reduces this by up to 97 per cent when paired with low-carbon electricity sources, and by approximately 66 per cent on average grid mixes. Additionally, secondary aluminium avoids the broader environmental costs of mining and refining, including land disturbance, water consumption and localised pollution, that accompany primary production in bauxite-extractive regions. By shifting material flows towards secondary sources, the sector can reduce reliance on imported primary inputs, supporting both supply chain resilience and decarbonisation objectives.

Economic incentives for aluminium recycling from PV could strengthen over time. The intrinsic scrap value of recovered aluminium, particularly high-purity 6-series alloys from module frames and racking, could grow as secondary markets tighten and low-carbon premiums become embedded in commodity pricing. While contamination from adhesives and fasteners can degrade scrap quality and therefore price realisation, clean, furnace-ready aluminium can command significant value. This creates a compelling case for investment in collection, sorting and processing infrastructure from PV.

Stakeholder engagement reflects growing recognition of these dual benefits. Recyclers increasingly see high-value applications for clean PV scrap across automotive, construction and engineering sectors. However, material quality, and consistency remain key barriers.

Chart 4-1: Emissions intensity of aluminium by source[1]



Source: 1. Primary Aluminium – Global Average – International Aluminium Institute, Global Aluminium Industry Greenhouse Gas Emissions Intensity Reduction Continues, With Total Emissions Below 2020 Peak (2023), Primary Aluminium – Low Carbon Grid – Aluminium Stewardship Initiative – Issue Brief: Low Carbon Aluminium (2021) , Recycled & Scrap Aluminium – average & Recycled & Scrap Aluminium – Low Carbon Grid – Hydro, Low-carbon and recycled aluminium (n.d.)

Impurities drive the ease of recycling and value received for end-of-life PV aluminium

End-of-life PV aluminium reaches recyclers with a wide range of alloys and surface conditions. Stakeholders identified value recovery from aluminium depends on how easily coatings and attachments can be removed to produce clean, furnace-ready scrap. High-purity 6-series aluminium from frames and racking can attract strong prices when free from steel fixings, sealants and heavy organic coatings, while mixed-alloy, heavily coated or composite sections are typically down-valued into casting grades.

Standard 6-series extrusions with clear anodised finishes or thin powder coatings are generally considered low friction for recycling. This is because coatings can be removed in pre-treatment while alloy chemistry remains within tight limits for extrusion or automotive feedstock. Challenges increase where components incorporate thick marine-grade coatings, fluoropolymer paints, bonded insulation or composite attachments, which raise processing costs and can push recovered material into lower-value applications.

Recyclers highlighted three priorities:

1. Design choices that use standard 6-series alloys, minimal coating systems and mechanically removable fixings directly influence future recycling revenue.
2. Markets that set clear end-of-life quality specifications, supported by chain-of-custody or digital product passport schemes, are better placed to capture "green aluminium" premiums for clean scrap streams.
3. Policy signals that discourage composite or difficult-to-separate designs in frames and racking lower processing costs and increase recycling likelihood.

Table 4-1: Barriers and enablers from different impurities

Impurities	Barriers	Enablers
Alloy Type	Mixing alloy types across 6-series or with other series lowers purity and end-value and can prevent recycled content meeting 6-series specifications, limiting markets for scrap dealers.	Use standard 6-series alloys for frames and racking, avoiding mixed-alloy and heavily coated sections so material remains suitable for high-value 6-series applications.
Coatings	Coatings reduce aluminium yield for scrap dealers and casthouses, lower the price paid to recyclers, and some coatings are incompatible with casthouse processes.	Use clear anodised or thin, easily removable coatings so that pre-treatment can strip coatings while preserving alloy chemistry for high-value recycling.
Contaminants	Contaminants, bonded insulation and composite or difficult-to-separate attachments increase processing costs and push material into lower-value casting grades.	Design mechanically removable fixings and minimise contaminants so recovered scrap is clean, furnace-ready and can access higher-value markets.

Variations in module design can inhibit the ease of recovery of aluminium

Module design choices strongly influence aluminium recycling feasibility. Designs that use standardised aluminium frames, minimal coatings and mechanical fixings allow frames and racking to be removed quickly, producing clean 6-series scrap that can be remelted into high-value product. By contrast, frames that are glued to laminates, incorporate complex composite profiles or rely on heavy fluoropolymer coatings increase processing steps and contamination risks, pushing scrap into lower-value casting applications and raising costs for recyclers.

Variation in dimensions and racking interfaces also matters. Where frame thickness, clamping zones and module sizes are broadly standardised, racking can often be reused when systems are repowered, and frames can be processed in uniform batches that support higher scrap prices. Where sites include multiple module generations and non-standard dimensions, recyclers must sort and cut smaller, more heterogeneous batches, which erodes economies of scale and leads to mixed-alloy streams. Overall, improving recyclability and value recovery for PV aluminium depends not only on alloy and coating choices, but on whole-of-system structure and design.

Source: 1. Deng, R., Chang, N., Ouyang, Z. and Chong, C., A techno-economic review of silicon photovoltaic module recycling (2019) 2. IEA Photovoltaic Power Systems Programme, PV Module Design for Recycling Guidelines (2021)

The maturity of aluminium recycling infrastructure varies by market

Infrastructure for recovering aluminium from end-of-life PV varies significantly across markets:

- Europe is the most advanced, with WEEE-driven take-back schemes, dedicated PV dismantling plants and multiple high-recovery recycling lines. Its large secondary aluminium and extrusion sectors can absorb high-purity billet.
- China and India are scaling integrated disassembly and remelting capacity to respond to growing end-of-life volumes, however quality control remains uneven outside major industrial hubs.
- Canada and the United States have mature general metals scrap and secondary smelting industries but only emerging PV-specific infrastructure.
- Australia's recycled aluminium supply chain is tailored toward export.

Stakeholders emphasised that without integrated PV disassembly, scrap collection and treatment and local remelting/extrusion capacity, recycling of aluminium will struggle. The business case strengthens where volumes are predictable, recycled material quality is assured, and policy settings favour low-carbon and recycled content in new products. Strengthening these mid-stream capabilities is therefore central to capturing the full economic and emissions-reduction potential of PV aluminium recycling.

