VIPERLAB

FULLY CONNECTED **VI**RTUAL AND **P**HYSICAL P**ER**OVSKITE PHOTOVOLTAICS **LAB**

D 10.4

ENVIRONMENTAL IMPACT ASSESSMENT FOR KEY DEVICE ARCHITECTURES AND SELECTED PROCESS ROUTES

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FULLY CONNECTED VIRTUAL AND PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB VIPERLAB

DELIVERABLE

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DISCLAIMER

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1. Executive Summary

VIPERLAB is a research infrastructure project that aims to create a European environment, where various physical and virtual infrastructures from 13 VIPERLAB partners can be accessed by different users from Europe and abroad. VIPERLAB identifies perovskite PV as the key emerging technology that will be the lever for a future market penetration of EU-based PV production with lowest costs and lowest carbon footprint.

The overall goal of the work package 10 is to provide guidance for the infrastructure and technology development within VIPERLAB by evaluating and optimizing the environmental, social and economic impact of new perovskite-based technologies. To this end, this work package will:

- Provide the data (material, process flows etc.) necessary for such an evaluation
- Evaluate the environmental (Life Cycle Assessment, LCA), social and economic (Levelized Cost of Electricity, LCOE) impact of new perovskite-based technologies and how this impact is affected by the application, device design, choice of equipment and process.

This report D10.4 presents the insights and methodology in life cycle assessment from four members of the project consortium – Fraunhofer, CEA, CENER and HZB for both single and multi-junction photovoltaic technologies. The aim is to provide the environmental impacts and their hotspots, specifically in the case of new technologies like perovskite and perovskite-silicon tandem solar cells and modules. Due to the use of critical material, it is important to understand not only the global warming potential of new photovoltaic technologies but also the impact on human toxicity and resource depletion. The report shows the hotspots and the environmental competitiveness of single and multi-junction photovoltaic technologies as well as the status and challenges in modelling new photovoltaic technologies. The results of the LCA are to be published in a peer reviewed journal as well as are aimed to be presented at an international conference in 2025. As such, this deliverable report will mainly focus on the methods followed to carry out the life cycle assessment and not contain any detailed results to maintain novelty and not hinder efforts to publish and/or present the results at a conference. However, the results of the analysis were presented and discussed with the project consortium at the final general assembly meeting held in Brussels in November 2024 and are briefly mentioned in the summary.

2. Introduction

In the photovoltaic sector life cycle assessment (LCA) is used to assess carbon footprint and resource efficiency, ensuring that solar energy remains a sustainable technology. For new photovoltaic technologies, LCA provides insight into potential benefits and challenges, guiding researchers and manufacturers to minimize impact as the production is scaled up.

LCA is an important tool in helping with energy transition. It helps identifying environmental impacts to ensure sustainability in new technologies as well as for mature technologies through optimization by identifying areas for environmental improvement.

High levels of efficiency can be achieved with multi-junction photovoltaic technology. But what about the environmental footprint compared to conventional single junction photovoltaic technologies. An LCA was carried out to identify hotspots and demonstrate the environmental competitiveness of two single junction modules with Heterojunction (HJT) solar cells and Tunnel Oxide Passivated Contact (TOPCon) solar cells, and two multi junction technologies pero-HJT and pero-TOPCon.

3. Methodology

The aim of the LCA is to analyse and compare different impact categories for scalable, multi-junction photovoltaic modules compared to single junction photovoltaic modules. The chosen system boundary is 'cradle-to-gate' as shown in the Figure 1 below, i.e. up to the module level. The system boundary cradle-to-gate indicates that the assessment starts from the sourcing of the raw material which refers to cradle and ends at the factory gate where the product is distributed referring to gate [1]. The system boundary was defined as cradle-to-gate due to the limited data available on the recycling of perovskite modules, as the technology is still in its early stages of development.

