Milestone n°7 "*LCA methodology defined*"

Work package	WP6. T6.1 Support to eco-design
Lead beneficiary	10-ULIEGE
Participants	EURAC, EPFL, CPT, CSEM
Means of verification	Agreement by all parties on LCA methodology and compatibility with EU regulation checked
Due date	Month 9 (July 2023)

Table of Contents

Milestone n°7

Description of the milestone

Milestone 7 has been achieved by setting the Life Cycle Assessment (LCA) methodology that will be used in PILATUS project to support the eco-design of the SHJ-IBC technology as well as to analyse the environmental profile of the designed solution (Subtasks 6.1.1 and 6.1.2 of the PILATUS work programme, respectively). This document addresses the methodological choices agreed with all parties involved in this task (ULIEGE as leader, and EURAC, EPFL and CPT as participants) as well as the compatibility with EU regulations.

The following sections provide a review of the legislations and guidelines involving LCA of photovoltaic technology and a preliminary goal and scope definition of the LCA according to ISO 14040 standards [1]. Also, the recommendations suggested during the LCA Methodology Harmonisation Workshop that took place in Brussels in March 2023 are included.

General method

The methodology was defined according to the Product Environmental Footprint (hereinafter PEF) framework. PEF was recently set by the European Commission as a common approach to measure the environmental performance of a product through the life cycle (EU Commission Recommendation 2021/2279). These studies are compliant with ISO 1040-44 [1, 2] and should be complemented by Product Environmental Category Rules (PEFCR) if they exist for the product under study. In the case of photovoltaic panels, there is the "PEFCR Photovoltaic modules used in photovoltaic power systems for electricity generation. Version 1.2". This document has expired in 2021, however since there is no further update, it will be used for some parts of the modelling as a guideline since it analyses mono- and multi-crystalline silicon PV technologies. The analysis performed will be updated if new requirements for eco-design of PV systems will be published within the PILATUS project, as foreseen by the European Commission.

The LCA task will be divided into three stages:

Table 1. Different LCA subtasks within T6.1

LCA sub-tasks	Type of LCA	Data source
Preliminary simplified LCA used for the eco-design	Attributional LCA, cradle-to-gate	Using already available life cycle inventory data and when possible primary data from technology manufacturers
Full LCA of the final technology	Attributional LCA, cradle-to-grave considering different EoL alternatives	Technology manufacturers, literature, databases, recycling feasibility assessment
Comparative LCA with other PV technologies	Comparative LCA, cradle-to-grave/gate E.g PERC, Top-Con, HJT	For the other PV technologies, data will come from literature with the needed updates and following existing guidelines[1]

[1] Further detailed in "System boundaries and modelling" as well as "Relevant legislation and guidelines" sections.

Lastly, performing an LCA is an iterative process between the four phases it comprises (Figure 1): goal and scope definition, inventory analysis, impact assessment and interpretation of the results, according to ISO 14040 and ISO 14044 [1, 2]. Therefore, the scope might need to be refined during the study.

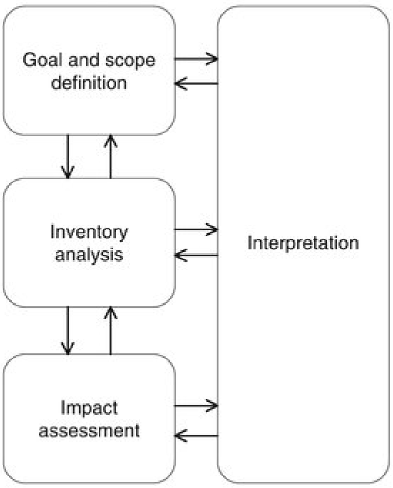

Figure 1. Life cycle assessment framework [1]

LCA methodology

Goal of the study

According to PEF methodology, the aspects in Table 2 need to be addressed to align the intended application of the LCA with the methods, results and aims of the study:

Table 2. Alignment of the LCA with PEF methodology

Aspects	**Detail for PILATUS**
1. Intended application(s)	Eco-design and potential environmental impacts assessment of digitalized pilot lines for silicon heterojunction tunnel interdigitated back contact solar cells and modules
2. Reasons for conducting the study and decision context	To provide guidance on the development of new photovoltaic technologies and to assess potential environmental impacts linked to its life cycle
3. Target audience	Consortium partners and European Commission
4. Commissioner of the study	European Commission, task included in PILATUS project and financed under the Horizon Europe program

5. Identity of the verifier	Internal verifiers: MBCH and TNO. There will not be an external verifier since the LCA report is confidential

Scope and modelling requirements

This section addresses the choice of the functional unit, method for impact assessment and system boundaries.

Functional unit

To fulfill the intended applications and according to the recommendations provided by the IEA task 12 guidelines [5], different functional units are selected depending on the (sub)goal of the studies:

- m^2 (i.e., area unit) and kWp will be used in the preliminary phase, to compare different alternatives of the configuration or materials in the layer. These functional units facilitate comparing a section of the SHJ-IBC modules with the same structure and production performance. Also, it is useful to compare the efficiency effect.
- The main purpose of the photovoltaic technology under development is to deliver AC electricity to the grid. Hence, kWh will be used to assess the environmental performance of the final design solution as well as to compare it with other energy technologies. Balance of system (mounting structure, cabling and inverter) will need to be included.

For PEF studies, the FU definition must include the following aspects (<u>for the full LCA</u>):

i. The function(s)/service(s) provided '*what*': production of electricity at the outlet of the system. Whether to consider DC electricity at the outlet of the DC connector attached to the junction box or to include the balance of system (inverter, cables, mounting structure) and use AC electricity going into the grid will depend on sub(goal) of the study (comparison with other PV technology or other energy source) and will be clarified later on depending on the primary data available.
ii. The extent of the function or service '*how much*': 1 kWh of DC or AC electrical energy without considering intermittency of electricity generation.
iii. The expected level of quality *'how well'*: DC electrical energy produced by the photovoltaic modules at a specific voltage.
iv. The duration/lifetime of the product 'how long': for 40 years (expected life time of the SHJ-IBC panel).
v. Reference flow: amount of photovoltaic module required to fulfil the defined function. It is expressed as maximum power output (kWp).

These choices are aligned with the PEFCR Photovoltaic modules used in photovoltaic power systems for electricity generation (Version 1.2).

For the comparative LCA with other PV technologies, a prospective LCA approach could be used to deal with differences in the technology maturity. Moreover, a sensitivity analysis will be done for the most relevant parameters such as: performance ration, degradation rate, irradiation, lifetime of the photovoltaic modules or manufacturing location.

System boundaries and modelling

For the eco-design part, a cradle-to-gate analysis will be conducted. It includes the raw material acquisition and production of the panels, together with material and energy inputs as well as emissions and waste outputs for each process analysed. The foreground system comprises the wafer, the cell, and the module lines (see Figure 2). However, the focus will be set on the process steps that are considered more critical or in which the environmental dimension could play a key role in deciding between different alternatives. These processes will be modelled, as much as viable, with primary data coming from the consortium partners.

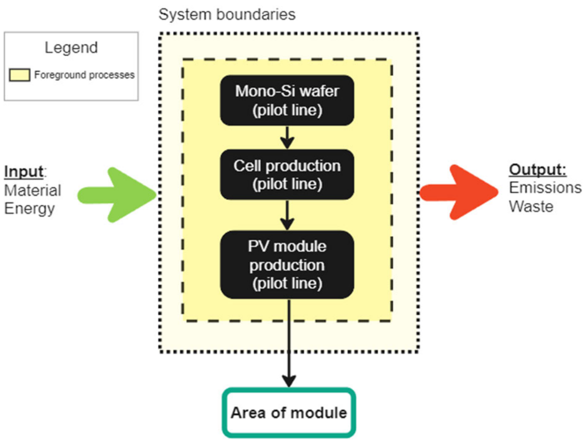

Figure 2. System boundaries diagram of the preliminary LCA

On the other hand, for the full LCA, a cradle-to-grave assessment will be performed. Including raw material acquisition and transport, the three pilot lines, installation, maintenance, operation, and end-of-life, with their respective input. In this case, the foreground system not only will include the wafer, cell, and modules lines but also operation, maintenance and end-of-life considerations. Different waste