Stakeholders identified six key risks which currently inhibit supply chains for recycling facilities (Figure 4-2 on page 33). Each of these risks need to be mitigated for aluminium recycling to grow.

Sources: 1. For sources, see appendix B.

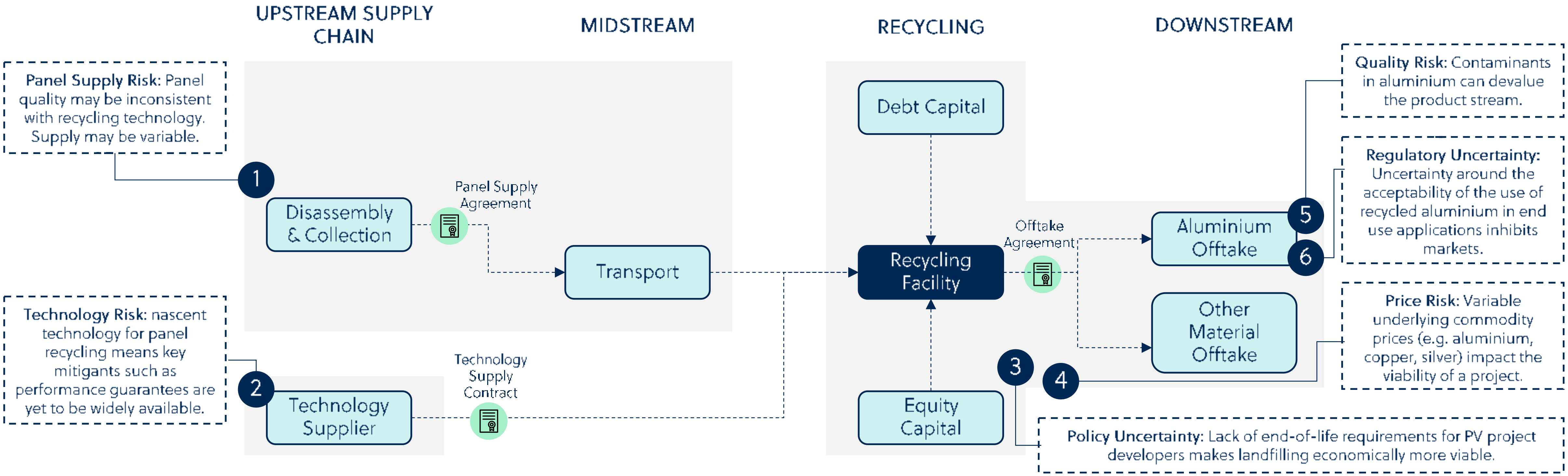
Table 4-2: Infrastructure assessment across markets[1]

Country	PV Disassembly	Solar PV Recycling	Aluminium Scrap Collection & Treatment	Casting & Remelting	Extrusion
Australia	Limited	Limited	Developing	Limited	Developing
Canada	Developing	Developing	Mature	Mature	Developing
China	Developing	Developing	Mature	Mature	Mature
Europe	Mature	Mature	Mature	Mature	Mature
India	Developing	Developing	Developing	Developing	Developing
United States	Developing	Developing	Mature	Mature	Mature

Mature | Developing | Limited

Six risks inhibit the commercialisation of the PV recycling supply chain; mitigating these risks can unlock aluminium recovery

Figure 4-2: Six key risks for recycling facilities in the PV supply chain



To develop supply chains for aluminium recovery, the economics of full PV end-of-life management needs to be improved

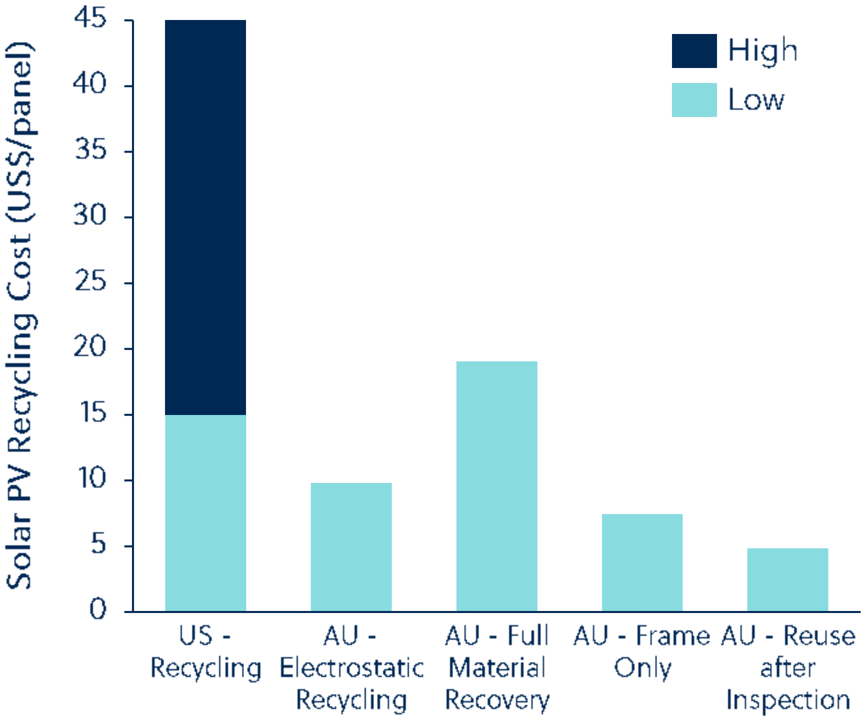
Developing economically viable aluminium recovery from end-of-life PV depends on improving the overall business case for PV recycling. Collection, disassembly and processing remain costly at current volumes, with many facilities relying on government support or schemes to operate. Existing plants process only a small fraction of projected PV waste, keeping unit costs high and landfill comparatively attractive.

Aluminium is one of several value streams in PV recycling. Racking and supports can be removed and sold as scrap, but frame recovery requires further mechanical processing at dedicated facilities. Recyclers emphasised that project economics improve significantly when aluminium is recovered alongside glass, silicon and copper, allowing combined revenues to support investment and operating costs.

Achieving profitability in PV recycling requires a critical mass of supply to achieve economies of scale. Stakeholders identified facilities need a steady and predictable flow of end-of-life panels to justify investment in automation and sustain operations. Without this consistency, recycling plants risk underutilisation, which undermines cost efficiency and delays the development of robust recycling infrastructure.