The functional unit (FU) selected was 1 m² of PV module. To present the results, additional units of 1 kilowatt peak (kWp) and 1 kWh of module electricity were also chosen. Different functional units (FUs) serve distinct purposes, which is why three separate units are used in this study. The FU of m² reflects the environmental impacts of the module without accounting for any technical factors. The FU of kWp, on the other hand, incorporates the efficiency of the PV module technology. Therefore, a module that performs well in terms of FU m² may not necessarily have a lower environmental impact when evaluated by kWp. The FU of kWh takes into account both efficiency and the effect of irradiation, as the module's performance may vary depending on location. This means that the same PV module could have different environmental impacts per kWh at different locations due to variations in irradiation [2].

As shown in Figure 1, the wafers are assumed to be supplied from China (CN electricity mix) and the cell and module are produced in Germany (DE electricity mix). Local datasets were used for modelling all consumables where available, with CN data applied to the wafer and DE data applied to the cell and module. If a local dataset is not available for the cell and module, the preferred regional dataset is one representing Europe. If neither of these datasets is available for the cell and module, and no Chinese dataset is available for the wafer, a global or rest-of-world dataset is used for the LCA modelling.

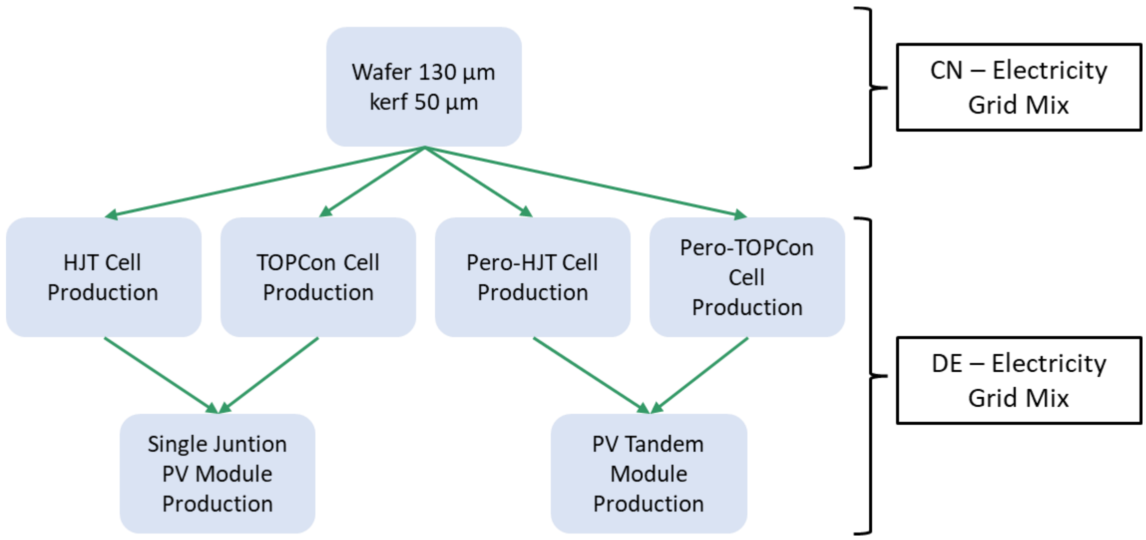

Figure 1 Simplified illustration of the LCA system boundary.

The following impact assessment categories were investigated within this analysis:

• **Global Warming Potential (GWP)**, measures the radiative forcing over a 100-year period, evaluating the potential impact of different gaseous emissions on climate change. The unit for GWP is kg CO2 equivalent [3]. This impact category is studied as it is the primary motivation for the development of photovoltaics in general.

• **Human Toxicity**, this impact category is split into cancer and non-cancer-causing impacts. The unit "CTUh" (Comparative Toxic Unit for Humans) quantifies the estimated increase in sickness rate across the global human population due to various types of emissions released into the environment. Spatial differentiation beyond continental and global compartments is not considered in the model. The impact indicator, Comparative Toxic Unit for Humans (CTUh), represents the projected increase in morbidity per unit mass of a chemical emitted, measured in cases per kilogram [3]. This impact category is included as there are concerns regarding the use of Pb, In and CS in perovskite solar cells.

