



Environmental, economic and social impact assessment of the EVERPV recycling process first period



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Lead organization	ENEA	
Main authors	Giuliana Ansanelli, Amalia Zucaro, Elina Bosch, Damien Gautier	
Contributions	Vanessa Forti	

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Coordinator – Administrative information	
Project Coordinator name	Philippe Thony
Project Coordinator organization	CEA
Address	INES campus F-73375 Le Bourget-du-Lac
Phone Numbers	+33 (0)4 79 79 28 17 +33 (0)7 84 51 52 40
Email	philippe.thony@cea.fr
Project web-sites	everpv.eu

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ABBREVIATIONS

ELU	Environmental Load Units
EoL	End of life
EU	European Union
EPS	Environmental Priority Strategies
FU	Functional Unit
ILCD	International Life Cycle Data
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
PV	Photovoltaic
S-LCA	Social Life Cycle Analysis
S-LCI	Social Life Cycle Inventory
S-LCIA	Social Life Cycle Impact Assessment
TRL	Technology Readiness Level
WP	Work Package
WTP	Willingness To Pay

1 INTRODUCTION

This is the public summary of the confidential report “Environmental, economic and social impact assessment of the EVERPV recycling process first period”. It summarizes the Life Cycle Thinking (LCT) methodology that will be applied for the evaluation of the environmental, economic and social aspects associated with the treatment processes for End-of-Life crystalline silicon photovoltaic panels (EoL c-Si-PVs), developed at TRL7 within the EVERPV project.

It provides a foundational understanding for those unfamiliar with the subject, facilitating their knowledge of sustainability assessments.

2 LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is a structured method for evaluating all potential environmental and health impacts of a product, process or service. It examines every stage of a product’s life, from raw material extraction to disposal and recycling, often referred to as assessing a product “*from cradle to grave.*” The purpose of LCA is to measure emissions and resources used across the product’s lifecycle to help achieve low waste and minimal environmental impact.

In 2006, the ISO (International Organisation for Standardization) standards 14040 and 14044 (ISO, 14040, 2006; ISO 14044, 2006) were published. These standards established LCA as a critical tool for environmental management globally. Moreover, the European Commission has released the International Reference Life Cycle Data System (ILCD) Handbook (ILCD Handbook, 2010), with best practices, helping governments and businesses use LCA to evaluate the environmental impact of products and supply chains.

2.1 Why Use LCA?

Originally, LCA was created to help organizations make environmentally friendly decisions when choosing products or services. Today, it’s used for various purposes, such as:

- **Product Development:** Helping companies design greener products.
- **Strategic Planning:** Assisting companies in setting long-term environmental goals.
- **Marketing:** Providing environmental information to consumers.
- **Policy-Making:** Guiding government policies on planning sustainable policies (Ecolabeling, Green Procurement, Product Declarations and so on).



In addition to analysing data, LCA follows a structured approach to ensure transparency, so stakeholders can fully understand the environmental impacts and the study's assumptions.

2.2 Main phases of an LCA

ISO 14040 and 14044 (2006) have defined **four phases** (Figure 1) of an LCA study.

