DSS5202 Sustainable Systems Analysis

Life Cycle Assessment

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1 Life Cycle Thinking

1.1 Six Products, Six Different Carbon Footprints

- Consider the following six products:
  1. Car
  2. Shoes
  3. Laundry detergent
  4. Fleece Jacket
  5. Milk
  6. Beer

- The objective is to determine the carbon footprint of these products.

- Each of the above products goes through five phases in its lifetime:

  1. Resource extraction
  2. Manufacturing
  3. Transportation
  4. Use
  5. End of life.

- Question: For each of these products, which two of the five phases do you think result in the most CO_2 emissions in their life cycle?

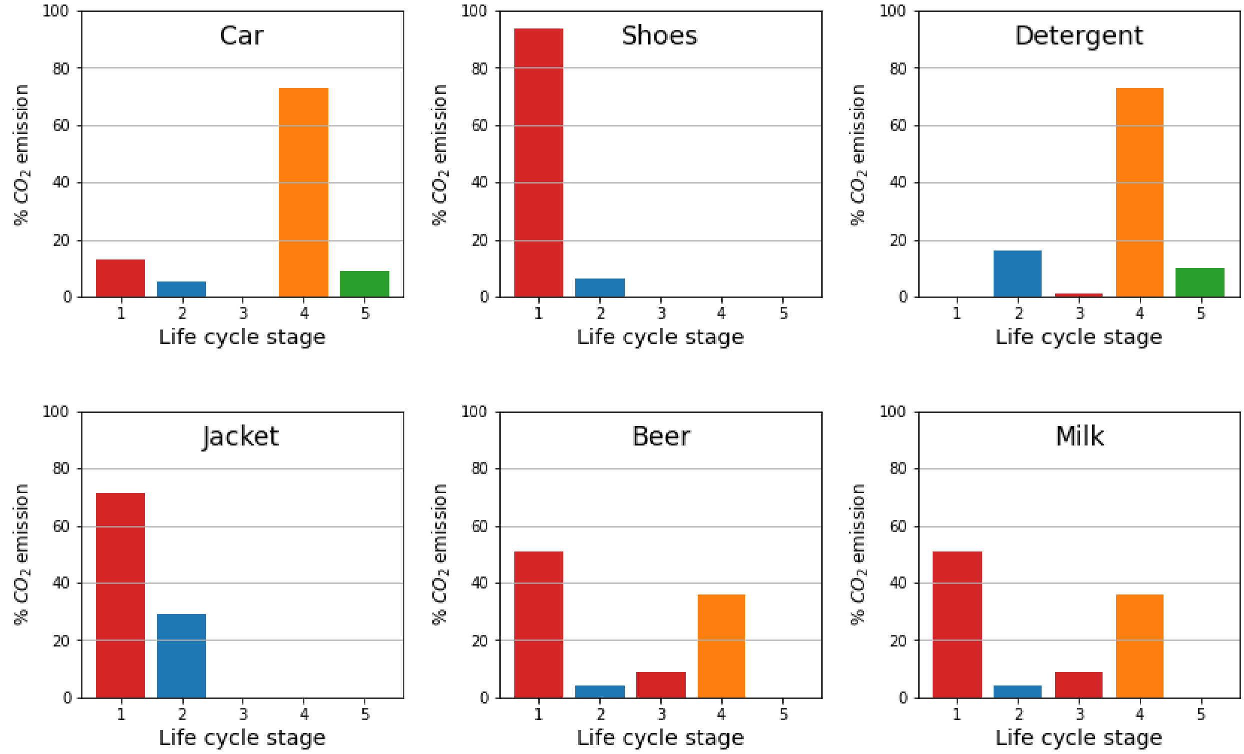
- More Information about the products:

	Product	**Functional Unit**
1	Car	2007 Prius driven 126,000 miles at 42 mpg
2	Shoes	1 pair of hiking boots
3	Laundry Detergent	1.5 liter, 20 load bottle
4	Fleece Jacket	1 Jacket
5	Beer	1 six-pack of beer
6	Milk	Half-gallon of organic milk

- Total emissions found:

	Product	**Total CO_2 emissions**
1	Car	44,000 kg
2	Shoes	55 kg
3	Laundry Detergent	14 kg
4	Fleece Jacket	30 kg
5	Beer	3.2 kg
6	Milk	3.3 kg

Results:



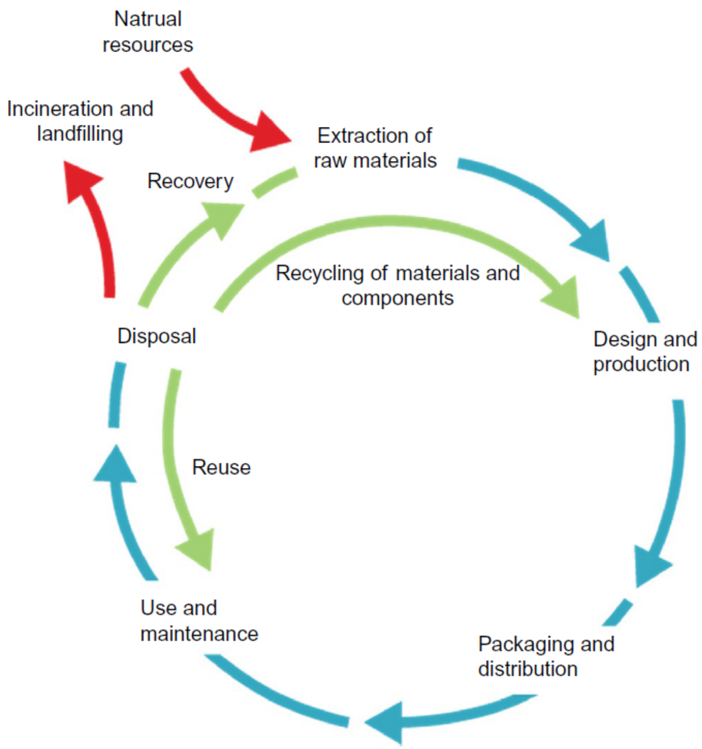
Conclusions:

- Different products have different dominant stages for environmental impacts.
- Consideration of all stages of the life cycle is important.
- Identification of impact "hotspots" can help provide a more targeted direction for improving the relevant phase of the product.

1.2 The Product Life Cycle Perspective

- The life cycle perspective of an environmental problem considers the totality of the system in the analysis, including the evaluation of the product's entire life cycle, with a long-term time horizon and a multi-dimensional view.

- A typical product life cycle may be depicted as follows:



Source: Ren and Toniolo (2020)

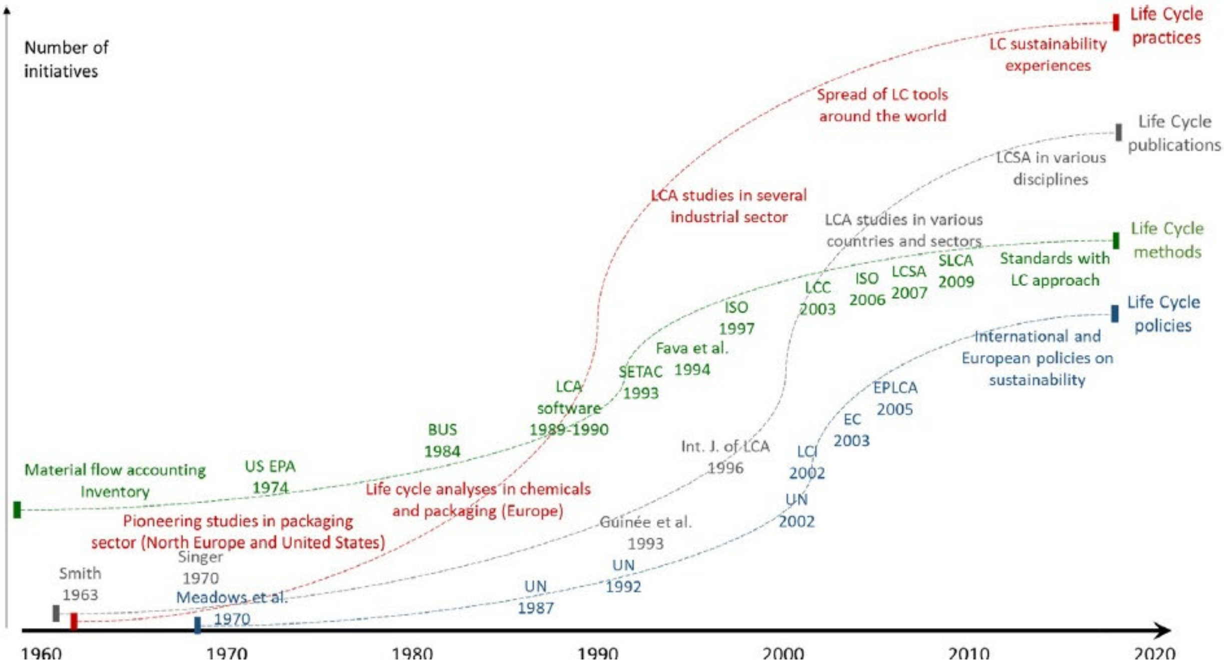
- A product's life cycle can begin with the extraction of raw materials from natural resources in the ground, and with energy consumption.

