LCA OF SEMI-TRANSPARENT PHOTOVOLTAICS UNDER DEVELOPMENT IN THE TRANSMIT PROJECT

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Abstract
Window-integrated solar panels offer a complementary solution to rooftop photovoltaics by converting building facades into energy-harvesting surfaces while improving energy efficiency. The TRANSMIT international research project develops semi-transparent photovoltaic (STPV) windows with a target average visual transparency of 50% and a power conversion efficiency of 8%, using micro-striped architectures based on CIGS and perovskite materials. Life Cycle Assessments (LCA) of laboratory-scale devices show climate change impacts of 251.69 kg CO_2 eq. per m² for CIGS type STPV, and 136.09 kg CO_2 eq. per m² for the perovskite type. Although these impacts reflect early-stage prototypes, significant reductions are expected with process optimization and scale-up. The project also investigates recycling strategies to support circular economy principles and reduce dependence on critical raw materials, highlighting STPVs' role in advancing net-zero energy buildings.

Introduction
Window-integrated solar panels are valuable supplements to traditional rooftop photovoltaic (PV) panels, primarily by maximizing a building's total energy-generating surface area. While conventional panels are limited to roof space, solar windows convert vertical facades—especially on skyscrapers—into massive, productive solar arrays. This expands the system's capacity without occupying extra land or compromising a building's aesthetic. Furthermore, they contribute to overall energy efficiency by reducing solar heat gain through the glass, which lowers the cooling load on HVAC systems. By combining electricity generation with reduced energy consumption from the building envelope, solar windows and rooftop panels work together to move a structure closer to net-zero energy status.
The TRANSMIT project aims to develop advanced semi-transparent photovoltaic (STPV) technology for energy-harvesting windows. The primary goal is to create devices with a high average visual transparency (AVT) of 50% and a power conversion efficiency (PCE) of 8%. The core innovation is a design based on micro-striped solar cells, which are indistinguishable to the human eye, separated by transparent gaps. This approach is intended to overcome the aesthetic drawbacks of current building-integrated photovoltaics (BIPV), such as the impeded view of crystalline silicon (c-Si) or the unpleasant orange color of amorphous silicon (a-Si) windows. The project utilizes two high-performing solar cell materials: CIGS (Cu (In,Ga) Se_2) which has been long-known for its stability and high efficiency and Perovskites (PSC) which is a newcomer but has tremendous potential for high performance.
Key objectives of the TRANSMIT project include fabricating STPV mini-modules and advancing the technology from a proof-of-concept stage (TRL3) to a validated prototype in a

relevant environment (TRL5). The consortium of partners will also conduct comprehensive assessments on the devices' performance, durability, environmental impact, and socio-economic acceptance. The project is coordinated by the International Iberian Nanotechnology Laboratory (INL), the participants are: Italian National Interuniversity Consortium of Materials Science and Technology (INSTM), Italy; University of Cyprus (UCY), Cyprus; Middle East Technical University (METU), Türkiye; ODTU Center for Solar Energy Research and Applications, (ODTU-GUNAM), Türkiye and Bay Zoltán Research Centre (BZN), Hungary.

Life Cycle Assessments
The LCA examinations evaluate the environmental impacts of laboratory-scale STPVs to identify production "hotspots" for improvement. The assessment used a declared unit of 1 m^2 of the solar panel. The system boundary was defined as "cradle-to-gate", meaning it covers the raw material supply and the manufacturing phases but excludes the transport of raw materials, as well as the product's use and end-of-life stages. The life cycle modelling was conducted in accordance with the ISO 14040 and ISO 14044 standards. The model was created using the LCA for Experts software (formerly known as GaBi Professional). Process data was sourced from the Managed LCA content (Sphera) database and the Ecoinvent (v3.10) database. Environmental impacts were calculated using the Environmental Footprint (EF 3.1) method. The analysis focused on four key impact categories: Climate Change, Resource use (fossils), Resource use (minerals and metals), and Water use. This study contains the life cycle models and results of the TRL3 devices.

CIGS
The specific input and output data for the CIGS manufacturing process were provided by the project partner INL. The European average electricity grid mix was used in the model, as the theoretical production is not tied to a single country. Nitrogen gas was excluded from the CIGS model because the amount used was not determined and was considered negligible. The model follows the seven main manufacturing stages: photoresist deposition, photoresist exposure, DC (direct current) sputtering, photoresist removal, selenization, buffer layer deposition and finally window layer deposition.

Results

- The total Climate Change impact was 251.69 kg CO_2 eq. per m^2, which converts to 0.082 kg CO_2 eq. per kWh for comparison purposes.
- The DC Sputtering manufacturing step was the one with the highest environmental impact in the Climate Change – total and both Resource use impact categories.
- In the Climate Change – total environmental impact category the impact was primarily driven by high electricity consumption due to the unoptimized, repetitive nature of laboratory-scale production.
- For the resource use of minerals and metals, indium and molybdenum were the main contributors for the DC Sputtering manufacturing step.

Perovskite
The data for material and energy flows was determined through allocation by the Italian National Interuniversity Consortium of Materials Science and Technology (INSTM), who developed the perovskite cell. The main stages of fabrication were the following: substrate cleaning, ETL (Electron Transport Layer) deposition, perovskite deposition, HTL (Hole Transport Layer) deposition, TCO (Transparent Conductive Oxide) deposition, laser ablation

and encapsulation. When data for specific precursor materials was not available, a similar, well-documented chemical was substituted as a proxy.

Results

- The total Climate Change impact was 136.09 kg CO_2 eq. per m^2, which converts to 0.044 kg CO_2 eq. per kWh.
- The most significant contributing steps were Substrate cleaning and TCO deposition in all four chosen environmental impact categories.
- The main drivers for these impacts for Substrate cleaning in the Climate Change – total impact category were the incineration of waste solvents (acetone and isopropanol) and the production of these two solvents.

A critical point which needs to be emphasized is that these results are for TRL3 laboratory prototypes and are not directly comparable to the lower environmental impacts of commercially produced (TRL 9-10), opaque solar cells reported in the literature. The environmental impacts are expected to decrease significantly as the technology matures and scales up to industrial production.

Conclusion

In the TRANSMIT project, early-stage LCA results highlight key environmental hotspots in CIGS and perovskite manufacturing. Future work will expand the system boundary of the studies for the whole life cycle of the STPVs: producing raw materials, PV manufacturing, installation, the use phase and recycling methods after the developed STPV product becomes waste. Supposed recycling procedures will enable applying circular economy principles; thus, the depletion of rare earth metals and other substances necessary to produce STPVs can be diminished.

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