Unlocking the economics of frame recycling therefore requires coordinated supply chains and policy settings that favour whole-of-module collection and treatment. Mandating or incentivising comprehensive PV recycling can lift throughput, reduce per-tonne costs and provide the certainty needed for commercial facilities to compete with landfill while delivering higher-value aluminium recovery.

Chart 4-2: Literature cost of recycling comparison under different configurations[1,2]



Sources: 1. U.S. Department of Energy, Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan (2022) 2. Australian Centre for Advanced Photovoltaics, Solar Panel Recycling or End of Life Management Scoping Study (2024)

05 Government & standard body approaches to recyclability for end-of-life PV and aluminium

Governments and standard bodies are taking different approaches to drive reuse and recycling of aluminium from the PV sector, with varying degrees of success.

EPR is a proven policy framework that has shown improvements in collection, recycling and material transparency

Extended Producer Responsibility (EPR) is a policy framework that shifts responsibility for products across their full life cycle, including end-of-life management, from governments to producers. This responsibility may be financial, operational, or both, and is intended to create incentives for improved product design and end-of-life performance. Evidence from long-running schemes shows that EPR mobilises long-term, dedicated funding, increases separate collection and recycling rates, and improves transparency in material and financial flows.[1]

For long-lived products, such as aluminium, EPR works particularly well because it creates predictable, long-term producer obligations before significant end-of-life volumes arise. This policy certainty can underpin stable, producer-funded investment in specialised sorting and recycling infrastructure and, where eco-modulated fees or design requirements apply, encourages product designs that are easier to disassemble and recycle at end-of-life.[1]

In the PV aluminium value chain, EPR and related product-stewardship frameworks can support more systematic collection and treatment of end-of-life modules and strengthen reporting on material composition and flows across the supply chain. Over time, these measures can improve the predictability, traceability and consistency of aluminium feedstock for recycling, making remelting and higher-value aluminium recovery more viable and helping address policy and coordination gaps that currently limit circular outcomes in the solar PV sector in other markets.

Key components of effective EPR schemes[1]

- **Clear producer responsibility:** Producers and their obligations are precisely defined to ensure accountability and compliance.
- **Target setting:** Ambitious but achievable collection and recycling targets drive performance and investment.
- **Stakeholder coordination:** Formal collaboration between producers, recyclers, governments and consumers underpins system effectiveness.
- **Transparency:** Regular reporting, audits and public disclosure enable monitoring, trust and benchmarking.
- **Government oversight:** Strong enforcement, producer registries and monitoring prevent free-riding and ensure a level playing field.

Source: 1. OECD, Extended Producer Responsibility: Basic facts and key principles, (2024)

Governments are responding unevenly to the PV end-of-life challenge, with EPR proving to be an effective policy tool

Government responses to EoL PV are highly uneven. In more advanced regions, clear product stewardship obligations, harmonised technical standards and dedicated collection systems are beginning to lift recovery rates and support investment in PV-specific recycling infrastructure.

In regions with mature, mandatory EPR frameworks for aluminium in solar PV, backed by robust regulation and long-term funding signals, regulatory clarity, harmonised standards and stable funding have translated into more consistent collection systems, higher-quality material recovery and stronger coordination across the PV value chain. Europe's mandatory WEEE-based EPR schemes, along with national programs, as seen in France, illustrate how harmonised rules, audited operators and EN 50625-aligned treatment standards can deliver reliable dismantling and high-quality aluminium recovery. China's standards-driven model achieves EPR-like outcomes by requiring operators to meet detailed GB/T recycling and reuse requirements as a condition of licensing and eligibility for government projects, which are likely to support separation of aluminium frames and scalable secondary production in the future.

Many markets remain constrained by fragmented regulations, inconsistent application of e-waste rules and unclear producer responsibilities. This patchwork of standards limits economies of scale, depresses investment confidence and slows the development of specialised recycling capacity needed to manage the coming wave of retired PV assets. Australia and India are progressing towards national stewardship or EPR for PV, but interim arrangements, exemptions and evolving guidelines and infrastructure mean recycling capacity and recovery performance remain variable. In Canada and the US, PV is covered inconsistently across provinces and states, with no overarching federal EPR scheme; where specific rules exist, authorised processors improve aluminium recovery, but non-covered regions follow general e-waste pathways, resulting in patchy collection, weaker traceability and a slower build-out of PV recycling infrastructure.

Source: 1. For sources, see appendix C and D.

Table 5-1: Comparison of end-of-life regulatory models across key regions[1]

Region	Maturity	Regulation / framework and purpose
Europe	High	**WEEE Directive 2012/19/EU (amended 2024/884) & EN 50625 standard:** Mandatory EPR for electrical products, including PV modules, ensuring proper collection, treatment and recycling
China	Medium	**GB/T 39753-2021, GB/T 45075-2024:** National technical requirements for recycling & reuse of PV modules to standardise treatment practices
Australia	Medium	**PV Product Stewardship Scheme (in development by DCCEEW):** A future producer-funded framework for the collection and recycling of end-of-life PV modules
India	Low	**E-Waste Management Rules 2022 – PV EPR:** Introduces mandatory EPR for PV modules, requiring producers to register and meet collection and recycling targets
Canada	Low	**Provincial EPR/EEE laws (e.g. Québec Q-2 r.4.01):** Assign responsibility for managing e-waste (including PV where included) to producers under province-specific rules
United States	Low	**State PV/Universal Waste law (e.g., WA Stewardship Law 2031):** State regulations govern safe handling, storage and recycling of PV modules; no unified federal producer responsibility.

Gaps in standards and regulation across markets are impeding improvements to the recyclability of PV aluminium

Existing standards governing the design and installation of solar PV focus on safety and durability. IEC 61215 established the design-qualification and type-approval requirements to demonstrate long-term outdoor performance.[1] Further to this IEC 61730 defines construction and testing requirements to control electrical, mechanical, thermal and fire safety risk.[1]

Global rules for designing PV modules for disassembly are still the exception rather than the norm. Europe is one of the few regions moving towards PV-specific requirements through WEEE and EN 50625 treatment standards.[2] Most other markets continue to treat PV as general e-waste, so frames, fasteners and laminates are not engineered with end-of-life recovery in mind, making clean aluminium separation more complex and costly.[3]

Standards which factor end-of-life into aluminium alloy choice, coatings and treatment pathways are also lacking.[4] This results in a mix of 6-series alloys, surface treatments and backsheets that complicate melt batching and limit closed-loop recycling potential for aluminium.[4] Without common specifications for PV frames and mounting systems, recyclers face variable scrap quality and higher contamination risks, reducing the value of recovered material and the incentive to invest in dedicated processes.

