kiutra

Life Cycle Assessment

CONCEPTS AND GUIDANCE FOR EARLY STAGE PRODUCTS

Life Cycle Assessment

CONCEPTS AND GUIDANCE FOR EARLY STAGE PRODUCTS

Version 4.0
June, 2026

HARRIS MUBEEN
Sustainability Manager
kiutra GmbH

PREFACE

Sustainability is no longer optional; it’s a design imperative. Life Cycle Assessment (LCA) is one of the most powerful tools for understanding the environmental footprint of products and technologies. Yet most resources on LCA focus on established systems with reliable datasets, leaving innovators at the early stages, where processes are fluid and data is scarce, without much guidance.

This guide aims to fill that gap. It introduces the key concepts, terms, and processes of LCA while showing how innovators can begin their LCA journey early on. By embedding sustainability thinking from the outset, teams can make smarter design choices, anticipate trade-offs, and transform constraints into opportunities.

To make learning practical, each chapter combines theory with application. We will explore the fundamentals of LCA and immediately put them into practice through a case study: the life cycle assessment of an incandescent bulb. This step-by-step approach allows you to see how concepts translate into analysis and makes it easier to adapt the methods to your own projects.

KNOWLEDGE CHECK

This guide is designed to be read, but also to be tested. Alongside each chapter, we have built a companion quiz: 50 questions covering the full arc of LCA, from fundamental concepts to EU regulatory requirements.

The quiz is entirely optional. You can work through it chapter by chapter as you read, pausing at the end of each section to consolidate what you have just learned. Or you can save it for the end and take it all at once as a final check.

After submitting, you will receive an immediate breakdown of your results — showing which answers you got right, where you went wrong, and the correct answer for each question. There are no time limits, no pass marks, and your results are not shared.

Scan the QR code below to get started.

CONTENTS

1 WHAT IS LIFE CYCLE ASSESSMENT ?

Life Cycle Assessment is a comprehensive methodology used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle, from raw material extraction to end-of-life treatment.

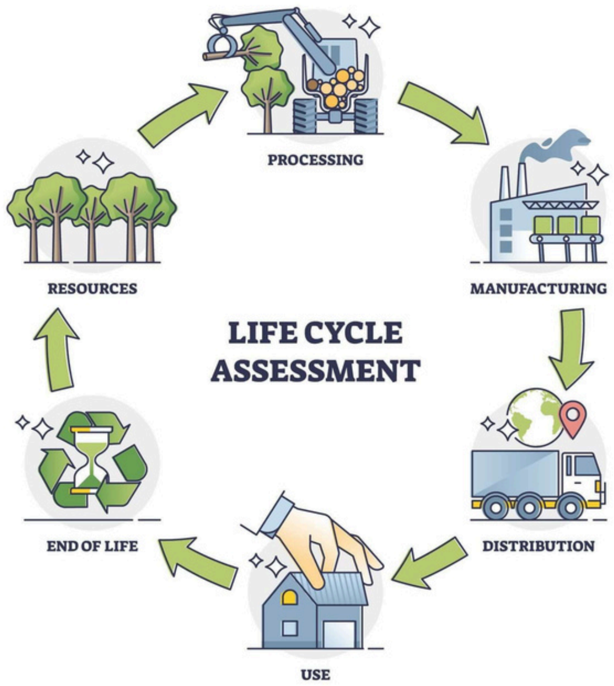


Image Source: Cape Crystal Brands/Chef Edmund

LCA emerged in the 1960s as an early energy analysis of packaging, most famously Coca-Cola's comparison of glass and plastic bottles.

The 1990s brought formal standardization with the ISO 14040/44 framework, establishing the four core phases still followed today.

In the last two decades, LCA gained policy relevance, underpinning EU initiatives like eco-labels, product carbon footprint, and circular economy strategies.

Today, in the 2020s, LCA is deeply embedded in ESG reporting, the EU Green Deal, and the wide range of regulations that stem from it.

2 WHY SHOULD YOU DO AN LCA?

The main goal of an LCA is to evaluate the environmental impact of a product or system throughout its entire life cycle. This holistic perspective serves several important purposes. It helps identify environmental hotspots, supports the optimization of design and manufacturing processes, and reduces material and energy costs. It also ensures that sustainability claims are scientifically grounded leaving no room for greenwashing.

Conducting an LCA helps companies anticipate and adapt to emerging environmental regulations and market expectations. By grounding sustainability strategies in transparent data, companies enhance their credibility. They demonstrate accountability to customers, investors, and regulators, which strengthens long-term trust and compliance.

An LCA also helps companies differentiate their products from competitors in the market. Demonstrating verified environmental performance can open new business opportunities, improve brand reputation, and contribute to achieving corporate sustainability goals.

3 HOW CAN YOU DESIGN YOUR LCA?

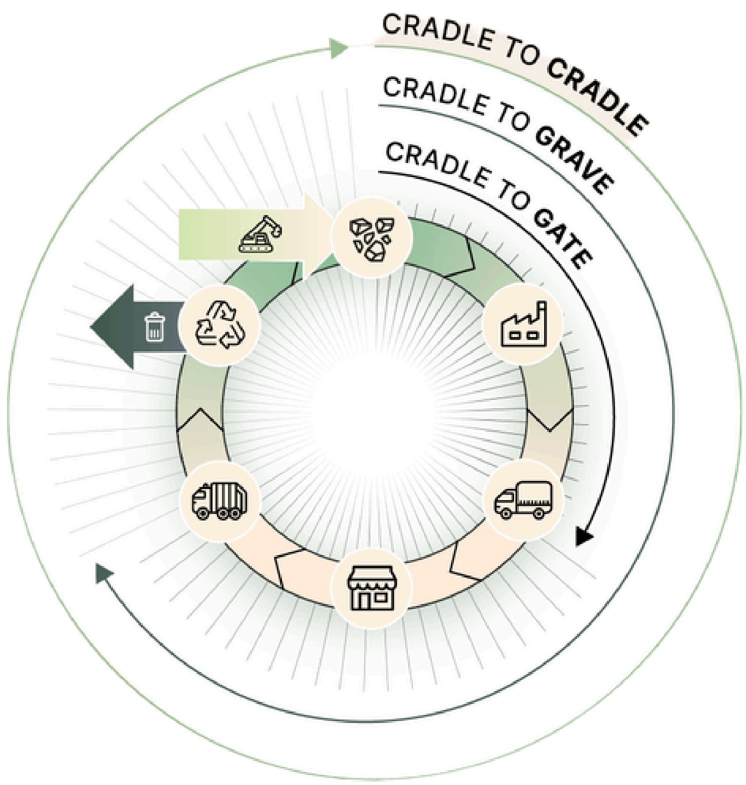


Image credit: Minespider / Anastasia Popova

Before starting any LCA, it is essential to establish the system boundary. The system boundary determines the scope of your assessment. In other words, which stages of your product's life are included in the analysis.

To understand what a system boundary means, it helps to think of a product's journey in three stages:

- **Cradle:** The very beginning where raw materials are extracted from the earth (mining, farming, drilling).
- **Gate:** The point at which the finished product leaves the manufacturer's facility.
- **Grave:** The end of the product's useful life where disposal, recycling, or another form of end-of-life treatment are carried bout.

The three most commonly used system boundaries for an LCA are:

- **Cradle to Gate:** Covers raw material extraction through to the factory gate. It excludes the use phase and end-of-life. Useful for manufacturers wanting to understand their direct production footprint.
- **Cradle to Grave:** Covers the full life cycle from raw material extraction through use to final disposal. This is the most comprehensive boundary.
- **Cradle to Cradle:** Extends the cradle-to-grave boundary by replacing final disposal with a recovery stage, where materials are recycled or reprocessed to re-enter a production cycle as inputs. It reflects circular economy principles, though recovery losses and recycling impacts remain part of the assessment.

Additionally, **Gate to Gate** LCAs focus solely on the environmental impacts occurring within a single facility or process step, without tracking upstream raw materials or downstream use.

Linking TRL and LCA

A large share of the ecological and social impacts of products is determined by decisions made in the early developmental stages. During requirement definition — when fundamental product features are chosen — it is especially valuable to integrate environmental considerations from the outset. This creates opportunities to evaluate alternative development strategies through a sustainability lens.

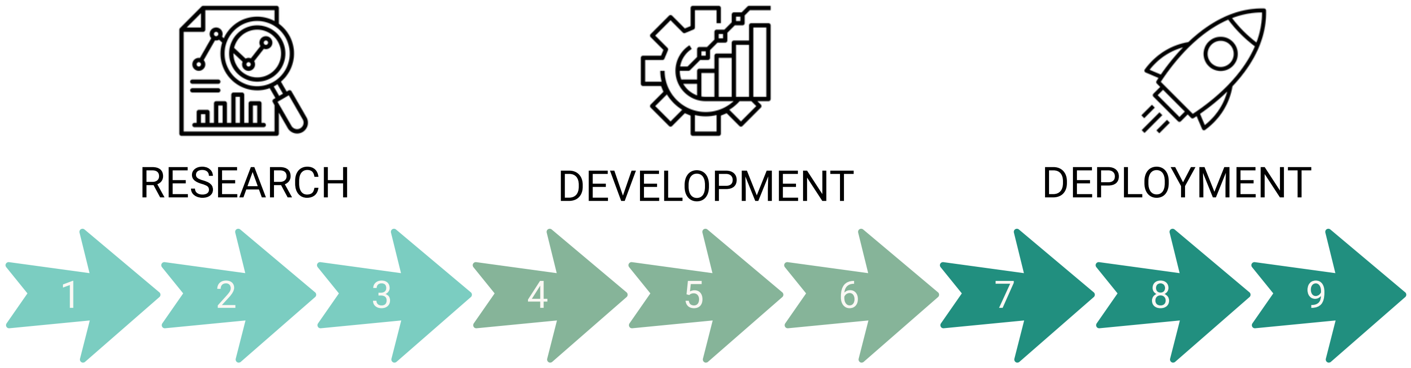
Embedding sustainability is not a one-time effort. It is an iterative process that evolves with the product roadmap. The level of detail in assessments should adapt to the stage of technology development: early-stage evaluations can focus on broad material and energy flows, while more granular LCAs become appropriate as the technology matures and more accurate data becomes available.

A commonly used scale for measuring a technology's maturity is the Technology Readiness Level (TRL), ranging from 1 to 9:

- At lower TRLs (1–3), a Screening LCA can provide quick, initial insights into the environmental impact of different raw materials and production processes.
- At mid TRLs (4–6), a semi-quantitative LCA approach — combined with energy models and material flow analysis — becomes useful.
- At higher TRLs (7–9), a comprehensive LCA with full scope, validated results, and third-party certification ensures the product is ready for market deployment.

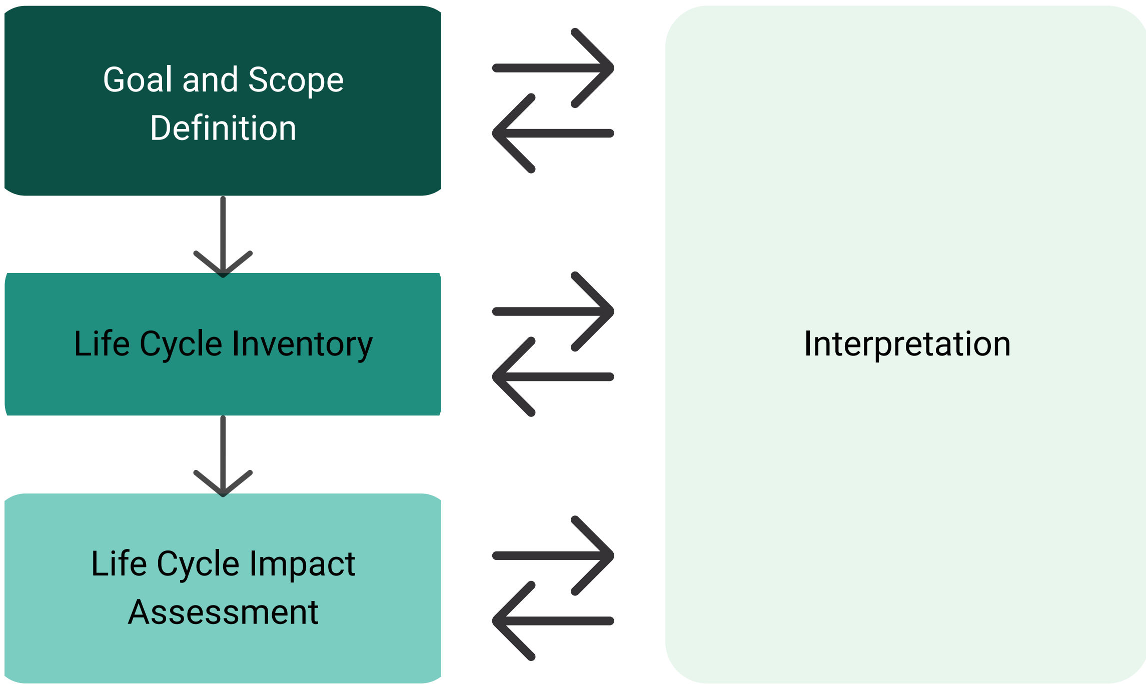
By increasing the scope and accuracy of the LCA as the product progresses, no significant impact is left unexamined and the chances of costly redesign are minimized.