- Materials and energy are then part of production, packaging, distribution, use, maintenance, and eventually recycling, reuse, recovery, or final disposal.

- In each life cycle stage, there is the potential to reduce resource consumption and improve the product's impacts on the environment.

1.3 History of Life Cycle Thinking

- The main evolutionary stages of life cycle thinking since 1960:



Source: Ren and Toniolo (2020)

- There were four interdependent directions:

  1. Life cycle practices
  2. Life cycle methods
  3. Life cycle publications
  4. Life cycle policies.

- The first life cycle reasoning was done in the 1960s, when environmental degradation and limited access to resources started becoming a concern.

- Life cycle thinking has taken shape since then and is gradually enriched through application, harmonization, and dissemination.

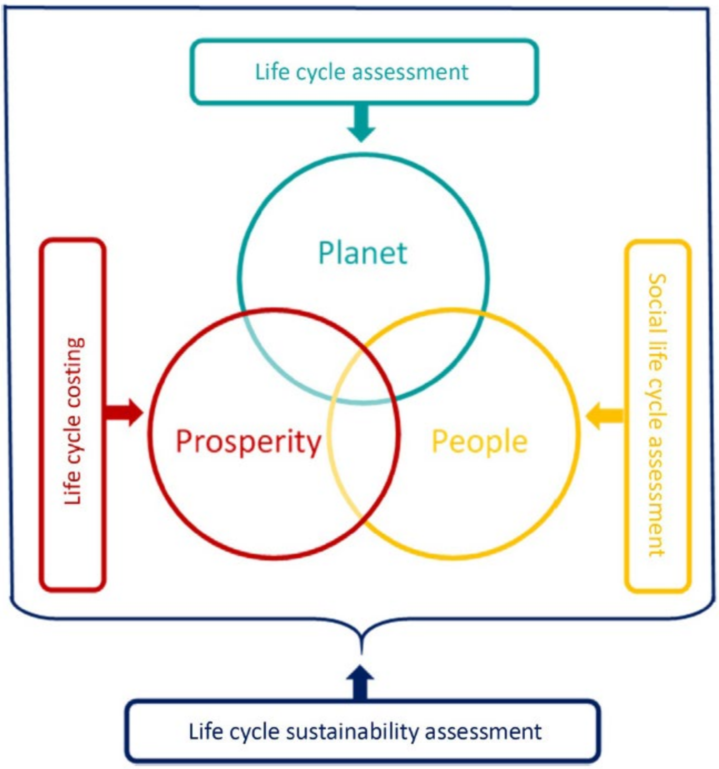
- Life cycle practices also started in the 1960s, as isolated experiences. It experienced strong growth during the 1990s due to the establishment of standards and software to support life cycle analysis.

- Government initiatives supporting the life cycle approach began in the 1990s and have since multiplied and scientific literature has exploded.

1.4 Life Cycle Thinking and Sustainability

1.4.1 Life Cycle Thinking and the Core Pillars of Sustainability

- The link between life cycle thinking and sustainable development through the three core pillars of sustainability as shown below:



- To meet the UN's 17 sustainable development goals by 2030, sustainability must gain strong prominence in decision-making support for all economic actors in the supply chain.

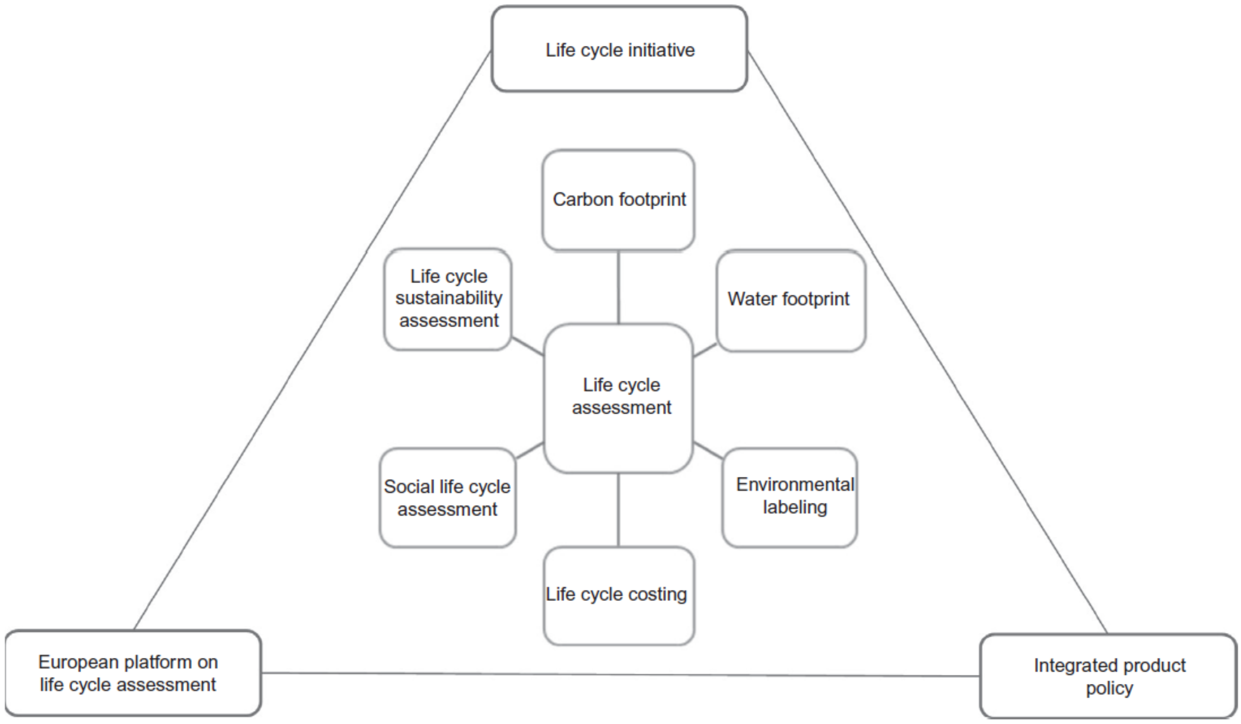
- Through the life cycle approach, decision makers must recognize how their choices influence what happens at each phase, so that they can balance trade-offs in economic and environmental consequences caused by their choices.

1.4.2 Tools and Actions in Life Cycle Thinking

- The tools and actions in life cycle thinking may be summarised as follows:

- **Life Cycle Tools** are standards and guidelines to assist researchers, practitioners, and companies in applying the principles of the life cycle approach to products, processes, and projects

- **Life Cycle Actions** include disseminating and supporting initiatives aimed at spreading the life cycle approach in international and local policies, as well as fostering the understanding and use of life cycle tools between companies and consumers.

