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Large-Area Perovskite Solar Module Manufacturing with High Efficiency, Long-Term Stability and Low Environmental Impact (Acronym: LAPERITIVO)

LAPERITIVO – Report

D6.1 – Data collection guidelines

Guidelines for LCA data collection and sustainable modules

Grant Agreement n°101147311

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Legal notice

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Disclaimer

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About LAPERITIVO

In recent years, organometal halide perovskite-based photovoltaics (PV) have attracted great interest for their high-power conversion efficiency at low manufacturing cost. Presently, East Asia especially China and North America are rapidly ramping up towards mass production of perovskite PV. More efforts are urgently needed for perovskite PV upscaling in Europe. LAPERITIVO focuses on the development of large-area stable perovskite solar modules, using processes with high manufacturability. Efficiency targets are 22% and 20% for 900 cm^2 opaque and semi-transparent (with >95% bifaciality) modules, respectively. Key research activities include the deposition of high-quality perovskite films as well as contacting layers over large substrate area using industrially viable techniques. Indoor and outdoor field tests, in line with International Electrotechnical Commission (IEC) standards, will be performed to monitor module reliability. Safety, circularity, and sustainability will be assessed to demonstrate products with minimized environmental impact. The developed semi-transparent modules will be applied to perovskite/silicon four-terminal tandem modules and also to Agrivoltaics. Design of perovskite PV pilot line of 200 MW and production capacity of 5 GW in Europe will also be explored. The well-balanced consortium consists of 20 complementary partners including 8 European leading research institutes/universities (IMEC, UNITOV, EMPA, Fraunhofer ISE, IPVF, CNRS, CSEM, Hellenic Mediterranean University), 1 African research institute (Green Energy Park, Morocco), 5 small and medium-sized enterprises (Becquerel Institute, Becquerel Institute France, Becquerel Institute Spain, Dyenamo, TSE Troller, SmartGreenScans, BeDimensional), and 6 big companies (Pilkington Technology Management Limited (PTML), Singulus Technologies, Voltec Solar, Engie, TotalEnergies, EDF). In this way, the project aims to establish the pathway to open the era of manufacturing perovskite-based next-generation PV products in Europe.

LAPERITIVO Consortium Members

PARTICIPANTS					
No.	**Role**	**Short name**	**Legal name**	**Country**	**PIC**
1	COO	IMEC	INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM	BE	999981149
2	BEN	UNITOV	UNIVERSITA DEGLI STUDI DI ROMA TOR VERGATA	IT	999844864
3	BEN	HMU	ELLINIKO MESOGEIAKO PANEPISTIMIO	EL	899132771
4	BEN	Fraunhofer	FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV	DE	999984059
5	BEN	IPVF	INSTITUT PHOTOVOLTAIQUE D'ILE DE FRANCE (IPVF)	FR	917662584
5.1	AE	EDF	ELECTRICITE DE FRANCE	FR	999926829
6	BEN	CNRS	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR	999997930
7	BEN	BI	ICARES CONSULTING	BE	928696916
7.1	AE	BI France	BECQUEREL INSTITUTE FRANCE	FR	883770493
7.2	AE	BI Spain	BECQUEREL INSTITUTE ESPANA SL	ES	879684174
8	BEN	DYN	DYENAMO AB	SE	943379612
9	BEN	Voltec	VOLTEC SOLAR	FR	911519962
10	BEN	BD	BEDIMENSIONAL SPA	IT	900899626
11	BEN	SMART	DE WILD-SCHOLTEN MARISKA	NL	989636002
12	BEN	Engie Lab	BELGISCH LABORATORIUM VAN ELEKTRICITEITSINDUSTRIE	BE	998728200
13	BEN	ST	Singulus Technologies AG	DE	985822350
14	BEN	TE	TOTALENERGIES ONETECH	FR	888088642
15	BEN	GEP	GREEN ENERGY PARK	MA	906552980
16	AP	EMPA	EIDGENOSSISCHE MATERIALPRUFUNGS- UND FORSCHUNGSANSTALT	CH	999907138
17	AP	TSE	TSE Troller	CH	940489303
18	AP	CSEM	CSEM CENTRE SUISSE D'ELECTRONIQUE ET DE MICROTECHNIQUE SA - RECHERCHE ET DEVELOPPEMENT	CH	999958839
19	AP	PTML	PILKINGTON TECHNOLOGY MANAGEMENT LTD	UK	959192455

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Abbreviations and acronyms list

Abbreviation	Meaning	Abbreviation	Meaning
PV	Photovoltaic	**RFI**	Request For Information
SSbD	Safe and Sustainable by Design	**WP**	Work Package
LCA	Life Cycle Assessment	**CSS**	Chemicals Strategy for Sustainability
CRM	Critical Raw Materials	**FTO**	Fluorinated Tin Oxide
ECHA	European Chemical Agency	**REACH**	Registration, Evaluation, Authorisation and Restriction of Chemicals
C&L	Classification and Labelling	**SVHC**	Substances of Very High Concern
DMF	DiMethyl Formamide	**E-LCA**	Environmental Life Cycle Assessment
S-LCA	Social Life Cycle Assessment	**LCIA**	Life Cycle Impact Assessment
PSILCA	Product Social Impact Life Cycle Assessment		

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1 Executive Summary

LAPERITIVO aims to develop (semi-transparent) large-area perovskite solar modules with very high efficiency, long-term stability, and minimized environmental impact to a technology readiness level of 7. Guidance on efficient collection of data is crucial for reliable assessments of safety, circularity, and sustainability of the envisioned PV modules. SmartGreenScans aims to apply a European assessment framework for Safe and Sustainable by Design (SSbD) as a guidance for data collection. The SSbD framework is a general approach to steer innovation towards safe and sustainable new or existing chemicals and materials throughout the entire life cycle and combines hazard and risk assessment approaches for chemicals, materials, processes and product with sustainability assessment techniques, such as Life Cycle Assessment (LCA) methods. A 5-step assessment phase targets 1) hazard properties of the chemicals, 2) human health and safety of the processes in the production phase, 3) environmental and human health risks in the use phase, 4) environmental impacts along the entire life cycle, and 5) socio-economic impacts. This 5-step assessment is used as an overall guidance to set up specific guidelines for the collection of data, based on an active involvement of the consortium and relevant external stakeholders.