3. HOW CAN YOU DESIGN YOUR LCA?



	Research	Development	Deployment
TECH FOCUS	Idea and Lab research	Prototypes in lab & test environments	Full Integration, certification, and use
LCA BOUNDARY	Gate to Gate	Cradle to Gate	Cradle to Grave or Cradle to Cradle
LCA APPROACH	Screening LCA (secondary data, early functional unit definition, proxies, checklists for critical materials / energy hotspots)	Semi-Quantitative LCA (mix of primary + secondary data, PCF Assessments, Critical Raw Materials assessments, starting migration to software)	Full LCA (expanding from use-phase & EoL assumptions (TRL 7) to ISO-compliant detailed studies (TRL 8), to third-party verified LCAs/EPDs (TRL 9))
LCA DELIVERABLES	1–2 page sustainability note highlighting risks & opportunities	Hotspot maps, simple flow diagrams, short LCA report (carbon + CRM focus)	Multi-impact LCA summaries, full ISO-aligned reports, Digital Product Passport prep, verified LCA/EPD

4 WHAT ARE THE FOUR PHASES OF AN LCA?



An LCA typically goes through four phases:

1. **Goal and Scope Definition** — The purpose, boundaries, and functional unit of the study are set. (See Chapter 5)
2. **Life Cycle Inventory (LCI)** — Data is collected on all relevant inputs (materials, energy) and outputs (emissions, waste) across the system. (See Chapter 6)
3. **Life Cycle Impact Assessment (LCIA)** — The inventory flows are translated into potential environmental impacts, covering categories such as climate change, resource depletion, toxicity, etc. (See Chapter 7)
4. **Interpretation** — Results are analyzed, uncertainties are considered, and conclusions are drawn in line with the study's goals. (See Chapter 8)

These phases are not strictly linear. Interpretation feeds back into earlier phases, refining the goal, scope, and data collection as the study progresses.

5 GOAL AND SCOPE DEFINITION

"A problem which is well defined is half solved"

Setting the goal is the first and arguably the most important step in an LCA. According to ISO 14040/14044, the goal statement should explicitly define:

- **The intended application:**
  What decisions will this LCA support?

- **Reasons for carrying out the study:**
  Internal design optimization, external communication, compliance, investment support, etc.

- **Audience:**
  Who will use or read the results? Engineers? Management? Investors? Regulators? Customers?

- **Comparison & Disclosures:**
  Will results be compared to another product/system? Will they be disclosed externally/published?

Before defining scope, it is important to understand the building blocks of a product system. These definitions are referenced throughout the remainder of the guide.

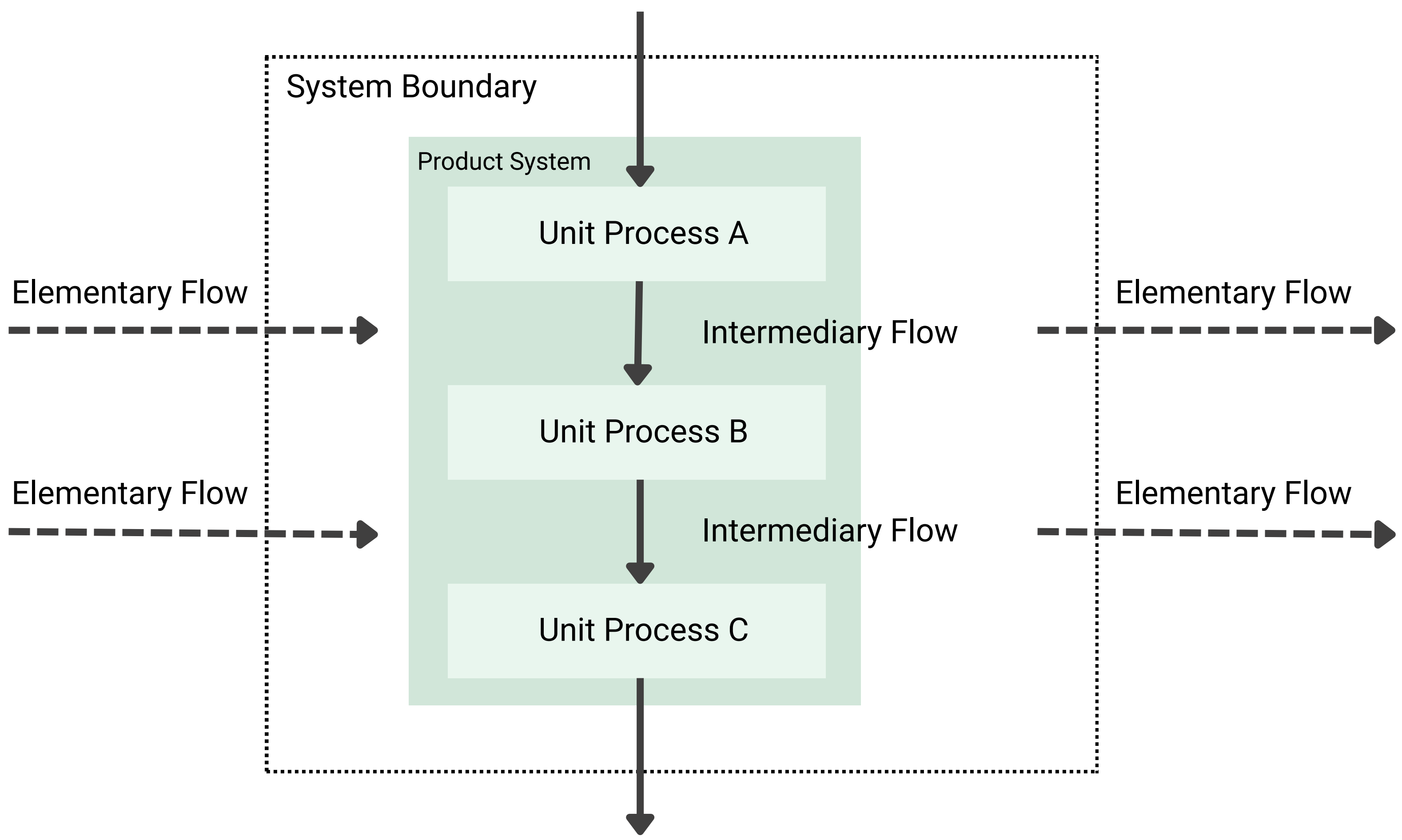
Unit processes are the smallest building block of a product system for which input/output data are quantified. For example, the transportation of raw materials by truck can be considered as a unit process.

The Product System is a collection of unit processes that perform one or more defined functions. The product system is confined inside the system boundary.

A system boundary is the criterion that decides which processes in the life cycle of a product are included in the assessment. Ideally, it includes all processes that are necessary to ensure the system function.

The intermediary flows connect different unit processes to form the product system. They are the products, materials, or energy exchanged between unit processes.

Elementary flows are inputs from the natural environment (such as crude oil in the ground or water) and outputs to the environment (such as CO_2 emissions to air). They cross the system boundary but do not pass between unit processes.



Defining the Scope

The scope of your assessment translates the study's goals into clear boundaries. It defines the rules of the game for your LCA by determining what is included and excluded in the analysis, the level of detail required, and how the results will be interpreted. The key elements of scope definition are:

1. The product system to be studied
2. The function of the system
3. The functional unit
4. The system boundary
5. Allocation procedures
6. Data quality requirements
7. Assumptions & Limitations
8. Type of critical review, if any
9. Type and format of the report required for the study
10. LCIA methodology and impacts

Keep the scope practical and aligned with your TRL. At early stages, a simplified scope with secondary data is perfectly acceptable; precision can grow as your product matures. Document your boundaries and assumptions transparently so that later refinements remain possible and quantifiable.

The Functional Unit

The functional unit is the reference unit in an LCA. It describes precisely what is being studied or compared, from the perspective of the end user. A well-defined functional unit answers the following six questions:

What
(function or service provided)

How much
(extent of the function or service)

How well
(expected level of quality of the function or service)

How long
(duration/lifetime of the function or service)

Where
(location/geography of the function or service)

For Whom
(beneficiary of the function or service)

Case Study — incandescent light bulb:

A weak functional unit: "1 light bulb" — this tells us nothing about what the bulb actually delivers.

A stronger functional unit: "Provision of 800 lumens of artificial light, continuously for 10,000 operating hours, at an average luminous efficacy of ≥90 lm/W, used in a residential living room in Germany."

In early-stage screenings or comparative assessments, the functional unit can be simplified to capture the core service without unnecessary detail and as long as it remains specific enough to allow fair comparisons.For the remainder of this case study, our functional unit is:

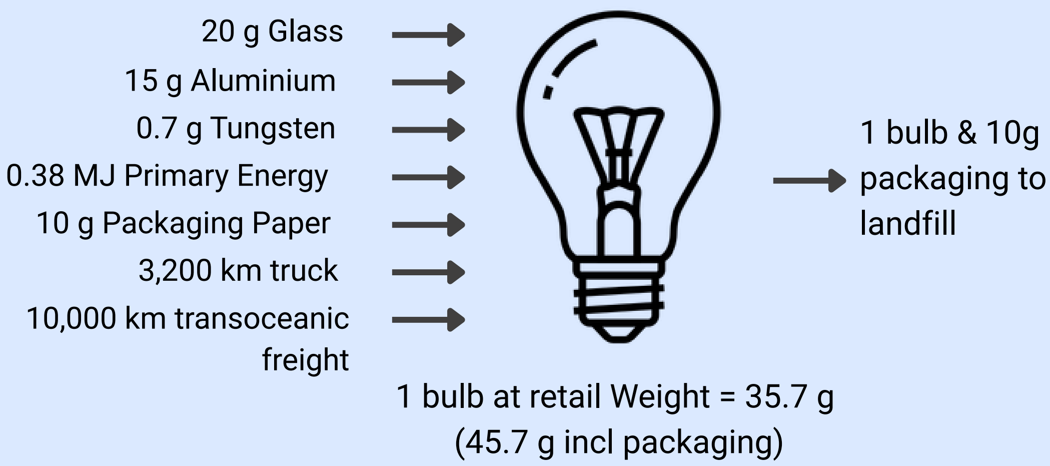
Providing 800 lumens of light for 10,000 hours.

Reference Flows

The functional units are linked to the unit processes using reference flows. They provide the amount of product or material required from a unit process to deliver one functional unit.

Incandescent bulb assumptions:
(i) The bulb is manufactured to have a lifespan of 1,000 hours
(ii) The bulb has a power rating of 12W
(iii) The bulb is manufactured in China and is transported to the EU via transoceanic freight (10,000km).
(iv) Once in the EU, it is distributed to the customers via truck (3,200km)

These four assumptions form the basis for the **reference flows.** But before we calculate the reference flows, we must what constitutes a bulb. From secondary sources, we have the following data for the bulb:



The reference flows now can be calculated as:

- Number of bulbs = 10,000 (hours/FU) /1,000 (hours/bulb) = 10 bulbs/FU
- Energy to light the bulbs = 10,000 Hours/FU * 12W = 120 kWh electricity / FU
- Transoceanic freight = [45.7g/bulb * 10 bulb/FU ÷ 1,000 g/kg] × 10,000 km = 4,570 kg·km/FU
- Truck transport = [45.7g/bulb * 10 bulb/FU ÷ 1,000 g/kg] × 3,200 km = 1,462.4 kg·km/FU

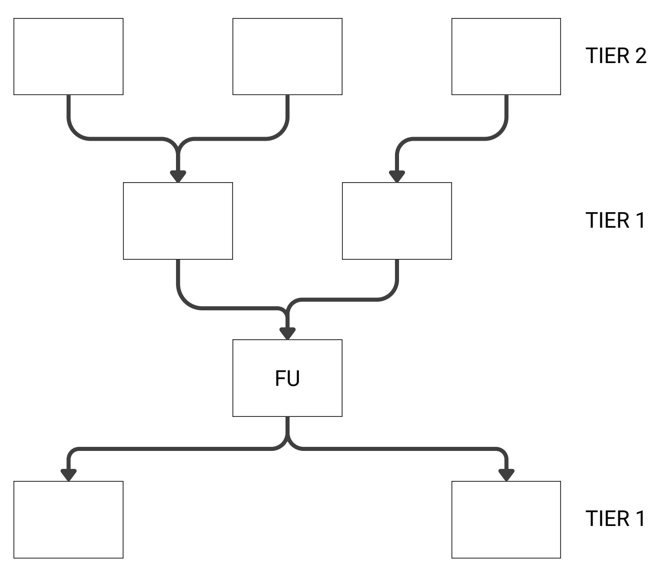
We can also organize what we calculated so far into a reference flow table

Product	Functional Unit	Reference Flows
Incandescent bulb	Providing 800 lumens of light for 10,000 hours	10 Incandescent bulbs / FU
		120 kWh electricity / FU
		4,570 kg.km/FU of transoceanic freight
		1,462.4 kg.km/FU of truck transport