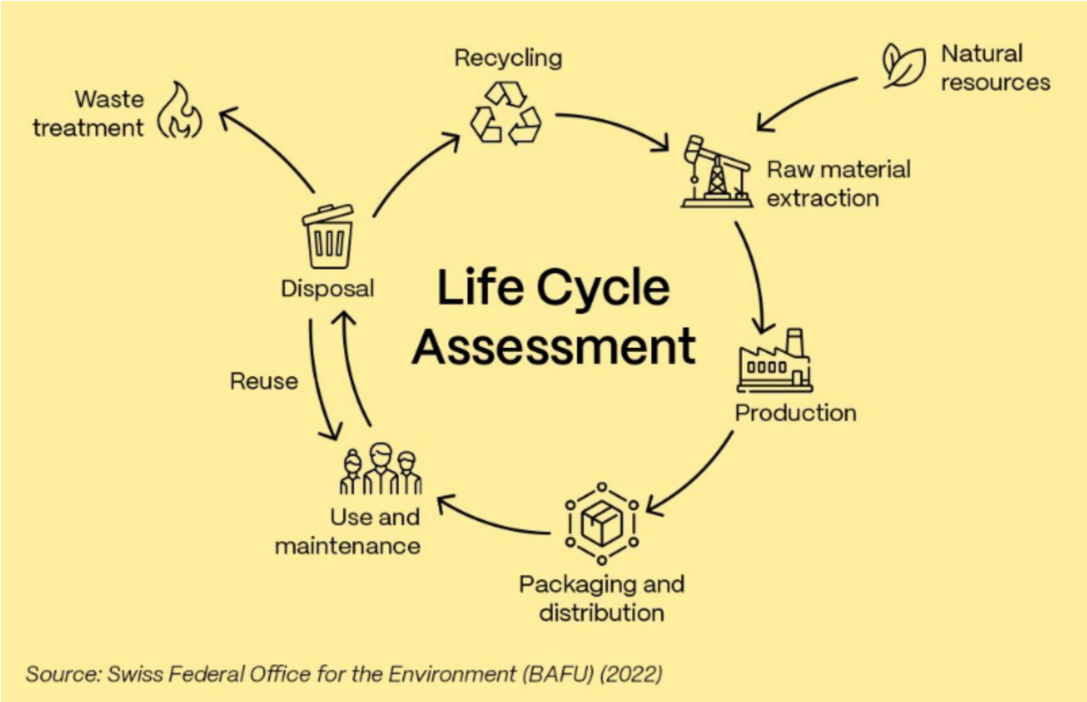


Life Cycle Assessment (LCA)

- LCA is a framework for assessing the potential environmental impacts of products.

- LCA assesses quantitatively the environmental impacts of goods and processes from throughout their entire life cycle, i.e., cradle-to-grave.

- LCA models cause-effect relationships in the environment and thus helps to understand the environmental consequences of human actions.



Life Cycle Costing (LCC)

- Life cycle cost refers to all costs associated with the system in a defined temporal life cycle.
- The LCC works consistently with the LCA model across the product's life cycle. It includes all costs borne by different actors with different perspectives and at different times.

Social Life Cycle Assessment (SLCA)

- The SLCA is a methodological approach aimed at evaluating social and socioeconomic aspects of products and their potential positive and negative impacts along their life cycle.
- Social impacts are those that may affect stakeholders along the product life cycle and may be linked to company behavior, socioeconomic processes, and impacts on social capital.

Life Cycle Sustainability Assessment (LCSA)

- There is no fixed definition of LCSA.
- An approach computes LCSA as the "sum" of the three studies: LCA, LCC, and SLCA, thereby broadening LCA methodology by including economic and social aspects in the life cycle evaluation.

Partial LCA Methods and Footprints

- Over the last half century, some critical environmental issues were identified and dealt with individually:

    1. The emission of greenhouse gases is the main cause of global climate change.

        - Carbon footprint (CF) of a product or service.

    2. The scarcity of freshwater availability is critical for healthy lives and a healthy planet.

        - Water footprint (WF) of a product or service.

    3. The energy consumption closely linked to the availability of non-renewable resources is a threat to economic development as well as the balance of the political and social world.

        - Energy footprint (EF) of a product or service.
        - Energy efficiency (EE) of a product or service.
        - Energy intensity (EI) of an economy.

    4. Increasing land use and fossil fuel combustion are leading to enhanced losses of reactive nitrogen to the environment.

        - Nitrogen footprint (NF) of a product or service.

- All the above "footprints" deal with only one or more specific areas of concern.

- They can all be systematically considered in the Life Cycle Assessment methodology.

2 Life Cycle Assessment Overview

2.1 Key Features of LCA

- Life Cycle Assessment (LCA) is a methodology used to systematically and adequately address, identify, compile, analyze and evaluate the environmental impacts and burdens of product systems, from raw material acquisition to final disposal.

- The depth of detail and time frame of an LCA study may largely vary, depending on the definition of the goal and scope.

- The environmental impacts assessed may include
  - Resource depletion
  - Energy consumption
  - Emissions of hazardous substances to air, water and soil
  - Waste generation
  - Land use

- The scope, assumptions, description of data quality, methodologies and output of LCA studies should be transparent.

- The studies should discuss and document the data sources and be clearly and appropriately communicated.

- Provisions should be made, depending on the intended application of the LCA study, to respect confidentiality and proprietary matters.

- LCA is not about reducing the results to a single overall score or number. Trade-offs and complexities exist for the systems analyzed at different stages of their life cycle.

- ISO 14040 is only a guideline. Organizations have the flexibility to implement LCA practically based on the specific application and the requirements of the user.

2.2 Phases of an LCA Study

- Specifically, LCA assesses the environmental aspects and potential impacts associated with a product, process, or service, by:

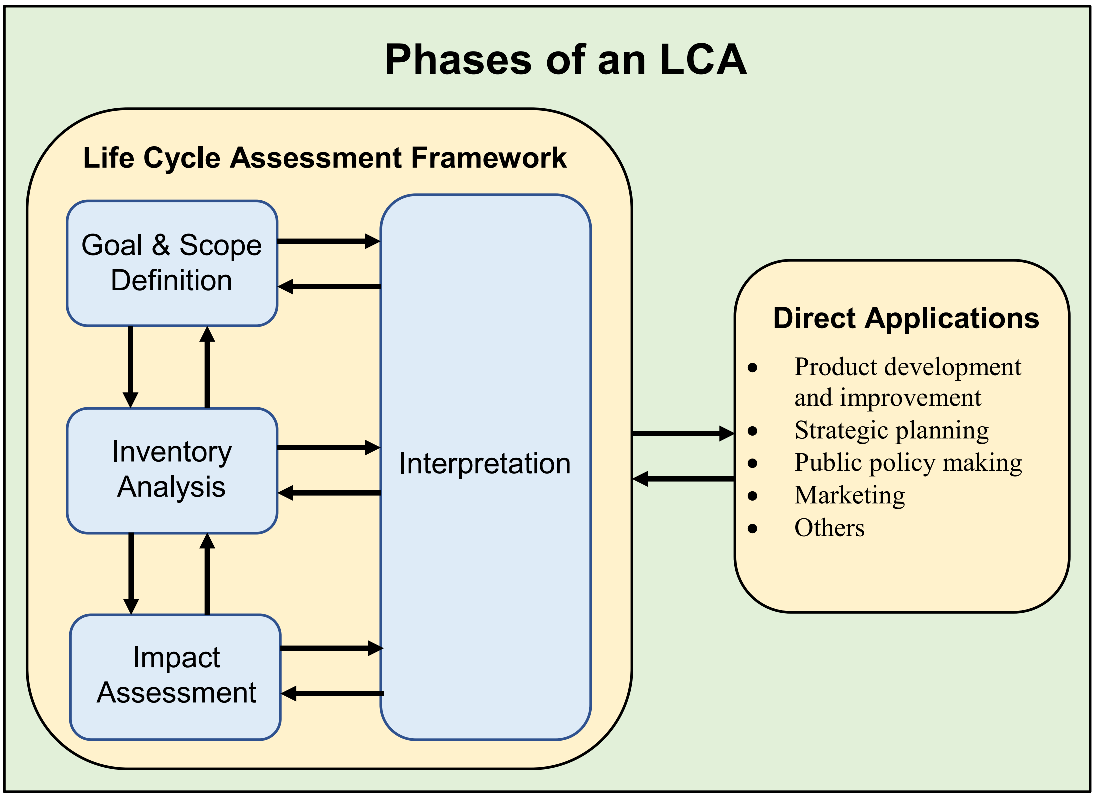
    1. Defining the Goal and Scope of the LCA.

    2. Compiling an inventory of relevant energy and material inputs and environmental releases. This step is typically called the LCI.

    3. Evaluating the potential environmental impacts associated with identified inputs and releases. This step is typically called the LCIA.