The application of the 5-step assessment phases is conducted via surveys of open literature and iterative Requests For Information (RFI) in the form of dedicated Excel fill-in templates to the relevant consortium partners regarding input and output data for the life cycle phase at hand. The conclusion from this work is that the European assessment framework for Safe and Sustainable by Design is a useful tool for data collection regarding the assessment of safety, circularity, and sustainability of the PV modules.

1.1 Description of the deliverable content and purpose

Deliverable D6.1 describes how the 5-step assessment within the SSbD framework can be used as an overall guidance to set up specific guidelines for the collection of data regarding safety, circularity, and sustainability aspects of the LAPERITIVO PV modules based on an active involvement of the consortium and relevant external stakeholders. Its purpose is to provide a streamlined and well-structured approach for collection of data.

1.2 Relation with other activities in the project

In LAPERITIVO, safety, circularity, and sustainability are covered in work package 6 which depends on an iterative data input from the work packages 1, 2, 3, 4, that deal with production and testing of the PV modules. Consequently, a close and fruitful collaboration has been established with these “operational” work packages from the start of LAPERITIVO and onwards.

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2 Safety, circularity and sustainability in LAPERITIVO (WP6)

2.1 Guidelines for data collection and sustainable modules (Task 6.1)

LAPERITIVO aims to develop (semi-transparent) large-area perovskite solar modules with very high efficiency, long-term stability, and **minimized environmental impact** to a technology readiness level of 7 [1]. This will enable acceleration of perovskite PV manufacturing and deployment in Europe. The concept of LAPERITIVO and its structure are presented in Figure 1.

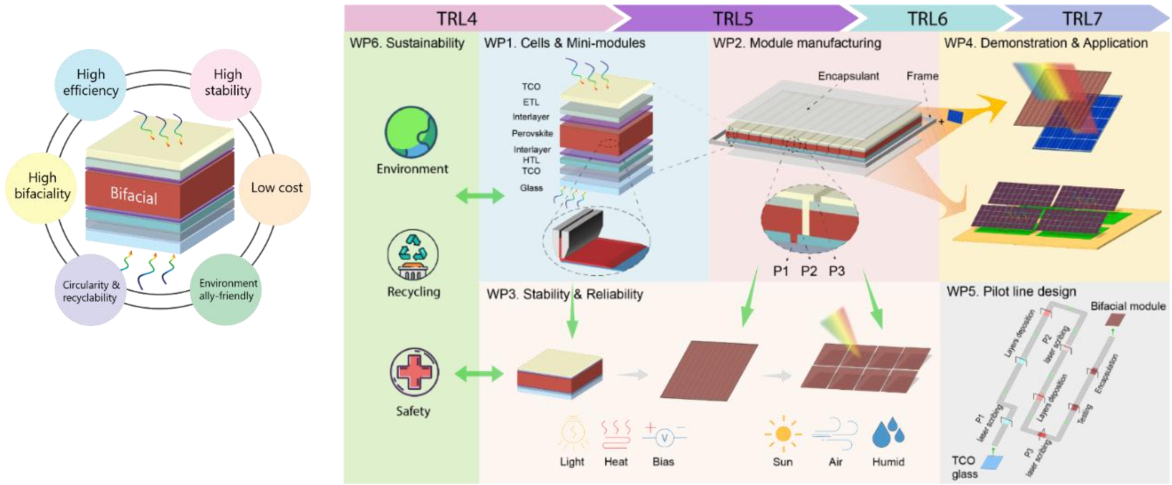

Figure 1 - Overall concept and schematic overview of the LAPERITIVO project structure

The full life cycle of the envisioned PV modules consists of a production phase, a use phase and an end – of – life phase. In work package 1 (WP1) and WP2, the production phase starts with the manufacturing of cells and mini-modules from various precursors, considering various end-of-life recycling options. Cells and mini-modules are then tested for stability and reliability in WP3 prior to the manufacturing of the final module. In the use phase, the final modules are demonstrated in WP4 under real conditions to estimate their energy yield, stability over time and reliability. Based on the demonstration results, a pilot line will subsequently be designed. The process development from production to demonstration takes place iteratively. In WP6, safety, circularity, environmental and socio-economic impacts during the full life cycle (production, use, end-of-life) of the envisioned PV modules are assessed using input data from WPs 1-5.

Guidance on an efficient collection of data is crucial for reliable assessments of safety, circularity, and sustainability of the envisioned PV modules.

SmartGreenScans aims to apply a European assessment framework for Safe and Sustainable by Design (SSbD) of chemicals and materials [2] for data collection regarding safety, circularity, and sustainability of the LAPERITIVO PV modules.

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2.2 The Safe and Sustainable by Design (SSbD) framework

2.2.1 Background of the SSbD framework

To support the implementation of the Chemicals Strategy for Sustainability (CSS) within Europe's Green Deal (2019), the European Commission adopted in 2022 a recommendation establishing a European assessment **framework** for **"Safe and Sustainable by Design (SSbD)" for chemicals and materials**, as a specific action of the CSS to promote the design, development, production and use of completely new safer and more sustainable chemicals and materials considering their entire life cycle, enabling substitution of hazardous and less sustainable chemicals and materials. The overall goal is to help in preventing pollution whilst also reducing society's environmental footprint [3,4,5]. The SSbD framework is a general approach to steer innovation towards safe and sustainable new or existing chemicals and materials throughout the entire life cycle. **SSbD combines hazard and risk assessment approaches for chemicals and materials, with sustainability assessment techniques, such as Life Cycle Assessment (LCA) methods.**

