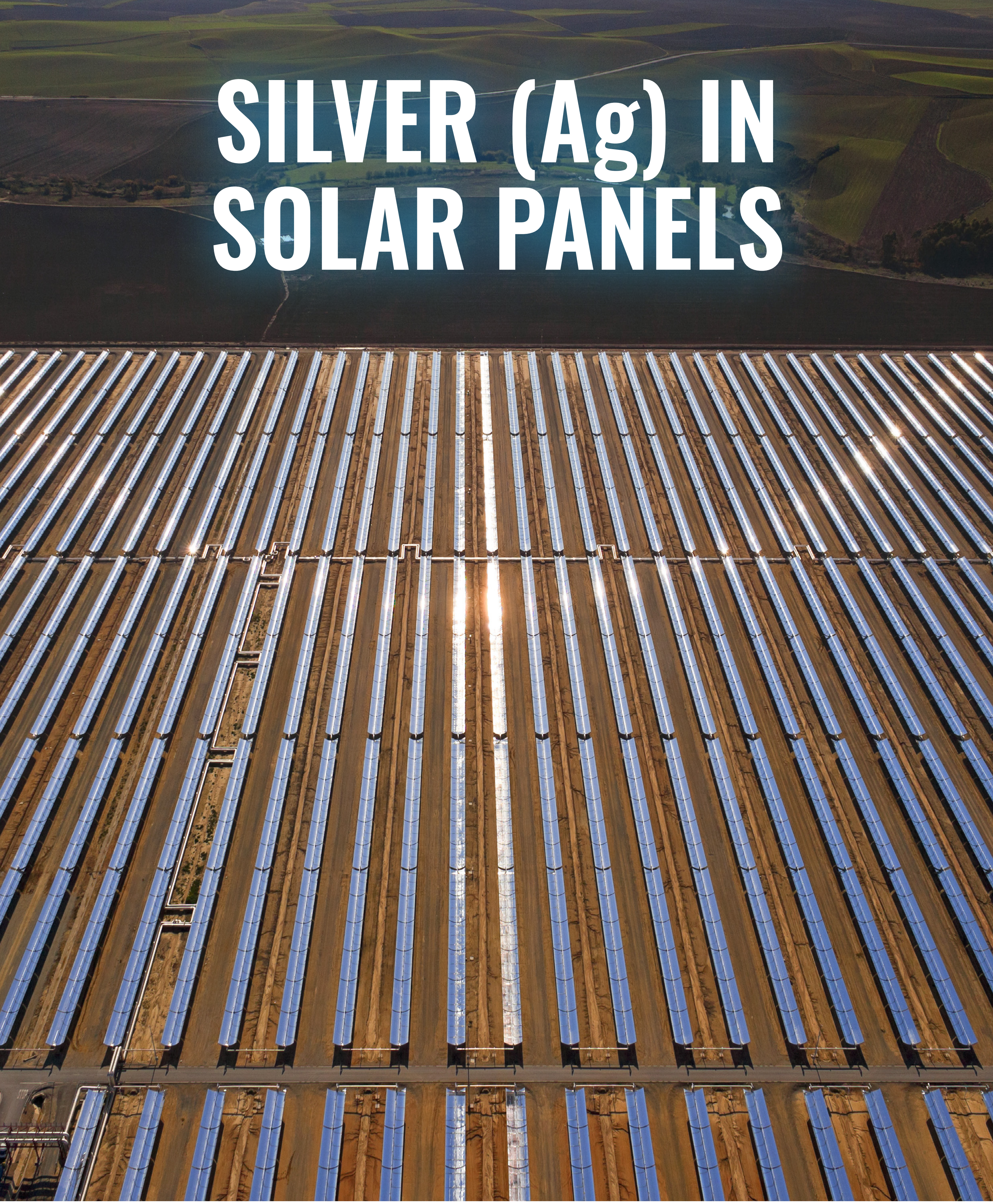
SILVER (Ag) IN SOLAR PANELS



SMART ENERGY COUNCIL

SILVER (Ag) IN SOLAR PANELS

EXECUTIVE SUMMARY

Silver (Ag) is a critical material for photovoltaic (PV) technology, used in conductive pastes that form essential electrical contacts in crystalline silicon solar cells. Although each module contains only 10–25 g of silver, the scale of global PV deployment makes the sector one of the largest industrial consumers.

Global PV capacity now exceeds 1.4 TW, embedding an estimated 120,000–160,000 tonnes of silver in operational modules. Australia alone holds 2,700–4,500 tonnes across its 34–36 GW fleet, representing both a future recycling opportunity and a potential resource-security risk.

Silver demand continues rising despite reductions in silver intensity, while primary mine supply remains constrained. This contributes to long-term structural market deficits, creating vulnerability for PV manufacturing and increasing reliance on secondary (recycled) sources.