    4. Interpreting the results to help decision-makers directly make informed decisions.

- The four phases are related as shown below:



2.3 Brief Descriptions of the Steps in LCA

- We describe here briefly the steps in each phase of LCA.
- More details will be provided in the next section.

Phase 1: Goal and Scope Definition

1. Identify the goal, objectives and the intended audience.
2. Describe the functions of the product system, or in the case of comparative studies, the systems.
3. Define the functional unit.
4. Define the product system to be studied.
5. Define the product system boundaries.
6. Select allocation procedures in the case of multiple products (if necessary).
7. Indicate the types of impact and methodology of impact assessment, and subsequent interpretation to be used.
8. Indicate the data requirements.
9. State the assumptions made in the assessment.
10. Describe the limitations of the assessment.
11. State the critical review for ISO compliance made (if any).

Phase 2: Life Cycle Inventory Analysis (LCI)

1. Identify and quantify all the input and output flows that are within the scope of the assessment.

   These inputs and outputs may include the use of resources and releases to air, water and land associated with the system.

   This step may also involve the computation of **scaling factors** for the unit processes to realize the functional unit.

   Allocation of flows may also be required when there are multiple products, co-products from a process.

2. The inventory analysis process is iterative.

   As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met.

3. Issues may be identified that require revisions to the Goal or Scope of the study.
4. The results of the life cycle inventory analysis (LCI) constitute the input to the life cycle impact assessment (LCI) in the next phase.

Phase 3: Life Cycle Impact Assessment (LCIA)

1. Select impact categories, category indicators and characterization models.

2. Assign the LCI results to impact categories (**classification**).

3. Compute the category indicator values (**characterization**).

4. The following are optional:

   - Calculate the magnitude of category indicator results relative to reference information (**normalization**).

   - Only if necessary and meaningful, aggregate the results in very specific cases (**weighting**).

5. Iteratively, review the goal and scope of the LCA study to determine when the objectives of the study have been met, or to modify the goal and scope if the assessment indicates that they cannot be achieved.

Phase 4: Life Cycle Interpretation

1. Evaluate the results of the LCA to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

2. Draw conclusions, identify hotspots (stages with the highest environmental impacts), and make recommendations for improvements.

3. Sensitivity analysis and uncertainty assessment may also be conducted to evaluate the robustness of the results.

2.4 The ISO Standards for LCA

1. ISO14040:2006/AMD 1:2020 Environmental management—Life cycle assessment - Principles and framework—Amendment 1.
   - Describes the principles and the framework for conducting LCA.

2. ISO14044:2006/AMD 2:2020 Environmental management—Life cycle assessment - Requirements and guidelines—Amendment 2.
   - Specifies the requirements and provides the guidelines for conducting LCA.

- These standards provide information about the steps/phases to develop an LCA study:
  1. Definition of the goal and scope of the LCA
  2. Life cycle inventory (LCI) analysis
  3. Life cycle impact assessment (LCIA)
  4. Life cycle interpretation

- They also include a critical review of LCA, the limitations of LCA, the relationship between the LCA phases, and the conditions for the use of value choices and optional elements.

3 Life Cycle Assessment in Practice

- In this section, we provide more details on how to conduct each phase of the LCA with specific examples.

3.1 Phase I: Goal and Scope Definition

- Phase I is the description of the Goal and Scope, which includes defining the objectives of the study and setting the methodological bases to develop the assessment.

- The goal and scope of an LCA study shall be clearly defined and consistent with the intended application.

- Questions raised during this phase may include:
  - Why are you conducting the LCA?
  - What do you hope to achieve?
  - Are you assessing the environmental impacts of a specific product, service, or process?
  - Are you comparing alternatives for informed decision-making?

Goal

- The **Goal** definition must be established unambiguously:

  - What is the intended application?
  - What are the reasons to carry out the study?
  - Who are the intended audiences?
  - Is this result to be used for a comparative study?

- A typical goal statement:

  "The goal of this LCA is to conduct a cradle-to-grave assessment of <product name> to identify environmental hotspots across its life cycle. The results will be used internally for process improvements and to inform public-facing environmental claims regarding the product's sustainability."

- A specific example goal statement:

  "The goal of this LCA is to understand the environmental impacts of both the most common artificial Christmas tree and the most common natural Christmas tree, and to analyse how their environmental impacts compare."

  "This comparative study is expected to be made publicly available to refute myths and misconceptions about the relative difference in environmental impact between real and artificial trees." (Source: American Christmas Tree Association, 2010)

Scope

- The **Scope** must clearly define the extent, depth, and detail of the study. It has three main components:

  1. The Functional Unit
  2. The Product System studied
  3. The System Boundary

Functional Unit

- The functional unit is a measure of the performance of the functional outputs of the product system specified in the scope of the LCA study.

- The primary purpose is to provide a reference to which the inputs and outputs are related.

- This reference is necessary to ensure comparability of LCA results.

- Comparability of LCA results is particularly critical when different systems are being assessed to ensure that such comparisons are made on a common basis.

- A system may have several possible functions, and the one selected for a study is dependent on the goals and scope of the study.

- The selected functional unit must be clearly defined, measurable, and consistent with the goal and scope of the study.

- The functional unit also serves as the basis for determining the "scaling factor" for all calculations of input and output flows of unit processes.

Examples

1. Food Products:
   - To assess the environmental impacts of beef pies from cradle to supermarket shelf.
   - Functional Unit: 1.1 kg of chilled and packaged beef pies (including 100 g of packaging).

2. Passenger Transportations:
   - To assess the environmental impacts of various transportation modes, such as buses, trains and private cars.
   - Functional Unit: One passenger-km

3. Goods Transportations:
   - To assess the environmental impacts of various goods transportation modes, such as diesel trucks and trains.
   - Functional Unit: One ton-km

4. Street Lighting Systems:
   - To compare the environmental impacts of different road lighting systems, including High-Pressure Sodium (HPS), High-Intensity Discharge (HID), and LED systems.
   - Functional Unit: Providing lighting for 1 km of a local road over 20 years with an annual use of 4,069 hours in a particular district.

5. Beverage Cups:
   - To compare the life cycle environmental impact of disposable paper cups, plastic cups, and reusable ceramic mugs.
   - Functional Unit: Serving 1,000 of 250 ml of coffee in a cafe in a particular city.

6. Food Containers:
   - To assess the environmental impacts of reusable and single-use food containers in a specific city.
   - Functional Unit: Providing 1,000 take-away meals.

7. Energy Generation Technologies:
   - To compare the environmental impacts of different electricity generation technologies, including Coal-fired power plants, Natural gas, Nuclear, Wind, Solar photovoltaic.
   - Functional Unit: 1 kilowatt-hour (kWh) of electricity delivered to the end user.

Product System

- A **product system** is a collection of processes or activities connected by material and energy flows, which together perform one or more defined functions.

Examples

1. Plastic Water Bottle (PET)
   - Function: To store and deliver drinking water.
   - Processes: Crude oil extraction, PET resin production, bottle manufacturing, bottling and packaging, distribution, use, end-of-life (recycling, incineration, or landfill).

2. Electric Vehicle (EV)
   - Function: Personal transportation.
   - Processes: Lithium mining, battery production, vehicle assembly, electricity generation for charging, use, end-of-life (battery recycling, vehicle disposal).

3. Solar Photovoltaic (PV) Panel
   - Function: Generate electricity from sunlight.
   - Processes: Silicon extraction, wafer and module production, PV panel assembly, installation, use phase (20–30 years), end-of-life (recycling or landfill).

4. Aluminum Beverage Can
   - Function: Contain and preserve beverages.
   - Processes: Bauxite mining, alumina refining, aluminum smelting and rolling, can manufacturing, filling, use, recycling.

5. Cotton T-shirt
   - Function: Provide clothing.
   - Processes: Cotton cultivation, yarn spinning, fabric manufacturing dyeing and finishing, garment manufacturing, retail, use (washing, drying), disposal or recycling.

6. Smartphone
   - Function: Personal communication and computing.
   - Processes: Raw material extraction, components manufacturing, assembly, packaging, distribution, use, end-of-life (e-waste recycling or disposal).

