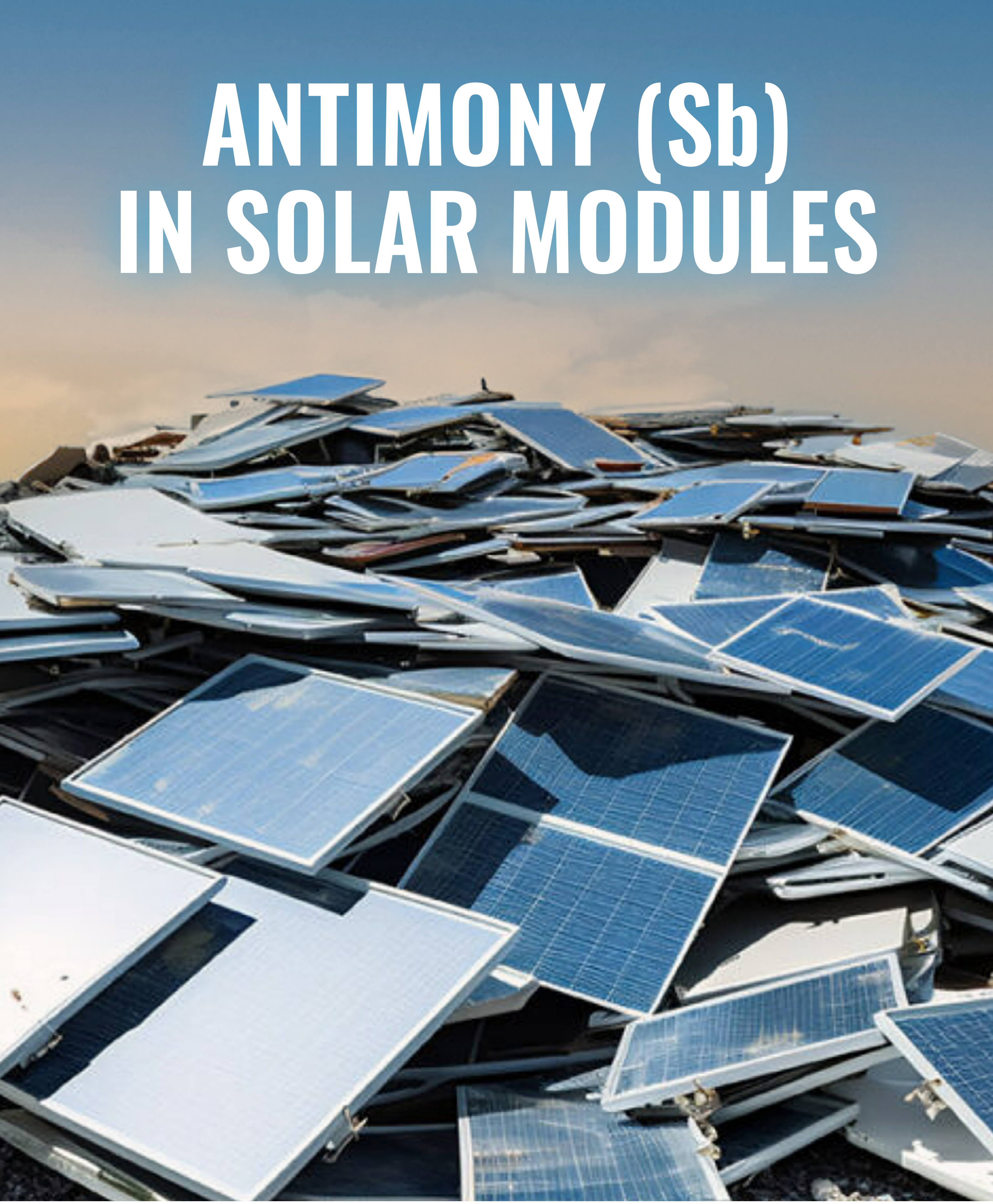
ANTIMONY (Sb) IN SOLAR MODULES



SMART ENERGY COUNCIL

EXECUTIVE SUMMARY

Antimony (Sb) is used in solar photovoltaic (PV) modules mainly within the front glass as a refining agent to improve optical performance. Small amounts may also be present in certain older encapsulants and backsheets. Although Sb is largely stable within intact glass, it remains both a valuable material for recovery and a potential environmental or health concern if poorly managed.