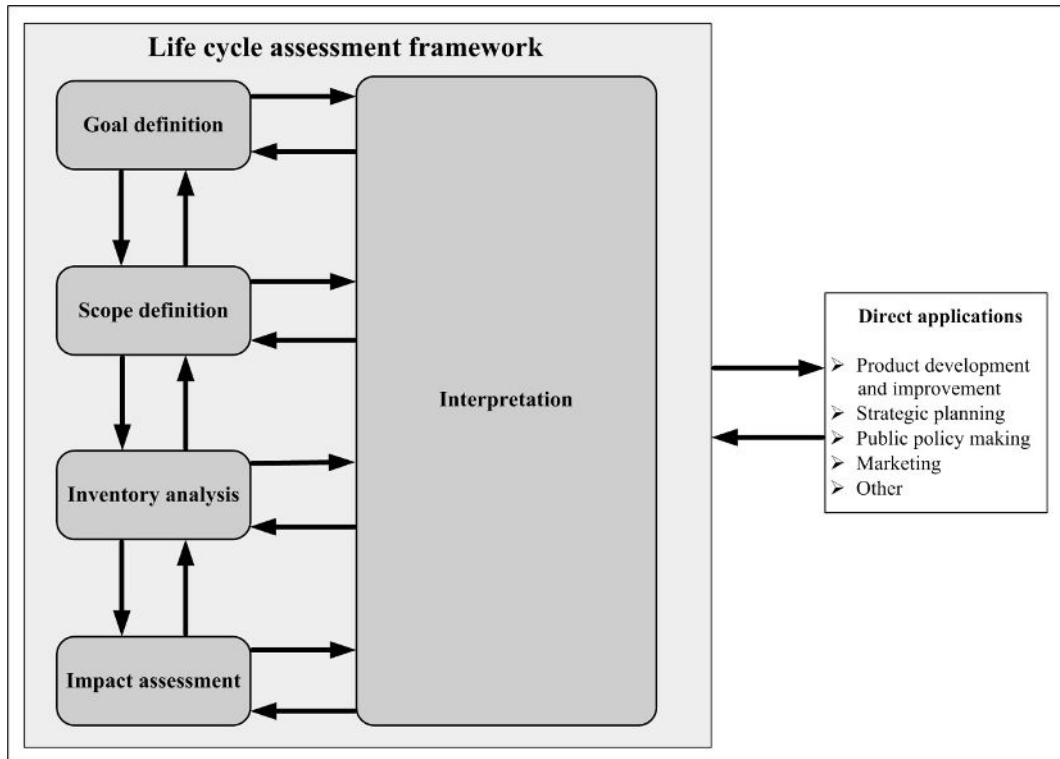


Figure 1 - Framework for life cycle assessment (from ILCD Handbook, 2010).

Goal and Scope definition

This phase sets the purpose of the study, defining its scope and intended audience and how the results will be used. For example, is the LCA designed to compare two products, or is it aimed at assessing a product's impact in general? Clear definitions prevent misuse or misinterpretation of results. In defining the scope, the study identifies what is being analysed (e.g., a specific product) and details on:

- **Functional Unit (FU):** It represents a specific quantity (e.g., producing one car) of the main function of the system under investigation (e.g. car manufacturing), taken as a reference for all input and output flows considered in the analysis. FU provides a common basis for comparison.
- **System Boundary:** Defines which phases (e.g., production, disposal) and processes (e.g., transport, infrastructure manufacturing etc.) of the investigated system are included in the analysis.
- **Management of complex systems producing multiple products:** various strategies can be applied to assign impacts fairly, such as (i) subdivision: Dividing processes so each product's impact can be isolated; (ii) substitution: Adjusting for additional functions provided by co-



products (system expansion); (iii) allocation: It determines how to divide environmental impacts between co-products based on their physic (e.g. mass, energy) or economic value.

- **Data Requirements and Quality:** Specifies the accuracy level needed for the study.

When comparing products, it's essential to ensure they are evaluated on equal terms, meaning all criteria (like Functional unit and system boundary) are applied consistently.

Life Cycle Inventory (LCI): quantifying resource consumption and emissions

This is the data-collection phase, where all material and energy inputs and outputs, such as energy usage, emissions and waste, are identified and quantified. This information helps create a detailed map of the product's environmental footprint. Data sources include:

- **Primary data:** Information directly collected from production sites.
- **Secondary data:** Average data from reliable sources like scientific literature and specialized databases, such as Ecoinvent used in the SimaPro software.
- **Tertiary data:** Assumptions and estimates based on models or previous studies.

Data are classified into "*foreground*" and "*background*" systems:

- **Foreground System:** Data related specifically to the product under study, such as factory emissions or water use.
- **Background System:** Broader industry data, like average energy sources or waste management practices common in the investigated geographical area.

Data quality is essential in LCA, especially for comparative studies that may be publicly disclosed. Important data quality factors include the age of the data, geographic location, and the type of technology used.

The collected data is then used to understand the environmental load of each flow in the product's lifecycle.

Life Cycle Impact Assessment (LCIA): quantifying potential environmental impacts

Life Cycle Impact Assessment (LCIA) is the third phase in an LCA study, focusing on understanding the potential environmental impacts of all materials, energy inputs, and emissions collected during the inventory phase. Rather than measuring actual environmental harm, LCIA provides an estimate of potential impacts, which are analysed in categories relating to effects on ecosystems (resource use, pollution etc.) and human health. For instance, emissions may be assessed for their contribution to climate change (as CO₂ equivalents) or their potential contribution to pollution. Each type of impact is measured separately to identify the product's environmental hotspots.