From the early 2030s, large volumes of modules installed between 2010 and 2020 will reach end-of-life (EoL), generating significant silver-rich waste: 3,000–5,000 tonnes by 2030, 20,000–30,000 tonnes by 2040, and 60,000–90,000 tonnes cumulatively by 2050. However, current recycling rates remain low, and silver recovery is technically challenging because it is finely dispersed and encapsulated within the module laminate.

Recovery technologies—pyrometallurgical, hydrometallurgical, and emerging selective leaching processes—can extract high-purity silver, but closed-loop recycling into new PV paste requires further refinement and investment. Upstream measures, including design-for-recovery and reduced silver usage (via copper metallisation and advanced printing techniques), will also be needed to mitigate future demand pressure.

Silver is environmentally stable during module operation, but leaching can occur under landfill conditions, and mechanical processing poses dust-inhalation risks without proper controls. Responsible EoL management is therefore essential.

To secure future supply and capture the economic value of EoL silver, coordinated policy action is required. Key priorities include traceability and material declarations to identify silver-rich modules, segregated collection systems to improve recovery economics, extended Producer Responsibility (EPR) and material recovery targets and advance planning for recycling capacity, ahead of the coming EoL wave.

Silver's availability will increasingly influence the cost, speed, and reliability of global PV deployment. Strengthening circularity and recovery pathways is essential to support the clean-energy transition at terawatt scale.

SILVER (Ag) IN SOLAR PANELS

SMART ENERGY COUNCIL

1 OVERVIEW AND USE IN SOLAR MODULES

1.1 Primary Application in Crystalline Silicon PV

Silver is a critical functional metal in crystalline silicon (c-Si) photovoltaic (PV) modules, which currently account for more than 90% of global PV deployment. Its primary use is in the front-side and rear-side metallisation of solar cells, where finely engineered silver conductive pastes are screen-printed onto the wafer surface and subsequently fired to form permanent electrical contacts.

- **Front-side (narrow fingers and busbars):** The front side of a cell contains a dense grid of ultra-fine silver “fingers” designed to capture photo-generated current and reduce resistive losses. These fingers feed into thicker “busbars” that transport current across the cell. Modern high-efficiency designs use increasingly fine line widths (often <30 µm), but silver remains essential due to its unparalleled conductivity and compatibility with high-temperature firing processes.
- **Rear-side contacts:** Although the rear side of many cells historically contained a mix of silver and aluminium paste, advanced architectures (e.g., PERC, TOPCon, HJT) often still rely on silver for at least part of the rear-side contact or for wrap-through interconnections. In heterojunction cells (HJT), silver usage can even be higher because both sides require low-temperature pastes to avoid damaging the amorphous silicon layers.

As a result, silver content per module has gradually decreased through engineering optimisation (e.g., narrower fingers, improved paste chemistry), but total sector demand continues to grow due to the rapid scale-up of PV manufacturing.

1.2 Chemical Form and Stability

The silver used in PV cells is not present as loose metal or particulate matter but is embedded within a complex paste matrix designed for durability and electrical performance.

Silver paste typically consists of micron-scale silver particles combined with glass frit and organic binders. During high-temperature firing (c. 750–900°C for c-Si cells), the organic components burn away while the glass frit softens and bonds the silver to the underlying silicon surface.

After cell fabrication and module lamination, silver is sintered into a solid conductive pathway, encapsulated beneath multiple protective layers (EVA encapsulant, glass), and chemically stable under normal operating conditions.

Because the silver is bonded to both silicon and glassy phases, it is extremely difficult to liberate selectively without high-temperature, chemical, or mechanical processing — an important factor in end-of-life (EoL) recycling economics. Silver does not migrate or oxidise significantly inside a module, but it also does not form recoverable “bulk” metal that can be easily extracted.

Overall, silver remains one of the most valuable and strategically important materials in PV manufacturing, but its use is highly technology-specific, with c-Si cells being the overwhelmingly dominant consumer.

2 QUANTITIES AND RESOURCE INTENSITY

2.1 Module-Level Silver Intensity

Silver is used in very small absolute quantities per PV module, but due to the sheer scale of global PV deployment, its cumulative resource footprint is highly significant. In c-Si modules, which is the dominant commercial technology, the metallisation pastes applied to the front and rear contacts typically contain 10–25 g of silver per module, depending on the cell architecture:

- **Older Al-BSF designs:** ~20–25 g/module
- **PERC (Passivated Emitter Rear Cell):** ~12–18 g/module
- **TOPCon (Tunnel Oxide Passivated Contact):** similar or slightly lower than PERC
- **HJT (Heterojunction):** can be higher (~20–30 g/module) due to double-sided low-temperature paste.