Patterned or textured solar glass typically contains higher levels of Sb and can complicate recycling by disrupting furnace processes. Newer modules increasingly use Sb-free or low-Sb float glass, which is easier to recycle and poses fewer risks. Identifying the type of glass is therefore essential to determine suitable processing routes.

Sb in intact modules is immobilised and presents negligible risk during normal use. Concerns arise mainly when glass is crushed into fine dust, exposed long-term to wet or acidic conditions, or processed at high temperatures without proper controls. Sb is not volatile, and reuse in concrete or ceramic products further stabilises it.

Sb cannot be identified visually. Practical detection relies on manufacturer documentation, testing, or laboratory analysis, enabling recyclers and regulators to distinguish Sb-rich materials from Sb-free ones.

Recycling pathways for Sb-containing PV glass include Closed-loop recycling into specialist glass (where composition is tightly controlled), advanced recovery technologies under development and down-cycling into materials such as concrete, where Sb remains immobilised. Global manufacturing is already shifting towards Sb-free glass, which will simplify future recycling.

To manage Sb responsibly, stewardship programs should:

- Require material declarations of Sb content;
- Collect Sb-rich and Sb-free glass separately;
- Prevent uncontrolled landfilling and ensure proper containment;
- Support research into Sb recovery and Sb-free glass;
- Prioritise procurement of Sb-free modules.

Overall, Sb in PV modules represents both a circular economy challenge and a resource opportunity. Effective identification, segregation, and controlled processing will be key to ensuring safe, sustainable and economically viable end-of-life management.

ANTIMONY (Sb) IN SOLAR MODULES

1. OVERVIEW

Antimony (Sb) is present in solar modules mainly in two ways:

1. Tempered/patterned solar glass for crystalline silicon modules: Sb compounds, primarily antimony trioxide (Sb_2O_3) and sodium antimonate ($NaSbO_3$) are added to the glass batch at roughly 0.1–1 wt% to improve light transmission and UV stability. The glass makes up about 70% of a typical silicon PV module's weight. Some industry estimates suggest the front glass of a single PV module uses approximately 32–48 g of antimony, implying that by 2030, 3,000–20,000 tonnes of Sb could be embedded in waste solar glass globally.
2. Emerging thin-film Sb chalcogenide technologies: Materials such as antimony sulfide (Sb_2S_3) and antimony selenide (Sb_2Se_3) are being developed as absorber layers for thin-film solar cells. These are still niche compared with crystalline silicon but growing in research interest.

In Australia-focused circularity work, Sb is explicitly listed as one of the toxic metals commonly found in PV modules, alongside lead and (in some cases) cadmium.

2. QUANTITIES AND RESOURCE IMPLICATIONS

Sb is primarily viewed as a valuable resource that must be recovered to support future PV growth, while also recognising that, if not properly managed, it can present toxicity risks.

At module level, glass is about 70% of a 20–25 kg module (14–18 kg of glass in one silicon-based module). If the glass contains ~0.1–0.4 wt% Sb_2O_3, this translates to tens of grams of Sb per module (broadly consistent with the 32–48 g estimate).

At a system level, a recent analysis of terawatt-scale PV deployment found that to support 3.4 TW/year of new PV installations using current Sb-doped solar glass, the sector would require around 0.42 million tonnes of Sb annually, more than five times current global production, and that existing reserves could sustain such demand for only about five years.

2.1 Sb in Backsheet Adhesives or Encapsulation

While Sb in PV modules is concentrated in the front glass, it can also appear in small amounts in polymer components, mainly as part of flame-retardant systems. The most common form is antimony trioxide (Sb_2O_3) used together with halogenated flame retardants.

It can occur in EVA[1] encapsulant as Sb_2O_3, which is used as a synergistic flame retardant. This is generally at low loadings and is not universal – many EVA formulations contain no antimony at all, relying on other additives.

It also may appear in backsheet layers (e.g. PVF/PET/PVF or PVDF-based backsheets), especially older module designs, that may incorporate Sb_2O_3 in one of the inner polymer layers to achieve fire classification requirements. Sb content here is typically much lower in mass compared with that in the glass, but can be more labile under thermal or mechanical stress because it is not locked in a glass matrix.