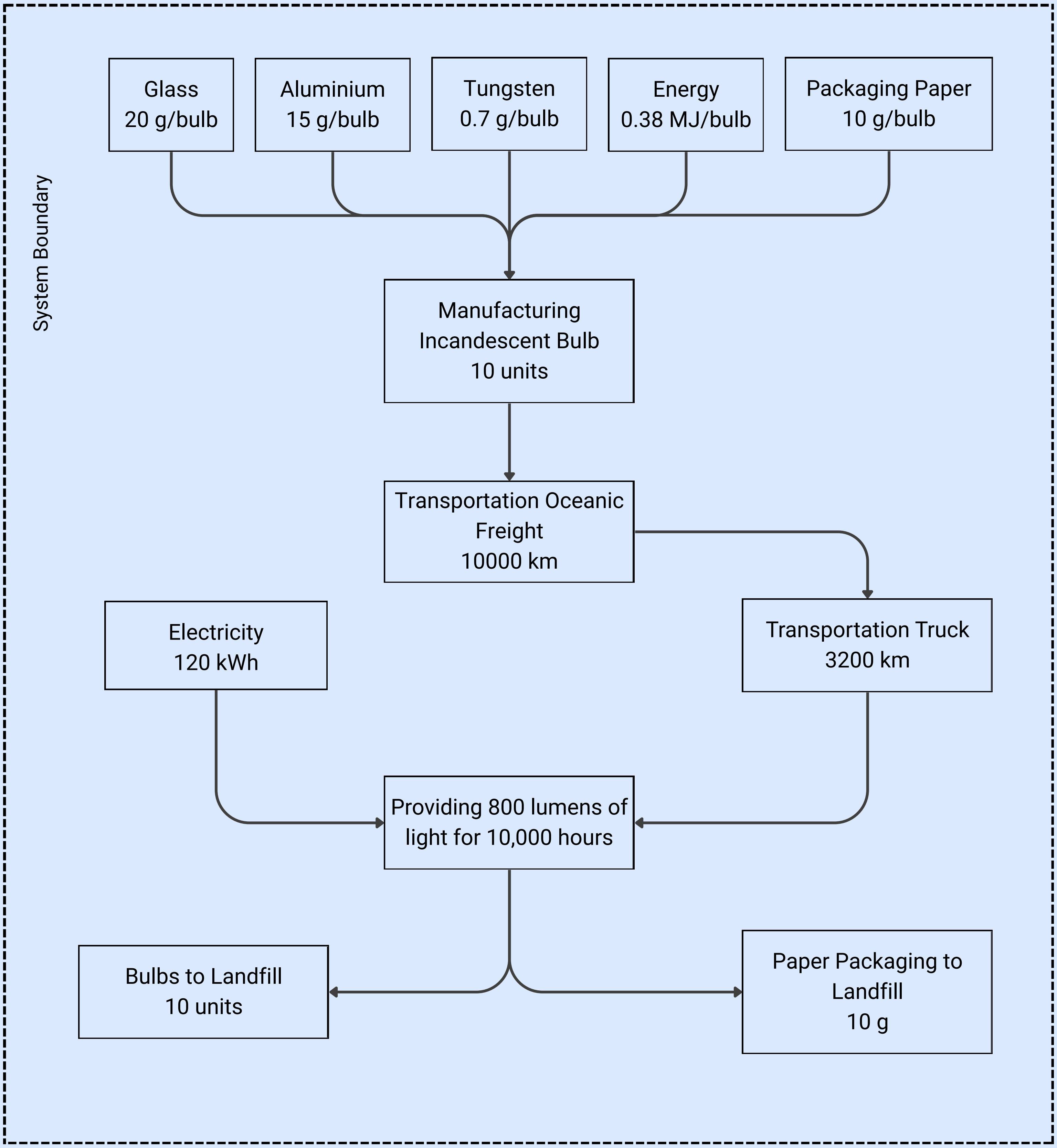
Building the process tree

Now let's see how we can build the process tree for our product system:

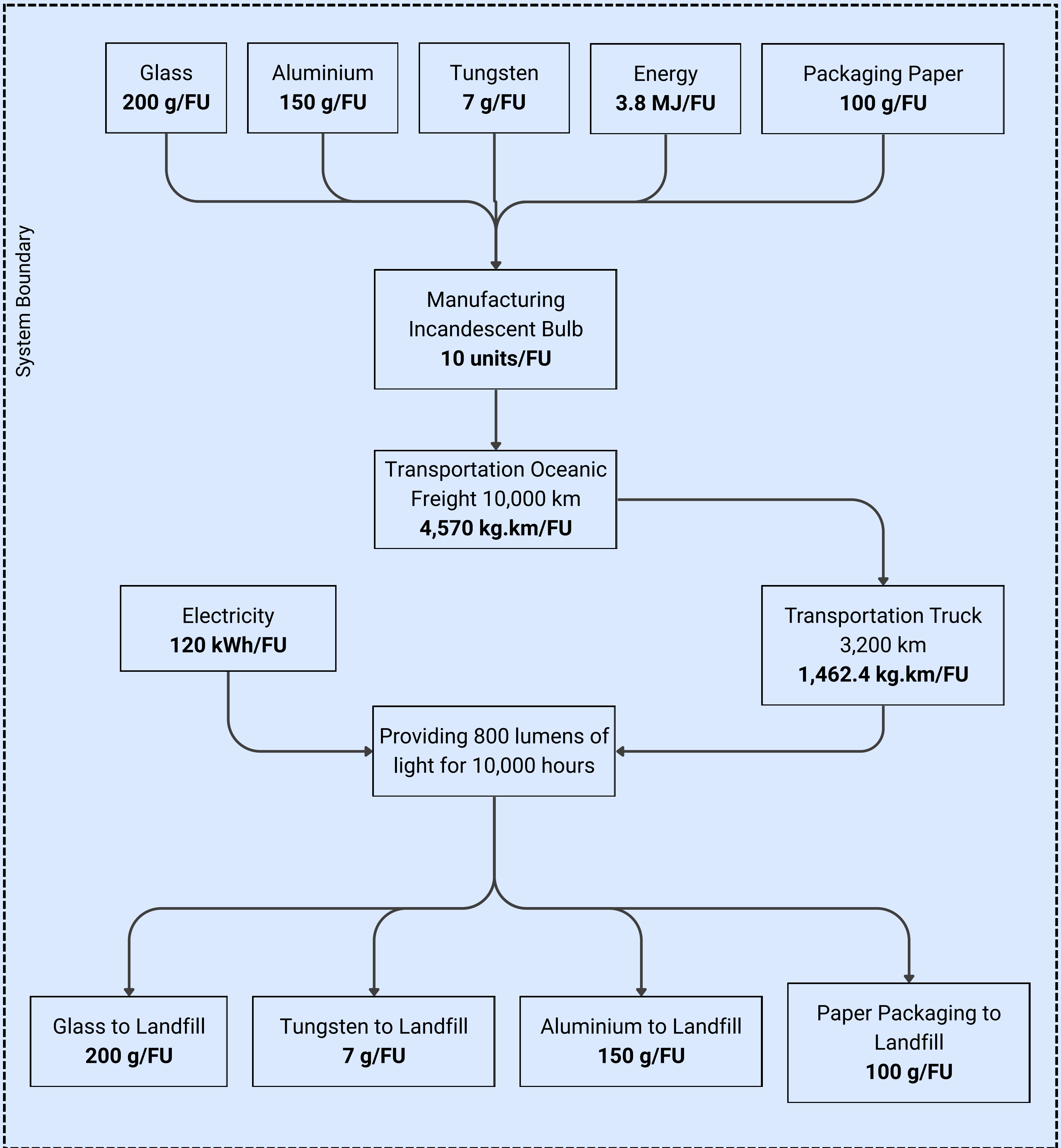
1. Start from the Functional Unit (FU).
2. Draw one box per reference flow and link it to the FU. These are also referred to as Tier 1 processes, as they contribute directly to the FU.
3. Follow the upstream and downstream intermediary flows of the Tier 1 processes to obtain the Tier 2 processes.
4. Repeat until you reach flows for which you have either primary data or data from LCA databases.
5. Adjust the process tree to reflect the flow of processes in the actual industrial context.
6. For each unit process, document the quantity needed per FU.



Following the steps on the previous page, the process tree for the incandescent bulb product system is developed as shown below.



Using the process we followed to calculate reference flows per FU, we can calculate all intermediary flows and unit processes per FU.



Allocation Procedures

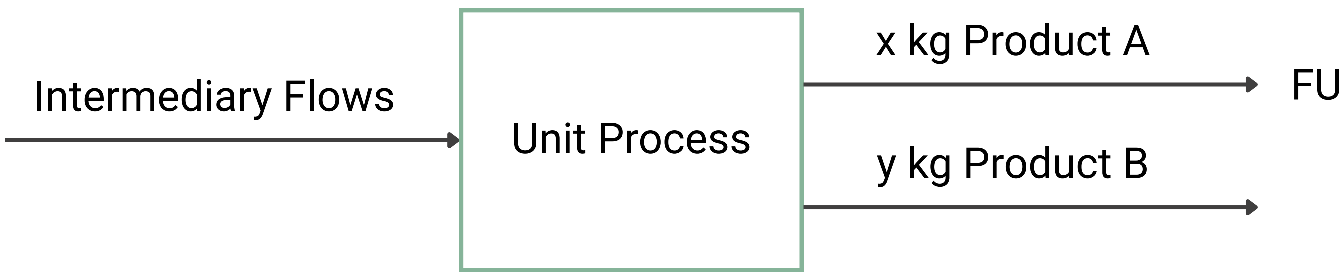
What happens when a unit process in your product system yields multiple valuable outputs? In that case, you need to consider only the portion of environmental inputs and outputs (elementary flows) that contribute specifically to your functional unit. This is handled through allocation.

Allocation is the process of dividing the environmental impacts of a single production activity that generates multiple outputs among those outputs. Imagine a chemical plant that produces both plastic pellets and a chemical by-product using the same energy and feedstocks. If you are only studying the plastic pellets, you should not assign all the environmental impacts of the plant to your product — only its proportional share.

The three most common allocation procedures are:

1. Physical allocation — Divides impacts based on physical characteristics such as mass, energy content, or volume.
2. Economic allocation — Divides impacts based on the market value or economic contribution of each co-product.
3. System expansion — Instead of splitting flows, the system boundary is expanded to include the additional outputs, avoiding the need to divide impacts at all.

For our incandescent bulb case study, allocation is not applicable because the manufacturing process yields only one product.



In the above physical allocation scenario, a fraction x/(x+y) of the environmental impacts associated with the intermediary flows should be allocated to product A, and in turn to its FU.

Data Quality, Assumptions, and Limitations

The usefulness of assessment results depends on the quality of the data used. When defining scope, it is important to specify:

- **Data quality requirements:** Will you use primary data (measured directly) or secondary data (from databases and literature)? What is the required level of precision?
- **Assumptions:** Any process excluded from scope based on the assumption that its impact is negligible should be clearly documented. For example: "Capital goods such as manufacturing equipment are excluded, as their contribution per FU is assumed to be negligible."
- **Limitations:** Constraints on the study, such as cut-off rules for small components or data gaps, should be stated clearly so that results are interpreted in context.

Once the study is complete, **a critical review (or peer review)** verifies that interpretations are consistent with the identified limitations and goals. It is good practice to involve reviewers from the beginning, incorporating their feedback as the work progresses.

It is also helpful to state how the results of the study will be used, as well as the methods of **reporting and publishing**. This ensures that all necessary requirements for reporting are addressed within the study.

Choosing an LCIA Methodology

While defining the scope, it is essential to determine which Life Cycle Impact Assessment (LCIA) methodology will be applied. Choosing it early ensures the correct system boundary is established and the right elementary flows are collected during the inventory phase. It also prevents costly rework later.

To ensure the LCA is fit for purpose, the methodology should be consistent, transparent, regionally relevant, and credible. Some of the commonly used LCIA methodologies are:

Methodology	Origin / Developer	Approach	Impact Categories	Notes / Use Cases
ReCiPe (2008/2016)	NL (RIVM, PRé, Radboud Univ.)	Midpoint + Endpoint	18 midpoints (climate, toxicity, land, water, resources) + 3 endpoints (health, ecosystems, resources)	Widely used; flexible; successor of CML & Eco-indicator.
IPCC 2013 (GWP)	Intergovernmental Panel on Climate Change	Single-issue (Midpoint)	Climate change (GWP 20, 100, 500 yrs)	Standard for GHG/climate-only studies.
ILCD 2011	EU Commission (JRC)	Midpoint	Climate, ozone, toxicity, particulate matter, acidification, eutrophication, land, water, resources	EU-recommended; basis for EF.
Impact World+	International consortium	Midpoint + Endpoint	11 Regionalized midpoint categories (19 total) + 3 endpoint damages	Strong in regionalized/global assessments.
Cumulative Energy Demand (CED)	ETH Zurich / Ecoinvent	Single-issue (Midpoint)	Renewable & non-renewable energy demand	Used for energy footprinting.
Environmental Footprint (EF)	EU Commission (DG Environment)	Midpoint	16 categories: climate, land, water, biodiversity, resources, etc.	Official EU method for PEF/OEF.
TRACI	US EPA	Midpoint	Climate, ozone, acidification, eutrophication, smog, toxicity, resources, land, water	US standard; used in EPDs and US-focused LCAs.

(For a full description of ReCiPe impact categories and midpoint-to-endpoint factors, see Chapter 7)

Case study: Incandescent Bulb LCA - Goal and Scope

GOAL

The goal of this LCA is to evaluate the environmental impacts associated with the production, use, and end-of-life treatment of an incandescent light bulb. The study identifies the most significant life cycle stages contributing to environmental burdens. It also provides insights to inform design improvements, material choices, and policy discussions about lighting technologies.

The intended application is educational and comparative, demonstrating the life cycle impacts of incandescent bulbs as a basis for comparison with alternative lighting technologies (e.g., LEDs, CFLs). The target audience includes product designers, sustainability practitioners, and academic researchers.