Traceability frameworks are underdeveloped, with limited use of durable labelling, digital product passports or harmonised reporting of module composition and origin across markets.[4,5] This weak visibility into alloy content and coatings makes it harder to route modules to appropriate treatment, manage hazardous substances and demonstrate high-quality secondary aluminium to downstream users.

Individual countries can sharpen their rules, but manufacturing of PV modules and frames is highly concentrated in a small number of producer regions, meaning most national efforts alone will not shift design or material standards at scale. A coordinated global push, linking design-for-disassembly standards, alloy and coating specifications, and common traceability tools, will be needed to unlock genuinely circular aluminium flows from the next wave of PV deployment.

Figure 5-2: Key characteristics of standards reform

Source: 1. NREL, Standards for PV Modules and Components – Recent Developments and Challenges (2024) 2. iTeh Standards, EN 50625 (2018) 3. IEA, End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies (2018) 4. IEA Photovoltaic Power Systems Programme, PV Module Design for Recycling Guidelines (2021) 5. Polverini, D., Alfieri, F., Spiliotopoulos, C. & Arcipowska, A., Towards a recyclability index for photovoltaic modules: Methodology, challenges and policy implications (2024)

Aluminium recyclers have a clear perspective on the necessary response

Stakeholders across the PV and aluminium value chains see a strong circularity opportunity but describe a system that is not yet set up to capture it. Their message is consistent: aluminium is not the problem; policy settings, market signals and product design are.

Across markets, recyclers, extruders and manufacturers emphasise similar pain points. They point to fragmented and under-developed recycling ecosystems, where PV dismantling and specialist remelting capacity lag rapidly rising scrap volumes. They also highlight PV module design as a structural barrier, with encapsulants, bonded laminates and diverse formats making delamination slow and expensive, eroding already thin margins on aluminium, glass and plastics

Recyclers are explicit that policy and regulatory change should unlock markets for all recycled PV materials at scale, including aluminium. Integrated circular models need scale to viably operate collection, sorting and remanufacturing. Large extruders emphasise that without whole-of-industry coordination linking recyclers, smelters, processors, end markets and government, a circular market will struggle to form. Recyclers emphasised a need for long-term partnerships and predictable feedstock, rather than short-term scrap trading. Extruders and product manufacturers are seeking coordinated standards, recycled-content signals and certification frameworks that give them confidence to specify low-carbon or recycled aluminium. While differences emerge in what policy response can drive market formation, downstream supply chain players are clear in the overall goal.

Source: Rennie interviews with various organisations in the PV and aluminium supply chain

06 Recommendations

A coordinated, global policy and industry response, integrating recycling pathways, standards, and upstream design choices, can unlock a more resilient and sustainable aluminium lifecycle in the PV sector.

Industry and government are both responsible for enabling the recycling of aluminium in the PV sector

Improving aluminium recovery from end-of-life PV requires coordinated action across the entire value chain. Industry stakeholders and market research have identified clear priorities and enablers needed to scale aluminium circularity from PV waste while improving project economics and supply chain resilience. This chapter outlines potential levers which can be pulled by different stakeholders to improve aluminium recycling outcomes. Further investigation is needed across markets to assess what the best approach is, capturing further idiosyncrasies between markets.

Governments can create the enabling policy and regulatory environment for circular PV and aluminium systems. This includes:

- Strengthen policy and market signals by introducing enforced product stewardship (e.g. EPR schemes for PV modules). This should be supported through internationally aligned frameworks,
- Support recycling and reuse infrastructure with dedicated grants or low-interest finance,
- Enable reuse pathways with national standards for second-life PV and racking and regulatory assurance for exports.

Standards bodies can embed recyclability considerations into PV and aluminium standards so circular pathways become the default. This includes design-for-disassembly requirements for modules and racking, rules for recyclable coatings and surface treatments, agreed testing procedures for second-life modules, and standards covering alloy composition and recycled content.

Upstream manufacturers influence recyclability through design choices. Manufacturers can continue to select standardised 6-series aluminium alloys, prioritise easy to recycle coatings and eliminate adhesive attachments. Project developers can also prioritise sourcing modules and racking designed for end-of-life recovery and establish take-back arrangements that secure material supply to domestic recyclers.

Downstream recyclers emphasise that investment in disassembly and remelting infrastructure is only justified where volumes are predictable, material quality is assured and markets for recovered billet exist. This requires certification systems that verify alloy composition and recycled content, enabling recyclers to command premiums for clean PV scrap while allowing casthouses and extruders to confidently procure low-carbon feedstock.

The International Aluminium Institute can catalyse cross industry alignment by developing global guidance on design practices, alloy specifications and closed-loop recovery models while leading global collaboration through the existing IEA Task Force 12 on aluminium recycling.

This section outlines specific recommendations for each stakeholder group and the policy levers that can unlock high-value aluminium recovery and support the transition to circular PV supply chains.