2.2.2 SSbD in a nutshell

SSbD consists of **a (re)design phase**, based on general SSbD design strategies and principles, which come from existing concepts, such as Green Chemistry, Green Engineering, Sustainable Chemistry and Circularity. The **scope** includes the chemicals/materials under assessment, their functions (final product/application) and the considerations of the life cycle, including relevant processes and products (value chain). The SSbD **system definition** encompasses (re)design aspects, involving the goal(s) of innovation, and a preliminary identification of potential hotspots along the life cycle that helps to frame the assessment on potential consequences due to the innovation. The life cycle perspective highlights the importance of the value chain, implying that the application of the SSbD framework envisages the involvement and collaboration of all stakeholders along the value chain. Hence, all the **actors** involved in the life cycle of a chemical/material have a role and a responsibility in ensuring that the chemical/material, process, and product are safe, sustainable, and functional. SSbD involves a **5-step assessment phase**, that targets 1) hazard properties of the chemicals, 2) human health and safety of the processes in the production phase, 3) environmental and human health risks in the use phase, 4) environmental impacts along the entire life cycle, and 5) (optionally) socio-economic impacts.

This document describes how the 5-step assessment within the SSbD framework can be used as an overall guidance to set up specific guidelines for the collection of data regarding safety, circularity, and sustainability aspects of the LAPERITIVO PV modules based on an active involvement of the consortium and relevant external stakeholders for providing data on chemicals, materials, production processes, products and environmental-socio-economic aspects.

3 Application of SSbD for safety, circularity, and sustainability

3.1 Introduction SSbD for LAPERITIVO

Figure 2 presents a schematic overview of the application of SSbD for the LAPERITIVO project.

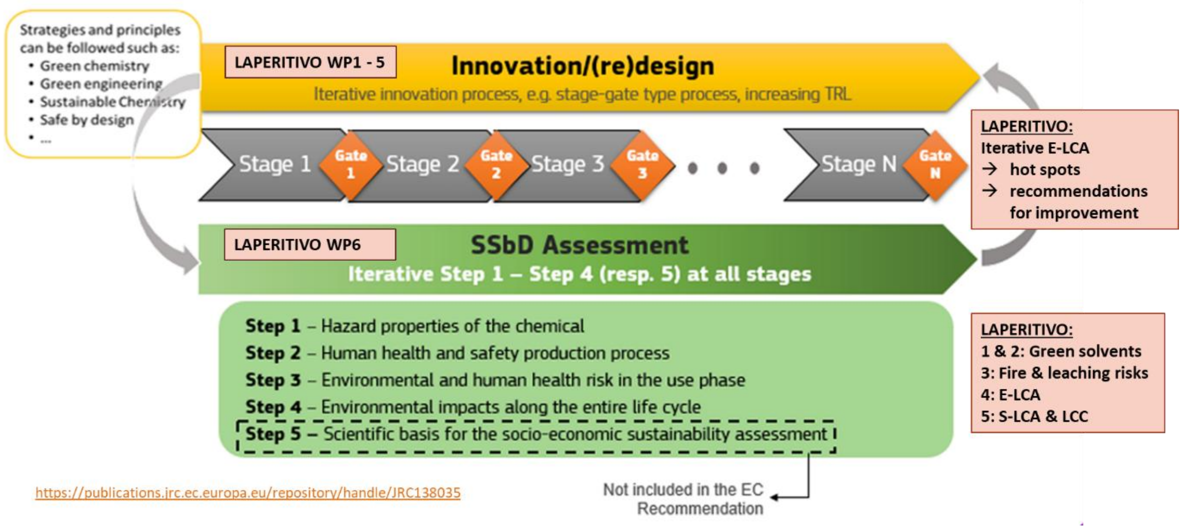

Figure 2 - SSbD and its relation to LAPERITIVO (adapted from E. Abate et al., 2024).

Basically, the 5-step assessment of the SSbD is the overarching guideline for data collection within each of the assessment phases.

In WP6, data collection regarding safety, circularity and sustainability of the PV modules will be conducted using the SSbD framework with help of a methodological guidance as published by E. Abate et al. (2024) [6]. The following examples illustrate the roles of the 5-step assessment phases of the SSbD framework in WP6. **Step 1** relates to (the identification of) hazard properties of the envisioned (green) solvents and other materials that are deployed in the production processes. Step 1 also deals with the assessment of chemicals that might be needed for end-of-life processes such as recycling. **Step 2** assesses human health and safety of the production process, for instance regarding the development of lead (Pb) sequestration technology. Environmental and human health risk in the use phase is targeted in **step 3**, for instance, by collecting data from fire safety and leaching tests on demonstrator modules. The assessment of environmental impacts along the full life cycle in **step 4** is through conducting environmental life cycle assessment (LCA) and the use of scarce or Critical Raw Materials (CRM) using collected data on inputs and outputs of materials and energy in the production and end-of-life phases and energy yield during the use phase. Finally, data from steps 1 – 4 will be used for socio-economic life cycle assessments (**step 5**) to verify improved social and economic sustainability. In the SSbD innovation / (re)design phase, the identified hotspots will be avoided as much as possible.

3.2 Approach: literature surveys and requests for information

The application of the 5-step assessment phases of the SSbD is conducted via surveys of open literature and iterative Requests For Information (RFI) to the relevant consortium partners regarding data for the life cycle phase at hand.

The first data to be collected are for the production phase of the PV module and include the envisioned product, type, amount, toxicity and criticality of chemicals and materials that are used, deployed production processes and their energy consumption, types and amounts of packaging of the ready product, type and amount of wastes and emissions of substances to the environment and transport (precursors and product). Figure 3 presents a typical process flow including the main production steps in the manufacturing of a bifacial PV module.