The amount of silver in solar modules can also be affected by efficiency and finger-line optimisation. Continuous reductions in finger width and improved paste chemistry have lowered silver usage per watt. Modern modules generally range between 50–80 mg Ag/Wp, though leading manufacturers are targeting <30 mg/Wp through copper or aluminium plating alternatives.

Silver quantities can also change depending on the module size, where larger-format modules (e.g., 550–600 W) have increased the total silver per unit, even if silver intensity per watt has decreased. A “typical” current-generation 400 W residential module therefore embeds roughly 12–16 g of silver, making it one of the highest-value materials in the bill of materials, despite its small mass fraction.

2.2 System-Level Silver Stock in the Global PV Fleet

When scaled across decades of PV deployment, the amount of silver contained in operating solar infrastructure becomes substantial. Current assessments based on cumulative installations and historical silver intensities indicate that the cumulative PV capacity installed globally (2024–2025) is >1.4 TW. Considering that the average historical silver intensity (weighted across technologies) was ~120–140 mg/Wp in the 2010s, declining to ~60–80 mg/Wp today, it can be estimated that total embedded silver stock in the global PV system is approximately 120,000–160,000 tonnes of silver currently locked within operational PV modules (worldwide). This makes the PV sector one of the most silver-intensive industrial applications in the world — surpassing electronics, jewellery, and photography in annual consumption.

2.3 Australia Context

Australia's unusually high uptake of rooftop and utility-scale PV makes it one of the most silver-intensive solar markets per capita worldwide. By 2024–2025, the national PV fleet exceeded 34–36 GW of installed capacity, the vast majority of which is c-Si technology — the sector identified as a major and growing driver of global industrial silver consumption. Applying historical and contemporary silver-intensity ranges (~80–140 mg/Wp for systems installed over the past decade), Australia now holds an estimated 2,700–4,500 tonnes of silver embedded across millions of modules currently in operation.

This dispersed yet sizeable "urban silver reserve" is strategically important for two reasons. First, these modules represent a valuable secondary resource stream in the context of the global silver deficits. Second, EoL solar panels are one of the most significant emerging secondary silver sources, with global PV waste projected to accelerate steeply and recovery rates potentially reaching ~95% with advanced processes. Australian PV waste is expected to exceed 100,000 tonnes per year by 2030, making recycling not only an environmental necessity but a future economic opportunity.

As early installation cohorts reach EoL from the early 2030s onward, Australia will see a rapid return flow of silver-bearing PV waste. If captured efficiently, this stream could help offset exposure to tightening global silver markets, support domestic recycling industries, reduce reliance on volatile primary imports, and align with circular-economy imperatives increasingly. In this context, Australia's existing PV stock represents both a looming waste challenge and a strategically valuable resource base — one that could play a meaningful role in national material security as global silver deficits continue to expand.

3 FUTURE END-OF-LIFE VOLUMES AND RESOURCE IMPLICATIONS

As large volumes of PV capacity installed between 2010 and 2020 begin reaching EoL from the mid-2030s onwards, a significant wave of embedded silver will enter the global waste stream.

Table 3.1: Expected EoL silver from retired solar panels by year.

BY 2030	BY 2040	BY 2050
Approximately 3,000–5,000 tonnes, largely from early-generation systems.	Expected to rise sharply to 20,000–30,000 tonnes, driven by both the first major replacement cycle and ongoing gigawatt-scale deployment.	Cumulative returns could exceed 60,000–90,000 tonnes, depending on installation growth rates and silver-thrifting innovations.

Even with declining silver intensity per watt, global PV scaling ensures that absolute silver demand continues to increase, unless alternative metallisation technologies achieve widespread adoption.

3.1 Implications for Resource Security and Circularity

As discussed, the PV industry now consumes approximately 10–15% of annual global silver production, placing it among the largest industrial consumers of the metal and making it a structurally important driver of long-term demand. As industrial uses continue to surge — led by PV manufacturing, electronics, electric vehicles (EVs), and emerging technologies — silver is transitioning from a commodity metal to a strategic resource with growing vulnerability.

3.1.1 Circularity Challenges: Recovering Silver from PV Modules

Recycling silver EoL PV modules is technically feasible, yet several characteristics limit recovery at scale:

- Silver's low mass fraction makes recovery inherently challenging and is finely dispersed across extremely thin metallisation lines, making mechanical separation insufficient.
- It is chemically bonded within complex paste and glass-frit matrices, requiring advanced hydrometallurgical or pyrometallurgical processes for liberation — many of which remain pre-commercial or uneconomic at present.
- Global PV recycling rates remain low, generally around 10% in most jurisdictions, which means the majority of deployed silver risks being lost to low-value waste pathways, down-cycling, or landfill.