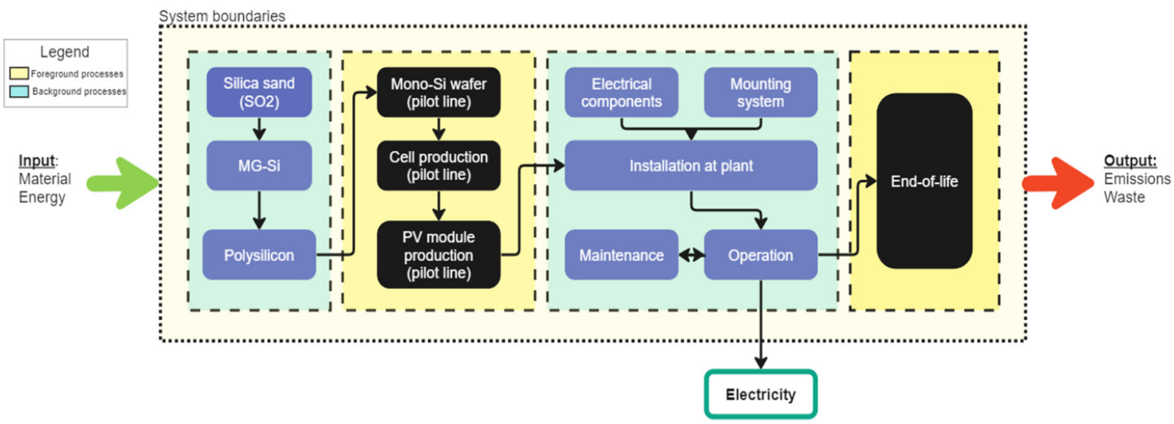

Figure 3. System boundaries diagram of the full LCA

management alternatives will be analysed. Figure 3 shows the system boundaries of the system under study. Lastly, to make the comparison with other PV technologies on the market, future scenarios will be considered, and system boundaries will be adapted to existing LCAs published.

Location of the different processes will be taken into consideration since electricity production, waste management or transport varies depending on the region considered. Furthermore, the environmental impact of some pollutant changes in different geographical areas [4].

LCA models will be conducted in the software Simapro version 9.5.0.0. The Ecoinvent 3.9.1 [3] database will form the basis for the background processes modelling, integrated with the most updated secondary data lifecycle inventories (LCIs) available in literature which are relevant for the PV industry (e.g., Müller et al. 2021 [8], IEA PVPS T12 LCI 2020 [6]).

Specific processes and flows will be added to model the foreground system. According to Ecoinvent [5], system models set the methodological rules necessary to calculate the database. For this study, the system model allocation cut-off by classification will be used to incentivize the recyclability of the products. In other words, the producer is responsible for the waste generated. Lastly, when allocation is required, it will be clearly specified.

Impact categories and method of impact assessment

The environmental impact categories analysed will be the ones considered in a PEF study. These categories constitute the Environmental Footprint (EF) impact assessment method. Version EF3.1 will be used. Table 3 shows the EF impact categories and the characterization models for each of them.