Governments and standard bodies can provide the market guardrails and incentive structures for aluminium circularity

Institution	Theme	Risk	Recommendation	Impact	Timing	Complexity
Government	Strengthen Policy and Market Signals	Policy Uncertainty	• Consider the introduction of EPR schemes for solar PV systems applied to project developers and installers at point of purchase with eco-modulated fees that reward design-for-recyclability. Key considerations for aluminium under an EPR scheme include non-coated or recyclable coatings, simpler frame attachment and traceable alloy specifications	High	Short Term	High
	Build Viable Recycling and Reuse Infrastructure	Policy & Technology Risk	• Provide grants or low-interest finance for establishing dedicated PV recycling facilities and regional dismantling hubs to improve aluminium recovery economics and unlock private capital • This could initially favour co-location of PV dismantling hubs with scrap-metal yards or transfer stations to leverage existing logistics infrastructure • Fund regional aggregation facilities to consolidate PV waste from remote areas, reducing transport costs and increasing material throughput	Moderate	Short Term	Moderate
	Support Product Stewardship and Transparency	Panel Supply Risk	• Require digital product passports for PV modules and racking to aid, including alloy compositions and coatings. Make passports a condition for government procurement and EPR compliance	Moderate	Long Term	Moderate
	Enable Reuse Pathways	Regulatory & Quality Risk	• Develop national standards for second-life PV and racking, including performance thresholds, testing requirements, and safety protocols, aligning with international protocols • Provide regulatory assurance frameworks that streamline export of certified second-life modules to responsible markets	Moderate	Short Term	Moderate

Standards Bodies (SA, IEC, ISO)	Standards for Recyclability	Panel Supply, Quality & Regulatory Risk	• Develop standards for:
			  • design-for-disassembly of PV modules and racking
			  • recyclable coatings and surface treatments
			  • testing procedures for second-life PV modules
			  • alloy composition and recycled content, working with governments
			• Create nationally recognised protocols for safe reuse, including electrical and mechanical tests
			• Align these protocols with export requirements to reduce administrative barriers for reuse markets
				High	Short Term	High

High Impact/Short Term (next 5 years)/High Complexity — Moderate Impact/Moderate Term (next 10 years)/Moderate Complexity — Low Impact/Long Term (15 years +)/Low Complexity

Upstream value chain players can improve material selection and design for recyclability to improve aluminium reuse and recycling

Supply Chain Player	Theme	Risk	Recommendation	Impact	Timing	Complexity
PV module and racking system manufacturers	Material Selection and Quality	Panel Supply & Quality Risk	• Adopt recyclable-friendly coatings and avoid those that inhibit recycling (e.g., thick powder coatings) • **Standardise preferred aluminium alloy families (e.g., 6063) that are easier to recycle and widely accepted by extruders and casthouses** • Voluntarily pilot recycled content procurement, supported by traceability and certification	High	Short Term	High
	Design for Recyclability	Panel Supply & Quality Risk	• **Redesign frames to avoid problematic adhesives and use detachable mechanical fasteners for easy separation** • Minimise or standardise non-aluminium components in frames to improve yield and reduce processing costs • Use labelled alloy grades on extrusion profiles to improve downstream identification and value recovery	High	Short Term	High
	Supply-Chain Collaboration	Price Risk	• Enter long-term contracts with aluminium recyclers and extruders to secure recycled aluminium volumes • Co-invest in joint recycling partnerships with recyclers to ensure consistent feedstock and quality • Engage with downstream players on initiatives which support aluminium and other component recyclability	Moderate	Moderate Term	High
Project developers and installers	Improve End-of-Life Practices	Panel Supply & Quality Risk	• Integrate end-of-life planning into procurement, selecting products with higher recyclability, known alloy content, and verified recycled content • Establish end-of-life offtake arrangements with recyclers	High	Moderate Term	High
	Enable Reuse	Panel Supply Risk	• Develop processes to test, grade, and document removed modules and racking, enabling secondary markets • Work with certified refurbishers to ensure modules pass electrical safety and insulation resistance tests for reuse or export	Moderate	Moderate Term	High

High Impact/Short Term (next 5 years)/High Complexity — Moderate Impact/Moderate Term (next 10 years)/Moderate Complexity — Low Impact/Long Term (15 years +)/Low Complexity

Downstream recycling players can support market formation and improve certification, and quality assurance practices

Supply Chain Player	Theme	Risk	Recommendation	Impact	Timing	Complexity
Disassemblers and PV Recyclers	Improve Recovery Efficiency	Panel Supply Risk	• Reduce contamination and module damage during disassembly which can impede recyclability through improved training and adoption of advanced technologies.	Moderate	High	Low
	Develop Commercial Pathways	Price Risk	• Establish co-located disassembly hubs with scrap-metal traders to capitalise on existing sorting, weighing, and logistics systems enabled to handle the multi-material nature of solar PV • Consider broader material collaborations in site selection which could support synergy with downstream processing	High	Moderate	Moderate
	Certification and Traceability	Quality Risk	• Work with standard bodies and governments to implement systems which provide certificates of recovered materials, including mass balance and purity levels • Work with refurbishers to certify PV modules destined for reuse markets	Moderate	Moderate	High
Scrap Metal Traders	Improve Quality Perceptions	Quality & Regulatory Risk	• Introduce dedicated streams for PV aluminium to avoid downgrading material quality • Invest in sorting equipment to verify alloy composition and improve downstream value	Moderate	Moderate	Moderate
	Market Development	Quality Risk	• Build direct relationships with solar PV supplying extruders and casthouses to align quality specifications and secure offtake for PV-derived aluminium	Moderate	Moderate	Moderate
Casthouses and Extruders	Build Closed-Loop Recycling Pathways	Quality Risk	• Create grade-specific demand for PV-derived 6063 aluminium scrap from solar PV and other markets such as construction and vehicle manufacture • Provide clear quality specifications to recyclers and traders to reduce contamination and reprocessing costs	Moderate	Moderate	Moderate
	Support Industry Decarbonisation	Quality Risk	• Offer transparent premium or differentiated pricing for clean, traceable aluminium scrap to promote domestic circularity • Publicly commit to increasing recycled content across extrusion products used in PV frames and racking	Moderate	Moderate	Moderate

High Impact/Short Term (next 5 years)/High Complexity — Moderate Impact/Moderate Term (next 10 years)/Moderate Complexity — Low Impact/Long Term (15 years +)/Low Complexity

IAI can undertake advocacy for policy and standard change and orchestrate a cross-value chain working group

Supply Chain Player	Theme	Risk	Recommendation	Impact	Timing	Complexity
International Aluminium Institute	Leadership and Advocacy	Policy, Panel Supply & Quality Risk	• Advocate for product stewardship (e.g. EPR) and standard improvements at the global and national level to support market formation • Develop global guidance on aluminium selection for PV frames and racking, including recommended alloys, coatings, and design-for-recyclability principles			
	Data and Market Development	Policy, Quality & Regulatory Risk	• Support development of a global recycled aluminium certification scheme aligned with PV industry needs • Facilitate data sharing on recycled content performance in PV frames and modules and from other industry pilots • Provide data tools on where and when PV waste is likely to emerge over time to support aluminium recyclers			