SCOPE

- **Product system:** The incandescent bulb product system (see process tree)
- **Function:** Providing illumination
- **Functional unit:** Providing 800 lumens of light for 10,000 hours
- **System boundary:** Cradle-to-grave — this includes raw material extraction, manufacturing, transoceanic and local transport, the use phase, and end-of-life (landfill). Note: because incandescent bulbs sent to landfill generate no significant CO_2 emissions during disposal, the end-of-life contribution to the Global Warming midpoint category is negligible and is noted as such in the results (see Chapter 8).
- **Allocation procedures:** Not applicable — no multifunctionality in the system
- **Assumptions:** Environmental impacts of capital goods (manufacturing equipment and plant infrastructure) are excluded, as their contribution per FU is expected to be negligible.
- **Limitations:** Small components such as adhesives, coatings, and ancillary materials are excluded under cut-off rules (generally < 1–5% of mass, energy, or economic value), which may omit certain toxicity or resource impacts.
- **LCIA methodology:** ReCiPe midpoint methodology, assessing the Global Warming impact category.

Imagine you're standing at the foot of a tall mountain, ready to climb — that's where our LCA journey begins. The goal is the flag at the summit, symbolizing what you want to achieve and why you're doing the study. The scope is everything between here and there: the trail you pick, the gear you pack, the approach you take. Some people ride the cable car; others hike steadily; some climb the rock face, questioning all their life choices. Each route leads to the same goal, but the learnings, the views, the challenges — these are unique to the chosen path.

6 LIFE CYCLE INVENTORY

Once the goal and scope are defined, we move to the **Life Cycle Inventory (LCI)** — the second phase of an LCA. In this phase, we create a detailed inventory of all the flows of matter, energy, and pollutants that cross our system boundary between the product system and the natural environment.

The two steps involved in LCI are:

1. Quantify the direct elementary flows of unit processes and intermediary flows.
2. Calculate the aggregated inventory flows.

Elementary flows can be thought of as emission or extraction factors. They describe what enters the system from nature, and what leaves it as pollution or waste. Data for most intermediary flows and unit processes are found in databases or in literature. Where this data does not exist, primary data must be collected through supplier questionnaires or direct measurement.

Unit-Level vs. Aggregated Data

LCA databases such as Ecoinvent provide elementary flow data in two forms:

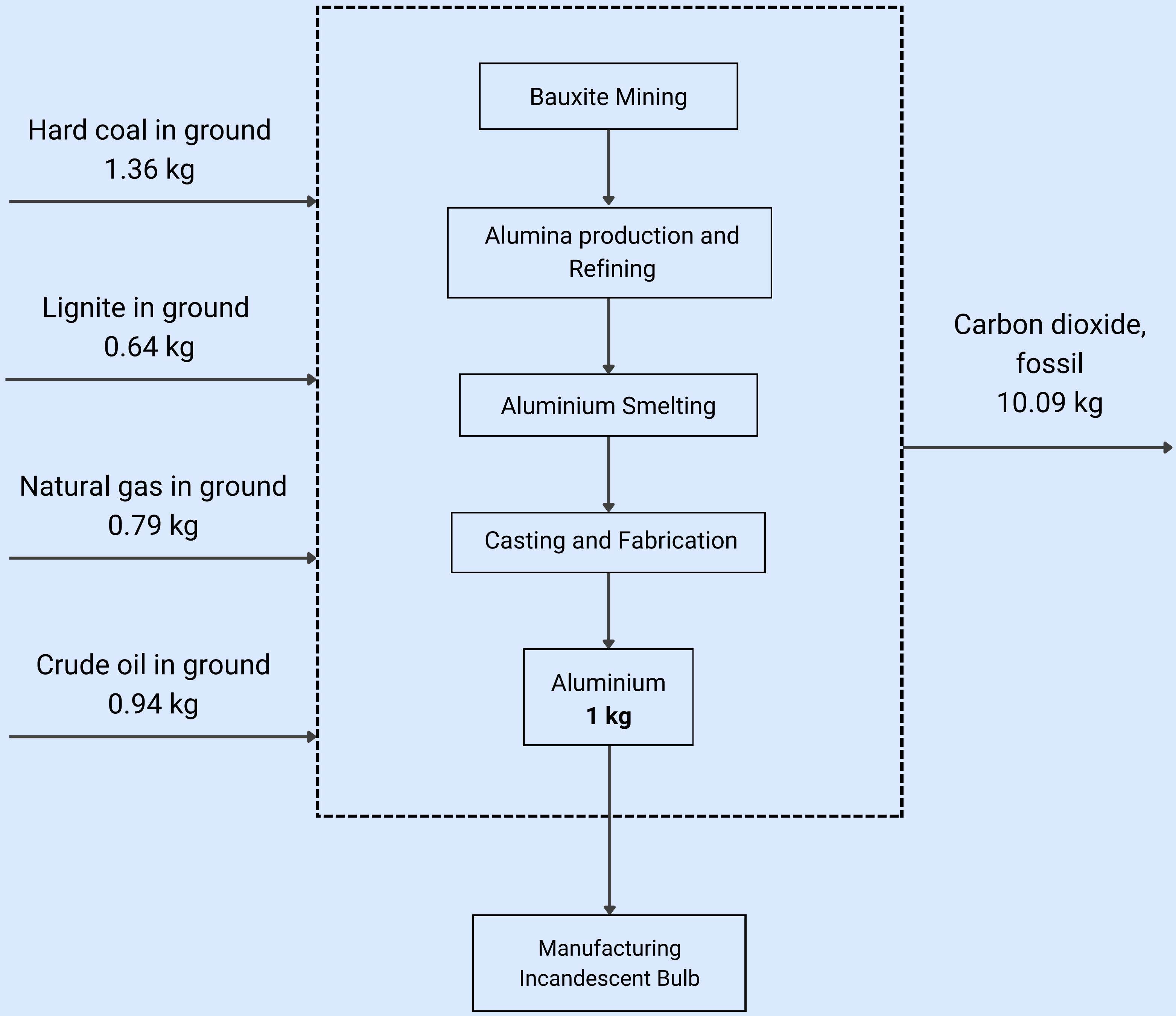
1. Direct elementary flows at the unit process level — data for a single step in the production chain (e.g., only the smelting of aluminium).

2. Aggregated cradle-to-gate elementary flows at the product system level — data covering the entire upstream chain (e.g., all steps from bauxite mining through to finished aluminium).

Using aggregated system-level data simplifies calculations considerably and is recommended whenever such data is available.

Case study: Incandescent bulb LCA - LCI
Lets take a look at the product system of Aluminium, which is used in the manufacturing of the incandescent bulb :

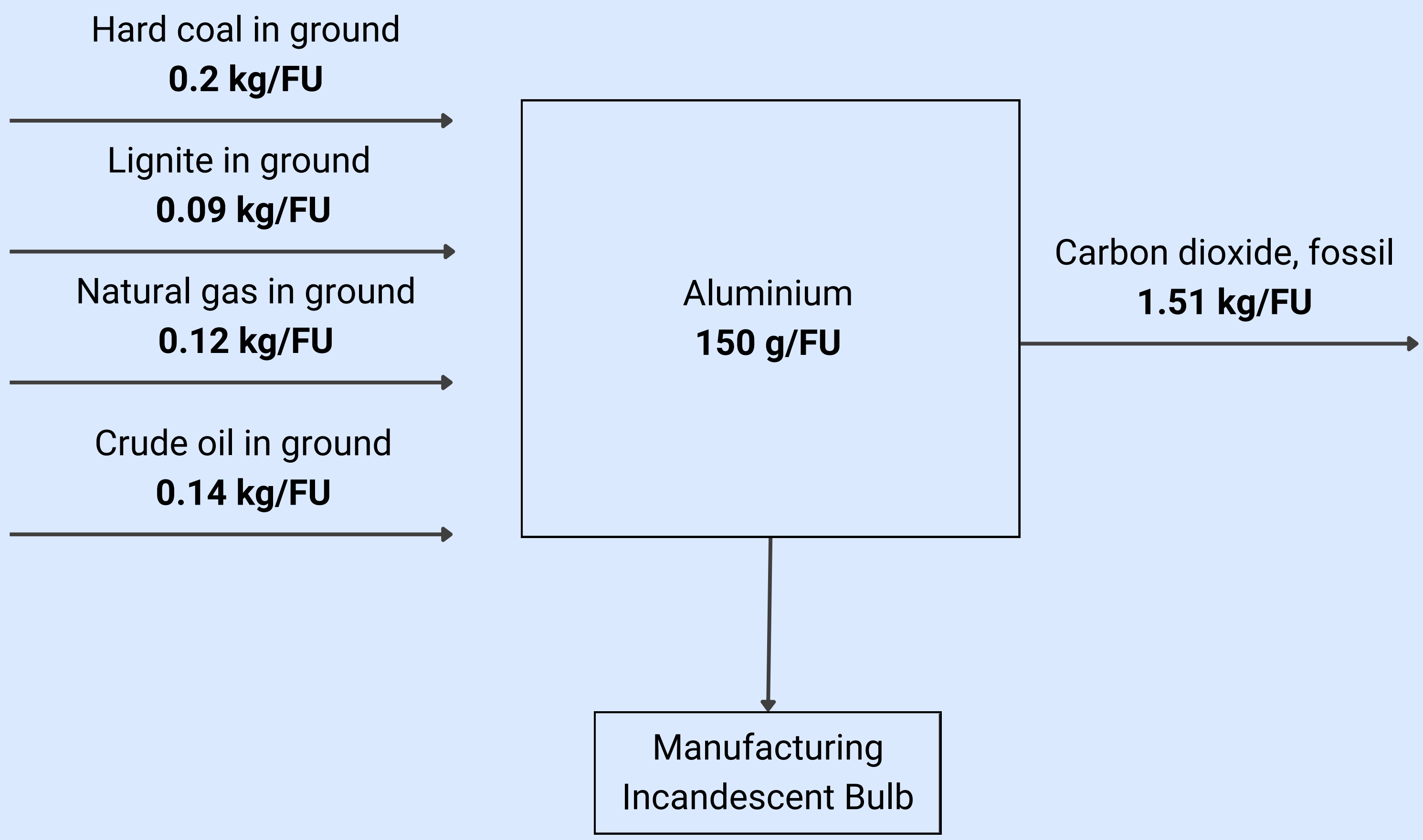
The production of 1 kg of primary aluminium involves bauxite mining, alumina refining, smelting, and casting. Because aluminium is extensively studied, aggregated cradle-to-gate data is available in Ecoinvent:



From our product system, we require 150 g of aluminium per FU. Converting to per-FU values:

$$10.09 \text{ kg CO2/kg Al} * 0.15\text{kg Al/FU} = 1.51 \text{ kg CO2/FU}$$

The final aggregated elementary flows of aluminium are:

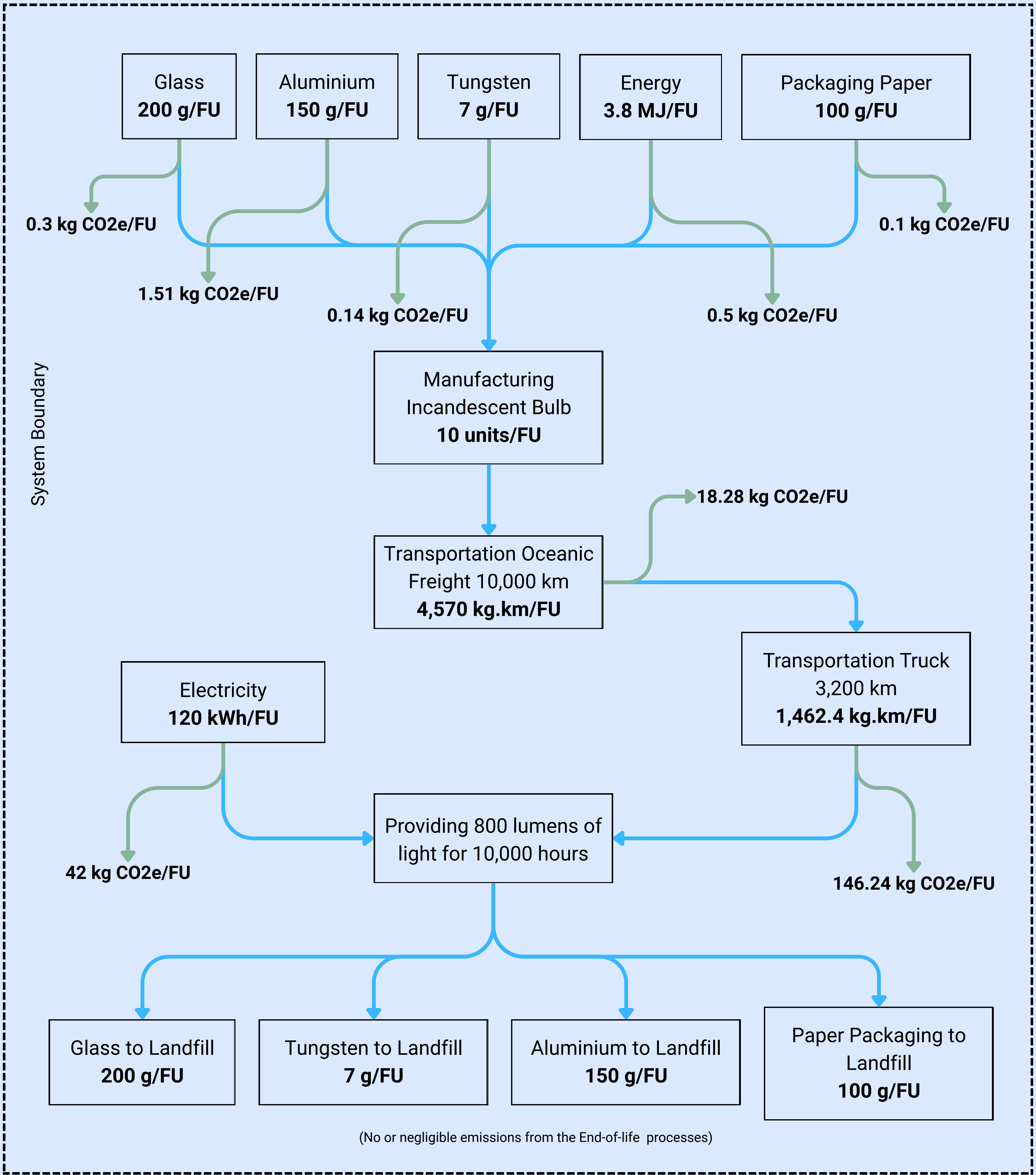


The same conversion is repeated for every unit process and intermediary flow in the product system. Once complete, we have the full inventory ready for impact assessment.