Table 3. EF3.1 impact categories

EF impact category[2]	Impact category indicator	Unit	Characterisation model
Climate change, total	Global warming potential (GWP100)	kg $CO_{2\ eq}$	Global warmingpotentials (GWP) over a 100-year time horizon (Baseline model of the IPCC 2021)
Ozone depletion	Ozone depletion potential (ODP)	kg CFC-11 $_{eq}$	EDIP model based on the ODPs of the World Meteorological Organisation (WMO) over an infinite time horizon (WMO 2014 + integrations)
Human toxicity, cancer	Comparative toxic unit for humans (CTUh)	CTUh	based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018

[2] According to EU Commission Recommendation 2021/2279: The indicator "Climate Change, total" is a combination of three sub-indicators: Climate change –Change fossil; Climate change –Change biogenic; Climate change – land use and land use change. The sub-indicators are further described in section 4.4.10 of Annex I. The sub-categories 'Climate change –fossil', 'Climate change – biogenic' and 'Climate change - land use and land use change' shall be reported separately, if they show a contribution of more than 5% each to the total score of climate change.

Human toxicity, non-cancer	Comparative toxic unit for humans (CTUh)	CTUh	based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018
Particulate matter	Impact on human health	Disease incidence	PM model (Fantke et al., 2016 in UNEP 2016)
Ionising radiation	Human exposure efficiency relative to U235	kBq U235 eq	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS model (Van Zelm et al, 2008) as applied in ReCiPe 2008
Acidification	Accumulated exceedance (AE)	mol H^+ eq	Accumulated exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication, terrestrial	Accumulated exceedance (AE)	mol N eq	Accumulated exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2009) as applied in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2009) as applied in ReCiPe
Ecotoxicity, freshwater	Comparative toxic unit for ecosystems (CTUe)	CTUe	based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018
Land use	Soil quality index	Dimensionless (pt)	Soil quality index based on LANCA model (De Laurentiis et al. 2019) and on the LANCA CF version 2.5 (Horn and Maier, 2018)
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 water eq of deprived water	Available WAter REmaining (AWARE) model (Boulay et al., 2018; UNEP 2016)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	van Oers et al., 2002 as in CML 2002 method, v.4.8
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)18	MJ	van Oers et al., 2002 as in CML 2002 method, v.4.8

Approach to data collection

Data collection is one of the most challenging parts when conducting an LCA. To deal with this problematic, at the beginning of PILATUS project an LCA training for technology developers was organised for the consortium. Following, interviews with people responsible of different product stages started.

Assumptions and limitations

Limitations might arrive when doing the analysis and assumptions will be made. For instance, when data is lacking for the manufacturing processes or when industrially scaled end-of-life scenarios are assumed. In such cases, limitations and assumptions will be transparently reported.

Harmonisation of LCA methodology for assessing PV technologies

The 13th – 14th of March an Harmonisation LCA workshop on PV technologies was co-organised by ULiège, TNO, ISE Fraunhofer and University of Siena. There were participants from more than 10 European founded photovoltaic projects, responsible of the environmental assessment tasks. Agreement was reached on the need make LCAs comparable to be able to make fair comparison of the different emerging PV technologies. Being transparent with the background energy mix from the grid utilised, showing separately its impact contribution as well using EF impact assessment method developed by the Joint Research Centre. Upcoming meetings will take place and further agreements will be followed.

Relevant legislation and guidelines

The following sections include the relevant guidelines that will be followed for the life cycle assessment as well as the environmental legislation and compliance requirements for photovoltaic technologies.

Guidelines

- **ISO 14040** – Environmental management – Life cycle assessment -Principles and practice [1]
- **ISO 14044** - Environmental management — Life cycle assessment — Requirements and guidelines [2]
- International Reference Life Cycle Data System **(ILCD)** Handbook - General guide for Life Cycle Assessment - Detailed guidance
- COMMISSION RECOMMENDATION (EU) 2021/2279 of 15th December 2021 on the use of the **Environmental Footprint methods** to measure and communicate the life cycle environmental performance of products and organisations
- **IEA PVPS Task 12: Life Cycle Inventories** and Life Cycle Assessments of Photovoltaic Systems (December 2020) [6]
- **IEA PVPS Task 12: Methodology Guidelines** on Life Cycle Assessment of Photovoltaic Electricity (4th edition – April 2020) [7]
- **PEFCR Photovoltaic modules used in photovoltaic power systems for electricity generation**. Version 1.2. (Date of publication: February 2020, Time validity: 31st December 2021)