2.2 Stability of Sb in Different Glass Compositions

Sb's behaviour and stability in a PV module depends strongly on the type of glass and how the glass was produced. This has direct consequences for how Sb behaves in recycling furnaces, how easily it may leach, and how realistic closed-loop recycling is.

2.2.1 Patterned/textured solar glass (front glass for many crystalline Si modules)

Sb_2O_3 is used as a fining/refining agent to help removing bubbles (fining) and controls the redox state of the melt to achieve the desired optical properties (high transmission, low iron appearance). This glass can contain 0.1–1 wt% Sb compounds, making it a significant Sb reservoir in the module. The Sb is largely chemically incorporated in the silicate network and is stable in normal use.

However, in glass recycling furnaces, excess Sb can shift the redox balance, cause foaming, and interact with the tin bath in float lines, leading to defects. Over time, Sb can accumulate in closed-loop systems, which is why many float-glass operators are reluctant to accept cullets with unknown or high Sb content.

In leaching scenarios, the higher Sb concentration means that even low leach rates can lead to measurable Sb release under adverse conditions (e.g. wet, acidic landfills).

1 Ethylene–Vinyl Acetate

2.2.2 Float glass (often used for Sb-free or low-Sb modules)

Modern float glass for PV can be fully Sb-free, especially in jurisdictions where Sb is restricted, or it may contain only trace amounts of Sb from raw materials or as legacy impurities.

Different from patterned/textured solar glass, float glass is made on a molten tin bath. Sb is generally not desired because it can disturb the tin/glass interface, create haze, or cause defects. As a result, many float glass lines are designed and operated assuming very low Sb levels, and cullet feed must respect that.

Because Sb concentrations are very low or zero, environmental and health risks from Sb in float glass are minimal to negligible, even under harsh conditions, compared with patterned solar glass. Closed-loop recycling of float glass (into other float products) is much easier to manage from a redox and quality standpoint.

2.2.3 Importance of the glass type

For resource recovery, Sb-rich patterned solar glass is both a valuable secondary Sb resource and a process risk for conventional glass furnaces. Sb-lean or Sb-free float glass is less problematic and can more easily be cycled through standard glass recycling streams.

For traceability systems, identifying whether a module uses Sb-rich patterned glass or Sb-lean/Sb-free float glass is critical for routing cullet to appropriate recyclers, designing segregated collection streams, and planning any future Sb recovery technologies.

3. ENVIRONMENTAL AND HEALTH IMPACTS

3.1 Toxicology of antimony

While intact solar-module glass poses very low risk in normal use, issues can arise when the glass is broken, crushed or disposed of in conditions where leaching can occur — especially in wet or acidic environments.

Sb and its compounds are considered pollutants of emerging concern. At high concentrations they can be toxic to ecosystems and may accumulate in the food chain. Under these conditions, small amounts of antimony can dissolve out of the glass and enter soil or water systems.

Human health impacts from long-term exposure to antimony compounds (particularly inhalation of fine particles such as Sb_2O_3 released during uncontrolled crushing or poor-practice recycling) can include respiratory irritation and pneumoconiosis, skin lesions, gastrointestinal symptoms, and potential carcinogenicity, as antimony trioxide is classified as ‘possibly carcinogenic to humans’.

Proper handling, containment and controlled recycling processes prevent these risks.

3.2 How to Identify Sb in Solar Glass

It is impossible to visually identify Sb in solar glass. However there are some tests that can be done, as follows.

3.2.1 Manufacturer and Model Information

The module label (usually on the backsheet) usually includes: manufacturer, model number, year of manufacture and country of origin. From this, you can check the manufacturer’s datasheets, request a Material Declaration (IEC 62944 / ISO 14021 style) and identify the typical bill of materials used for that model. Some patterns are observed:

- Chinese-manufactured crystalline silicon modules (pre-2023) commonly use antimony-doped patterned glass.
- European and some North American modules more often use antimony-free float glass due to regulatory pressures.

Import history and BOM documentation also shows If the installer, EPC, or importer has purchase records, customs documents and factory BOM certificates. These often state the front-glass type (patterned solar glass with Sb vs. Sb-free float glass). Administrative and manufacturer information is the most accessible real-world method.

