ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF RECYCLING PATHWAYS FOR PEROVSKITE-SILICON TANDEM MODULES

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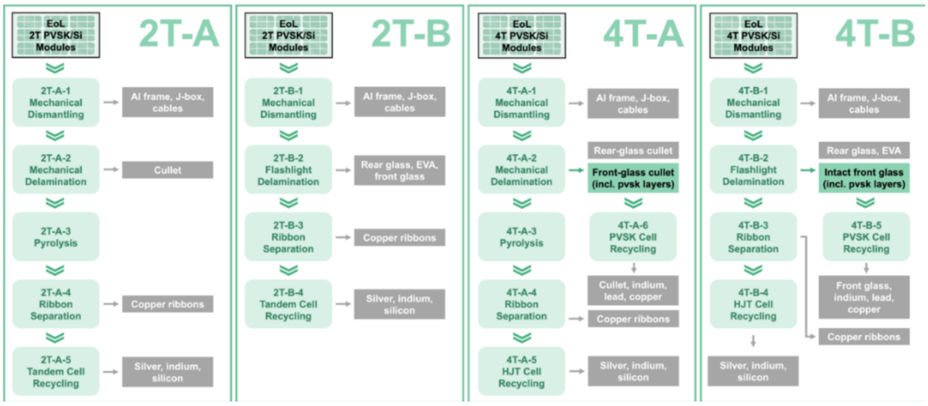
Perovskite-silicon tandem modules are promising candidates for next-generation photovoltaics due to their high efficiency potential. However, end-of-life (EoL) management strategies for these technologies remain underexplored, as industrial-scale production and installation volumes are still low. Nevertheless, it is crucial to consider the various stages of the supply chain to ensure viable and sustainable EoL treatment processes for these modules.



This study presents a comprehensive techno-economic analysis (TEA) and life cycle assessment (LCA) to evaluate the viability of four recycling routes (2T-A, 2T-B, 4T-A, 4T-B, see Fig. 1) for two-terminal and four-terminal tandem PV modules. The analyses consider two delamination methods (flashlight and mechanical), the presence or absence of pyrolysis, and chemical processes for recovering materials from both the silicon solar cells and the perovskite layers. All scenarios assume treatment at a recycling facility in France with an annual throughput of 13,000 tons of PV modules. The LCA is based on a functional unit of treating 1 ton of modules and excludes transport and storage stages.

TEA results indicate that all four recycling pathways are economically viable, with treatment costs ranging from €3.3 to €5.3 per module and recovered material values ranging from €7.5 to €8.5 per module. Labor is the main cost driver across all routes, accounting for approximately 60% of total costs, see Fig. 2. From an environmental perspective, all routes show net positive impacts. The most significant impact category is *Resource use, minerals and metals* (~60%), followed by *Climate change* (~12%). Recycling routes employing flashlight delamination (2T-B, 4T-B) generally perform better than those using mechanical delamination combined with pyrolysis due to energy requirements and ethylene vinyl acetate (EVA) encapsulant recovery rates, see Fig. 3. Silver and aluminum are identified as the most valuable recovered materials, both economically and environmentally. Sensitivity analysis reveals that silver recovery rates and the purity of recovered silicon are critical factors influencing both the net economic value and environmental benefits of the recycling processes.

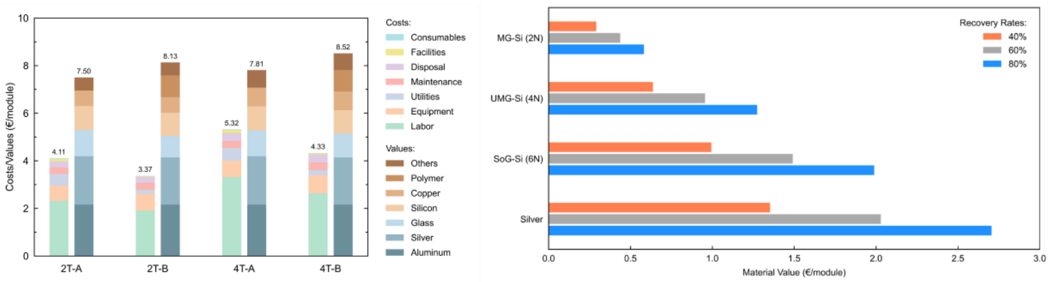


Fig2. Results from the techno-economic analysis and sensitivity analysis.

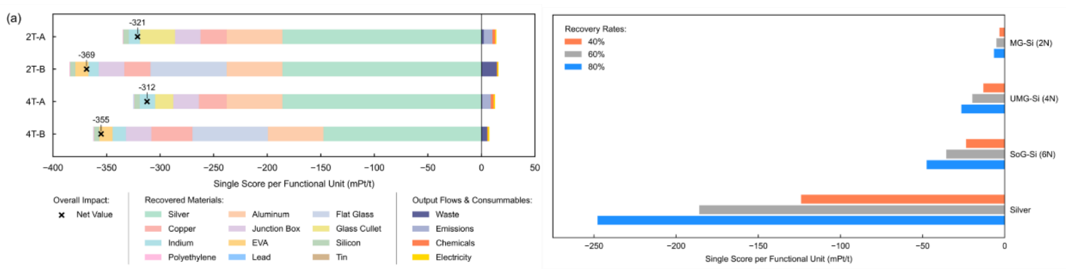


Fig3. Results from the life cycle assessment and sensitivity analysis.