According to ISO guidelines, LCIA has some mandatory steps:

- 1) **Selecting Impact Categories:** This involves choosing environmental categories to assess, such as climate change, water use, or resource depletion, and setting up indicators and models to measure each. Indicators can be defined at midpoint and endpoint level. Midpoint indicators



focus on immediate environmental changes (like resource usage), while endpoint indicators consider long-term consequences, such as effects on human health or ecosystems. Midpoint indicators are generally more straightforward and have lower uncertainty, making them easier to interpret.

2) **Classification:** All inputs and outputs from the inventory are sorted into relevant impact categories, depending on their potential effects.

3) **Characterization:** The categorized items are converted into standard units to measure their impacts consistently. For example, different greenhouse gases are converted into “CO₂ equivalents” to measure their contribution to “*Climate change*” category.

In LCIA, impact categories are generally divided into two types:

- **Upstream Categories:** These relate to the amount of resources used to create the product, like the depletion of raw materials or water usage.
- **Downstream Categories:** These focus on the environmental consequences of emissions, like the potential for acid rain, contribution to global warming, or toxicity to humans and ecosystems.

Each material or emission can influence multiple categories, meaning that one resource or emission might contribute to various environmental issues. For instance, carbon dioxide contributes to both global warming and ocean acidification.

LCIA also includes optional elements that make results easier to understand and compare:

- **Normalization:** By dividing the impact results by a reference value (typically an average value over a specific geographic area and time period), normalization quantifies the relative magnitude of each environmental impact. This allows for a comparison to a broader context, revealing the scale of each impact and highlighting the most significant contributors to the overall environmental footprint of the system under investigation.
- **Weighting:** Different impact categories are assigned values based on their importance, which reflects societal or cultural values. This step is more subjective as it depends on social, political, or ethical factors rather than purely scientific data.
- **Single Score:** After normalization and weighting, all impacts are combined into a single score, providing a quick, overall view of a product’s environmental impact.

For the EVERPV project, the LCIA uses the **Environmental Footprint (EF) 3.1 method** (adapted), developed by the European Commission (Zampori & Pant, 2019), to assess midpoint impacts. The version used in this study has been modified (adapted) to ensure compatibility with the SimaPro LCA software.

Interpretation: summing up findings

The **interpretation phase** is the last part of an LCA. where results are reviewed to form conclusions and recommendations in a final report, aimed at reducing the product's environmental impact, aligning with the original goals of the study. This phase focuses on:

- **Summarizing key results:** Synthesizing the data and main findings to highlight essential insights that support decision-making.



- **Ensuring robustness:** Verifying the reliability of results by addressing uncertainties or sensitivity in the data, while offering a comprehensive view of environmental performance.
- **Transparency:** Clearly stating assumptions, data sources, and any limitations to give readers a well-rounded understanding.

Throughout the process, LCA remains flexible. If new information arises at any phase, the goal and scope may be adjusted accordingly, following an iterative approach.

In **conclusion**, LCA is a powerful tool to assess and compare the environmental impacts of products and services. By examining all stages of a product's life, LCA provides a comprehensive understanding of its environmental footprint, guiding decisions for more sustainable practices. Whether used by industries or governments, LCA helps identify where improvements can be made to reduce environmental harm and promote sustainable development.



3 LIFE CYCLE COSTING (LCC) METHODOLOGY

3.1 Definition and objectives

A Life Cycle Costing Assessment (LCC assessment) is a tool to assess every economic impact associated with all the stages of a process from “cradle to gate”, including, in the case of a photovoltaic (PV) panel recycling process, the PV system dismantling, the collection of End of Life (EoL) PV modules, the transportation to the recycling plant and the module storage before recycling. The LCC is a tool for:

- identifying opportunities to improve the economic performance of processes and products at various steps;
- informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign), for the selection of relevant indicators of economic performance, including measurement techniques;
- comparing different processes (e.g. recycling pathways).

