Solar panels – A global e-waste and a secondary source of CRM

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The current global growth of photovoltaics is very dynamic, reaching >1TW of total installed capacity in 2021, with Asia (mainly China), North America, and Europe as the leading regions (IRENA, 2022). In fact, crystalline silicon (c-Si) solar panels (SPs) are the most widely used type worldwide, accounting for ~90% of the total market share.

With the average lifetime of SPs being <25 years, society is beginning to be faced with a large amount of solar electronic waste (e-waste) (Preet and Smith, 2024). Beyond the general strategy of proper recycling of this or any other e-waste, there is evidence of unsustainable disposal of SPs, including landfilling (Fig. 1), which exposes the environment to a range of chemical hazards. This means that in countries without strict e-waste regulations and/or ineffective e-waste management, damaged (and non-functioning) SPs are likely to end up in landfills or elsewhere/natural sites – soil…

Since the solar cells in SPs consist of metallic conductors (electrodes) and metalloid-containing semiconductors, damage to the protective glass and cell encapsulant can result in the mobilization of major/trace elements and their introduction into the adjacent soil, or sediment environment. Most importantly, the degradation of SPs can clearly lead to the release of toxic trace elements, making them emerging contaminants. In addition to major constituents such as glass (~70%), plastic polymer (~10%), Al (~8%), Si (~5%) and hundreds to thousands ppm of Ag, Cu, Sb, Sn and Pb are typically found in e-waste from c-Si SPs (IRENA, 2022).

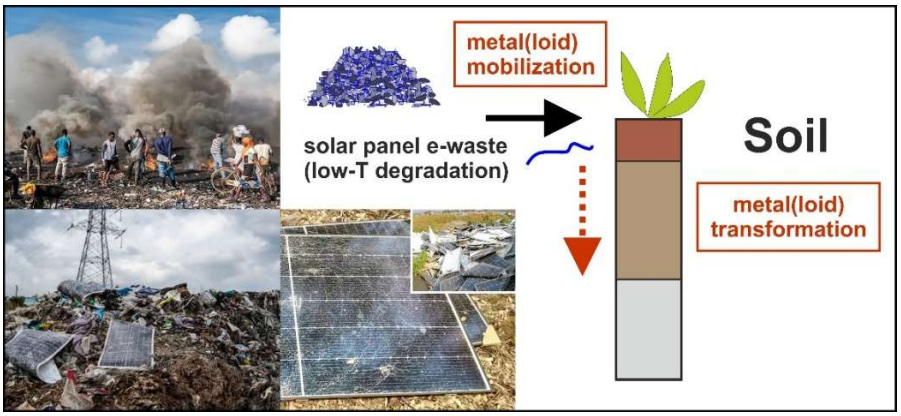

Figure 1. A simplified scheme of solar panel e-waste degradation during low-T alteration processes in soils, resulting in the release, migration, accumulation and transformation of trace metal(loid)s, i.e., at e-waste disposal sites, or elsewhere/natural sites – soils.

Some of these elements are also listed as priority pollutants by the USEPA and/or the Critical Raw Materials by the EU. Knowledge of the environmental stability of SPs and the leaching potential of pollutants may serve as a novel tool to understand their fate within the e-waste end-of-life phase(s). Currently, no systematic study provides complex (geo)chemical data on major trace metal(loid)s, such as Ag, Sb, and Cu (Table 1), in any e-waste from SPs and their subsequent behavior in the environment (Fig. 1).

Table 1. List of elements emphasized in this research.

Element	Symbol	Priority pollutant[a]	Critical/strategic raw material[b]
Silver	Ag	+++	+++ (U.S.)
Antimony	Sb	+++	+++ (EU)
Copper	Cu	+++	+++ (EU)

[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).

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 Republic), show an apparent variability in metal(loid) concentrations (Fig. 2).

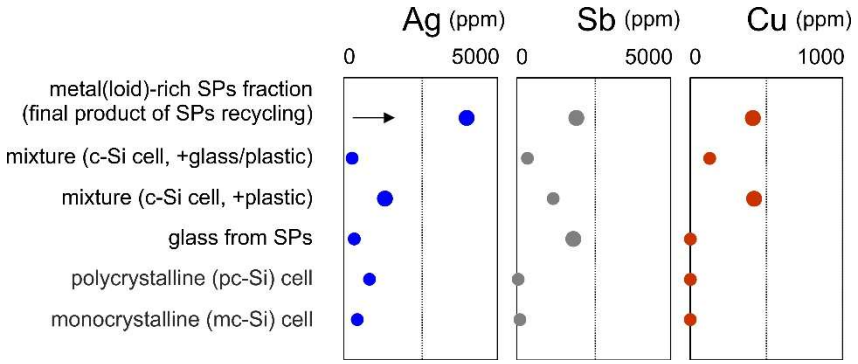

Figure 2. Distribution of metal(loid)s (Ag, Sb and Cu, in ppm) in different (operationally defined) samples of SPs and pc/mc-Si cells. The individual materials were obtained from the Solar Panel Recycling Division of DEKONTA Inc. (Prague, Czech Rep.); https://www.dekonta.cz/en/. Concentration data represent approximate values as they were obtained from different types of SPs samples and specific (pc/mc-Si) cells.

Regarding individual metal(loid)s, the highest concentrations were found in the final product of SPs recycling – metal(loid)-rich SPs fraction, and the mixture of c-Si cells (without protective glass). These concentrations reached ~4,000, ~2,000, and 400 ppm for Ag, Sb, and Cu, respectively (Fig. 2). Clearly, both Ag and Cu are used in SPs for their conductivity, i.e., their ability to collect and transmit electrical energy through contacts, coatings and wires. As for Sb, there is an apparent enrichment in/on the glass matrix of SPs, in contrast to Ag and Cu. It should be highlighted that Sb-based compounds (Sb_2Se_3, Sb_2O_3 etc.) are commonly added here as antireflective coatings to enhance light absorption and solar performance.

Model batch (static) leaching experiments are planned to assess/quantify the stability of SPs and the rate of contaminant leaching when exposed to environmental solutions. Specifically, synthetic rainwater (SRW; EPA Method 1312, USEPA, 1994) and model rhizosphere solutions composed of low-molecular-weight organic acids (LMWOAs) will be used. Different size fractions of the shredded (bulk) SPs samples (~1 mm-1cm), including fresh and old ones (<2016) are planned to be involved within the project. **Importantly, these experiments will be carried out in spring 2026. Selected key findings will be presented in person at the conference (KOS, 2026).**

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