• The following impact categories within Environmental Footprint 3.0 are chosen to represent **resource depletion**. The below given environmental impact categories are important in the light of the anticipated large-scale deployment of tandem photovoltaics.

- *Land Use* refers here to the deficit in the quantity and quality of the land that is occupied or transformed. The basis of this model is the soil quality index, as is the case with the LANCA model. Impacts on the biodiversity from land transformation or occupation are not considered in this model. This category has the unit Pt (Point).
- *Water Use* is the evaluation of the use of water in relation to the local scarcity of water in the different countries. The unit is m^3 deprived.
- *Resource Use, Fossils*, this describes the abiotic resource depletion of fossil fuels. Which is based on the lower heating value of the fossil fuels. The unit for this category is Mega Joule equivalent (MJ eq).
- *Resource Use, Minerals and Metals* this model is based on the CML 2002 model. The model considers the annual production and the availability of resources. The depletion model is based on use to availability ratio, and it is assumed that fossil energy carriers have full substitution between themselves. The unit for this category is kilogram Antimony equivalent (kg Sb eq) [3].

The impact categories given above have been analysed in this study using the Environmental Footprint 3.0 impact assessment method. The background model is created using the Ecoinvent 3.9.1 database. The system model “Allocation, cut-off by classification” was used with the LCA software SimaPro. Figure 2 shows a screen shot of the HJT tandem cell from the SimaPro software. While modelling the components of a photovoltaic module each process step was modelled on its own, represented as rectangles in the figure below.

The blue rectangle represents the HJT solar cell, and the rectangles below show each production step and their respective consumables. Due to the high number of processes, not all of them are shown in the network display mode of the software. This LCA corresponds to the framework presented in the ISO standards 14040-4/14044 [4,5] and the recommendations of the IEA PVPS 12 'Methodology Guidelines for LCA on PV' [6].

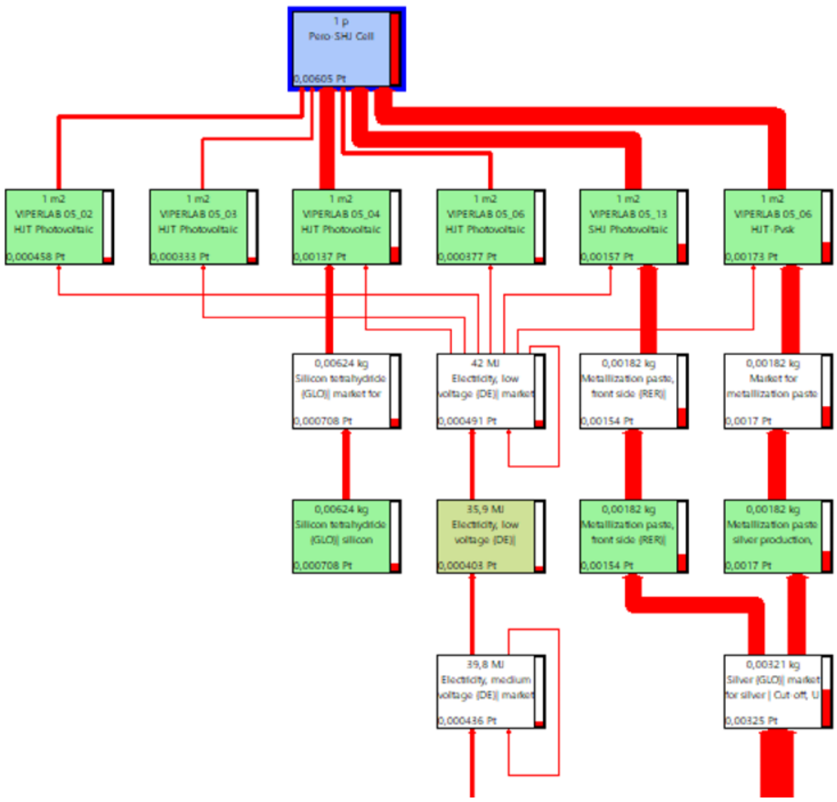

Figure 2 Screen shot from the LCA software SimaPro where partly the Tandem HJT Cell is visible.