3.2.2 Laboratory Methods

Suitable for stewardship programs, recyclers, and research. X-Ray Fluorescence (XRF) is the best practical laboratory/field tool, as portable XRF guns can detect Sb in glass down to parts per million (ppm) to percentage (%) levels. It works on intact or broken glass, is non-destructive, and is fast (5–30 seconds). It is commonly used in recycling plants. Some limitations are that glass composition may require calibration, and Sb in glass is often in compound form (Sb_2O_3 or $NaSbO_3$), but XRF still detects the total Sb. If you choose only one method, this is the industry standard.

There is also the Laboratory Analysis called ICP-OES[2] or ICP-MS[3] which require dissolving a sample of the glass using acid digestion or fusion. This test is extremely accurate and can measure very low Sb levels. It is used for regulatory testing, environmental risk assessment, or R&D, however it is not suitable for on-site screening.

Lastly there is the SEM-EDS[4] test, which is a highly precise scientific test generally reserved for research or sophisticated failure analysis. It accurately maps the presence and distribution of Sb within the glass matrix. While too intensive for routine checks, its scientific precision is invaluable.

3.2.3 Indirect Indicators

Performance clues during recycling. Glass cullet that discolours unexpectedly, causes foaming or instability in a glass furnace, or interferes with tin-bath float processes. Often contains antimony (Sb_2O_3 is a known refining agent causing these behaviours). Recyclers sometimes detect Sb by how the cullet behaves operationally. The age of the module can also indicate the presence of Sb. This is not a guarantee — but statistically useful:

- Older silicon-based modules (pre-2015) almost always used antimony-doped patterned glass.
- Post-2020 European modules increasingly use Sb-free glass.

3.2.4 Summary of testing methods

Summary Table: How to Identify Sb in Solar Glass

METHOD	INTACT GLASS	ACCURACY	PRACTICALITY	NOTES
Visual inspection	✘	None	✘	Not possible to see Sb
Manufacturer/ BOM lookup	✔	Medium	✔✔✔	Best for field identification without equipment
Portable XRF	✔	High	✔✔	Standard for recyclers
ICP-MS / ICP-OES	✔	Very high	✔	Lab-only
SEM-EDS	✔	Very high	✘	Research-grade
Recycling behaviour indicators	N/A	Low – Medium	✔	Useful operational clue, not a formal test

3.3 Risks of Sb

Sb in solar glass is safely bound within the glass matrix and does not pose a risk in intact modules or in normal handling. Antimony only becomes a potential concern when the glass is crushed into fine particles that can become airborne, or when broken glass is exposed for long periods to wet, acidic or alkaline conditions that promote leaching. It is not volatile and cannot enter the atmosphere as a gas. When Sb-containing glass is reused in concrete, for example, the glass and cement both immobilise it, resulting in negligible exposure during construction or use.

So, under what circumstances can Sb become a risk? It can only affect humans or the environment under specific conditions where it can escape from the glass in a usable form (unless the worker is dry-handling very fine, dusty Sb-rich glass powder without PPE).

2 Inductively Coupled Plasma – Optical Emission Spectroscopy
3 Inductively Coupled Plasma – Mass Spectrometry
4 Scanning Electron Microscopy with Energy-Dispersive Spectroscopy

These are the main pathways:

CONDITION	SB EXPOSURE	NOTES
Intact solar glass	Extremely low	Sb is locked inside the glass.
Broken glass (large pieces)	Extremely low	No dust, very little leaching.
Crushed/ powdered glass (dry)	Moderate if inhaled	Dust is the main exposure pathway. This mostly occurs in poorly controlled recycling environments or industrial processing without proper dust control.
Concrete with glass cullet	Extremely low	Glass + cement immobilise Sb (exposure is near zero because: Coarse cullet does not create respirable dust, Sb is encapsulated inside the glass, and concrete itself further binds and immobilises the glass).
Leaching in landfill[5]	Possible	Requires long-term wet/acidic conditions (landfills, especially unlined, wet, or acidic ones. Improper stockpiles exposed to rain. Long-term environmental exposure of broken glass)
High-temperature glass recycling	Possible	Requires industrial furnaces (This is an issue more specific for glass manufacturing plants, and these facilities use filtration systems to capture emissions). Controlled via filters.

