Life Cycle Assessment of Laboratory Scale $Cu_2ZnSn(S,Se)_4$ Solar Cells

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With the motivation of absorber layers which contain Earth-abundant, cheap and low-toxicity elements, the material $Cu_2ZnSn(S,Se)_4$ (CZTSe) has been a popular choice in the inorganic thin-film photovoltaics (PV) research community. After an extended period with no improvements to efficiency, recent records of ~13.8% [1] suggest a possible resurgence in research. Here we explore quantifying the environmental impacts of fabricating a CZTSe solar cell at the laboratory-scale using a mix of vacuum techniques (sputtering, electron beam evaporation, tube furnace annealing) and non-vacuum techniques (CZTS nanocrystal synthesis, slot-die coating, chemical bath deposition) with a structure of glass/Mo/CZTSe/CdS/i-ZnO/ITO/Ag,Ni. The intention is to determine which processes or layers are the most significant on the overall environmental impact of the fabrication and hence which may inhibit future scale-up. A life cycle assessment (LCA) is conducted which includes the materials used, electricity consumed as well as the waste produced. Previously we have used LCA to show how to reduce environmental impacts during the synthesis of CZTS nanocrystals [2]. We now extend the LCA analysis to the whole device. The selenization step (where selenium substitutes for sulfur), whilst essential for improved device performance, contributes significantly to the overall environmental impacts of cell fabrication. This results in the impacts from the solution-processed absorber layer to be similar to the vacuum-deposited transparent conducting oxide (TCO) layer due to the necessity of a high temperature, low pressure anneal. This work is hence a timely contribution to discussions surrounding the environmental impacts of vacuum versus non-vacuum deposition. In future work, a functional unit of 1 kWh is chosen such that device performance is included. This will allow for comparison to other research-scale solar cells with absorber layers such as $Sb_2(S,Se)_3$ and $BaZrS_3$.

[1] Zhou J. *et al.* Nature Energy, 8, 526-535 (2023)

[2] Jones M. *et al.* ACS Sustainable Chemistry & Engineering, 12,31,11613-11627 (2024)