The life cycle inventories (LCI) for metallurgical silicon, solar grade silicon, ingot and wafer were taken from Fraunhofer ISE's existing material flow analysis and LCA models, which are to be published in the near future. The data for the top perovskite cell was taken from the information available on the VAPO platform [7] and was part of the deliverable report D10.2. The HJT and TOPCon bottom solar cells and single junction cells are from Fraunhofer's SCost Tool [8], which has data received from the industry. A bill of materials was created within the SCost model and scaled per m² cell or m² module for each consumable to create the LCI to input in the LCA software SimaPro.

Table 1 shows the technical properties of the four photovoltaic modules being modelled. This table is also the base with which the conversion factor from m² to kWp are used shown in Table 2.

Table 1 Technical data for the modules investigated in this study.

Parameter	Unit	TOPCon	Pero-TOPCon	HJT	Pero-HJT
Module Efficiency	%	22.50	24.50	22.50	24.50
Module area	m^2	2.58			
Module Power	Wp	581	633	581	633

After the life cycle impact assessment (LCIA) result were exported from the LCA software per m² they were scaled to kWp and from kWp to kWh with the conversion factors given in the table below. As a sensitivity analyses for the perovskite tandem modules 20- and 30-year lifetimes were assumed and the impact in kWh were studied. Deliverable Report D10.6 further explains the procedure and methodology for the energy yield modelling, specifically for tandems. Note that the yield for the single junctions and tandems was assumed to be the same even though recent outdoor measurement data and numerical model simulation work done by HZB, and the University of Ljubljana suggests otherwise, elaborated in deliverable D10.6. The yields given in the table below were calculated within the scope of this report.

Table 2 Conversion parameters for the LCIA in m².

Parameter	Unit	TOPCon	Pero-TOPCon	HJT	Pero-HJT
Power/area	kWp/m^2	0.23	0.25	0.23	0.25
Yield for 20 years	kWh/kWp	-	22,012	-	22,221
Yield for 30 years	kWh/kWp	33,672	33,672	33,992	33,992

4. Challenges

The challenges in conducting an LCA for perovskites primarily arise from the lack of datasets for specific consumables. For the missing materials, proxy datasets are used, or available LCI data from literature is applied and modelled in the software. The missing data and their respective modelling solutions are outlined below:

- Phosphoric acid. industrial grade. without water. in 85% solution state' was used as proxy for SAM 2PACz.
- Since no dataset is available for the ultra-low temperature silver metallization paste, the same silver paste dataset was used for both tandem and single junction Si-based cells.
- For the module, all components and amounts for tandem and c-Si based modules are the same with only the edge sealants different. The c-Si based modules are assumed to have silicone while tandems are assumed to have poly-iso butylene (PIB) as a sealant for which the LCI was taken from literature.
- Other materials used in the perovskite cell which are modelled based on literature data is as the following: C60 [9], FaI [10], FaBr [11], CsI [10], PbI_2 [10], NF_3 [12], PIB [13].