Results should be presented in sufficient detail to allow the reader (technical or non-technical expert) to understand the complexities and trade-offs inherent in the study and LCC in general.

3.2 Main phases of an LCC

As for the other types of Life cycle assessment presented in this report, the following different phases for the analysis can be defined:

- Goal and scope definitions.
- LCC model development.
- Data needs definition and data collection.
- Assessment & interpretation.

Goal and scope definitions

The goal of the LCC assessment is to contribute giving a precise cost overview of the developed recycling process(es) in EVERPV project, helping to identify points to improve and enabling comparisons with competing recycling pathways.

LCC data needs

The recycling processes developed in the project will be described precisely looking into the following aspects:

- (i) the collection of modules, including system dismantling;
- (ii) transportation;



- (iii) storage;
- (iv) the CAPEX, such as the cost of machines and equipment;
- (v) the OPEX, such as the cost of consumables and input materials, the cost of labour, the cost of energy or the cost maintenance.

Assessment & Interpretation

Using the developed model and collected data, the life cycle costs of the investigated systems will be assessed. Specifically, the assessment will include absolute and relative result analysis:

- (i) Absolute LCC result (e.g., for a given process). Including a sensitivity analysis 1- to mitigate uncertainty for certain data entry if any and identify the impact of different assumptions on the end results and 2-to identify the most influential factors in recycling costs. This will allow to **highlight areas of improvement to prioritize to achieve cost reductions.**
- (ii) Relative LCC result. Including **comparisons between different systems** having the same function (e.g. EVERPV recycling process and alternative benchmark recycling pathways).

3.3 Economic costs of the environmental impacts (external costs)

Environmental Life Cycle Costing (eLCC) expands traditional cost analysis by including the “external costs” of environmental impacts, or externalities. Externalities are costs that arise from the environmental damage caused by a service, product or process but are not paid for by the responsible party. Instead, they fall on others, such as communities or the environment. For example, when a factory’s emissions contribute to climate change or pollute local air and water, the cost of addressing these issues often affects society as a whole, rather than the factory itself.

Calculating Environmental Externalities for EVERPV

In the EVERPV project the externalities are calculated in monetary value, through the Environmental Priority Strategies (EPS) method, developed in the Life Cycle Assessment (LCA) framework (Medina-Salgado et al., 2021). EPS estimates environmental economic costs, based on the damage caused, by emissions and resource usage, in specific areas such as Ecosystem Services, Human health, Biodiversity, and Access to Water. These areas are referred to as “*Safeguard Subjects.*” The EPS method converts environmental damages into monetary values called Environmental Load Units (ELUs), where one ELU equals one euro in damage costs. These values are calculated based on people’s “willingness to pay” (WTP) to avoid environmental harm. WTP is the amount that an average person would pay to prevent damage from issues like pollution or resource depletion.

The EPS method’s goal is to make environmental costs as visible and accessible as traditional costs (like materials or labor), helping analysts evaluate the full impact of environmental damage in monetary terms.



4 SOCIAL LIFE CYCLE ASSESSMENT (S-LCA) METHODOLOGY

4.1 Definition and objective

To conduct a comprehensive sustainability study of a product throughout its life cycle, it is essential to also examine social impacts, such as labour conditions and community effects, ensuring the product's development aligns with social responsibility.

S-LCA is a method used to evaluate the social impacts associated with products and services throughout their entire life cycle, from raw material extraction to disposal. This approach combines both quantitative and qualitative data to create a comprehensive analysis framework. S-LCA provides valuable insights into the social and socio-economic factors that influence decision-making, with the goal of enhancing the social performance of an organization or product.

The UNEP/SETAC Life Cycle Initiative first published guidelines for Social Life Cycle Assessment in 2009. Since then, S-LCA's importance has grown, with many initiatives emphasizing the need for value chain due diligence, which addresses social issues in both private and public sectors. Two key developments have increased the focus on understanding social impacts in value chains: the UN's Sustainable Development Goals (SDGs) launched in 2015, which set global targets for issues like poverty, inequality, and environmental protection, and the UN's 2011 Guiding Principles on Business and Human Rights, which stress that governments and businesses must protect human rights.