Scope Note — Cradle-to-Gate vs. Cradle-to-Grave

This guide's incandescent bulb example is a cradle-to-grave study — it includes the use phase (electricity consumption) and end-of-life (landfill). However, data on CO2 emissions from the landfill disposal of glass, aluminium, tungsten, and paper packaging are treated as negligible for the Global Warming midpoint category, as inert material disposal to landfill does not generate significant greenhouse gas emissions. This assumption is stated explicitly as a limitation (see Goal and Scope).

The elementary flows (CO2e emissions in this case) associated with each unit process and flow have been calculated using freely available emission factors, adjusted to our system boundary:



7 LIFE CYCLE IMPACT ASSESSMENT

Life Cycle Impact Assessment (LCIA) is the third phase of an LCA, where the inventory results are translated into potential environmental impacts. The hundreds of elementary flows quantified during the LCI, emissions, resource extractions, land and water use, are on their own difficult to interpret. LCIA addresses this by classifying these flows into impact categories, such as global warming or acidification, and converting them into common units using characterization factors.

Midpoint vs. Endpoint Damages
LCIA results can be calculated at two levels, midpoint and endpoint.

Aspect	Midpoint Damages	Endpoint Damages
Definition	Represents environmental problems at an intermediate stage of the cause-effect chain	Represents the final damage or effect on areas of protection (human health, ecosystems, resources)
Focus	Specific impact mechanisms (e.g., climate change, acidification, eutrophication)	Who or what is affected by the impacts
Units	Mechanism-specific (e.g., kg CO2e, kg SO2-eq)	Aggregated units (e.g., Disability Adjusted Life Years (DALY), species.yr, USD)
Scientific robustness	More robust, less uncertain	More policy-relevant, but more uncertain

Steps in LCIA

Step 1 - Classification: Emissions and resource extractions from the LCI are assigned to the midpoint impact categories they affect. One substance may contribute to several categories. For example, methane (CH_4) contributes to both Global Warming and Photochemical Ozone Creation.

Step 2 - Midpoint Characterization: Emissions and extractions are converted into a common unit for each impact category using Characterization Factors (CF) which are values derived from natural science.

For example, the main greenhouse gases contributing to climate change are CO_2, CH_4, and N_2O. In most LCIA methodologies, the reference unit for the Climate Change midpoint category is kg CO_2-equivalent (kg CO_2e). To express CH_4 and N_2O in this unit, characterization factors are applied.

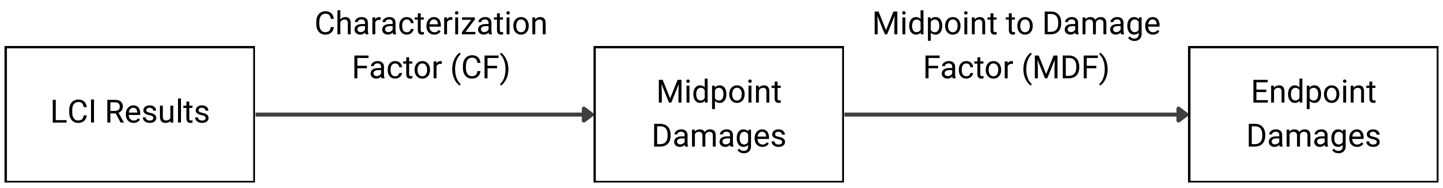
According to ReCiPe (100-year horizon), the characterizetion factors associated with gloabal warming potential are:

- CO_2 = 1
- CH_4 = 34
- N_2O = 298

So, 1 kg of CH_4 emitted is treated as equivalent to 34 kg of CO_2 in terms of its global warming effect. Midpoint characterization does not tell you the relative importance of each impact category but only its potential impact in its own reference unit. To compare across categories, endpoint characterization is needed.

Step 3 - Endpoint characterization: Endpoint characterization converts midpoint impacts into damage on the three main Areas of Protection (AoP):

- Human Health — expressed as DALY (Disability-Adjusted Life Year): the loss of one year of healthy life due to disease or premature death. One DALY = one year of healthy life lost.
- Ecosystems — expressed as species·year: the loss of a species from an ecosystem over a given period of time.
- Resource Availability — expressed as USD or MJ: the additional economic or energy cost of future resource extraction due to depletion.

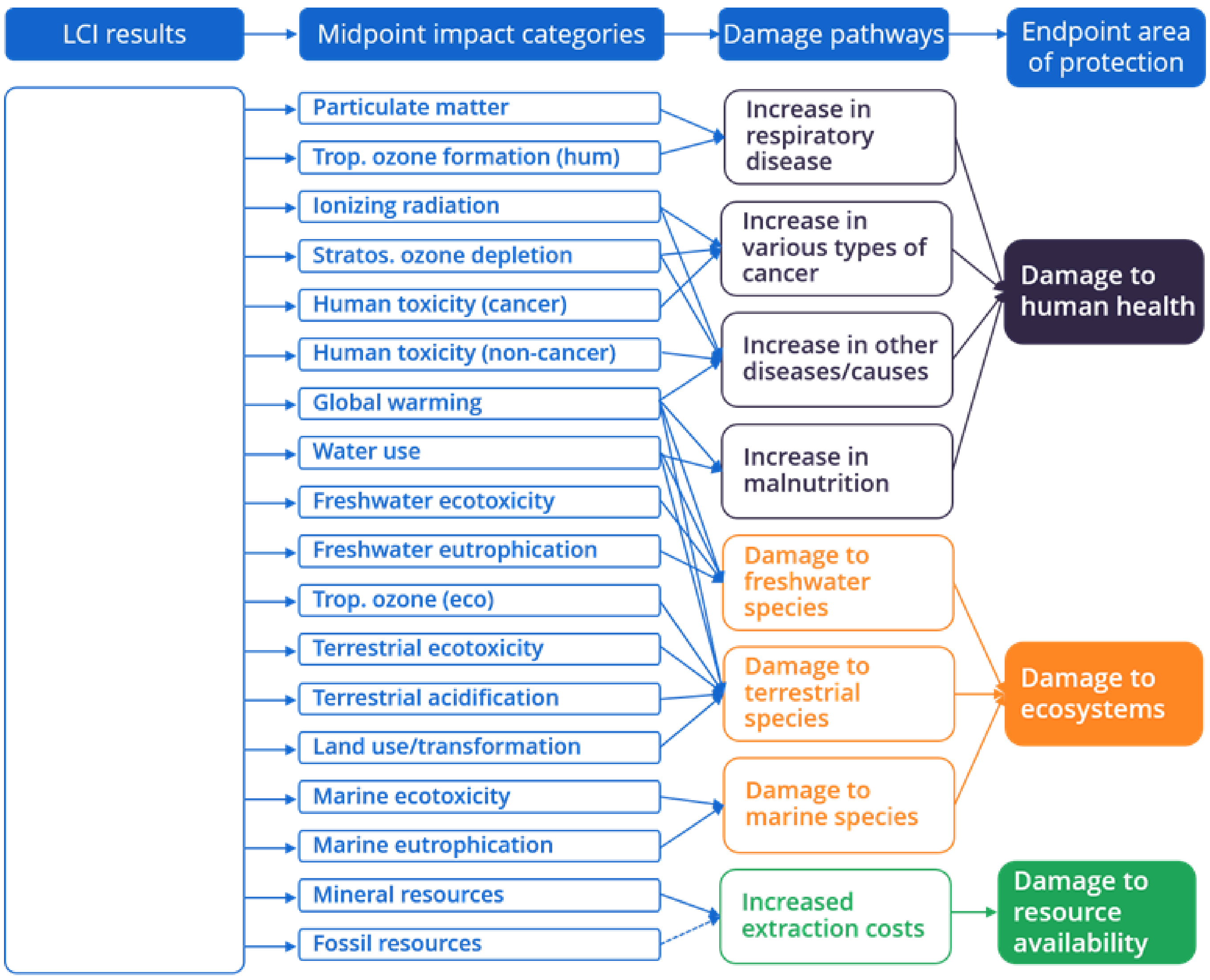


The conversion uses a **Midpoint to Damage Factor (MDF)**, also called the Endpoint Characterization Factor (ECF). The formula is:

$$\text{Endpoint damage score (d)} = \Sigma\ \text{MDF(m,d)} \times \text{Midpoint score (m)}$$

In plain language: for each midpoint impact category (m), multiply its score by the relevant damage factor (MDF) to get its contribution to a given endpoint area (d). Sum across all midpoint categories that affect that area.

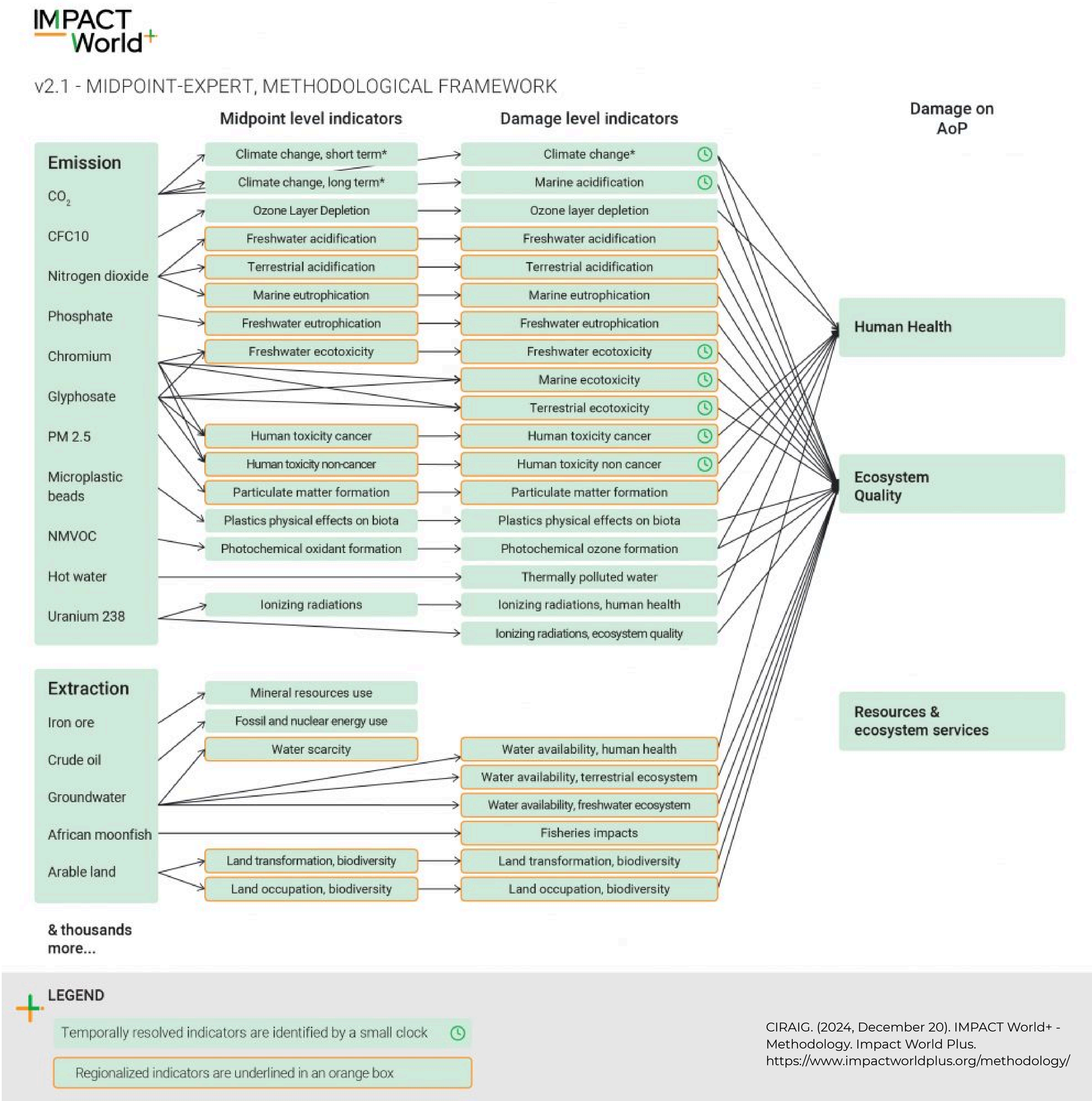
The framework diagram shown below illustrates how the midpoint impact categories are linked to endpoint areas of protection in the ReCiPe LCIA methodology.



Framework of the ReCiPe model

ReCiPe - PRÉ Sustainability. (2025, June 2). PRé Sustainability. https://pre-sustainability.com/articles/recipe/

The pathways linking midpoint categories to endpoint AoPs, as well as the MDFs, vary across LCIA methodologies. Impact World+ is another such LCIA methodology, providing regionalized midpoint categories and endpoint AoPs.