7. Concrete for Building Construction
   - Function: Provide structural material.
   - Processes: Cement and aggregate production, concrete mixing, transportation to construction site, use in building, demolition, recycling or landfills.

8. Milk in Tetra Pak Carton
   - Function: Provide nutritional beverage.
   - Processes: Dairy farming, milk processing, carton manufacturing, filling and packaging, distribution, refrigeration (use phase), disposal of carton (recycling, incineration).

9. Electricity Generation – Grid-Connected Power Plant
   - Function: Generate and supply electricity to the grid.
   - Processes
     - Coal-fired power plant: Coal mining and transportation, power plant construction, coal combustion (electricity generation), emission control (e.g., flue gas desulfurization), ash handling and disposal, decommissioning
     - Natural gas combined cycle (NGCC) plant: Natural gas extraction and processing, gas turbine + steam cycle, emissions control, end-of-life

Challenges in Defining the Product System

1. The product system can be very complex comprising a very large number of processes.

   - It might be necessary to aggregate some of the processes into a single higher-level process to reduce the total number of unit processes.

   - The use of appropriate **system boundaries** (see below) to bound the scope of the study may help to reduce the complexity of the system.

2. There may be multiple or co-products from a single process.

   - Appropriate and accurate allocation methods must be used.

3. Reliable data on the input and output flows may not be available for all processes.

   - It may be necessary to use data from technologically similar processes or from previous studies to fill the gaps.

System Boundary

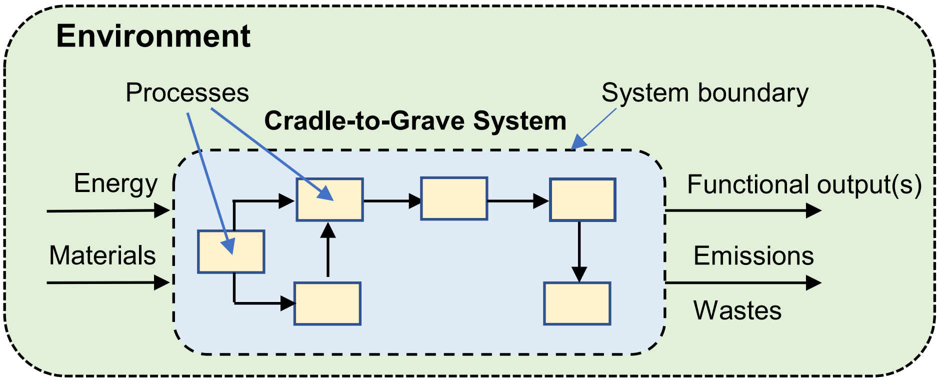
- Define the boundaries of the LCA by specifying which processes, inputs, and outputs will be included in the analysis that is consistent with the scope of the study.

- Consider the entire life cycle of the product, service, or process, from cradle to grave, including raw material extraction, manufacturing, distribution, use, and disposal.

- Decide whether to include upstream and downstream processes, as well as indirect impacts such as transportation or waste management.

Product System Diagram

- When the system boundary, all the relevant processes, and their connections have been defined, a product system diagram may be presented.



Partial Life Cycle Assessment

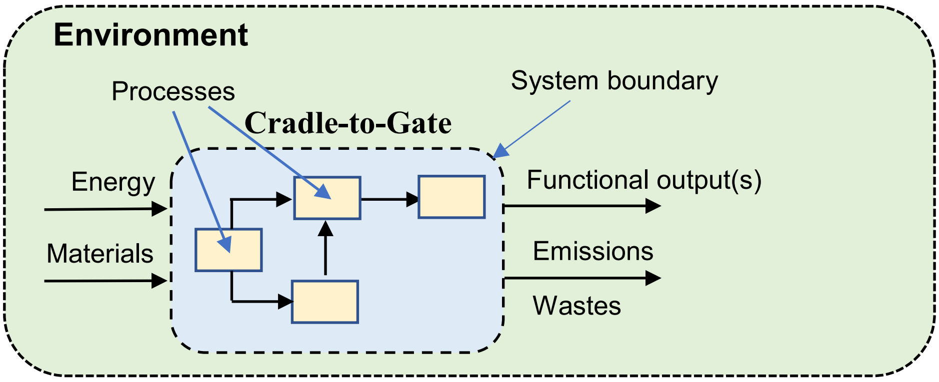
- The cradle-to-grave system boundary attempts to consider all processes starting from the beginning to the end of the activities and products being assessed.

- For some specific studies, part of the system may be ignored for convenience or because it is common to the activities for the products being compared.

- Depending on the goal and objectives of the analysis, the scope study may be restricted by adjusting the system boundary to:
  - Cradle-to-Gate
  - Gate-to-Gate
  - Gate-to-Grave

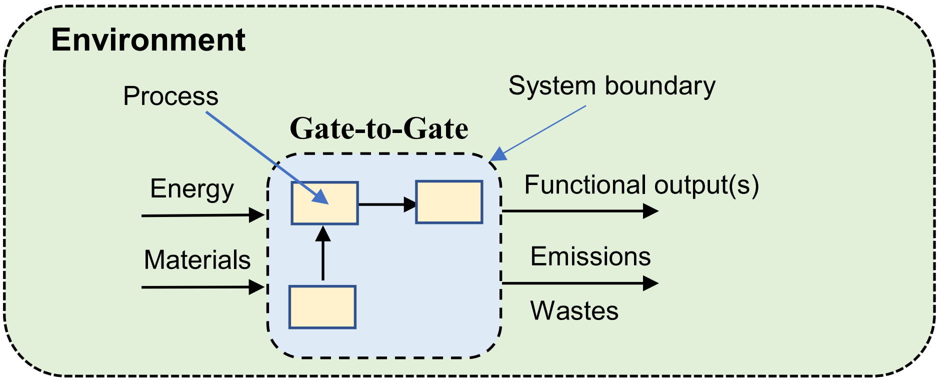
Cradle-to-Gate:

Example: When the end-of-life is not considered in the scope of the study.



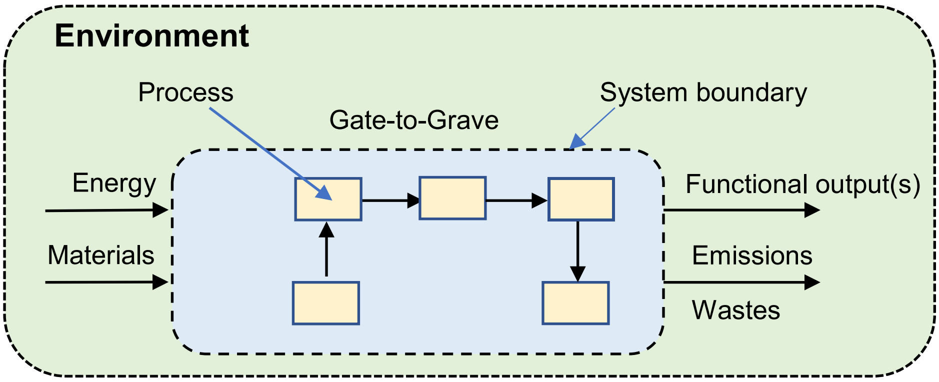
Gate-to-Gate:

Example: When the extraction of raw materials and end-of-life are not considered in the scope of the study