Despite these challenges, EoL PV modules represent one of the largest untapped secondary silver resources. The recycling potential could exceed hundreds of millions of ounces annually under high-capture scenarios in the next few years. However, realising this opportunity requires beneficiation and processing infrastructure orders of magnitude larger than what currently exists.

3.1.2 Strategic Forecasting and Coordinated Infrastructure Development

Given the scale of projected primary supply shortfalls by 2040, strategic forecasting becomes essential. Long-range planning must integrate:

- Accurate modelling of future silver intensity in PV manufacturing, including the pace and practicality of thrifting and copper-plating substitution.
- Infrastructure planning for PV recycling, ensuring future EoL streams — from 2030 onward — are captured rather than lost.
- Cross-sectoral material demand assessments, recognising that PV, EV, and electronics growth cannot be planned independently.

Without coordinated action, the PV sector risks facing material constraints that could slow global decarbonisation efforts — mirroring the risk seen in copper markets but intensified due to silver's limited substitutability and high dispersion in end products.

3.1.3 Strategic Implications for Circularity and Industry Planning

To ensure long-term resilience, transitioning to a high-circularity silver system will require:

- Large-scale investment in advanced PV recycling technologies and domestic processing capacity.
- Improved EoL PV collection frameworks to prevent leakage to landfill or informal waste pathways.
- Incentives for design-for-recycling, lowering complexity and enabling easier silver recovery.
- Policies that align PV deployment targets with realistic metal availability scenarios, ensuring material constraints do not undermine climate goals.

Ultimately, the intersection of rising PV demand, constrained primary silver supply, and underdeveloped recycling infrastructure underscores an urgent need for material security strategies. Silver — much like copper and antimony, for example — is becoming a foundational mineral for the net-zero transition, and its availability will shape the pace, cost, and feasibility of future PV deployment globally.

4 ENVIRONMENTAL AND HEALTH CONSIDERATIONS

The environmental and occupational health implications of silver in PV modules vary significantly across the product life cycle. During normal operation, silver is chemically stable and poses negligible risk. However, risks can arise during EoL handling, improper disposal, and uncontrolled mechanical processing. These pathways — though generally low compared to some other metals — warrant careful consideration as global EoL PV volumes accelerate.

SILVER (Ag) IN SOLAR PANELS

Table 4.1: Environmental and Health Profile of Silver in PV Modules

LIFE-CYCLE STAGE	ENVIRONMENTAL/HEALTH RISK LEVEL	KEY CONSIDERATIONS
Operational Life	Very Low	Silver is immobilised beneath glass and EVA; no migration or exposure.
Landfill/Improper Disposal	Moderate	Possible silver mobilisation under acidic/wet conditions; there is a potential pathway for silver compounds to leach into surrounding soils and groundwater..
Mechanical Processing/ Recycling	Moderate and Localised	Inhalation risk from fine dust during crushing and grinding; requires controls and PPE.

4.1 Handling Risks During Processing: Inhalation and Worker Safety

Common recycling methods such as mechanical processing — crushing, shredding, grinding, delamination, thermal treatment, or milling — can generate fine respirable dust containing: silver particles, silver oxides, glass particulates containing trace silver, silicon dust, and EVA decomposition products.

The primary health concern in these scenarios is inhalation exposure. Fine particulate matter (<10 μm, especially <2.5 μm) can enter the deep lung and contribute to irritation of the respiratory tract, potential bioavailability of silver compounds, occupational exposure to mixed-metal and silica dust, and cumulative respiratory burden for unprotected workers.

While silver compounds generally exhibit lower toxicity than metals such as lead or cadmium, chronic exposure to silver dust or fumes can cause argyria (skin/eye discoloration from chronic absorption), respiratory irritation, and inflammatory responses in high-dose scenarios.

- To effectively mitigate these risks, EoL processing facilities must implement:
- Enclosed mechanical handling systems to limit airborne dust.
- Local Exhaust Ventilation (LEV) and particulate capture (e.g., HEPA filtration).
- Appropriate PPE, including P2/P3 respirators, gloves, and protective clothing.
- Workplace exposure monitoring, ensuring compliance with occupational exposure limits for respirable dust and silver compounds.
- Safe operating procedures that prevent dust migration into surrounding environments.

These requirements parallel the controls recommended for handling PV materials containing other trace metals, including antimony, lead solder, and copper dusts.

4.2 Identification and Traceability

Accurately identifying the presence and concentration of silver in PV modules is essential for recycling, material recovery planning, and environmental assessments. Unlike some bulk metals or glass additives, silver in PV cells is embedded in extremely fine metallisation lines and fully encapsulated within the laminate structure, making visual identification impossible. As a result, reliable differentiation between module generations, architectures, and silver loadings requires a combination of administrative documentation, portable analytical tools, and laboratory-based methods.