3.4 Antimony in solar glass – leaching and waste aspects

Testing of waste solar glass in some jurisdictions (specially in Europe) has shown that, while Sb is present, the concentrations in bulk glass may fall below thresholds for “hazardous waste” classification.

But leaching risk exists. Studies warn that Sb can leach out of glass under wet landfill conditions, creating potential groundwater contamination issues. Sb-containing solar glass cullet is problematic for standard glass recycling streams: Sb can interfere with float glass production (by reacting with the tin bath), and its presence must be carefully controlled for quality and environmental reasons.

Because of both toxicity and recycling complications, bans and restrictions on Sb use in solar glass are increasing, driving demand for Sb-free, low-iron solar glass formulations.

3.5 Thin-film antimony chalcogenides

For some thin-film cells (Sb_2S_3/Sb_2Se_3), the Sb is more concentrated in the absorber layer rather than dispersed in glass. The environmental and health risk in this case will depend strongly on end-of-life handling (e.g., controlled recycling vs. uncontrolled crushing and disposal).

Detailed LCA work is ongoing, but they are generally treated with the same caution as other heavy-metal-containing thin-films (e.g., CdTe).

4. RECOVERY AND RECYCLING PATHWAYS

4.1 Closed-loop recycling of antimony-containing solar glass

The concept proposes using PV glass cullet that contains Sb back into the production of new solar glass (still with Sb) or other specialist glass products. Since patterned solar glass manufacturers outside Europe frequently utilise Sb, Sb-containing cullet could, theoretically, be reintroduced directly into the production of new Sb-containing patterned glass. To enable closed-loop recycling, traceability and composition data for the glass are critical.

The highly variable and often unknown Sb content in imported solar glass makes it difficult to guarantee consistent glass properties; furthermore, in float glass lines, Sb can react with the tin bath, causing discolouration and damaging furnace performance, which makes operators reluctant to accept such cullet.

4.2 Advanced PV recycling processes with antimony recovery

In a typical mechanical PV recycling line, modules are typically shredded/crushed into smaller pieces and then further ground/milled to liberate glass from metals and polymers (sorted by size and density of glass fraction, metals, plastics, etc.). If the front glass contains Sb, it remains inside tiny glass particles. It does not turn into a gas; it stays as part of the solid material. So the key risk pathway is dust inhalation, not vapour.

When PV modules are dry-crushed or ground, they can generate fine respirable dust (PM10 / PM2.5 range) which may contain Sb compounds (mainly Sb_2O_3 within the glass). If workers inhale large amounts of

5 Most studies show very low leaching (<1% of total Sb) under neutral conditions but elevated leaching under acidic or long-term wet landfill conditions.

this dust over time, there is a potential for respiratory irritation (coughing, sore throat, bronchitis-like symptoms), pneumoconiosis-type effects (chronic lung changes from long-term dust exposure) and other effects associated with chronic Sb_2O_3 inhalation (some evidence for "antimony spots" on skin, GI symptoms, and possible carcinogenicity at high occupational levels).

It is important to highlight that the dust is glass dust containing Sb, not pure Sb_2O_3 powder, which likely reduces bioavailability compared with handling loose Sb chemicals, but the conservative approach is to treat it as potentially hazardous dust and control exposure. Sb can theoretically be ingested if dust contaminates hands, food, or smoking materials. With basic hygiene (hand washing, no eating in the processing area), this pathway is usually minor compared with inhalation.

ENGINEERING CONTROLS	ADMINISTRATIVE CONTROLS	PPE
• Enclosed crushers and conveyors where possible • Local exhaust ventilation (LEV) at crushing and transfer points • Dust extraction with filters (e.g. baghouse filters, HEPA where needed) • Design material flows to minimise free-fall drops that generate dust clouds	• Keep dusty tasks in designated zones • Housekeeping procedures: vacuum systems rather than dry sweeping • Avoid storage of fine crushed glass in open heaps exposed to wind and rain • Training workers on Sb presence and dust hazards	• Respiratory protection (e.g. P2 or better) for workers near crushers and screens • Protective clothing (coveralls) to prevent dust transfer to clean areas • Gloves and eye protection as part of standard handling

However, several R&D and pilot recycling processes go beyond simple shredding:

- Thermal-mechanical delamination + selective treatment of glass
  - Processes like the FRELP (Full Recovery End-of-Life PV) concept mechanically and thermally separate module layers, then treat glass to recover high-value materials.
  - A scenario study suggests that recycling Sb from PV glass within such advanced flows could significantly improve climate benefits (e.g., ~2,274 kg CO -eq avoided per tonne of recycled PV compared with a baseline scenario).
- Hydrometallurgical leaching of Sb from glass cullet
  - More generally, Sb removal from industrial wastes (soils, sludges, mining residues) uses acid or chelating leachants followed by precipitation, adsorption, or membrane treatments.
  - Translating these methods to PV glass would involve: crushing the glass to increase surface area, leaching Sb under controlled conditions and recovering Sb as a salt or oxide for reuse (e.g., in flame retardants, alloys, or potentially new glass batches).
  - This is technically feasible but energy- and reagent-intensive, and so far more discussed at research level than deployed at scale for PV glass.

4.3 Reuse of glass with immobilised Sb (down-cycling)

When direct Sb recovery is not economical, an alternative is to immobilise Sb-bearing waste glass into other materials such as concrete or ceramic products, reducing its leaching potential. Recent studies have explored embedding PV waste (including Sb and other metals) into concrete matrices to stabilise contaminants while recovering some material value. This is effectively a down-cycling pathway where the Sb is not recovered as a separate stream but is prevented from entering the environment.

4.4 Upstream solutions: antimony-free solar glass

From a systems-design perspective, the most effective "recovery" strategy in the long term is avoiding the problem. Sb-free high-transmission solar glass is now commercially available, using very low-iron silica sand and alternative refining strategies. Germany's recent PV manufacturing tenders explicitly require Sb-free solar glass, and companies in Europe and Brazil are investing in production capacity for 100% Sb-free solar glass.

For stewardship programs, this creates a clear long-term direction: *"Progressively phase down Sb use in new modules while designing traceable, segregated recycling streams for legacy Sb-containing glass."*

4.5 Behaviour of Sb in Thermal Decomposition

During thermal delamination, a process used by some recyclers to remove EVA at temperatures around (~300–600°C), Sb mostly remains immobilised in the glass. The formation of fine particulates is possible if the glass is mechanically stressed during heating. This is a significant consideration because many end-of-life recycling systems incorporate thermal delamination as a potential step.

4.6 How Sb affects downstream recycling

Besides furnace foaming, tin-bath reactions, and other processes already mentioned in this document, it is important to highlight that when antimony accumulates in closed-loop glass furnaces, it alters oxidation–reduction balance, which can cause bubble formation, changes in melt viscosity and optical defects. This explains why glass manufacturers avoid Sb-containing cullets even beyond contamination concerns.

5. IMPLICATIONS FOR STEWARDSHIP AND TRACEABILITY

Bringing it back to policy and practical design:

1. **Inventory and data collection:** Record, where possible, whether panels use antimony-containing patterned glass or Sb-free float glass, especially in new installations. Require manufacturers or importers to provide material declarations including Sb content bands (e.g. <0.1%, 0.1–0.3%, >0.3%).
2. **Segregated collection & sorting:** At end-of-life, separate antimony-rich glass streams from Sb-free glass where feasible, enabling: dedicated routes to Sb-tolerant secondary users, or pilot projects for Sb recovery / immobilisation.
3. **Environmental safeguards in disposal:** Avoid uncontrolled landfilling of PV glass, particularly where wet conditions could promote Sb leaching. Where landfill is unavoidable, require engineered containment and leachate monitoring.
4. **Support R&D and pilots:** Co-fund or partner in:
   - Glass-to-glass recycling pilots that test Sb-containing cullet in new solar glass,
   - Hydrometallurgical Sb recovery trials from PV glass cullet,
   - Immobilisation options (e.g., concrete, geopolymers) with robust leaching tests.
5. **Drive antimony-free design standards:** Encourage or mandate Sb-free glass in public procurement and incentive schemes for new PV projects. Link this to broader eco-design criteria (lead-free, cadmium-free, PFAS-free, etc.) to align with international best practice.

SMART ENERGY COUNCIL

6. REFERENCES

1. 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
2. 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
3. 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
4. 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
5. 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
6. 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
7. 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.
8. 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.
9. 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.
10. 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
11. 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.
12. 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
13. 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.