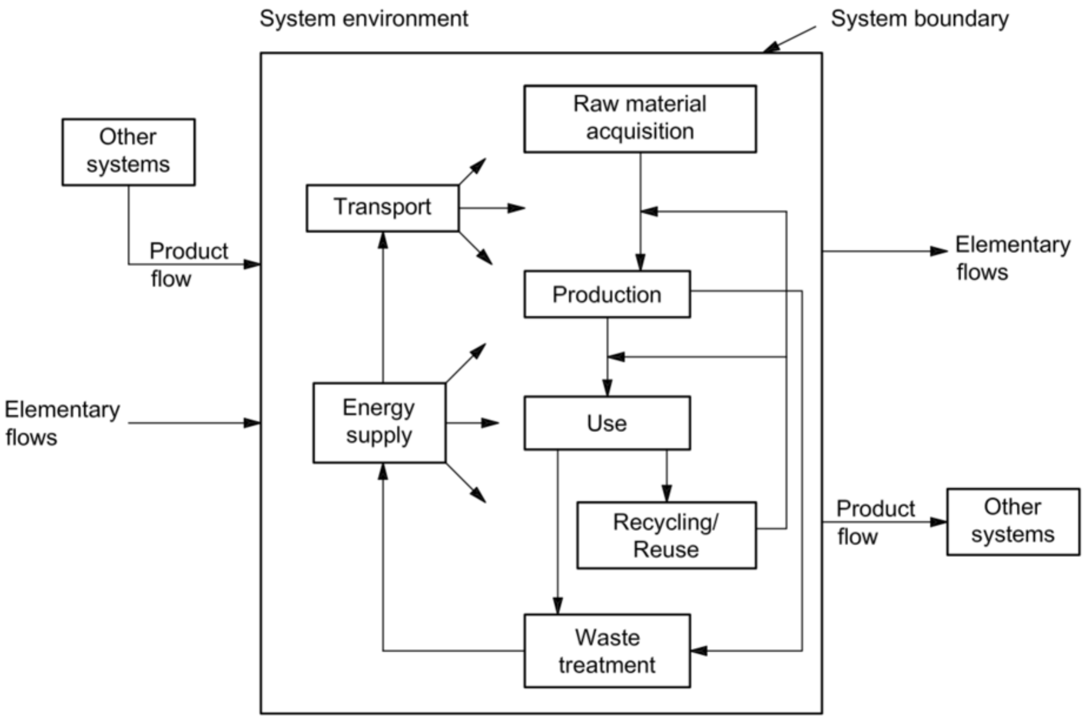


Gate-to-Grave:

Example: When the extraction of raw materials is not considered in the scope of the study.



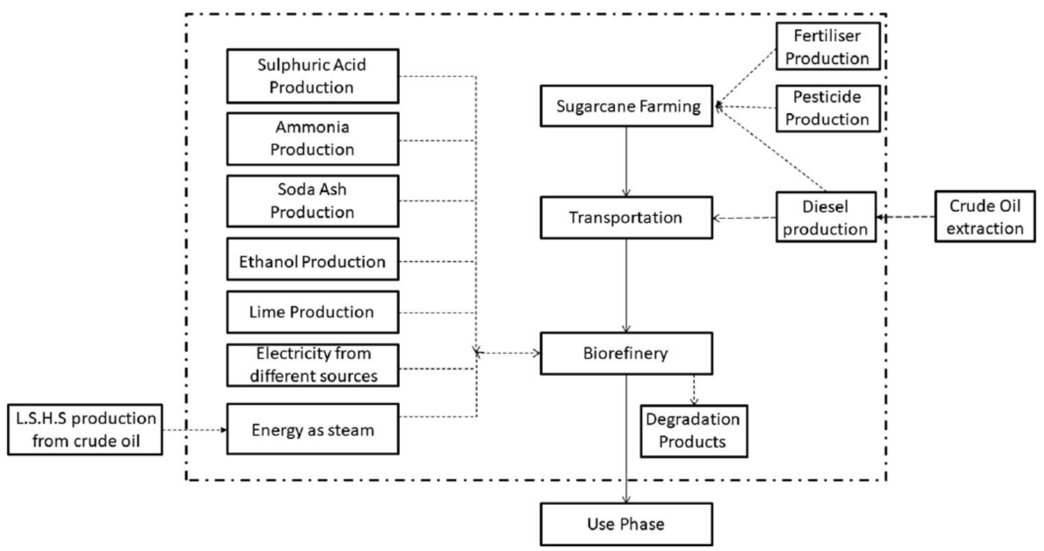
Example: A Generic Product System and System Boundary



- Boxes represent various form of processes
- Arrows represent flows
- Solid or dashed lines represents system boundaries.

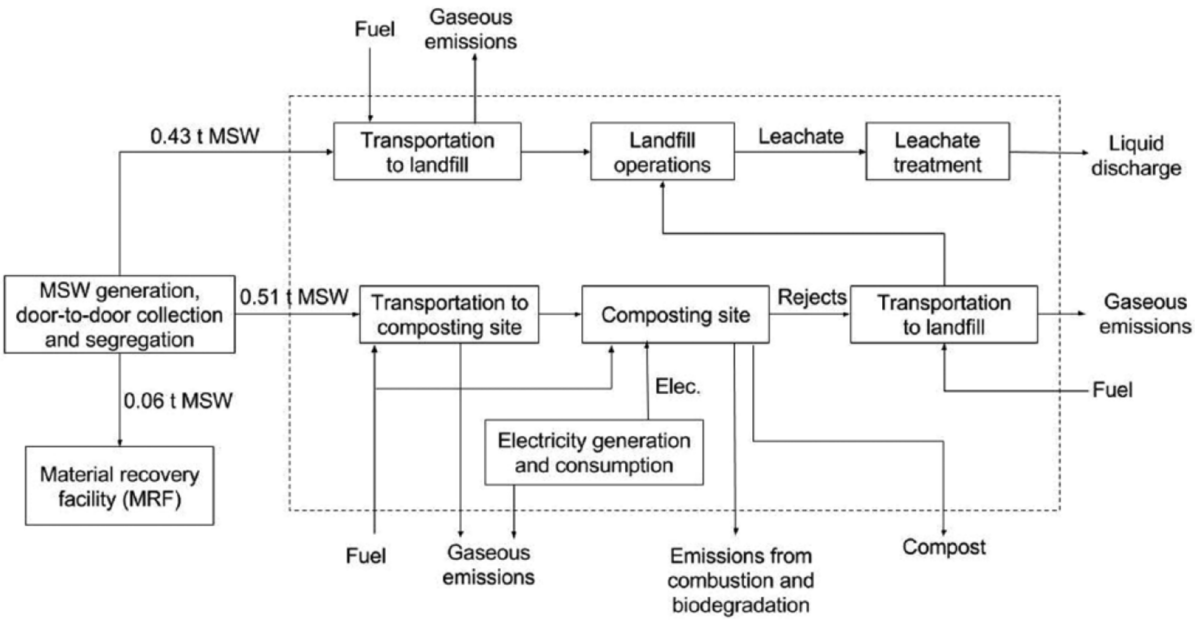
Example: Biofuel Production

- Crude oil extraction is excluded from the system boundary.



- Crude oil extraction is excluded from the system boundary.

Example: Municipal Solid Waste (MSW) Disposal



- MSW generation, door-to-door collection and segregation are not included.
- Material recovery facilities are not included.

Impact of System Boundary

- Different system boundaries of the same product system can result in drastically different results.
- It is important to ensure that the system boundary is consistent with the goal and objective of the study.

Examples:

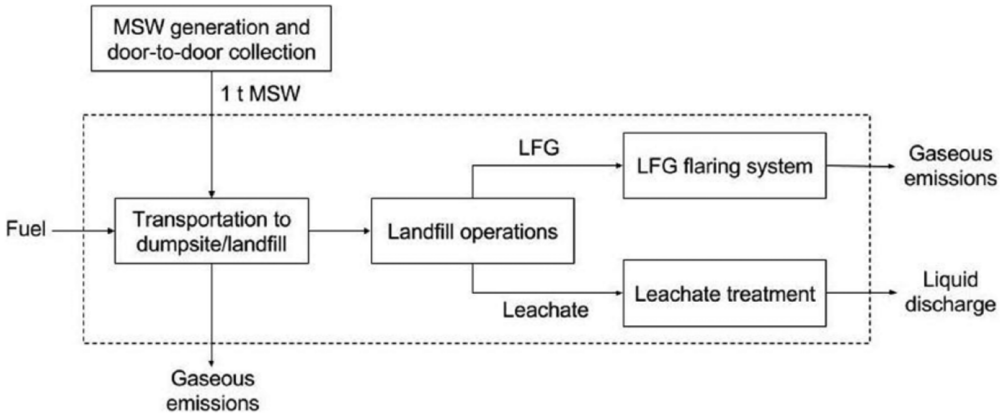
- In comparing EV and Petrol cars, whether we include or do not include the electricity generation within the system boundary, the results will be very different.

- In biofuel production, whether we include or do not include land use within the system boundaries, the results will be much different.