Over the past decade, S-LCA has matured into an independent methodology. The 2020 Guidelines for Social Life Cycle Assessment of Products and Organizations, published by the United Nations Environment Programme, expand on the 2009 Guidelines and offer a comprehensive guide for evaluating the social and socio-economic impacts of products and their value chains.

4.1 Main phases of a S-LCA

S-LCA follows the ISO 14040 (2006) framework used for LCA and is divided into the same main four stages:

- Goal and scope definitions
- Social Life Cycle Inventory (S-LCI)
- Social Life Cycle Impact Assessment (S-LCIA)
- Interpretation

Goal and scope definition

The first phase of an S-LCA study is defining the Goal and Scope. The S-LCA's goals, intended use of the results, and target audience need to be established. The study should clearly specify the



improvements it seeks to achieve or the support it aims to provide for decision-making. Additionally, identifying the affected stakeholders is essential.

The scope outlines the focus of the study, sets the framework for the methodology and should address the following components:

- product system to be studied;
- functions of the product system or, in case of comparative studies, of the systems;
- functional unit;
- system boundary;
- allocation procedures;
- life cycle impact methodology and types of impacts (impact categories);
- interpretation to be used;
- data required;
- assumptions;
- value choices and optional elements;
- limitations;
- data quality requirements;
- type of critical review, if any;
- type and format of the report required for the study.

Social Life Cycle Inventory (S-LCI)

The life cycle inventory (LCI) involves gathering all relevant data on the flows within this system, adjusted to the functional unit.

The LCI process involves several steps similar to LCA and LCC:

1. The system is broken down into interconnected processes.
2. For each process, the amounts of inputs and outputs are determined and normalized.
3. Social data related to stakeholders, like worker wages, is collected for all processes.

This process can be done manually or with the help of software like SimaPro or OpenLCA, which use linear models to calculate these flows automatically.

Collecting specific data from organizations and sites in a value chain can be very time-consuming and expensive, especially without prioritizing what is most important. To make this process more efficient, it is essential to focus on the most relevant activities. There are three main ways to prioritize data collection:



1. **Literature Review:** Reviewing existing studies to identify key social issues related to the product can be a first step of the process.
2. **Activity Intensity:** It is also possible to determine which activities or processes are the most intensive in the product's life cycle. This can be done by identifying an activity variable like worker-hours. This helps pinpoint where the most effort should be allocated for data collection.
3. **Social Hotspots:** One can use a database and software to identify "social hotspots" in the product's life cycle – regions or processes where significant social issues, risks, or opportunities exist. These hotspots are areas where data collection should be prioritized, especially if the goal is to identify real-world impacts. On-site visits may be necessary to gather specific data in these critical areas.

Social Life Cycle impact assessment (S-LCIA)

In S-LCA, impact indicators measure the extent of social impacts, while impact categories or subcategories define the types of impacts.

There are two approaches to carry out a Social Life cycle assessment: RS S-LCIA and IP S-LCIA.

1. The **Reference Scale Assessment** approach is more widely used and operational, with numerous case studies available. It involves developing scales for each indicator, which might be ascending, descending, or binary (e.g., presence or absence of impact). Aggregation, or combining different elements into a single score, is a common practice in S-LCA. It simplifies complex information, making it easier to understand and communicate. However, aggregation should be done carefully to avoid losing important context, especially when dealing with global supply chains. When aggregating, weights are typically used to show how important each performance indicator is.
2. **Impact pathway assessments** in S-LCA focus on understanding the social impacts of a product by analysing the cause-and-effect relationships within a system. To assess these impacts, social mechanisms that link activities to their consequences are identified and categorized. These mechanisms help determine how social activities, such as a company's operations, lead to social impacts.

Interpretation

The Interpretation phase follows the guidelines of ISO 14044:2006 and involves several key steps, including checking the completeness and consistency of the data, assessing sensitivity and data quality, and identifying important aspects of the study. This process is iterative, meaning that the findings from this phase may require revisiting earlier stages of the study to refine the data or reassess the goals. Results are not only discussed and summarized but also broken down and analyzed at different levels, such as life cycle stages, impact categories, and stakeholder groups. This helps to extract insights that can guide improvements and recommendations. It is important to involve stakeholders in this phase, especially those who might be affected by the study's outcomes, to ensure that the conclusions are well-rounded and representative.

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