Some examples of practical approaches available to industry are listed below (highlighting that visual Inspection is impossible):

- **Administrative Methods:** Prioritising manufacturer documentation, bill of materials lookup, and Material Declarations (IEC 62944 style) to distinguish module generations or types with higher or lower silver content.
- **Laboratory and Field Methods:** Portable X-Ray Fluorescence (XRF): Assessment of XRF as the industry standard for rapid, non-destructive, on-site screening of silver concentration in the cell/glass laminate.
  - **High-Accuracy Laboratory Analysis (ICP-MS/OES):** Use for regulatory testing, verification, and precise quantification of low concentrations, requiring acid digestion.
- **Indirect Indicators:** Operational clues from recycling (though less relevant than for Sb in glass, which causes furnace instability).

5. RECOVERY AND RECYCLING OF SILVER

The circular economy and critical minerals policies are increasingly prioritising silver recovery from PV modules. As the volume of global PV waste is projected to increase significantly from the 2030s, cost-effective silver recovery will be vital for ensuring long-term PV manufacturing resilience and resource security. The sustained, structurally elevated market demand for silver across various high-tech sectors, including PV manufacturing, electronics, and electric vehicles, has resulted in a multi-year structural deficit in the global silver market. Consequently, high and potentially volatile silver prices make recovery an economically attractive proposition. As prices rise:

- Recycling becomes profitable even at low ppm concentrations.
- Investment in advanced metallurgical and hydrometallurgical processes increases.
- High-value secondary silver streams (e-waste, catalysts, PV modules) attract dedicated processing capacity.

In contrast to low-value metals, the economics of silver recovery justify specialised equipment, selective leaching, and advanced refinery steps—particularly where silver purity requirements for PV-grade paste are stringent.

5.1 Recovery Pathways

Silver recovery from PV modules traditionally follows a combination of pyrometallurgical and hydrometallurgical methods. These processes aim to recover silver from the metallisation paste embedded in the silicon wafer.

- Pyrometallurgy (High-Temperature Smelting)
  - This process involves crushing and size reduction of modules, thermal treatment or smelting to burn off organics and melt remaining solids and recovery of silver as part of a metal-rich alloy or slag phase.
  - While effective, this approach is: Energy-intensive due to high furnace temperatures, best suited to multi-metal recovery streams (e.g., PV mixed waste, e-waste) and less selective, requiring additional refining to produce PV-grade silver.
  - Pyrometallurgy remains widespread due to its robustness and compatibility with existing metals-processing infrastructure.
- Hydrometallurgical Leaching
  - This process is frequently used after mechanical delamination or as a selective follow-on to pyrometallurgical pre-treatment. Typical steps include: acid or cyanide-based leaching to dissolve silver compounds, precipitation, electrowinning, or cementation to recover elemental silver and refining to achieve high-purity output.
  - This pathway is more selective and lower-energy than smelting, but requires: Chemical handling and wastewater treatment, efficient liberation of metallisation lines from silicon and glass matrices, and optimisation to manage low metal concentrations in PV cells.
  - Hydrometallurgy is currently the most viable pathway for scaling selective silver extraction at moderate cost.

To meet future PV waste volumes and reduce processing energy, researchers are developing selective leaching and advanced chemical processes designed to extract silver without full module smelting. These include targeted leachants that dissolve silver paste without attacking silicon or glass, ionic liquids or deep eutectic solvents for low-temperature extraction, electrochemical leaching systems that reduce reagent use, ultrasound- or microwave-assisted leaching to increase reaction efficiency and bioleaching approaches using bacteria that selectively mobilise silver ions.

These techniques aim to increase silver recovery efficiency, reduce energy consumption, lower reagent use and waste production and enable onshore or smaller-scale processing facilities. Although many are currently in the pilot or laboratory stage, rapid development is expected due to strong economic incentives and rising EoL PV volumes.

5.2 Closed-Loop Recycling Challenges

Returning recovered silver into new PV silver paste — the ideal "closed-loop" outcome — requires extremely high purity and precise particle characteristics. Challenges include:

- The metallisation pastes used in PV manufacturing have tight impurity tolerances, often requiring multi-stage refining.
- Silver recovered via pyrometallurgy may contain trace contaminants (e.g., lead, copper, arsenic) requiring extensive purification.

SMART ENERGY COUNCIL

- Hydrometallurgical silver recovery must be followed by controlled precipitation or electrowinning to achieve the correct crystalline properties.

PV-grade silver paste requires refining beyond the standard bullion purity of recycled silver. Closed-loop success depends on dedicated refining infrastructure, standardised feedstock qualities, and industry-wide specifications for secondary PV-suitable silver.