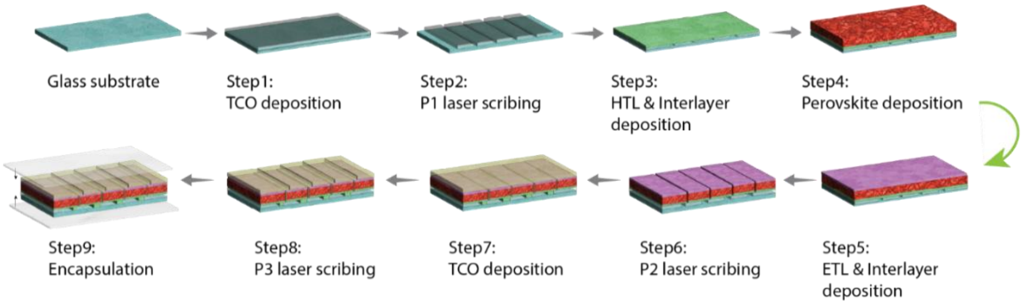

Figure 3 - Bifacial perovskite module fabrication process flow in the LAPERITIVO project.

Upon the progress of LAPERITIVO, data on energy yield, stability and reliability and recyclability will be obtained via subsequent RFIs during use and end-of-life phases. Regarding circularity aspects, recycling of (parts of) the final PV module is the end-of-life option that will be investigated, using the final PV modules after the demonstration (use) phase. A flow chart of the recycling option that is foreseen is presented in Figure 4.

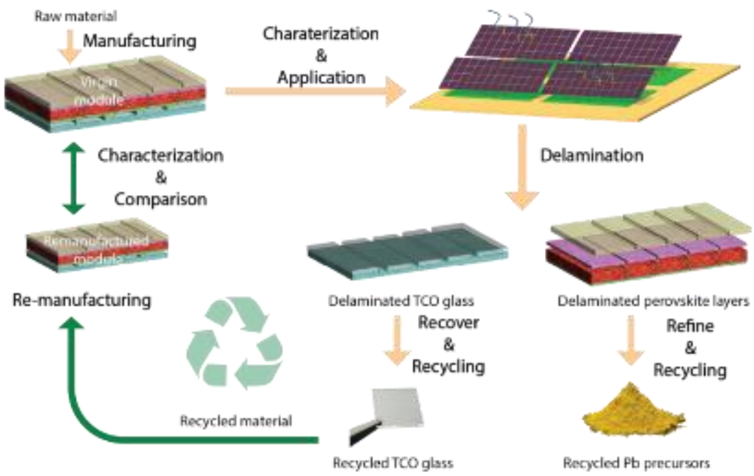

Figure 4 - Schematic flow chart on circularity and recyclability in LAPERITIVO.

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4 Energy efficiency improvements in manufacturing

Regarding energy efficiency improvements in manufacturing, relevant recommendations are obtained from: *SEMI S23-1021 Guide for energy, utilities, and materials use efficiency of semiconductor manufacturing equipment* [9]. These recommendations encompass the following items:

- Monitoring
- Ideas to reduce energy consumption:
    - Use the highest available voltage.
    - Use warmer cooling water.
    - Increase cooling water mean temperature difference.
    - Decrease exhaust and cooling water pressure drops.
    - Reduce bulk gas minimum supply measures.
    - Use less pure processing chemicals.
    - Use clean dry air for pneumatic controls instead of nitrogen.
    - Use control systems to activate exhaust only when needed.

5 Critical raw materials

The Fifth list 2023 of critical raw materials for the EU [11] will be used to evaluate the LAPERITIVO modules.

Table 1 - Fifth list 2023 of critical raw materials for the EU

Bauxite	**Coking Coal**	**Lithium**	**Phosphorus**
Antimony	**Feldspar**	Light rare earth elements	Scandium
Arsenic	Fluorspar	Magnesium	Silicon metal
Baryte	Gallium	**Manganese**	Strontium
Beryllium	Germanium	Natural Graphite	Tantalum
Bismuth	Hafnium	Niobium	Titanium metal
Boron/Borate	**Helium**	Platinum group metals	Tungsten
Cobalt	Heavy rare earth elements	Phosphate Rock	Vanadium
		Copper	**Nickel**

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6 Guidelines for primary data collection

In the context of Life Cycle Assessment (LCA), **primary data** refers to the directly measured or collected data that is specific to the product, process, or facility being assessed. It's often called the "foreground system" because it represents the actual operations under your control or within your supply chain. **Secondary data** refers to information collected and analysed by third parties and then made available. For instance, the commercially available database Ecoinvent contains existing environmental data on various chains and products, eliminating the need to request primary data from your supplier.

Upscaling of data

The lab- and pilot scale data collected by project partners need to be upscaled to industrial scale. Therefore, recipe information is also collected, so equipment manufacturers can be requested to upscale data referring to specific equipment.

6.1 Manufacturing and Assembly

6.1.1 Data template

Regarding the module production phase, primary data collection is conducted via the distribution of a **dedicated Excel-based template**. This data template contains numerical data on type, amount and transport distances of the deployed chemicals and materials for the production of PV modules and associated wastes (solid, liquid and/or gaseous), corresponding energy consumption, infrastructure such as equipment and buildings and final product characteristics. The content of the Excel template is further described in detail as follows:

6.1.2 Data inventory per process step

Material input

Input **materials** are divided between materials, that end up in the modules and materials, that do not end up in the modules (auxiliaries) such as solvents. Raw material data collected by the project partners, are typically expressed as amounts per substrate or per several substrates. Data, corresponding to the processing of one or several substrates, is converted to amounts per m^2 of substrate for easy process comparison. Collected raw data may be expressed in non-mass units, such as volume [m^3 or litre]. These units are converted by the LCA expert to kg, the unit, that is used by the LCA software.

Energy input

Direct **electricity** consumption of the production equipment [kWh] is estimated by the project partners developing the processes. The amounts needed for utilities such as cooling of the cooling water, generation of compressed dry air (CDA), heating ventilation and air conditioning (HVAC), onsite generation of nitrogen and oxygen will be estimated in Work package 5 (Pilot line design).