Framework of the Impact World+ Model

ReCiPe Midpoint-to-Endpoint Factors

Endpoint Area	Midpoint Impact Category	Unit	Conversion Factor
Human health	Global warming	Disability-adjusted life years (DALY)/kg CO_2 eq.	1.25×10^{-5}
	Stratospheric ozone depletion	DALY/kg CFC11 eq.	1.34×10^{-3}
	Ionizing radiation	DALY/kBq Co-60 emitted to air eq.	1.40×10^{-6}
	Fine particulate matter formation	DALY/kg $PM_{2.5}$ eq.	6.29×10^{-4}
	Photochemical ozone formation	DALY/kg NO_x eq.	9.10×10^{-7}
	Toxicity (cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	3.32×10^{-6}
	Toxicity (non-cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	2.28×10^{-7}
	Water consumption	DALY/m^3 consumed	2.22×10^{-6}
Terrestrial ecosystems	Global warming	Species·year/kg CO_2 eq.	2.50×10^{-8}
	Photochemical ozone formation	Species·year/kg NO_x eq.	1.29×10^{-7}
	Acidification	Species·year/kg SO_2 eq.	2.12×10^{-7}
	Toxicity	Species·year/kg 1,4-DCB emitted to industrial soil eq.	1.14×10^{-11}
	Water consumption	Species·year/m^3 consumed	1.35×10^{-8}
	Land use	Species/(m^2·annual crop eq.)	8.88×10^{-9}
Freshwater ecosystems	Global warming	Species·year/kg CO_2 eq.	6.82×10^{-13}
	Eutrophication	Species·year/kg P to freshwater eq.	6.71×10^{-7}
	Toxicity	Species·year/kg 1,4-DCB emitted to freshwater eq.	6.95×10^{-10}
	Water consumption	Species·year/m^3 consumed	6.04×10^{-13}
Marine ecosystems	Toxicity	Species·year/kg 1,4-DCB emitted to sea water eq.	1.05×10^{-10}
	Eutrophication	Species·year/kg N to marine water eq.	1.70×10^{-9}
Resources	Mineral resource scarcity	USD/kg Cu	0.23
	Fossil resource scarcity – Crude oil	USD/kg	0.46
	Fossil resource scarcity – Hard coal	USD/kg	0.03
	Fossil resource scarcity – Natural gas	USD/Nm^3	0.3
	Fossil resource scarcity – Brown coal	USD/kg	0.03
	Fossil resource scarcity – Peat	USD/kg	0.03

Li, Chengzhou & Wang, Ningling & Zhang, Hongyuan & Liu, Qingxin & Chai, Youguo & Shen, Xiaohu & Yang, Zhiping & Yang, Yongping. (2019). Environmental Impact Evaluation of Distributed Renewable Energy System Based on Life Cycle Assessment and Fuzzy Rough Sets. Energies. 12. 4214. 10.3390/en12214214.

Case study: Incandescent bulb LCA - LCIA
The total global warming midpoint impact of the incandescent bulb product system is calculated as the sum of the global warming impacts of unit processes and intermediary flows (see page 28).

Total damage on the global warming midpoint impact =
(0.3 + 1.51 + 0.14 + 0.5 + 0.1 + 18.28 + 146.24 + 42) kg CO2e/FU =
209.07 kgCO2e/FU

Endpoint damage scores (Note: outside the defined scope of this study):

The global warming midpoint score for the incandescent bulb is 209 kg CO_2e/FU. Using the ReCiPe MDF for human health, Damage on Human Health as a result of CO2e emissions = 209 kg CO_2e × 1.25 × 10^{-5} DALY/kg CO_2e = **2.61 × 10^{-3} DALY/FU**

This means providing 800 lumens of light for 10,000 hours, using incandescent technology, the health issues associated with the CO2e emissions causes approximately 0.003 years of healthy life to be lost.

Endpoint AoP	Midpoint Impact Category	MDF	Midpoint Score	Endpoint Damage Score
Human Health	Global Warming	1.25 × 10^{-5} DALY/kgCO2e	209 kgCO2e/FU	2.61E-03 DALY/FU
Terrestrial Ecosystem	Global Warming	2.50 × 10^{-8} Species·year/kg CO2e	209 kgCO2e/FU	5.22E-06 Species.year/FU
Freshwater Ecosystem	Global Warming	6.82 × 10^{-13} Species·year/kg CO2e	209 kgCO2e/FU	1.43E-10 Species.year/FU
Resources	Global Warming	-	209 kgCO2e/FU	-

Damage on Human Health = **2.61E-03 DALY/FU**
Damage on Ecosystem Quality (Terrestrial + Freshwater) = **5.22E-06 Species.year/FU**

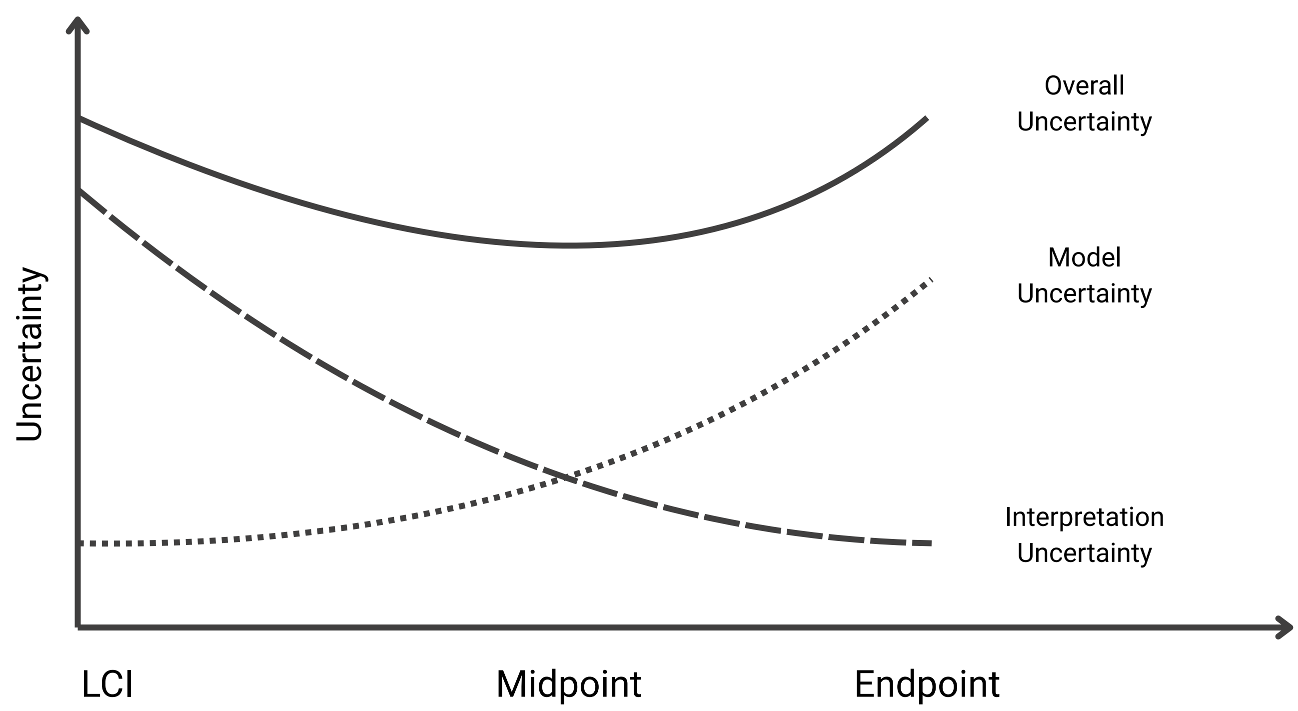
Uncertainty in LCA

As an LCA progresses through its stages, two types of uncertainty interact:

- **Interpretation-related uncertainty** arises from incomplete knowledge about how to draw conclusions from the data. It tends to decrease as more data is collected and the product system becomes better understood.

- **Model uncertainty** arises from the assumptions embedded in the LCIA methodology itself, for example, the spatial or temporal validity of characterization factors, or the assumed time horizon (20 years vs. 100 years for GWP). It tends to increase at the endpoint level, because more modeling steps and assumptions are involved.

For this reason, many LCA experts prefer to focus primarily on midpoint damages, where overall uncertainty is minimized. Endpoint results are valuable for communication and policy relevance, but should always be presented alongside their uncertainty context.



Uncertainty in LCA

Normalization and Weighting (Optional Steps)

Normalization places endpoint damages in context by comparing them to the average annual environmental impact of one person globally. The endpoint damages are divided by normalization factors to express results in units of person·year/FU.

Normalization factors (Impact World+ methodology):

Endpoint AoPs	Normalization factor	Units
Human Health	0.0216 or 1.86	DALY/pers.year or DALY/pers.lifetime
Ecosystem Quality	8,500	PDF.m2.year/pers.year
Resources	63100 or 313	MJ/pers.year or $/pers.year

*(PDF stands for **Potentially Disappeared Fraction** — it quantifies the fraction of species potentially lost in an area over time due to a given environmental pressure.)*

Note: Normalization factors and methods differ across LCIA methodologies. In ReCiPe, normalization factors are applied at the midpoint level rather than the endpoint level.

Weighting goes one step further: it assigns relative importance to each AoP based on social, political, or ethical values (e.g., how much society values one DALY vs. one species·year).

Weighted damage on human health ($/FU) = Endpoint damage on human health (DALY/FU) * Value attributed to Human Health ($/DALY)

This converts diverse impact scores into a single aggregated value in $/FU. Because weighting factors are not scientifically derived — they emerge from expert panels or stakeholder surveys — this step is not covered by ISO standards and should be used with care.

8 INTERPRETATION

Interpretation is the final phase of an LCA. It brings together the results from the Goal and Scope Definition, Life Cycle Inventory, and Life Cycle Impact Assessment phases, and translates them into meaningful, reliable conclusions.

The aim of this phase of assessment is to:

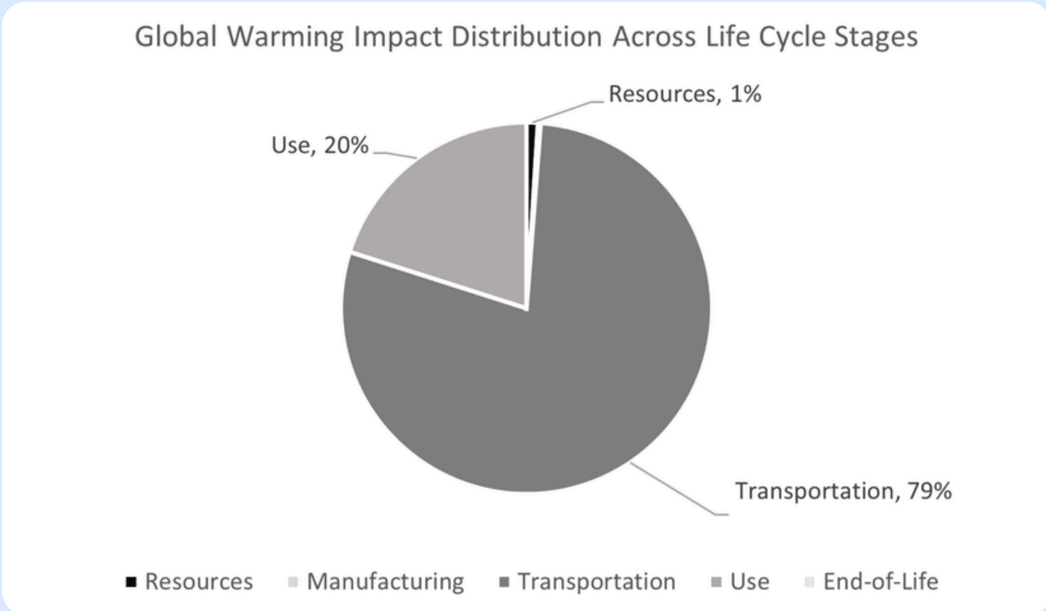
- Evaluate results, draw conclusions, and explain limitations of the study based on the results from previous stages.
- Identify critical areas in the life cycle of products
- Assess the quality and robustness of results based on a series of checks such as quality control, sensitivity analysis, and uncertainty analysis.

Some of the main questions this phase should answer are:

- What are the largest contributions to the environmental impacts in terms of production phase, in terms of pollutants?
- Where is the greatest potential to reduce impact?
- Why are some results surprising?
- If you are comparing different scenarios in your study, is the difference between them significant?

Interpretation in LCA is like pausing during a mountain hike. At every turn, the view changes — sometimes you see the whole valley, sometimes only the path ahead. After each phase of the study, taking a moment to reflect reveals new insights. These pauses ensure the journey leads to meaningful conclusions, rather than getting lost in the details.

Case study: Incandescent bulb LCA - Interpretation



Based on the Global Warming impact distribution across life cycle stages (see pie chart), the following conclusions can be drawn:

- **Transportation (79%):** Transportation is the dominant contributor to global warming impact. The main driver is the truck transport leg within the EU (3,200 km, contributing 146.24 kg CO_2e/FU). Ocean freight, despite covering a far greater distance (10,000 km), contributes significantly less per kg·km because ocean vessels are much more carbon-efficient than road trucks. Mitigation options include near-shoring production and transitioning to low-emission fuels for both transport modes.