Process Flows

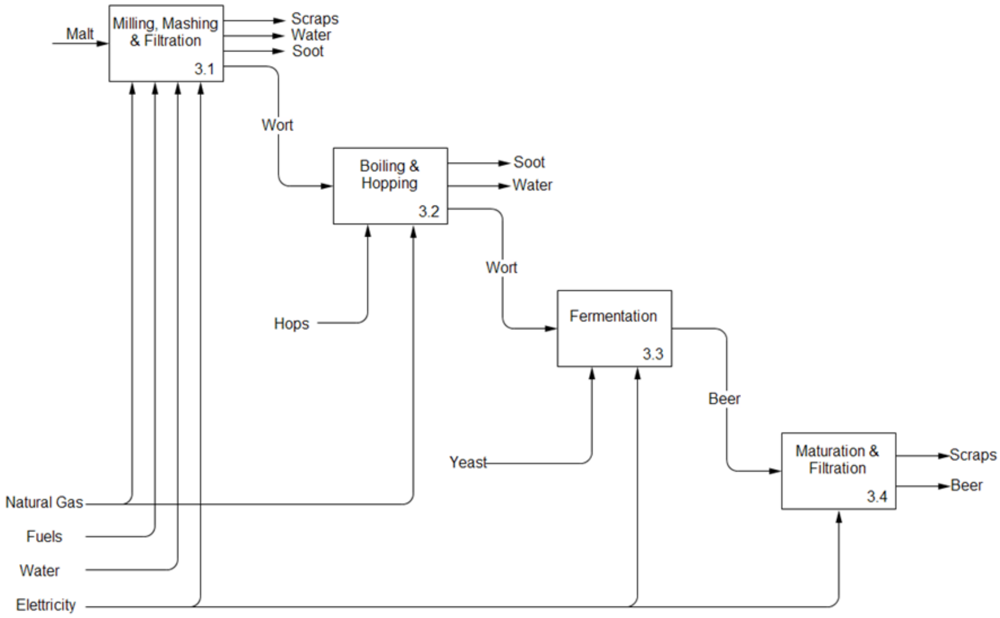
1. **Elementary flows**

- Elementary flows are material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system that is released into the environment without subsequent human transformation.



2. **Product flows**

- Products are outputs of product systems, and a product flow represents the connection of a product between product systems, where it may be an output of and an input to another.



3. **Reference flows**

- Reference flow is the measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.

- Their values may be computed by determining the "scaling factors" of the processes required to fulfil the functional unit.

Examples

1. PET water bottle

- Functional unit: Provide 1 L of drinking water in single-use plastic bottles.
- If each bottle is 0.95 L in volume, then 1/0.95 = 1.0526 bottles are needed to deliver 1 L of water.
- Reference flow = 1.0526 PET bottles

2. Electricity generation in a coal-fired power plant

- Functional unit: Deliver 1 kWh of electricity to the grid.
- If 0.3 kg of coal produces 1 kWh of electricity.
- Reference flow = 0.3 kg of coal at the power station.

3. Electricity generation using solar PV

- Functional unit: Deliver 1 kWh of electricity to a residential user.
- Assume 0.002 m^2 of panel is required to generate 1 kWh.
- Reference flow = 0.002 m^2 of solar PV panel.

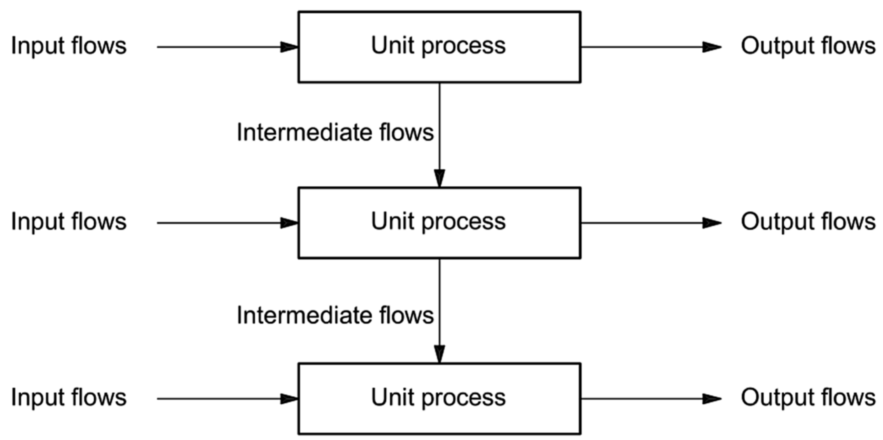
Scaling Factor

- Reference flows in a product system can usually be computed applying a **scaling factor** on the **unit processes.**

Unit Process and Flows

- A unit process is the smallest element considered in a product system for which input and output data are quantified.

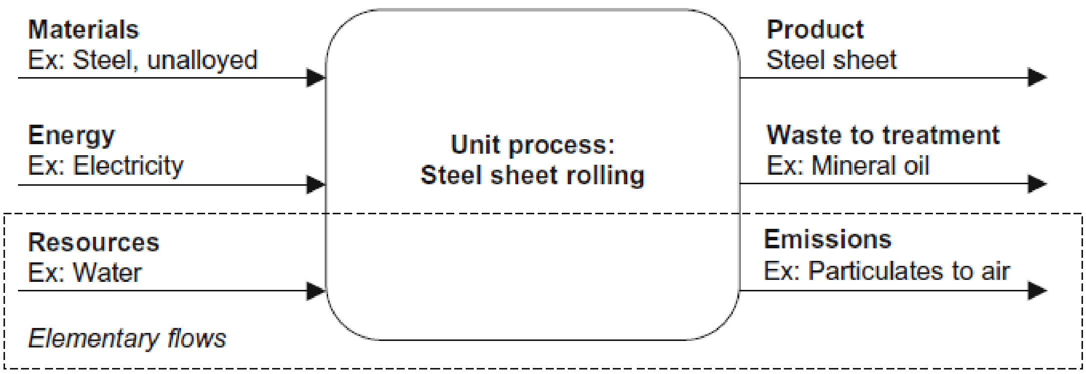
- An example of a generic interacting series of three unit-processes that may a subcomponent of a product system.



- Unit processes can be considered as the building blocks of a life cycle inventory model that are linked together by input and output data, which can be organized into six categories of physical flows:
    - Input Flows:
        1. Materials
        2. Energy
        3. Resources
    - Output Flows:
        1. Products
        2. Waste to treatment
        3. Emissions

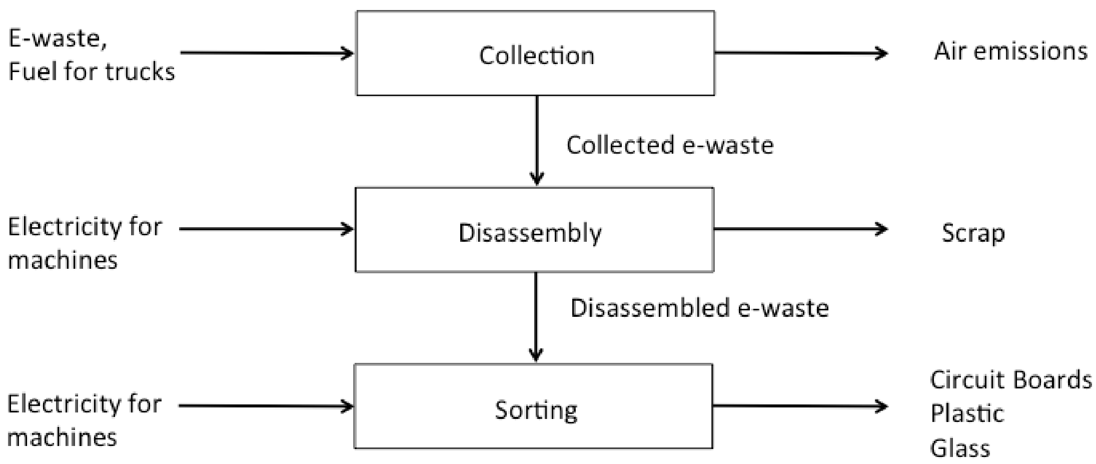
Example

- A simplified unit process of steel sheet rolling and examples of flows.