5. Summary

In total, four modules were modelled - two single junction modules TOPCon and HJT, and two tandem modules, pero-TOPCon and pero-HJT. The modelling was performed in units of m^2 module in the LCA software SimaPro. The LCIA exported from the software were then converted into kWp and kWh. For the tandem modules, two energy yields were calculated based on different system lifetimes of 20 and 30 years to compare the environmental impacts throughout these different lifetimes. The result of the analysis, which are to be presented in detail in a subsequent journal paper, shows that single junction TOPCon provides a slightly lower GWP footprint for all functional units compared to HJT. For single junction's (SJ) vs tandems, SJs show a lower GWP on a square meter basis. However, on a per kWp and kWh basis, tandems have a lower GWP due to a higher efficiency but only with the same system lifetimes of 30 years as the single junctions. The perovskite top cell has a minor contribution to the overall GWP (~1%) of the tandem cell for both the pero-TOPCon and the pero-HJT case. Also, for tandem modules, Pero-HJT has a slightly lower GWP than Pero-TOPCon per kWh due to higher energy yield values owing to the assumed higher module efficiency.

6. Publication Bibliography

[1] Samruddha Kokare, J.P. Oliviera, Radu Godina, (2023) Life cycle assessment of additive manufacturing processes: A review, Journal of Manufacturing Systems 68 (2023) 536–559

[2] Christian Reichel, Abeer Khan, Pamela Molina, Friedrich Lorenz, Dilara Subasi, Sebastian Nold, Dirk Holger Neuhaus. (2023) 'Einfluss des Energiemix und des Energieertrags auf die CO2 Emissionen von Silizium Photovoltaikmodulen.' 38 PV Symposium, Bad Staffelstein.

[3] ESU-services Ltd, Description of life cycle impact assessment methods, Supplementary information for tenders, 28 June 2024, https://esu-services.ch/fileadmin/download/tender/ESU-Description-of-LCIAmethods.pdf

[4] ISO 14040, Environmental management – Life cycle assessment – Principles and framework, 2009.

[5] ISO 14044, Environmental management – Life cycle assessment – Requirements and guidelines, 2006.

[6] Frischknecht, R.P. Stolz, G. Heath, M. Raugei, P. Sinha, and M. de Wild-Scholten, Methodology Guidelines on Life Cycle Assessment of Photovoltaic 2020: Task 12-18 (2020). Prog. Photovolt. Res. Appl. 11 (8), 2003, 499-513, DOI: 10.1002/pip.

[7] Vapo Platform, https://www.viperlab-vapo.eu/manufacturing/, Accessed on 4 November 2024

[8] Nold, S., 2019. Techno-okonomische ¨Bewertung neuer Produktionstechnologien entlang der Photovoltaik-Wertschopfungskette:¨ Modell zur Analyse der Total Cost of Ownership von Photovoltaik-Technologien. Dissertation. Fraunhofer Verlag.

[9] Tsang, Michael P., Guido W. Sonnemann, and Dario M. Bassani. "A comparative human health, ecotoxicity, and product environmental assessment on the production of organic and silicon solar cells." Progress in Photovoltaics: Research and Applications 24.5 (2016): 645-655.

[10] Sherif A. Khalifa, Sabrina Spatari, Aaron T. Fafarman, Jason B. Baxter. ,'Environmental sustainability of mixed cation perovskite materials in photovoltaics manufacturing.', (2020) https://pubs.acs.org/doi/10.1021/acssuschemeng.0c05619

[11] Alberola-Borràs, Jaume-Adrià, Rosario Vidal, and Iván Mora-Seró. "Evaluation of multiple cation/anion perovskite solar cells through life cycle assessment." Sustainable Energy & Fuels 2.7 (2018): 1600-1609.

[12] Jungbluth, N., M. Stucki, K. Flury, R. Frischknecht and S. Büsser (2012). "Life cycle inventories of photovoltaics." ESU-Services Ltd.: Uster, Switzerland: 250.

[13] Dmitry Bogachuk, Peter van der Windt, David Martineau, Stephanie Narbey, Anand Verma, Salma Zouhair, Andreas Hinsch, Markus Kohlstädt , Lukas Wagner, A novel recycling method for encapsulated perovskite mesoscopic photovoltaic devices with minimal performance loss, Proceedings of International Conference on Hybrid and Organic Photovoltaics (HOPV22)València, Spain, 2022 May 19th - 25th