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Packaging

The development of dedicated packaging of the modules falls outside the scope of the LAPERITIVO project. The LCA expert can make estimations based on inventory data available from industrial scale crystalline silicon module production.

Waste treatment

In lab- or pilot scale production amounts of waste are not monitored, but the LCA expert can estimate the amounts of waste. Recovery and reuse of solvents is not explicitly tested in LAPERITIVO and educated guesses need to be made.

Exhaust treatment and emissions to the environment

In lab- or pilot scale production emission amounts of solid, liquid and/or gaseous substances to the environment (air, water) are not measured. In work package 5 (Pilot line design) estimations will be made.

Transport

Transport of materials to the site and waste to external treatment are included at a later stage in the project when the type of materials in the cell stack and the module have been fixed. Means of transport (road, train, ship, etc) and distance data [km] are estimated based on supply chain preferences.

Infrastructure - Equipment

Primary data regarding equipment are: equipment name, process name, equipment weight [kg/piece], equipment footprint [m^2/piece), equipment cost [euro/piece], number of equipment pieces in 200 MWp production line, calculation of totals (number and weight of equipment pieces).

Infrastructure - Buildings

Regarding infrastructure buildings, primary data refer to areas including utilities [m^2] for 5 GWp production.

Products

Regarding products, primary data refer to length, width, thickness and module efficiency. Pictures will show the demonstrator modules.

Specific data for S-LCA: Region of manufacture

In social life cycle assessment, the country of manufacture is a crucial factor, as social impacts—such as labour conditions, human rights, and community well-being—can vary significantly between regions. Therefore, knowing where a product is made is essential for accurate evaluation.

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Specific data for the economic assessment: cost per unit

To perform the economic assessment, the amounts need to be multiplied with **cost per unit.** Also, data about **labour** to operate the factory is needed.

First, the cell stack and module design and process type need to be fixed. Since the unit cost depends on how much you buy, the amounts needed for a 5 GWp factory are calculated. Then data is collected to calculate Capital expenditures CAPEX (€/piece of equipment, and € for infrastructure) and Operating expenses OPEX (€/kg of material input and waste; €/kWh electricity, €/hour of labour).

6.2 Distribution & Installation [out-of-scope]

6.3 Use and Maintenance

Tables 2 – 5 present the data templates, that are deployed to collect use phase data on energy yield (kWh) and degradation rate (% of power per year), obtained through field / demo tests. These data serve as input to enable the estimation of various impacts per kWh produced over the lifetime of the PV module (for instance kgCO_2-eq / kWh for the climate change impact category).

Table 2 - LAPERITIVO outdoor test locations

Location					
Country, City	Street, Postal code, City	Organization	Latitude	Longitude	GPS
Belgium		Engie			
France, Paris		IPVF			
Germany, Freiberg		Fraunhofer			
Greece, Crete		HMU			
Morocco		GEP			

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Table 3 - LAPERITIVO outdoor test installations

Location	Installation			
Country, City		Slope type	Slope	Azimuth
			[°]	[°]
Belgium	#1	Optimized/vertical		
	#2			
France, Paris	#3			
	#4			
Germany, Freiberg	#5			
	#6			
Greece, Crete	#7			
	#8			
Morocco	#9			
	#10			

Table 4 - LAPERITIVO outdoor energy yield

Location	Installation	Energy yield					
Country, City		Data source	Irradiation	System loss	Reference	Solar radiation database	Energy yield
			kWh/m2.year	%			kWh/kWp.yr
Belgium	#1	Database			PVGIS v5.3	PVGIS-SARAH3	
	#2	Measured					
France, Paris	#3						
	#4						
Germany, Freiberg	#5						
	#6						
Greece, Crete	#7						
	#8						
Morocco	#9						
	#10						

Table 5 - LAPERITIVO degradation rate

Location#	Location	#1	#2	#3	#4
1					
2					
3					
4					
5					

6.4 End-of-Life Treatment

The same approach as for the manufacturing processes is followed for the end-of-life treatment processes.

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7 Guidelines for secondary data collection

7.1 Step 1 – 2: Safety and human health aspects

The SSbD targets the hazards of the used chemicals, human health and safety of the production process (**step 1 and 2 in Figure 2**).

Regarding hazards and human health aspects of the used chemicals, the provided information will be checked via ECHA, the European Chemicals Agency that carries out technical, scientific, and administrative tasks related to the implementation of EU's chemicals legislation and policy [7] (https://echa.europa.eu/echa-chem). ECHA provides transparent, independent and high-quality scientific opinions and decisions, serving as the basis of Union measures. It collaborates and partners with EU bodies and institutions, Member State authorities, third countries and international organisations. ECHA provides tools, advice and support to industry, with a particular focus on small and medium sized enterprises. It is ensured that relevant, reliable, and objective information is available for the public and interested parties.
ECHA CHEM is ECHA's public chemicals database, launched in early 2024. Currently, it includes data that companies have submitted in their REACH registrations and information from the Classification and Labelling Inventory (C&L). REACH is a regulation of the European Union, adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry. REACH also promotes alternative methods for the hazard assessment of substances to reduce the number of tests on animals. REACH stands for Registration, Evaluation, Authorisation and Restriction of Chemicals. It entered into force on 1 June 2007.
ECHA CHEM can be deployed to check whether envisioned solvents for the LAPERITIVO processes are substances of very high concern (SVHC), i.e. not safe regarding human and environmental health aspects. For instance, if it is required to use dimethyl formamide (DMF) as solvent, Figure 5 presents information that can be extracted from the ECHA CHEM database.

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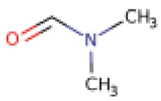
N,N-dimethylformamide

Substance identity

EC / List no.: 200-679-5

CAS no.: 68-12-2

Mol. formula: C3H7NO



Hazard classification & labelling

Danger! According to the **harmonised classification and labelling** (CLP00) approved by the European Union, this substance may damage the unborn child, is harmful in contact with skin, causes serious eye irritation and is harmful if inhaled.

