Tracking the fate of contaminants from solar panels using stable isotopes

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The general interest in renewable energy resources is growing exponentially as the world's population enters the 21st century, with photovoltaic solar technology playing an important role in the attempt to replace non-renewable resources. In fact, crystalline silicon (c-Si) solar panels (SPs) are the most widely used type worldwide, accounting for ~90% of the total market share (Preet and Smith, 2024).

Regarding the toxicity of SPs, the USEPA Toxicity Characteristic Leaching and Synthetic Precipitation Leaching Procedures (TCLP and SPLP) applied to different types of shredded c-Si SPs showed the mobilization of a wide range of trace elements (Sharma et al., 2021). Interestingly, Pb significantly exceeded both TCLP and international drinking water (acceptable) limits. **The authors highlight the important role of SPs e-waste aging in the overall rate of contaminant release.** Another study focusing on CdTe-based SPs reported extreme Cd mobilization during TCLP testing, with a >600-fold increase over the USEPA drinking water limit (Ramos-Ruiz et al., 2017). Su et al. (2019) focused on evaluating the stability of CuInGaSe-based panels during different strategies of anthropogenic acid leaching and documented the preferential mobilization of Zn, Cu, and Ni. Consistent with this, increased release of Pb, Cd, Ag, and Cr from different types of SPs has been previously documented under certain water-based simulated conditions (Zapf-Gottwick et al., 2015; Nover et al., 2017).

To date, there is no systematic study that would provide combined data on stable metal(loid) isotopes, i.e., Ag, Sb and Cu (Table 1), in any e-waste from SPs and their subsequent behavior in the environment, soil (Fig. 1). **Importantly, the isotopic ratios, variations and associated isotopic fractionations (expressed as δ or ε, a deviation in parts per 10^3 and per 10^4, respectively, relative to the standard material) can be used to trace contamination source(s) or as tracers for environmental (industrial?) processes.**

Table 1. List of isotope systems emphasized in this research.

Element	Symbol	Priority pollutant[a]	Critical/strategic raw material[b]	Isotopes (abundance, %)	Typical notation of isotope ratio
Silver	Ag	+++	+++ (U.S.)	^{107}Ag (51.84) ^{109}Ag (48.16)	ε^{109}Ag or δ^{109}Ag
Antimony	Sb	+++	+++ (EU)	^{121}Sb (57.21) ^{123}Sb (42.79)	ε^{123}Sb or δ^{123}Sb
Copper	Cu	+++	+++ (EU)	^{63}Cu (69.17) ^{65}Cu (30.83)	δ^{65}Cu

[a] Priority pollutant list (USEPA, 2014).
[b] Report on Critical Raw Materials and the Circular Economy (EU, 2018, 2023), EC's Raw Material Information System (RMIS2.0; http://rmis.jrc.ec.europa.eu).

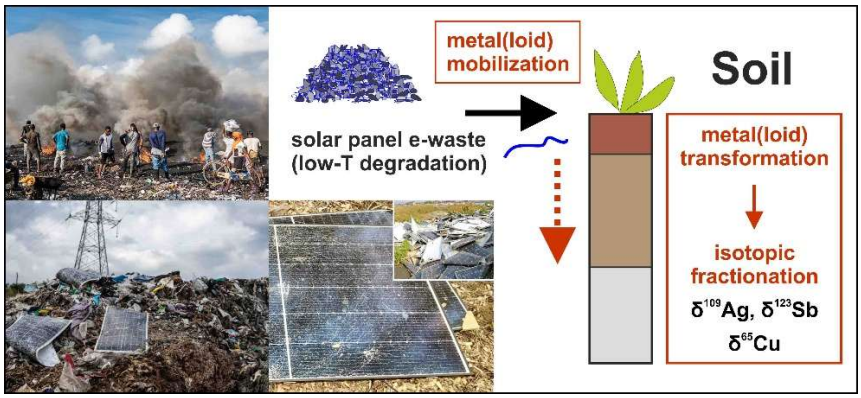

Figure 1. A simplified scheme of solar panel e-waste degradation during low-T alteration processes in soils, resulting in the release, migration, accumulation and transformation of trace metal(loid)s (Ag, Sb and Cu) and associated isotopic fractionation, i.e., at e-waste disposal sites, or elsewhere/natural sites – soils.

Our preliminary results from different (operationally defined) samples of SPs, including pc/mc-Si cells, obtained from the SPs recycling division of DEKONTA Inc. (Czech Rep.), show an apparent variability in both Ag concentrations and Ag isotopic composition (Fig. 2). The identified δ^{109}Ag values, which are in the range of +0.03 and +0.11 (±0.02, 2σ) (Fig. 2), suggest both the isotopically lighter Ag fraction present in the SPs glass as well as different source origins of Ag in the mc- and pc-Si cell samples. However, the question that clearly remains is to what extent the chemical form of Ag and/or specific industrial processing could have produced the Ag isotopic fractionation. Regarding the environmental systems, redox reactions are generally considered the primary factor influencing metal(loid) isotopic fractionation.

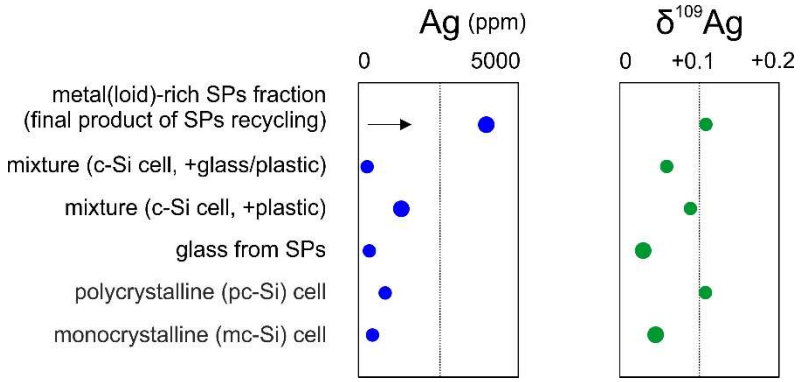

Figure 2. Distribution of Ag and Ag isotopic ratios (with δ^{109}Ag notation) in different (operationally defined) samples of SPs and pc/mc-Si cells. The individual materials were obtained from the Solar Panel Recycling Division of DEKONTA Inc. (Prague, Czech Rep.); https://www.dekonta.cz/en/. Silver concentration and isotopic data represent approximate values as they were obtained from different types of SPs samples and specific (pc/mc-Si) cells (PI data, Vaněk et al.).

The first stage of this project involves determining the isotopic composition of Ag, Sb, and Cu in various SPs types and their subcomponents. Then, model (bag) incubation experiments in contrasting soil types are planned. Three working hypotheses will be addressed: (A) Changes in the isotopic signatures of Ag, Sb, and Cu reflect redox-driven leaching, (B) Silver and Cu isotopes serve as indicators of specific sorption to soil oxides, and (C) Linking Ag, Sb, and Cu concentration and isotope data in a model system identifies soil sub-processes following SPs degradation and the origin of contaminant sources (anthropogenic vs. geogenic). **Appropriate experiments are set to be carried out in 2026 and 2027, with selected findings to be presented in person at the conference (KOS, 2026).**

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