- **Use Phase (20%):** Electricity consumption during the 10,000 operating hours is the second-largest contributor. This reflects the carbon intensity of the EU electricity grid. As the grid transitions to renewables, this impact will decrease — which illustrates why the energy source assumed in the LCA matters greatly and should be clearly stated.

- **Resources (1%):** Extraction of raw materials (glass, aluminium, tungsten) contributes approximately 1% of global warming impact. While small from a climate perspective, materials such as tungsten may carry significant impacts in other categories (e.g., resource scarcity, toxicity) that are outside the scope of this single-category study.

- End-of-Life (~0%) The disposal of incandescent bulb components (glass, metals, paper packaging) to landfill generates negligible greenhouse gas emissions for this impact category. This is why no end-of-life contribution appears in the chart. Note that a cradle-to-grave scope does not mean all life cycle stages will show measurable impact in every category — only that they are within scope and have been assessed.

Further Analysis

Sensitivity Analysis: Sensitivity analysis tests how results change when individual assumptions are varied:

- How do results change with different electricity grid mixes (e.g., 100% renewable vs. current EU average)?
- How sensitive is the total impact to the power rating of the bulb?
- What effect does luminous efficacy have on the number of bulbs required per FU, and therefore on manufacturing impact?

Scenario Analysis: Scenario analysis examines the effect of systemic choices on the outcome:

- What if the bulbs were manufactured in Germany rather than China? (Shorter truck and ocean distances; potentially different manufacturing energy mix.)
- What if incineration was assumed instead of landfill?

Uncertainty Analysis: Uncertainty analysis quantifies how confident we are in the results:

- How reliable is the inventory data collected? Are emission factors from secondary sources representative of actual operations?
- What uncertainties arise from spatial variability (e.g., regional electricity grids)?
- What uncertainties arise from temporal variability (e.g., grid emission factors changing over time)?

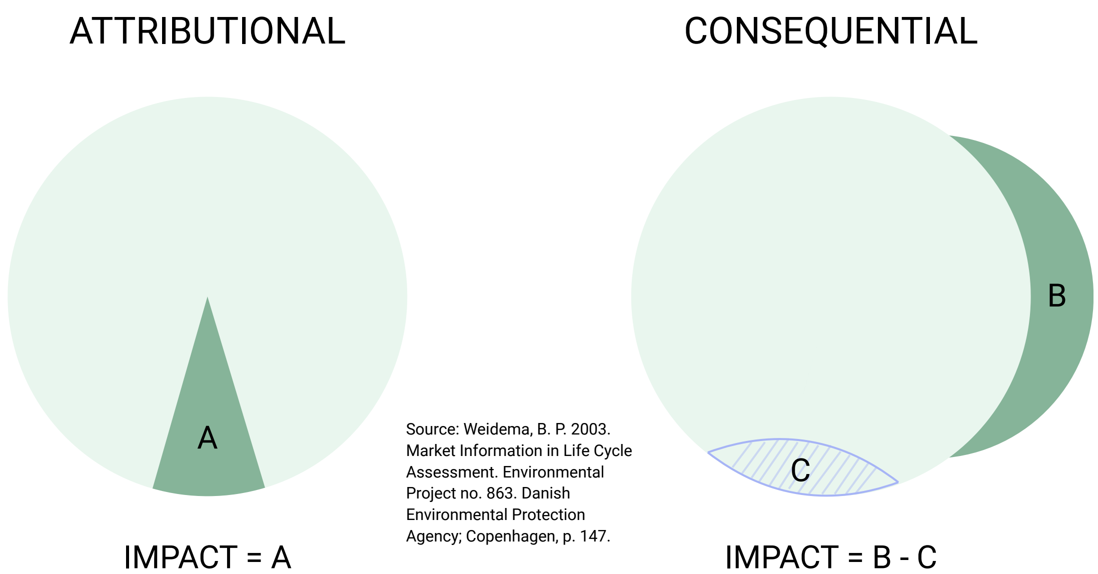
Example of uncertainty in this study: The truck transport emission factor used here is a European average. If the actual distribution network uses newer, lower-emission vehicles, the transport impact could be 20–30% lower — which would shift the overall result meaningfully.

9 DIFFERENT TYPES OF LCA

Attributional vs. Consequential LCA

- **Attributional LCA (ALCA)** Describes the environmental burdens directly associated with producing and using a product or service. It focuses on "what is" — the current system. It is often used for Environmental Product Declarations (EPDs), labeling, and compliance.

- **Consequential LCA (CLCA)** Assesses how environmental impacts change as a consequence of decisions or changes in demand. It focuses on "what if" scenarios. It is most useful for policy-making, market change studies, and long-term strategies.



What part of the global environmental burdens should be assigned to the product?

What is the change in global environmental burdens as a result of a change in the use or production of a product?

Comparative vs. Stand-alone LCA

- Comparative LCA: Compares two or more products, services, or systems performing the same function (e.g., plastic vs. paper bags).
- Stand-alone LCA: Focuses on a single product or system to identify hotspots or improvement potentials.

The incandescent bulb LCA we discussed is a stand-alone, attributional LCA.

In comparative LCAs, processes that are identical across the compared systems can often be excluded from scope — simplifying the assessment and focusing attention on the differences that actually matter. For early-stage products, this is particularly valuable:

For early-stage products and technologies, comparative LCAs are particularly useful.

- They help to identify the best option early in the design phase of the product by comparing which alternative has a lower environmental impact.
- By excluding processes that are similar across scenarios, it reduces the need for exhaustive data collection. This is especially helpful because inventory data is often scarce in the case of early-stage products.
- By comparing your product to your competitors, you can identify and prioritize design improvements, and depending on the results, position your product as the better choice.
- Comparative LCAs also make communication of results to stakeholders effective, as they are mostly interested in knowing which is the better product, rather than the absolute impact.

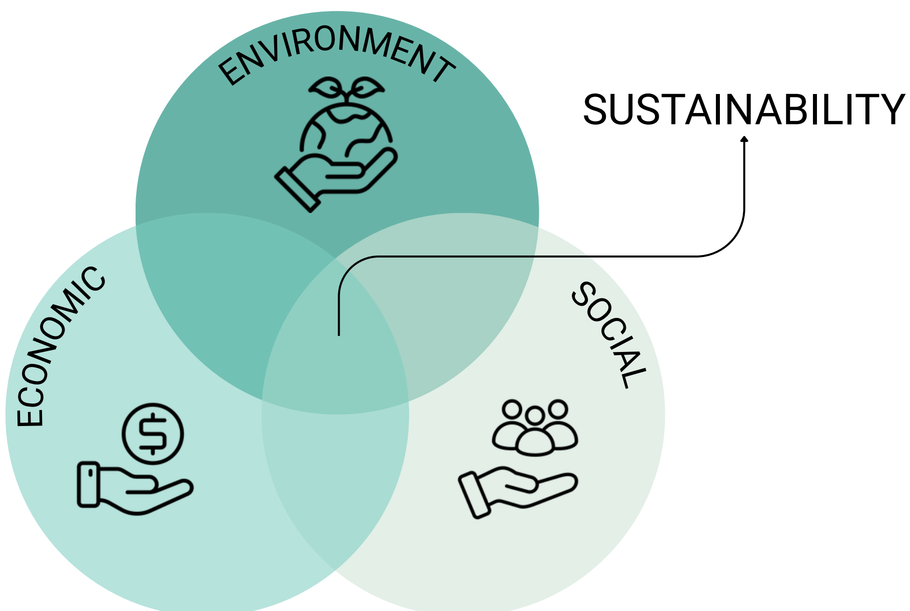
Social LCA (S-LCA)
S-LCA evaluates the social and sociological impacts of products across their life cycle. Indicators such as labor conditions, human rights, community well-being, stakeholder involvement, and similar social topics fall within the scope of S-LCA.

Like environmental LCA, it follows Goal & Scope, Inventory, Impact Assessment, and Interpretation steps, but with different data types (e.g., worker hours, wages, safety incidents).

Life Cycle Costing (LCC)
Life Cycle Costing complements environmental LCA by analyzing the economic dimension of the product system. In LCC, all costs borne by the product during its entire life cycle are summed up. Costs such as material, energy, operation, maintenance, and end-of-life fall within the scope of this assessment.

LCC is designed to support decision-making where trade-offs between environmental performance and financial feasibility must be considered.

Together, Environmental LCA, Social LCA, and Life Cycle Costing form the **Life Cycle Sustainability Assessment (LCSA)** — a holistic framework that addresses environmental, social, and economic sustainability in an integrated way.



10 LCA SOFTWARE PLATFORMS

As a product progresses through its TRLs, design choices stabilize and the volume of data grows. At a certain point, it becomes necessary to expand the assessment scope to cover more processes, components, and impact categories. At this stage, it is recommended to transition from manually calculated screening LCAs to a dedicated LCA software platform — enabling more accurate, comprehensive, and reproducible analyses.

At advanced development stages, products may require environmental certifications or an Environmental Product Declaration (EPD). LCA software platforms can streamline these activities.

Open-source options (recommended for startups and early-stage companies):

- OpenLCA — A widely used open-source platform. Cost-effective and flexible; compatible with major LCA databases including Ecoinvent.
- Brightway — An open-source Python package. Well-suited for teams with coding capability; enables automation, scripting, and integration with multiple LCA databases.

Commercial platforms:

- SimaPro — Industry standard; widely used for EPD generation and third-party verified LCAs.
- Sphera (formerly GaBi) — Common in industrial and manufacturing contexts.
- Ecochain — Cloud-based; designed for sustainability teams without deep LCA expertise.
- One Click LCA — Widely used in the built environment sector; streamlined for construction product LCAs and EPDs.

SimaPro openLCA Brightway One Click LCA Ecochain sphera™

11 PRACTICAL TIPS FOR AN LCA

Start simple. Begin with a screening LCA or hand calculations to identify the major hotspots. Focus on the most significant processes rather than modeling everything in detail.

Define a functional unit early. A clear functional unit ensures comparability between design alternatives and prevents scope creep.

Leverage existing data. Use secondary data from databases like Ecoinvent, or peer-reviewed literature, to reduce data collection effort. Document your sources and assumptions clearly.

Focus on key impact categories. Start with the most relevant midpoints (e.g., Global Warming Potential) rather than attempting to cover all possible impacts at once.

Compare alternatives. Even simple comparative LCAs help guide design decisions and identify better options early.

Iterate as design evolves. Update your LCA when design choices or data availability change. Treat it as a decision-support tool, not a final report.

Plan for software transition. As the design stabilizes, adopt LCA software to handle growing complexity and enable future certifications or EPD generation.

Involve reviewers early. A critical review does not have to wait until the end of the study. Early reviewer involvement reduces rework and improves credibility.

12 LCA AND EU REGULATION

The EU is building a legislative architecture that makes life cycle data a condition of market access. Five regulations, already in force or entering their binding phases now, either directly require LCA or create strong commercial incentives for it.

- **Ecodesign for Sustainable Products Regulation (ESPR)**, in force July 2024, extends mandatory sustainability requirements to virtually all physical goods on the EU market. Its most LCA-relevant obligation is mandatory Global Warming Potential reporting, calculated using life cycle assessment, for products covered under product-specific delegated acts. Priority sectors in the 2025–2030 Working Plan include iron and steel, textiles, aluminium, tires, and furniture. Lower-GWP products will also receive preferential treatment in public procurement, making a product's carbon intensity a commercial differentiator, not just a compliance metric.

- **The Battery Regulation** (EU 2023/1542) is the most immediately binding for deep-tech energy companies. It requires mandatory carbon footprint declarations for EV batteries from February 2025 and for industrial batteries from February 2026, calculated using ISO 14040/44. The stakes escalate quickly: from 2026, batteries must carry a carbon footprint performance class; from 2027, batteries exceeding maximum carbon thresholds will be blocked from the EU market entirely. From February 2027, EV and industrial batteries must also carry a battery passport, a machine-readable record of carbon footprint, recycled content, and supply chain data. LCA here is not a reporting exercise. It is a market access condition.

- **Corporate Sustainability Reporting Directive (CSRD)**, in force January 2024, requires large companies to report Scope 3 emissions: the full upstream and downstream value chain, under auditable European standards. This covers the same system boundary as a cradle-to-grave LCA. Following the 2025 Omnibus simplification, the obligation focuses on companies with more than 1,000 employees, meaning most early-stage companies are not directly in scope yet. But the supply chain pressure effect arrives sooner: large customers subject to CSRD will require verified emissions data from their suppliers. A startup that cannot provide it risks being replaced by one that can.

- **Carbon Border Adjustment Mechanism (CBAM)** entered its definitive phase in January 2026, attaching a direct financial cost to the carbon embedded in imported goods across six sectors: iron, steel, aluminium, cement, fertilizers, and hydrogen. For companies developing lower-carbon processes in these sectors, this creates an immediate commercial case for LCA-based carbon communication — a lower-carbon material reduces the CBAM liability of every EU customer who buys it.

- **The Digital Product Passport (DPP**), introduced under ESPR and the Battery Regulation, is the connective tissue of this whole system. From July 2026, a standardized machine-readable record — accessible via QR code — will follow products through their entire life cycle, carrying verified GWP, material composition, recycled content, and supply chain origin. The LCA is the analysis; the DPP is its auditable, permanent record. Companies with existing ISO-compliant LCAs can meet DPP requirements largely as a data infrastructure exercise. Those without face a much steeper path.

Each of these regulations asks the same underlying question: what is the environmental impact of this product, measured across its life cycle? An investment in LCA data infrastructure does not serve one regulation it serves multiple simultaneously. Data built at TRL 4 becomes the foundation for market compliance at TRL 9.