5.3 Down-Cycling and Immobilisation Pathways

Because silver is a high-value critical metal, down-cycling or immobilisation (e.g., incorporating silver-rich waste into concrete or ceramics) is economically unjustified except as a last resort for contaminated or mixed waste streams.

Where immobilisation may be considered:

- Only when silver recovery is technically unfeasible or uneconomic.
- When materials are combined with hazardous residues that limit metal extraction.
- In legacy waste streams where processing capacity is not available.

However, silver's high intrinsic value means that responsible waste strategies overwhelmingly favour recovery over immobilisation.

5.4 Upstream Solutions and Material Efficiency

Reducing future pressures on silver supply requires not only effective recycling but also upstream interventions in module design and metallisation technologies. These strategies improve circularity by lowering the amount of silver entering the system in the first place.

- **Design-for-Recovery (DfR):** It aims to modify module construction so that silver and other critical materials can be separated cleanly and efficiently at EoL. DfR parallels the solar glass industry's transition toward Sb-free glass, where upstream materials innovation reduces future recycling burdens. Relevant strategies include:
  - Easier delamination techniques (e.g., reversible encapsulants, adhesives that debond under controlled conditions).
  - Modular architectures allow mechanical separation of layers.
  - Avoidance of complex composite materials that hinder silver recovery.
  - Standardised metallisation patterns that support automated separation.
  - Reducing glass–cell adhesion where appropriate to facilitate downstream hydrometallurgy.
- **Dematerialisation and Metallisation Efficiency:** These strategies include and mitigate future supply constraints. The approaches focus on material substitution to reduce reliance on a constrained and increasingly costly metalloid. These include:
  - Copper metallisation and copper-plating as partial or full substitutes for silver paste.
  - Ultra-fine line screen-printing, reducing silver volume per busbar/finger.
  - Low-temperature paste innovations that require less silver for equivalent performance.
  - Novel deposition techniques (e.g., inkjet, aerosol jet printing).
  - Dual- or multi-metal strategies combining silver with cheaper conductive materials.
  - Thin-film PV technologies with inherently lower or negligible silver content.

6. POLICY AND STEWARDSHIP FRAMEWORKS

As the global PV market accelerates toward multi-terawatt scale, silver is emerging as a critical resource whose availability can influence the pace and cost of renewable energy deployment. Policy settings must anticipate constrained primary silver availability and ensure efficient management of the growing EoL PV waste stream., and rapidly increasing EoL module volumes require a coordinated policy and stewardship response. Effective governance must ensure that silver-containing PV waste is traceable, collected efficiently, processed responsibly, and reintegrated into supply chains where possible.

6.1 Traceability and Inventory Systems

A robust traceability framework is the foundation of effective silver recovery. Because silver cannot be identified visually and varies across cell technologies, module generations, and manufacturers, policies must mandate:

- Bill of materials transparency, including precise declarations of silver content.
- Material Declaration standards aligned with IEC 62944 or equivalent frameworks.
- Digital tagging or serialisation of modules to record material composition, production date, and architecture (PERC, TOPCon, HJT, etc.).

- Centralised national or regional registries of installed PV capacity, permitting real-time estimation of silver stocks and future EoL flows.

These measures will enable recyclers, regulators, and manufacturers to identify high-silver-content modules (earlier generations, HJT cells, etc.), route them to appropriate recovery facilities and optimise economic returns and avoid processing inefficiencies. Such traceability mirrors the requirements already emerging for other strategic materials (e.g., copper, cobalt, nickel) where reliable material flow data is critical for circular-economy planning.

6.2 Segregated Collection of Silver-Rich PV Waste

A major barrier to efficient silver recovery is the commingling of PV waste streams. When high-silver modules are mixed with low-silver or contaminated waste, the economic viability of selective recovery is reduced. Segregation supports higher recovery yields, lower processing costs, cleaner feedstock for hydrometallurgical and electrochemical processes, and more efficient allocation of capacity in recycling facilities. To address this, policies should promote:

- Segregated collection systems that classify modules by generation, composition, and contamination level.
- Standardised sorting protocols at aggregation sites, informed by documentation or portable XRF screening.
- Differentiated waste handling requirements, where high-silver-content modules follow a dedicated recycling pathway.
- Prohibitions or disincentives against landfill disposal of PV waste, particularly for modules containing valuable metals.