	Collaboration with PV Industry	Panel Supply, Quality & Regulatory Risk	• Launch a joint working group under the IEA Photovoltaic Power Systems Programme Task 12 on PV Sustainability to capture the aluminium supply chains perspective. This should incorporate PV manufacturers, recyclers, casthouses, and standards bodies focused on:
			  • Driving high-yield recycling of PV-derived aluminium
			  • Standardisation of coatings and alloys
			  • Implementing closed-loop and open-loop recycling models where appropriate in each market
			  • Providing a forum to advocate for the benefits of recycled content sharing of research findings (e.g. on performance of recycled content in PV systems)			

High Impact/Short Term (next 5 years)/High Complexity

Moderate Impact/Moderate Term (next 10 years)/Moderate Complexity

Low Impact/Long Term (15 years +)/Low Complexity

Five immediate next steps for further exploration emerge for IAI

Standards

IAI needs to engage with the IEA Photovoltaic Power Systems Programme to understand the present status of progress on design-for-recyclability standards. In doing so, IAI needs to understand the intention of regions to uptake changes and position to influence these standards to drive aluminium circularity based upon aluminium specific gaps.

Timing and Location

IAI needs to support its members to understand where and when aluminium recycling from Solar PV is likely to emerge by developing an open source, geospatial outlook based upon existing installations. This should be designed to support supply chain infrastructure planning for aluminium recyclers.

Advocacy

The IAI, in conjunction with national aluminium councils and members, needs to develop a collective aluminium industry perspective on policy mechanisms to support solar PV recycling and recycled content use. This includes a position on product stewardship schemes.

Risk Management

Liquid, global recycled-content benchmarks for aluminium are still nascent. IAI should:

(a) assess members' current hedging practices for secondary aluminium,

(b) engage with key exchanges and data providers on standardising recycled-aluminium specifications and reference prices, and

(c) publish guidance on using physical contracts, indices and emerging futures to manage price risk on PV-grade scrap and recycled billet.

Facilitating Recycled Content Pilots

IAI can sponsor multi-partner pilots that take PV-derived aluminium through certified, traceable closed-loop routes into new frames, racking and other structural products.

These pilots should include third-party life-cycle assessment, alloy-performance testing and digital traceability demonstrations, with results fed back into standards development, policy advocacy and the business case for dedicated secondary capacity serving the solar and clean-energy value chains.

07 Appendices

Appendix A: Country comparison of key metrics

Table 7-1: Comparison between regions across policy, recovery and infrastructure

Item	Australia	Europe	India	China	US	Canada
Policy & Standards	Victoria landfill ban for PV; national framework lagging; proposals for point-of-sale levy [1,2] AS/NZS 5377 (e-waste), Clean Energy Council certification for panel types; Green Star/EPD growing for construction, but rare PV	Strong EPR, landfill bans, mandatory recycling, CBAM, sectoral targets [1] EN 50625-2-4 for WEEE-PV EoL; EPD, CE certification, EN 485/573 for aluminium; sectoral traceability standards [1,4]	No binding EPR for PV; some state waste policies developing; research focus increasing BIS standards for aluminium grades; no PV-specific recycling standard; draft proposals emerging for e-waste [4]	No PV-specific regulation; upstream supply under green aluminium controls, EoL policy weak [1,4] GB/T aluminium standards for upstream; no PV EoL standard; voluntary green labelling for modules, limited adoption [4]	Federal recycling incentives; landfill allowed; state-level pilots for PV recovery only [1] ASTM (aluminium alloys), EPA regulations for waste; no PV aluminium recycling standard [4]	Provincial EPR expanding; national landfill reduction incentives; PV-specific regulation developing CSA standards for e-waste, including PV; ISO/ASTM for aluminium; EPR references but no PV-specific recycling standard [1,5]
Recycling Rate (PV Modules) [3]	Minimal	>80%	Minimal	Nascent	~10%	Limited
Collection Infrastructure	Disaggregated collection by smaller players - main flow to scrapyards Few dedicated facilities; export-centric; modular trials expanding, but not at scale [1,2]	Mandatory, centralised collection; specialist contractors for PV/aluminium Robust and widespread, many foundries and circularity pilots; risk from scrap exports [1,4,5]	Small proportion of PV collected Emerging: informal and small-scale sector predominant; government focus shifting	Informal sector dominant for collection Large, vertically integrated plants for primary; informal sector is critical for recycling [1]	Disaggregated collection by small and medium sized players - main flow to scrapyards Mature for mainstream scrap, patchy for PV; automotive circularity more advanced [1,4]	Disaggregated collection by small and medium sized players - main flow to scrapyards Strong core recycling infrastructure, gaps for PV-specific recycling and batch sorting [1,4,5]
Supply Chain Barriers	Transport, permitting, low volume, lack of market incentives, panel contamination [1,2]	Scrap export drains local processing; alloy contamination; varying regulatory enforcement [1,4]	Lack of formalised sector, awareness, and standards; logistics [4]	Informal sector dominance; policy gaps; system tracking incomplete [1,4]	Panel tracking, contamination, lack of PV aluminium-specific incentives; market value low	Provincial fragmentation, infrastructure gaps, slow EPR rollout for PV [1,4,5]
Traceability/Certification for Recycled Aluminium	Market-led voluntary schemes [1,2]	EPD (Environmental Product Declaration) and EN standards for full traceability; aggregate recycling rates and reporting required [1,5]	Traceability limited; supply chain audit rare; recycling batch tracking in pilot phase only [4]	Market-led voluntary schemes [1]	Market-led voluntary schemes [1,4]	Progressive EPD/CSA uptake; traceability pilot in e-waste frameworks; aluminium tracking limited for PV [1]

Sources: 1. Stakeholder consultation 2. Hamilton Locke, Australia's Solar Panel Recycling Challenge and Market Outlook (n.d.) 3. See Table 2-4 for references. 4. Al Circle, From price surges to policy shifts: Key trends driving aluminium sustainability and recyclability (2025) 5. Eunomia, Global League Table (2024)