Additionally, the classification provided by companies to ECHA **in REACH registrations** identifies that this substance may damage fertility or the unborn child and is a flammable liquid and vapour.

Properties of concern

R Toxic to Reproduction

Regulatory context

- Substance of very high concern (SVHC) and included in the candidate list for authorisation.
- Some uses of this substance are restricted under Annex XVII of REACH.

About this substance

This substance is registered under the REACH Regulation and is manufactured in and / or imported to the European Economic Area, at ≥ 10 000 tonnes per annum.

This substance is used by professional workers (widespread uses), in formulation or re-packing, at industrial sites and in manufacturing.

This substance is used by professional workers (widespread uses), in formulation or re-packing, at industrial sites and in manufacturing.

Consumer Uses

ECHA has no public registered data indicating whether or in which chemical products the substance might be used. ECHA has no public registered data on the routes by which this substance is most likely to be released to the environment.

Article service life

ECHA has no public registered data on the routes by which this substance is most likely to be released to the environment. ECHA has no public registered data indicating whether or into which articles the substance might have been processed.

Widespread uses by professional workers

This substance is used in the following products: laboratory chemicals and pH regulators and water treatment products.
This substance is used in the following areas: scientific research and development and health services.
This substance is used for the manufacture of: .
Release to the environment of this substance can occur from industrial use: in processing aids at industrial sites and as an intermediate step in further manufacturing of another substance (use of intermediates).
Other release to the environment of this substance is likely to occur from: indoor use (e.g. machine wash liquids/detergents, automotive care products, paints and coating or adhesives, fragrances and air fresheners).

Formulation or re-packing

This substance is used in the following products: adhesives and sealants, coating products, leather treatment products, plant protection products, laboratory chemicals, perfumes and fragrances, pharmaceuticals, polymers and textile treatment products and dyes.
Release to the environment of this substance can occur from industrial use: formulation of mixtures.

Uses at industrial sites

This substance is used in the following products: laboratory chemicals, adhesives and sealants, coating products, leather treatment products, plant protection products, perfumes and fragrances, pharmaceuticals, polymers and textile treatment products and dyes.
This substance has an industrial use resulting in manufacture of another substance (use of intermediates).
This substance is used for the manufacture of: chemicals, , textile, leather or fur, plastic products, mineral products (e.g. plasters, cement) and furniture.
Release to the environment of this substance can occur from industrial use: in processing aids at industrial sites, as an intermediate step in further manufacturing of another substance (use of intermediates), of substances in closed systems with minimal release and as processing aid.

Manufacture

Release to the environment of this substance can occur from industrial use: manufacturing of the substance.

The InfoCard summarises the non-confidential data on substances as held in the databases of the European Chemicals Agency (ECHA), including data provided by third parties. The InfoCard is automatically generated. Information requirements under different legislative frameworks may therefore not be up-to-date or complete. Substance manufacturers and importers are responsible for consulting official publications. This InfoCard is covered by the ECHA Legal Disclaimer.

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Figure 5 - DMF substance info card, extracted from ECHA CHEM [7]

As can be seen from this substance info card, DMF is a substance of very high concern.

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7.2 Step 3: Environmental and human health risk in the use phase

Data on environmental and human health risks in the use phase will be collected via RFIs, using a dedicated fill-in template for **fire and leaching test** results on PV products (**step 3 in Figure 3**). Relevant data include type and amount of gaseous emissions of hazardous chemicals when PV modules catch fire and aqueous emissions to the soil of leachates from damaged PV modules as a result of bad weather conditions such as hailstorms and heavy rain showers.

7.3 Step 4: Environmental life cycle impact assessments

Regarding the environmental impacts along the entire life cycle (**step 4 in Figure 3**), for each life cycle phase, the collection of numerical data for both environmental life cycle impact assessments is conducted through the distribution of a dedicated data template to be filled in by relevant partners in the project consortium. These data templates serve to construct the full life cycle inventory that is used for the life cycle impact assessments.

After life cycle inventory data have been collected from the project partners (primary data), the actual environmental impact assessment is performed using dedicated software and databases. In LAPERITIVO the life cycle inventory database **ecoinvent** will be used for secondary data because it is the most transparent database available. The impact assessment method to be used will be the **Environmental Footprint method** as recommended by the European Commission, which includes the following impacts (v3.1 adapted, in simapro software):

1. **Climate Change:** Impact indicator: Global Warming Potential 100 years.
2. **Ozone depletion:** Impact indicator: Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.
3. **Ionising radiation** - human health: Impact indicator: Ionizing Radiation Potentials: Quantification of the impact of ionizing radiation on the population, in comparison to Uranium 235.
4. **Photochemical ozone formation** - human health: Impact indicator: Photochemical ozone creation potential (POCP): Expression of the potential contribution to photochemical ozone formation.
5. **Particulate matter: Impact indicator:** Disease incidence due to kg of PM2.5 emitted.
6. **Human toxicity, non-cancer:** Impact indicator: Comparative Toxic Unit for human (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram).
7. **Human toxicity, cancer**: Impact indicator: Comparative Toxic Unit for human (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram).
8. **Acidification, terrestrial and freshwater:** Impact indicator: Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.

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9. **Eutrophication, freshwater:** Impact indicator: Phosphorus equivalents: Expression of the degree to which the emitted nutrients reach the freshwater end compartment (phosphorus considered as limiting factor in freshwater).
10. **Eutrophication, marine:** Impact indicator: Nitrogen equivalents: Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water).
11. **Eutrophication, terrestrial:** Impact indicator: Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit.
12. **Ecotoxicity, freshwater:** Impact indicator: Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 day/kg).
13. **Land Use:** Impact indicator: Soil quality index.
14. **Water use:** Impact indicator: m3 water eq. deprived.
15. **Resource use, fossils:** Impact indicator: Abiotic resource depletion fossil fuels (ADP-fossil).
16. **Resource use, minerals and metals**: Impact indicator: Abiotic resource depletion (ADP ultimate reserve).