6.3 Regulatory Support and Incentives

Regulation will play a decisive role in driving investment and operational readiness for silver recovery. Key instruments include:

1. **Extended Producer Responsibility (EPR) for PV Modules:** EPR schemes shift responsibility for EoL management to manufacturers, importers, or distributors. For silver, this may involve funding or directly operating take-back and recycling systems, meeting material-specific recovery targets, reporting annual recovery performance, and financing R&D into recycling and substitution. EPR schemes have proven effective in other critical mineral sectors—such as battery metals and copper-rich e-waste — where they create predictable, long-term material flows to recycling industries.
2. **Mandated Recovery Targets for Critical Materials:** Policies should establish minimum recovery requirements for high-value metals, including silver. These targets could be technology-specific (e.g., %-recovery of silver from silicon-based modules), facility-specific (e.g., licensing conditions for recyclers), and national or regional (integrated into critical minerals strategy targets). Targets encourage:
   - Investment in advanced metallurgical processing,
   - Higher throughput in recycling facilities,
   - Technological innovation to improve recovery efficiency.
3. **Economic Incentives:** To accelerate development of silver recovery capacity, governments may consider capital grants or tax credits for recycling facility construction, differential landfill levies to discourage improper disposal, "recovery bonus" payments for meeting or exceeding silver yield thresholds, and priority procurement for PV products with recycled silver content. These measures align with the broader policy landscape driving secondary copper and rare-metal recycling growth globally.

6.5 Strategic Imperative

Effective stewardship of silver in PV modules is no longer optional—it is essential for:

- Maintaining PV manufacturing competitiveness,
- Supporting national renewable energy targets,
- Strengthening critical mineral resilience,
- Preventing unnecessary environmental contamination,
- Building economically viable circular-economy industries.

A coordinated policy framework that integrates traceability, segregation, regulation, and long-term planning will enable the recovery of a high-value metal that is increasingly central to the global clean energy transition.

7. REFERENCES

EUROPEAN SOLAR PV INDUSTRY ALLIANCE, RECOMMENDATIONS PAPER SERIES II. Addressing uncertain antimony content in solar glass for recycling. Brussels, 04.Oct.2023. solaralliance.eu/wp-content/uploads/2023/10/Recommendation-on-Addressing-uncertain-antimony-content-in-solar-glass-for-recycling.pdf.

Concept Note/ Blue Print on Management of Antimony Containing Glass from End-of-Life of the Solar PV Panels. www.eqmagpro.com/wp-content/uploads/2019/03/DraftBluePrintAntimony.pdf.

Environment Friendly Solar Glass From Interfloat. Borosil Renewables Subsidiary To Manufacture Antimony-Free Glass In Germany For European Market. Published on: 26.Jul.2023 taiyangnews.info/business/environment-friendly-solar-glass-from-interfloat.

Band Versus Polaron: Charge Transport in Antimony Chalcogenides. Xinwei Wang, Alex M. Ganose, Seán R. Kavanagh, Aron Walsh. 11.Aug.2022. arxiv.org/abs/2206.15389.

AUS02 PV Circularity. Policy Recommendations Report. Overview Report. Brett Hallam (ITP Renewables), Drew Thompson (ITP Renewables), Rong Deng (UNSW Sydney). www.eeas.europa.eu/sites/default/files/documents/2024/23039%20-%20GIZ%20Solar%20PV%20Circularity%20Report%20Overview.pdf.

Piyal Chowdhury, Tamal Chowdhury, Hemal Chowdhury, Richard Corkish, Nathan L. Chang, Necessity for recycling photovoltaic glass: Managing resource constraints and environmental impacts of antimony in terawatt scale photovoltaics, Solar Energy Materials and Solar Cells, Volume 295, 2026, DOI: doi.org/10.1016/j.solmat.2025.114012.

Nanthi Bolan, Manish Kumar, Ekta Singh, Aman Kumar, Lal Singh, Sunil Kumar, S. Keerthanan, Son A. Hoang, Ali El-Naggar, Meththika Vithanage, Binoy Sarkar, Hasintha Wijesekara, Saranga Diyabalanage, Prasanthi Sooriyakumar, Ajayan Vinu, Hailong Wang, M.B. Kirkham, Sabry M. Shaheen, Jörg Rinklebe, Kadambot H.M. Siddique, Antimony contamination and its risk management in complex environmental settings: A review, Environment International, Volume 158,2022, DOI: doi.org/10.1016/j.envint.2021.106908.

Cooper RG, Harrison AP. The exposure to and health effects of antimony. Indian J Occup Environ Med. 2009 Apr;13(1):3-10. doi: 10.4103/0019-5278.50716.

Cynthia E. L. Latunussa, Lucia Mancini, Gian Andrea Blengini, Fulvio Ardente, David Pennington. Analysis of Material Recovery from Silicon Photovoltaic Panels. Life Cycle Assessment and Implications for Critical Raw Materials and Ecodesign. March 2016. https://www.unige.ch/antimony/application/files/2614/7723/8074/Analysis_of_material_recovery_from_photovoltaic_panels.pdf.