Appendix B: Cross-country infrastructure assessment

Table 7-2: Infrastructure assessment across markets

Country	PV Disassembly	Solar PV Recycling	Aluminium Scrap Collection & Treatment	Casting & Remelting	Extrusion
Australia	Few dedicated PV disassembly plants; one Queensland facility capable of full panel dismantling, most treatment still frame/junction-box removal only.[1]	PV recycling in early stage; majority of capacity focused on aluminium frames and junction boxes, limited glass/silicon recovery.[5]	Limited domestic remelt; much scrap exported, with only a small number of local remelters handling clean scrap streams.[7]	Limited domestic remelt; much scrap exported, with only a small number of local remelters handling clean scrap streams.[9]	Some extrusion manufacturers remelt clean in-house scrap; broader recycled billet use still emerging.[7]
Canada	Established take-back schemes and PV-dedicated dismantling facilities under WEEE; significant capacity in Germany, France, Italy, Spain.[3]	Most mature PV recycling market globally, with multiple lines targeting high recovery rates and growing capacity.[6]	Large secondary aluminium sector serving automotive, packaging and construction, with growing billet/slab capacity.	Large secondary aluminium sector serving automotive, packaging and construction, with growing billet/slab capacity.[10]	Extensive extrusion industry able to absorb high levels of recycled billet, supported by low-carbon and ASI certification schemes.[10]
China	Emerging informal disassembly; formal PV-specific infrastructure still limited, concentrated around industrial hubs.[2]	PV recycling market growing rapidly from a small base, with a handful of formal recyclers and many informal handlers.[6]	Expanding secondary aluminium capacity serving automotive and construction, though quality control can be variable.[3]	Expanding secondary aluminium capacity serving automotive and construction, though quality control can be variable.[10]	Significant extrusion capacity, but use of traceable recycled billet and certification is still emerging.[10]
Europe	Several large PV manufacturers and utilities now operate integrated disassembly and recycling lines, but coverage is uneven outside major provinces.[2]	Rapidly scaling PV recycling to respond to large EoL volumes; a mix of advanced lines and conventional shredding.[2]	World's largest secondary aluminium producer with significant remelting and alloying capacity[7]	World's largest secondary aluminium producer with significant remelting and alloying capacity.	Large extrusion industry with increasing interest in low-carbon and recycled billet, though traceability varies.[11]
India	Limited PV-specific disassembly; most panels handled as general e-waste or exported to US/EU recyclers[3]	PV recycling facilities exist but at small scale; regulatory frameworks still developing.[6]	Significant secondary smelting capacity integrated with North American market.[7]	Significant secondary smelting capacity integrated with North American market.	Established extrusion with growing use of recycled billet, but PV-linked closed loops are rare.[10]
United States	Several PV disassembly and recycling facilities in operation, but coverage is patchy and largely state-driven.[3,4]	Growing PV recycling market, led by specialised recyclers and utilities; still modest relative to installed capacity.[6]	Large, sophisticated secondary aluminium sector serving automotive and aerospace.[7]	Large, sophisticated secondary aluminium sector serving automotive and aerospace.	Extensive extrusion capacity; low-carbon and recycled-content products increasingly available but not yet standard for PV.[10]

Sources: 1. ABC News, First solar panel recycling plant in Queensland opens, expected to recycle 240,000 panels a year (2024) 2. IEA Photovoltaic Power Systems Programme, Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries (2022) 3. Preet, S. & Smith, S., A comprehensive review on the recycling technology of silicon based photovoltaic solar panels: Challenges and future outlook (2024) 4. U.S. Department of Energy, Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan (2022) Hamilton Locke, Australia's Solar Panel Recycling Challenge and Market Outlook (n.d.) 6. Future Market Insights, Solar PV Recycling Market (n.d.) 7. Australian Aluminium Council, Scrap Aluminium Recycling in Australia (2021) 8. Nieto-Morone, M., Alonso-Garcia, M., Rosillo, F., Santos, J. & Munoz-Garcia, M., State and prospects of photovoltaic module waste generation in China, USA< and selected countries in Europe and South America (2023) 9. Australian Aluminium Council, Opportunities in the Circular Economy (2024) 10. Future Market Insights, Secondary Smelting and Alloying of Aluminium Market (n.d.) 11. European Aluminium, Circular Aluminium Action Plan (2020)

Appendix C: Comparison of policy tools in key markets (1/2)

Table 7-3: Comparison of end-of-life regulatory models across key regions and implications for PV and aluminium recovery

Region	Maturity	Regulatory model, legal basis & other levers	PV in scope and dates	Who pays / core obligations	Aluminium recovery implications
Europe (General)[1,2,3]	High	Mandatory EPR under WEEE Directive 2012/19/EU, amended by 2024/884. Enforced through national registers, compliance schemes and harmonised reporting. CENELEC EN 50625 standards guide treatment.	PV covered since 2012. Directive 2024/884 was required to be transposed by Member States by October 2025.	Producers register in each Member State, finance collection/treatment, fulfil take-back, information and labelling requirements, and report quantity placed on market and EoL volumes.	Harmonised rules and reference standards support consistent dismantling, reliable aluminium-frame separation and good-quality secondary aluminium.
France (EU example)[1]	High	WEEE transposed via Code de l'environnement under Décret n° 2014-928 [8], with PV managed nationally by Soren, the State-approved EPR operator. Scheme aligns with EN 50625-based requirements.	PV EPR scheme operating since 2014.	Producers join Soren, pay eco-fees based on module type, and report quantities. Soren ensures nationwide collection, transport and audited treatment.	Centralised coordination supports high collection volumes and standardised treatment with separated, traceable material fractions (including aluminium).
Germany (EU example)[1]	High	PV regulated under ElektroG. Producers must register with Stiftung ear, provide financial guarantees and follow strict take-back and reporting obligations.	PV explicitly covered since 2018.	Producers register, finance treatment, provide a guarantee against orphan waste, and report annual placed on market and EoL data.	Controlled routing to authorised facilities enables systematic frame removal and production of sorted aluminium fractions.
China[1,4]	Medium	Standards-driven approach using GB/T 39753-2021 (recycling) and GB/T 45075-2024 (reuse), supported by NDRC 2023 guidance on PV/wind recycling. Compliance enforced via permits, approvals and procurement criteria.	GB/T 39753 (recycling) effective 2022 and GB/T 45075 (reuse) effective 2025.	Operators must comply with national standards to maintain approvals and eligibility for government projects and recycling licences.	Detailed dismantling requirements mandate separation of aluminium frames and other fractions, enabling production of sorted aluminium scrap suitable for secondary production.