7.4 Step 5a: Social LCA

Socio-economic sustainability assessment is -partly- based on literature surveys and data, acquired for the life cycle impact assessments.

In LAPERITIVO the software and database **PSILCA** (Product Social Impact Life Cycle Assessment) will be used. A PSILCA was specifically designed for S-LCA and has data on social and environmental risks and opportunities, including information from around 15,000 industry sectors across 189 countries. This data is organized into 19 subcategories. 65 different indicators covering both social and environmental factors. Indicator assessment is based on a scale, typically ranging from no risk to very high risk, with some indicators also reflecting positive opportunities. Indicator selection, focusing on certain indicators can be relevant given their large number and can be determined for example based on partners' indicator ranking (e.g., best-worst ranking methodology).

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Table 6 - Stakeholders, impact categories and indicators with units in the PSILCA database v4

Stakeholder	Subcategory	Indicator	Unit of measurement	New Indicator (Yes/No)	Coverage[1]
Local Community	Access to material resources	Certified environmental management systems	Number of CEMS per 10.000 employees	No	S
		Extraction of biomass (related to population)	annual ton/cap	No	C
		Extraction of fossil fuels	annual ton/cap	No	C
		Extraction of industrial and construction minerals	annual ton/cap	No	C
		Extraction of ores	annual ton/cap	No	C
		Level of industrial water use	% of total actual renewable water resources per year	No	C
		Level of industrial water use	% of total water	No	C
		Extraction of biomass (related to area)	annual ton/cap	No	C
		Waste management	Score	New	C

Stakeholder	Subcategory	Indicator	Unit of measurement	New Indicator (Yes/No)	Coverage[1]
	Environmental footprints	Embodied agricultural area footprint	Hectare/ 1USD	No	S
		Embodied forest area footprint	Hectare/1 USD	No	S
		Embodied water footprint	Mm3/USD	No	S
		Embodied CO_2-eq footprint	ton per USD	No	S
	GHG footprints	Embodied CO_2 footprint	ton per USD	No	S
	Respect of indigenous rights	Indigenous People Rights Protection Index	6-point scale	No	C
		Presence of indigenous population	yes/no	No	C
	Secure living condition	Homicides	Rate per 100,000 population	Yes	C
		Internally displaced people	Rate per 10,000 people	Yes	C
Society	Contribution to economic development	Contribution to economic development	% of GDP	No	S
		Embodied value-added total	USD/USD	No	S
		Labour productivity	USD/hour	Yes	C
		Informal employment, total	% Informal employment rate	Yes	S
		Informal employment, male	% Informal employment rate male	Yes	S

Stakeholder	Subcategory	Indicator	Unit of measurement	New Indicator (Yes/No)	Coverage[1]
		Informal employment, female	% Informal employment rate	Yes	S
	Secure living condition	Global Peace Index	Index	No	C
		Global Terrorism Index	Score	Yes	C
		Social Protection Expenditures	% of GDP	No	C
	Health and safety	Health expenditure, domestic general government	% of total health expenditure in reference year	No	C
		Health expenditure, external resources	% of total health expenditure in reference year	No	C
		Health expenditure, out-of-pocket	% of current health expenditure	No	C
		Health expenditure, total	% of GPD	No	C
		Life expectancy at birth	Years	No	C
		Household air pollution attributable DALYs, female	DALY rate per 1,000 inhabitants in the country per year	Yes	C
		Household air pollution attributable DALYs, male	DALY rate per 1,000 inhabitants in the country per year	Yes	C
		Internet freedom scores	Score	Yes	C

Stakeholder	Subcategory	Indicator	Unit of measurement	New Indicator (Yes/No)	Coverage[1]
	Censorship and oppression	Freedom of the press	Score	Yes	C
	Access to immaterial resources	Global freedom scores	Score	Yes	C
	Ethical Treatment of animals	Animal protection	Score	Yes	C
	Nature	Biodiversity & Habitat	Score	Yes	C
		Ecosystem services	Index	Yes	C
		Number of threatened species	Number of species / 1USD	No	S
	Governance	Political stability and absence of violence	Normalized units for governance	Yes	C
		State of democracy	Score	Yes	C
	Poverty alleviation	Population below national poverty line	% of population	Yes	C
		Food Insecurity	Score	Yes	C
		Safe access to drinking water coverage	% of population	No	C
		Sanitation coverage	% of population	No	C

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Stakeholder	Subcategory	Indicator	Unit of measurement	New Indicator (Yes/No)	Coverage[1]
	Technology development	R&D expenditures	% of GDP	Yes	C
		Rate of researchers	No. of researchers per one million inhabitants	Yes	C
		Access to electricity	% of population	Yes	C
		Access to internet	% of population	Yes	C
	Education and Upskilling opportunities	Illiteracy rate, female	% of female population 15+ years	No	C
		Illiteracy rate, male	% of male population 15+ years	No	C
		Illiteracy rate, total	% of total population 15+ years	No	C
		Public expenditure on education	% of GDP	No	C
		Youth illiteracy rate, female	% of female population 15-24 years	No	C
		Youth Illiteracy rate, male	% of male population 15-24 years	No	C
		Youth illiteracy rate, total	% of total population 15-24 years	No	C
		Youth Unemployment	% of youth not in employment, education or training	Yes	C
		Gender inequalities	Score	Yes	C