13 CONCLUSION: FROM ASSESSMENT TO ACTION

Life Cycle Assessment is not just a technical exercise, it is a journey, and ultimately, a mindset. From defining the goal and scope, to building the inventory, to translating raw data into environmental impacts, and finally stepping back to interpret what it all means, each phase adds a new layer of understanding to the story of a product. No phase stands alone. The goal shapes what data you collect. The inventory determines what impacts you can calculate. The impact assessment reveals what matters most. And interpretation brings it all into context. Together, these four phases ensure you do not just measure environmental burdens, but rather you understand them in a way that guides better decisions.

What the incandescent bulb case study illustrates is that LCA results can be genuinely surprising. Transportation, and not manufacturing or the raw materials, emerged as the dominant contributor to global warming impact, accounting for 79% of the total. Without the full life cycle perspective, that hotspot would have remained invisible, and improvement efforts would have been directed at the wrong stages entirely. This is the core value of LCA: it reveals the full picture, so that the choices that actually matter can be identified and acted on.

It is equally important to know what a study cannot say. The bulb's manufacturing phase contributed only 1% of the global warming impact — but this study assessed a single impact category. Tungsten, aluminium, and glass carry significant burdens in other categories: resource scarcity, toxicity, water use. A result of zero is never the same as a result of not measured. One of the most important skills in LCA is knowing the limits of your own analysis, and being honest about them.

Every LCA is a model, and every model is a simplification of reality. The assumptions you document, the boundaries you draw, and the data you use all shape the result. This is not a weakness, but a feature. By making those choices explicit and transparent, LCA creates a basis for honest comparison, iterative improvement, and genuine accountability. As practitioners often say with a wry smile: an LCA is never finished, it is only abandoned. The goal is not perfection. The goal is to know more than you did before, and to use that knowledge to build something better.

For early-stage innovators, this perspective is especially powerful. You have a unique opportunity: to embed sustainability into your product from the very beginning, rather than retrofitting it later. Every design choice you make now, every material selected, every process chosen, can ripple through the product's entire lifetime. The environmental footprint of a product is largely determined not in the factory, but at the drawing board.

But an LCA should not remain a report on paper. Its real value emerges when it becomes part of a broader strategy: guiding R&D priorities, shaping business models, and aligning with the regulations and market expectations that are arriving faster than most product timelines anticipate. When embedded into a product development roadmap, LCA transforms from a calculation tool into a compass.

Sustainability is no longer optional — it is becoming a license to operate. By embracing LCA early and integrating it into your decisions, you are not just better positioning your product. You are contributing to a more resilient and responsible future.

ABBREVIATIONS

Core LCA methodology

Abbreviation	Full term
AoP	Area of Protection
CF	Characterization Factor
DALY	Disability-Adjusted Life Year
FU	Functional Unit
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MDF	Midpoint to Damage Factor
PDF	Potentially Disappeared Fraction

LCA types and frameworks

Abbreviation	Full term
ALCA	Attributional Life Cycle Assessment
CLCA	Consequential Life Cycle Assessment
CRM	Critical Raw Materials
EoL	End of Life
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
PCF	Product Carbon Footprint
S-LCA	Social Life Cycle Assessment

Standards, certifications and tools

Abbreviation	Full term
CED	Cumulative Energy Demand
EF	Environmental Footprint
EPD	Environmental Product Declaration
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
OEF	Organisation Environmental Footprint
PEF	Product Environmental Footprint
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts

ABBREVIATIONS

Technology and development

Abbreviation	Full term
ESG	Environmental, Social and Governance
EV	Electric Vehicle
LMT	Light Means of Transport
NFC	Near Field Communication
R&D	Research and Development
RFID	Radio Frequency Identification
SME	Small and Medium-sized Enterprise
TRL	Technology Readiness Level

EU regulations (Chapter 12)

Abbreviation	Full term
CBAM	Carbon Border Adjustment Mechanism
CSRD	Corporate Sustainability Reporting Directive
DPP	Digital Product Passport
ESPR	Ecodesign for Sustainable Products Regulation
ESRS	European Sustainability Reporting Standards
EU ETS	EU Emissions Trading System
GHG	Greenhouse Gas

Chemical and emissions notation

Abbreviation	Full term
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
$PM_{2.5}$	Particulate matter (2.5 micron)
SO_2	Sulfur dioxide

GLOSSARY

Allocation	The process of dividing the environmental impacts of a production activity that generates multiple outputs among those outputs.
Area of Protection (AoP)	The three categories of endpoint damage: Human Health, Ecosystems, and Resource Availability.
Attributional LCA (ALCA)	An LCA approach that describes the environmental burdens directly associated with the current product system ("what is").
Battery passport	A mandatory Digital Product Passport for EV and industrial batteries, required from February 2027, containing the carbon footprint declaration, recycled content data, supply chain records, and state-of-health information.
Carbon footprint declaration	A verified disclosure of the total greenhouse gas emissions associated with a product across its life cycle, expressed in kg CO2-equivalent. Required for EV batteries from February 2025 and industrial batteries from February 2026 under the EU Battery Regulation.
Carbon footprint performance class	A label assigned to batteries from 2026 indicating their carbon footprint relative to market benchmarks - analogous to an energy efficiency label but for embodied carbon.
Carbon leakage	The displacement of carbon-intensive production from countries with strong climate policy to those with weaker regulation, resulting in no net reduction in global emissions. CBAM is designed to prevent this.
CBAM certificate	A financial instrument purchased by EU importers of covered goods, equivalent in price to an EU ETS allowance, representing the carbon cost of embedded emissions in imported products.
Characterization Factor (CF)	A science-based factor used to convert an inventory flow into its contribution to a midpoint impact category (e.g., 34 kg CO2e per kg CH4).
Embedded emissions	The greenhouse gas emissions associated with the production of a good, including all upstream processes from raw material extraction through to the factory gate. The basis for CBAM certificate calculations.
Endpoint indicator	An impact indicator at the damage level, expressing harm to one of the three Areas of Protection (e.g., DALY for human health).
Environmental Footprint (EF)	The European Commission's own LCA-based methodology for calculating and comparing the environmental performance of products (PEF) and organizations (OEF), used as the official EU method for environmental performance claims.

Consequential LCA (CLCA)	An LCA approach that assesses how environmental impacts change as a consequence of decisions or demand changes ("what if").
Cradle to Cradle	A system boundary covering the full life cycle, assuming materials are fully recovered and re-enter the production cycle at end-of-life.
Cradle to Gate	A system boundary covering raw material extraction through to the point the finished product leaves the factory.
Cradle to Grave	A system boundary covering the full life cycle from raw material extraction to final disposal.
DALY (Disability-Adjusted Life Year)	A measure of endpoint damage to human health. One DALY = one year of healthy life lost due to disease or premature death.
Delegated act	Secondary legislation issued by the European Commission under a framework regulation, defining specific sustainability requirements for individual product categories under ESPR.
Digital Product Passport (DPP)	A standardized, machine-readable record - accessible via QR code, RFID, or NFC - that follows a product through its entire life cycle, carrying verified environmental performance data, material composition, recycled content, and supply chain origin.
Double materiality	A CSRD requirement to assess both how sustainability issues affect a company's financial position (financial materiality) and how the company's activities affect people and the environment (impact materiality).
Elementary flow	A flow that crosses the system boundary between the product system and the natural environment - either extracted from nature (e.g., crude oil) or released to it (e.g., CO_2 emissions).
Environmental Product Declaration (EPD)	A standardized, third-party-verified document reporting the environmental performance of a product based on an ISO-compliant LCA, aligned with ISO 14025 and EN 15804. Expected to serve as a primary data source feeding into Digital Product Passports.
ESPR Working Plan	A document published by the European Commission listing the product categories that will receive delegated acts under ESPR during a given period. The first Working Plan (2025-2030) was adopted in April 2025.
EU Green Deal	The European Commission's overarching policy program to make Europe climate-neutral by 2050, under which ESPR, CSRD, CBAM, the Battery Regulation, and the DPP all sit.

EU Taxonomy	An EU classification system defining which economic activities can be considered environmentally sustainable, used by financial institutions and investors to direct capital toward green investments.
Functional unit (FU)	The quantified performance of a product system used as a reference unit for the LCA (e.g., 1 tonne-km of freight transport).
Gate to Gate	A system boundary covering only the processes within a single manufacturing facility.
Intermediary flow	A flow of materials or energy between unit processes within the product system (not crossing the system boundary to nature).
LCA (Life Cycle Assessment)	A systematic methodology for evaluating the environmental impacts of a product, process, or service across its entire life cycle.
LCI (Life Cycle Inventory)	The phase of LCA involving data collection and quantification of all inputs and outputs crossing the system boundary.
LCIA (Life Cycle Impact Assessment)	The phase of LCA that translates inventory data into environmental impact scores using characterization factors.
Maximum carbon threshold	A binding upper limit on the life cycle carbon footprint of a battery, applying from 2027 for EV batteries. Products exceeding the threshold cannot be placed on the EU market.
Midpoint indicator	An impact category measured at an intermediary point in the cause-effect chain (e.g., Global Warming Potential in kg CO2e).
Midpoint-to-damage factor (MDF)	A conversion factor linking a midpoint result to endpoint damage (e.g., converting kg CO2e to DALY via climate-health modeling).
Normalization	An optional LCIA step that expresses impact scores relative to a reference value (e.g., per-capita annual impacts) to aid comparison across categories.
Omnibus simplification package	A 2025 EU legislative package that revised several sustainability regulations, including narrowing CSRD's mandatory reporting scope to companies with more than 1,000 employees.
PDF (Potentially Disappeared Fraction)	A measure of endpoint damage to ecosystems, representing the fraction of species potentially lost in a given area over time.
Product Environmental Footprint (PEF)	The EU's standardized method for calculating the environmental impact of a product across its life cycle, based on ISO 14040/44 and covering 16 impact categories. Used as the basis for carbon footprint declarations under the Battery Regulation.

Reference flow	The specific quantity of product needed to fulfill the functional unit, serving as the calculation basis for all inventory flows.
Scope 1 emissions	Direct greenhouse gas emissions from sources owned or controlled by a company - for example, emissions from on-site combustion or company-owned vehicles.
Scope 2 emissions	Indirect greenhouse gas emissions from the generation of purchased electricity, heat, or steam consumed by a company.
Scope 3 emissions	All other indirect greenhouse gas emissions in a company's value chain - both upstream (suppliers, raw materials) and downstream (product use and end-of-life). Scope 3 covers the same system boundary as a cradle-to-grave LCA.
Sensitivity analysis	A systematic procedure to test how changes in assumptions, data, or methodological choices affect the LCA results.
Substances of concern	Hazardous or restricted chemical substances that ESPR requires manufacturers to disclose across the life cycle of their product, to support safe disassembly, recycling, and circular material flows.
System boundary	The set of criteria defining which unit processes, inputs, and outputs are included in the LCA study.
Uncertainty analysis	A procedure to quantify how data variability and model imprecision propagate through the LCA, typically using Monte Carlo simulation.
Unit process	The smallest element in the life cycle inventory for which input and output data are quantified (e.g., one step in a manufacturing line).
Weighting	An optional, value-based LCIA step that assigns relative importance factors to different impact categories to produce a single aggregated score.

SOURCES & INSPIRATIONS

This guide was shaped by a range of resources that helped clarify methods and provide examples of how Life Cycle Assessment is applied in practice. For readers who wish to go deeper into the field, the following materials are especially valuable:

- University of Michigan — Life Cycle Assessment Course (Coursera): An accessible and structured introduction to LCA concepts, methods, and applications.
- ISO 14040 and ISO 14044 Standards: The internationally recognized frameworks for conducting environmental LCAs, defining principles, requirements, and terminology.
- Weidema et al. — Stepwise Method: A practical guide to normalization and weighting in LCIA, useful for understanding how results can be aggregated and interpreted.
- International Aluminium Institute — Life Cycle Inventory (LCI) Data and Environmental Metrics: A data-rich resource offering global aluminium industry LCI datasets from multiple years (2010, 2015, 2019).
- Li, Chengzhou et al. (2019). Environmental Impact Evaluation of Distributed Renewable Energy System Based on Life Cycle Assessment and Fuzzy Rough Sets. Energies, 12, 4214.
- PRé Sustainability. ReCiPe Methodology Framework. https://presustainability.com/articles/recipe/
- CIRAIG. (2024). IMPACT World+ Methodology. https://www.impactworldplus.org/methodology/

CREDITS

Images

- Cape Crystal Brands / Chef Edmund
- Minespider / Anastasia Popova

Icons

- srip via www.flaticon.com
- vectorspoint via www.flaticon.com
- Freepik via www.flaticon.com
- Sofía Trujillo Quesada via www.thenounproject.com
- noomtah via www.flaticon.com
- Olena Panasovska via www.thenounproject.com
- IconBaandar via www.flaticon.com
- JoyPixels via www.creazilla.com
- Ragil Heru Fitriyan via www.flaticon.com
- Gowi via www.flaticon.com
- Iyikon via www.flaticon.com
- Eucalyp via www.flaticon.com
- surang via www.flaticon.com
- Grow studio via www.flaticon.com
- waqasshah via www.flaticon.com
- Good Ware via www.flaticon.com
- IconPai via www.flaticon.com
- Shashank Singh via www.flaticon.com
- Kmg Design via www.flaticon.com
- ekays.dsgn via www.flaticon.com
- Iconjam via www.flaticon.com