Padala Abdul Nishad, Anupkumar Bhaskarapillai, Antimony, a pollutant of emerging concern: A review on industrial sources and remediation technologies, Chemosphere, Volume 277, 2021, DOI: doi.org/10.1016/j.chemosphere.2021.130252.

K, D., & S, M. (2025). Immobilizing toxic solar waste into sustainable concrete for fortifying biosphere. Toxicological & Environmental Chemistry, 107(7), 1391–1408. https://doi.org/10.1080/02772248.2025.2531514.

FRELP - Full Recovery End of Life Photovoltaic. 28/06/2021. https://frelplife.wordpress.com/#:~:text=The%20FRELP%20%E2%80%93%20Full%20Recovery%20End,in%20an%20economically%20viable%20way.

References from The Criticality of Secondary Copper

Australian PV Institute (APVI) 2024, National solar installation statistics, APVI, viewed 2024.

BloombergNEF (BNEF) 2023, New Energy Outlook 2023, BloombergNEF.

BloombergNEF (BNEF) 2024, Energy-transition metals and materials analyses, BloombergNEF.

Blue Tribe Foundation & NSW Environment Protection Authority (EPA) 2023, PV reuse and recycling trials, NSW EPA, Sydney.

Clean Energy Council 2024, Clean Energy Australia Report 2024, Clean Energy Council, Melbourne.

Commodity Research Unit (CRU) 2024, Copper market outlook 2024, CRU Group.

Commodity Research Unit (CRU) 2023, Copper scrap and recycling market outlook 2023–2024, CRU Group.

Commodity Research Unit (CRU) 2023, Global copper smelting & refining review 2023–2024, CRU Group.

CSIRO 2023, Solar PV recycling and end-of-life waste flows report, CSIRO, Canberra.

Green Industries South Australia 2024, Circular economy & recycling reports, Government of South Australia.

International Copper Association (ICA) 2022–2024, Copper recycling & circular economy reports, ICA, viewed multiple years.

International Copper Study Group (ICSG) 2023, Statistical yearbook 2023, ICSG, Lisbon.

International Copper Study Group (ICSG) 2024, Copper market forecasts 2024, ICSG, Lisbon.

International Energy Agency (IEA) 2023, Energy Technology Perspectives 2023, IEA, Paris.

International Energy Agency (IEA) 2023, World Energy Outlook 2023, IEA, Paris.

International Energy Agency (IEA) 2023, Global EV Outlook 2023, IEA, Paris.

International Energy Agency (IEA) 2024, Critical Minerals Market Review 2024, IEA, Paris.

International Energy Agency (IEA) 2024, Global EV Outlook 2024, IEA, Paris.

International Energy Agency (IEA) 2024, World Energy Outlook 2024: Materials and minerals annex, IEA, Paris.

International Energy Agency (IEA) 2023, Net Zero by 2050: A roadmap for the global energy sector (2023 update), IEA, Paris.

Journal of Cleaner Production 2022–2024, Circularity and end-of-life solar PV materials, Elsevier, viewed various years.

McKinsey & Company 2023, The future of energy transition metals, McKinsey & Company.

Nature Energy 2022–2023, Materials demand for net-zero infrastructure, Springer Nature.

Pan Pacific Recycling 2024, Copper and silver recovery from PV modules: Technical data, Pan Pacific Recycling, Brisbane.

PV Industries 2023–2024, Solar panel recycling and recovery rates, PV Industries, Sydney.

Rystad Energy 2024, Copper market projections and metals demand outlook, Rystad Energy.

S&P Global 2023, The future of copper: Will the looming supply gap short-circuit the energy transition? (2023 update), S&P Global.

S&P Global Market Intelligence 2024, Copper mining outlook 2023–2024, S&P Global.

S&P Global 2024, Mine project pipeline database, S&P Global Market Intelligence.

Solar Victoria 2019–2024, Solar waste and recycling data, Solar Victoria, Melbourne.

UN Environment Programme (UNEP) 2023, Global resource outlook 2023, UNEP, Nairobi.

United States Geological Survey (USGS) 2024, Mineral commodity summaries: Copper, USGS, Reston, VA.

Wood Mackenzie 2024, Copper supply–demand balance 2023–2040, Wood Mackenzie.

Wood Mackenzie 2024, Copper long-term market outlook 2024, Wood Mackenzie.

Wood Mackenzie 2023–2024, Mine project tracking and capital cost inflation reports, Wood Mackenzie.

World Bank 2023, Minerals for climate action: The mineral intensity of the clean energy transition, World Bank, Washington, DC.

World Bank 2024, Commodity markets outlook 2023–2024, World Bank, Washington, DC.