Stakeholder	Subcategory	Indicator	Unit of measurement	New Indicator (Yes/No)	Coverage[1]
	Gender equalities and empowerment	Female genital mutilation 15-49	% of youth	Yes	C
		Female with account at a financial institution	% of population ages 15+ female	Yes	C
	Local Employment	Unemployment rate in the country	% of population ages 15-64 in reference year	No	C
	Migration	Emigration rate	% of population in reference year	No	C
		Immigration rate	% of population in reference year	No	C
		International migrant stock	% of population	No	C
		Net migration rate	% (per 1,000 persons)	No	C
		Asylum seekers rate	% of population in the time frame (2 years)	No	C
		International migrant workers in the sector	% of international migrant workers in total employed population	No	S
	Safe and healthy living conditions	Pollution level of the country	Pollution Index in reference year	No	C
Value Chain Actors	Corruption	Active involvement of enterprises in corruption and bribery	% of sector-related cases out of all registered foreign bribery cases in the time frame (15 years)	No	S

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Stakeholder	Subcategory	Indicator	Unit of measurement	New Indicator (Yes/No)	Coverage[1]
		Public sector corruption	Index score	No	C
	Fair competition	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Cases per 10,000 employees in the time frame (5 years)	No	S
	Promoting social responsibility	Social responsibility along the supply chain	Number of companies	No	S
Workers	Child labour	Children in employment, female	% of female children ages 5-17	No	S
		Children in employment, male	% of male children ages 5-17	No	S
		Children in employment, total	% of male children ages 5-17	No	S
	Discrimination	Gender wage gap	% difference male and female wages in reference year	No	S
		Men in the sectoral labour force	% man	No	S
		Women in the sectoral labour force	% female	No	S
	Fair salary	Living wage, per month	USD/ month	No	C
		Minimum wage, per month	USD/ month	No	C
		Sector average wage, per month	USD/month	No	S

Stakeholder	Subcategory	Indicator	Unit of measurement	New Indicator (Yes/No)	Coverage[1]
	Forced labour	Frequency of forced labour	Cases per 1000 inhabitants in the country in reference year	No	C
		Goods produced by forced labour	Score	No	S
		Trafficking in persons	Tier placement	No	C
	Freedom of association and collective bargaining	Freedom of association and collective bargaining	Scale from 1 to 10	Yes	C
		Number of strikes	Number of strikes	Yes	S
		Trade union density	% of employees	No	C
	Health and safety	Presence of sufficient safety measures	OSHA cases per 100,000 employees and year	No	S
		Rate of fatal accidents at workplace	cases per 100,000 employees	No	S
		Rate of non-fatal accidents at workplace	cases per 100,000 employees	No	S
		Violations of mandatory health and safety standards	ratio number of cases/available labour force in reference year	No	C
	Social benefits, legal issues	Evidence of violations of laws and employment regulations	cases per 1,000 employees in the time frame (5 years)	No	S

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Stakeholder	Subcategory	Indicator	Unit of measurement	New Indicator (Yes/No)	Coverage[1]
		Paid maternity leave	Days of paid leave for childbirth and early childcare for the mother	Yes	C
	Working time	Weekly hours of work per employee male	Mean weekly hours	Yes	S
		Weekly hours of work per employee female	Mean weekly hours	Yes	S
Children	Children Welfare	Child marriage, female	% of women	Yes	C
		Child marriage, male	% of male	Yes	C
		Female genital mutilation 0-14	% of girls	Yes	C
	Education	Mean years of schooling, total	years	Yes	C
		Mean years of schooling, female	years	Yes	C
		Mean years of schooling, male	years	Yes	C
	Health and Safety	Under-five mortality rate	Deaths per 1,000 live births	Yes	C
Consumer	Consumer protection	Online Consumer Protection Legislation	Legislation exits (Yes/No)	Yes	C
		Data protection and privacy	Legislation exits (Yes/No)	Yes	C

This table is taken from reference [10].

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7.5 Step 5b: Economic assessment

For the **economic** assessment the inventory data from the environmental LCA will be complemented with cost per unit of material and energy, and infrastructure (depreciation).

External costs

First, life-cycle emissions of key pollutants are quantified using LCA software:
- Main air pollutants (NO_x, SO_2, PM_{10}, $PM_{2.5}$, Non-Methane Volatile Organic Compounds (NMVOCs), NH_3)
- Heavy metals (arsenic, cadmium, chromium VI, lead, mercury, nickel)
- Organic pollutants (1,3-butadiene, benzene, benzo[a]pyrene, dioxins/furans, formaldehyde)
- Greenhouse gases (CO_2, CH_4, N_2O)

Next, we estimate the external costs associated with these emissions by applying the European Environment Agency's average European marginal damage costs (MDCs) for air pollutants [8].

8 Conclusion

Guidance on an efficient collection of data is crucial for reliable assessments of safety, circularity, and sustainability of the envisioned LAPERITIVO PV modules.

The conclusion from this work is that a recent European assessment framework for Safe and Sustainable by Design (SSbD) for chemicals and materials was identified as a useful tool for data collection regarding safety, circularity, and sustainability of the PV modules following the 5-step assessment phase within the SSbD framework. Table 7 summarises the findings from the application of the 5-step assessment for data collection regarding the safety, circularity, and sustainability of LAPERITIVO PV modules.

Table 7 - Data collection guidelines via the SSbD Framework methodology

Safe and Sustainable by Design framework for chemicals and materials: The 5-step assessment phase as guidance for data collection regarding safety, circularity, and sustainability of the LAPERITIVO PV modules			
Step	**Description**	**Relates to**	**Data collection via**
1	Hazard properties of the chemical	Production and end-of-life phases (manufacturing of the PV module and its end-of-life processing, e.g. via recycling)	Dedicated Excel templates and literature surveys (ECHA CHEM, MSDS)
2	Human health and safety of the production process	Production phase	Dedicated Excel templates and literature surveys (ECHA CHEM, MSDS)
3	Environmental and human health risks in the use phase	Use phase (field demonstration tests)	Dedicated Excel templates
4	Environmental impacts along the entire life cycle	Environmental life cycle impact assessment from cradle to grave	Dedicated Excel templates

5	Scientific basis for the socio-economic sustainability assessment	Socio-economic life cycle impact assessment from cradle to grave	Dedicated Excel templates, literature surveys and results from step 4.

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