Sources: 1. IEA PVPS, Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries, (2022); 2. European Parliament & Council, Directive 2012/19/EU on WEEE, (2012); 3. European Parliament & Council, Directive 2024/884 amending Directive 2012/19/EU on WEEE, (2024); 4. Standardization Administration of China, GB/T 45075-2024 Recycling and reuse of photovoltaic modules, (2024)

Appendix C: Comparison of policy tools in key markets (2/2)

Table 7-3: Comparison of how end-of-life regulatory models differ across key regions and what this means for PV and aluminium recovery

Region	Maturity	Regulatory model, legal basis & other levers	PV in scope and dates	Who pays / core obligations	Aluminium recovery implications
Australia[1]	Medium	National PV stewardship scheme under development (DCCEEW). Interim controls rely on Victoria's 2019 e-waste landfill ban and PV's listing on the national Product Stewardship Priority List.	No national start date. Victoria's e-waste landfill ban applies since 2019.	A future national scheme is expected to be producer-funded. Currently, obligations vary by state; in Victoria, PV must be sent to approved collectors/recyclers.	Landfill bans increase diversion to recyclers, supporting aluminium recovery, but outcomes vary without national standards or uniform treatment rules.
India[2,3]	Medium	National EPR for PV via E-Waste Rules 2022. Producers must register on the CPCB portal. CPCB has issued 2025 draft PV storage/handling guidelines and is developing recycling-efficiency rules.	PV covered since 2023. PV storage / reporting obligations are exempt until 2034-35, when recycling targets begin.	Producers/importers register, report quarterly/annually, ensure compliant storage and transfer to authorised recyclers. Recyclers must meet CPCB authorisation conditions.	Growing regulatory structure improves and safe handling; aluminium recovery is expected to strengthen as recycling standards and capacity are finalised.
Canada[4,5,6]	Low	PV managed under provincial EPR/EEE laws where designated (e.g., Ontario O. Reg 522/20, Québec Q-2 r.40.1). The CCME's Action Plan for EPR provides guidance but is not binding. Coverage and obligations differ across provinces; some do not yet include PV.	PV coverage differs by province. Ontario's regulation came into effect in 2020 and Quebec in 2011. The CCME's Action Plan for ERP was approved in 2009.	In designated provinces, producers register with the authority/producer responsibility organisation, finance management, meet service standards and report annually. Elsewhere PV follows general waste or commercial pathways.	Where PV is regulated, authorised processing enables more consistent aluminium recovery. Non-covered provinces have more variable, less traceable recovery outcomes.
United States[1,7]	Low	No federal PV EPR. EPA developing a rule to add PV to Universal Waste (RCRA Part 273). States act independently (e.g. California's Universal Waste and Washington's PV module stewardship and takeback program under Chapter 70A.510)	California rules apply since 2021. Washington stewardship plans required by 2030; sales ban of PV modules with non-approved plan from 2031. EPA rule is pending.	California requires Universal Waste handling (labelling, storage, transport to authorised facilities). Washington will require producer-funded stewardship. No federal producer obligation yet.	State rules direct PV to authorised facilities, improving aluminium recovery locally, but national performance remains inconsistent without federal alignment.

Sources: 1. IEA PVPS, Status of PV Module Recycling in Selected IEA PVPS Task 12 Countries, (2022); 2. CPCB, FAQ under E-Waste Rules 2022, (2024); 3. CPCB, Draft Guidelines for Storage and Handling of Waste Solar Photo-Voltaic Modules or Panels or Cells, (2025); 4. Government of Québec, Regulation Q-2, r. 40.1: Regulation respecting the recovery and reclamation of products by enterprises, (2025); 5. Government of Ontario, O. Reg. 522/20 Electrical and Electronic Equipment, (2020); 6. CCME, Canada-Wide Action Plan for Extended Producer Responsibility, (2009); 7. U.S. EPA, End-of-Life Solar Panels: Regulations and Management (2023);

Appendix D: Key success factors for an EPR scheme with learnings from similar metals

Proven models in comparable material systems contain key learnings for nations and regions considering EPR

Steel Packaging (EU)[1]

- Across the European Union, producer-funded EPR schemes implemented under the Packaging and Packaging Waste Directive set binding recycling targets and eco-modulated fees for steel packaging, resulting in a record recycling rate of about 80.5% for steel packaging in 2022.

Aluminium Beverage Cans (South Korea and EU)[2,3]

- In South Korea, long-standing EPR rules requiring producers to fund collection, sorting and recycling have achieved recycling rates of around 96%, among the highest globally. In Europe, mandatory packaging EPR combined with deposit-return systems has also delivered strong outcomes, with aluminium beverage cans reaching recycling rates of roughly 75% across the EU, UK and EFTA region.

Electronics (Japan)[4]

- Across Japan, the Home Appliance Recycling Law requires producers and retailers to collect and recycle specified appliances, delivering material-recycling of roughly 90% for air conditioners and washing machines/dryers, 86% for LCD/plasma TVs, 79% for refrigerators/freezers, and 71% for CRT TVs, consistently above the statutory recycling standards.

What these model show for PV aluminium

- High recycling rates are achieved where producer funding is mandatory and long-term, not voluntary or project-based.
- Clear material ownership at end-of-life (e.g. packaging, appliances) supports higher-quality material recovery.
- Eco-modulated fees and design rules drive simpler disassembly and cleaner metal streams over time.
- Dedicated collection pathways outperform mixed waste systems for metals requiring alloy integrity.
- Scale and predictability of feedstock are critical to enabling investment in sorting and remelting capacity.

Sources: 1. Packaging Europe, Steel for Packaging confirms new 80.5% steel recycling record, (2024); 2. IAI, New IAI Study Reveals Environmental Benefits of Increasing Global Aluminium Can Recycling, (2023); 3. European Aluminium, Beverage Can Recycling Results Press Release, (2025); 4. Association for Electronic Home Appliances; Recycling of Used Home Appliances under the ACT on Recycling of Specified Home Appliance in Japan, (2021)

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