Legislation

- **DIRECTIVE 2012/19/EU** OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 4 July 2012 on **waste electrical and electronic equipment (WEEE)**
- **DIRECTIVE 2009/125/EC** OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009 establishing a framework for the setting of **ecodesign requirements** for energy-related products
- **Directive 2011/65/EU** OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 8 June 2013 on the **restriction of the use of certain hazardous substances in electrical and electronic equipment (recast), referred to as the RoHS Directive**, lays down rules on the restriction of the use of hazardous substances in electrical and electronic equipment (EEE). These restrictions apply to the following substances, to which maximum concentration values in products apply:
  Lead (0,1 %), Mercury (0,1 %), Cadmium (0,01 %), Hexavalent chromium (0,1 %), Polybrominated biphenyls (PBB) (0,1 %), Polybrominated diphenyl ethers (PBDE) (0,1 %), Bis(2-ethylhexyl) phthalate (DEHP) (0,1 %), Butyl benzyl phthalate (BBP) (0,1 %), Dibutyl phthalate (DBP) (0,1 %), Di isobutyl phthalate (DIBP) (0,1 %)

  In terms of the product scope considered by this directive, it is relevant to highlight that an **exception** in the restrictions is applied to photovoltaic modules, according to the following definition:

  '**photovoltaic panels** intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications;'

Further actions

- COM (2022) 221 FINAL COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU Solar Energy Strategy. Brussels, 18.5.2022.

  "The European Commission plans to propose in the first half of 2023 **two mandatory internal market instruments that would apply to solar PV modules**, inverters and systems sold in the EU: an **Ecodesign Regulation** and the **Energy Labelling Regulation**. These measures would concern the **efficiency, durability, reparability and recyclability** of products and systems, to incentivise environmentally sustainable devices. The Commission is also assessing options covering the quality of the manufacturing process and the carbon footprint of PV modules."

References

[1] ISO. 2006a. Environmental management – Life cycle assessment – Principles and framework. ISO 14040. Geneva: International Organisation for Standardisation.

[2] ISO. 2006b. Environmental management – Life cycle assessment – Requirements and guidelines. ISO 14044. Geneva: International Organisation for Standardisation.

[3] Ecoinvent, Allocation, cut-off by classification, ecoinvent database version 3.9.1 (2023).

[4] Baumann, H., and A.-M. Tillman. 2004. The Hitchhiker's guide to LCA: An orientation in life cycle assessment methodology and application. Lund, Sweden: Studentlitteratur.

[5] System models (2023) ecoinvent. Available at: https://ecoinvent.org/the-ecoinvent-database/system-models/ (Accessed: 12 June 2023).

[6] R. Frischknecht, P. Stolz, L. Krebs, M. de Wild-Scholten, P. Sinha, V. Fthenakis, H. C. Kim, M. Raugei, M. Stucki, 2020, Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, International Energy Agency (IEA) PVPS Task 12, Report T12-19:2020.

[7] R. Frischknecht, P. Stolz, G. Heath, M. Raugei, P. Sinha, M. de Wild-Scholten, 2020, Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 4th edition, IEA PVPS Task 12, International Energy Agency Photovoltaic Power Systems Programme

[8] Amelie Müller, Lorenz Friedrich, Christian Reichel, Sina Herceg, Max Mittag, Dirk Holger Neuhaus, A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory, Solar Energy Materials and Solar Cells, Volume 230, 2021, 111277, ISSN 0927-0248, https://doi.org/10.1016/j.solmat.2021.111277

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