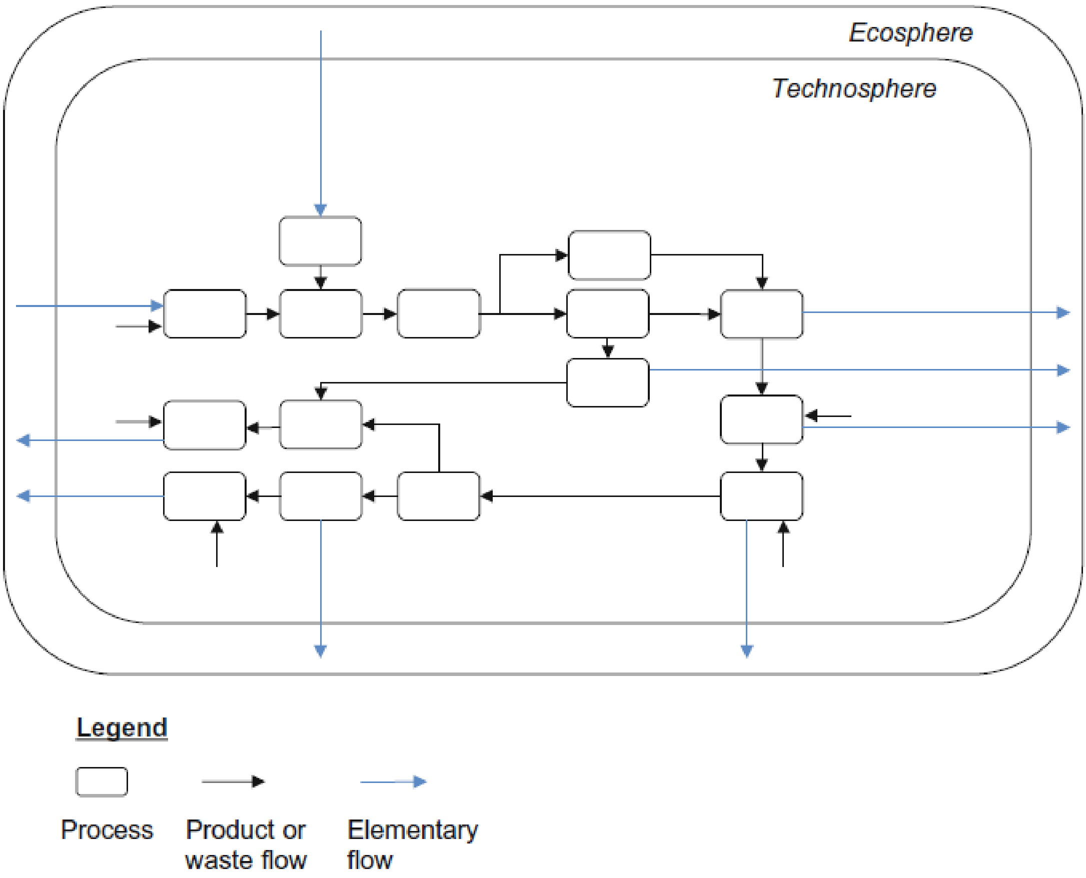
Example: e-Waste Management Product System

- The e-waste management product system comprises several unit processes including collection, disassembly, and sorting.



Technosphere and Ecosphere

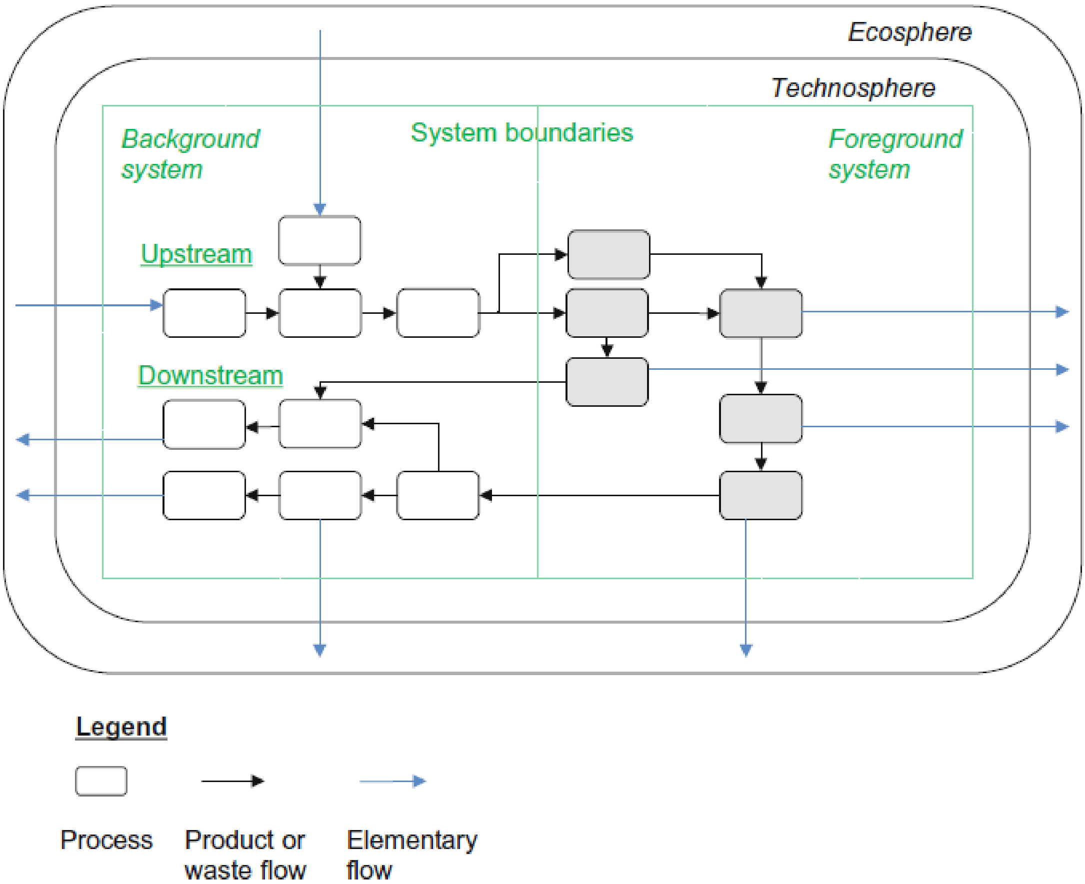
- LCA divides the world into a **technosphere** and an **ecosphere.**
  - The technosphere is everything that is intentionally "manmade" and also includes processes that are natural in origin, but manipulated by humans, such as photosynthesis when part of an agricultural system. All unit processes belong to the technosphere.
  - The ecosphere is sometimes referred to as "the environment". It is everything which is not intentionally "man-made" and contains those qualities that LCA has been designed to protect, i.e., ecosystems, human health, and resource availability.



Foreground and Background System

- The **foreground system** is commonly defined as comprising those processes of a product system that are specific to it.

- The **background system**, in contrast, is commonly defined as those processes of a system that are not specific to it. Such processes take part in numerous product systems besides the one studied.



Selection of Impact Categories

- Identify the relevant environmental impact categories that will be assessed.
- Some common impact categories are:

  1. **Climate change**: Assessing impacts related to greenhouse gas emissions (e.g., CO_2, CH_4) and their contribution to global warming and climate change.
  2. **Ozone depletion**: Evaluating impacts on the ozone layer caused by substances like chlorofluorocarbons (CFCs) and their effect on stratospheric ozone.
  3. **Acidification**: Measuring the contribution to acid rain through emissions of acidifying substances like sulfur dioxide (SO_2) and nitrogen oxides (NOx).
  4. **Eutrophication**: Assessing impacts related to excessive nutrient inputs (e.g., nitrogen and phosphorus) into ecosystems, leading to algal blooms, oxygen depletion, and ecosystem degradation.
  5. **Ecotoxicity**: Evaluating the potential for substances to harm ecosystems and wildlife, including acute and chronic effects on organisms.
  6. **Photochemical ozone formation**: Assessing contributions to the formation of ground-level ozone through chemical reactions involving nitrogen oxides (NOx) and volatile organic compounds (VOCs).
  7. **Depletion of resources**: Measuring the depletion of non-renewable resources such as minerals and fossil fuels, or the use of resources at rates exceeding their regeneration.
  8. **Water depletion**: Evaluating impacts related to the withdrawal of water resources from rivers, lakes, or aquifers, affecting water availability and ecosystems.
  9. **Land use**: Assessing impacts related to changes in land cover and land use patterns, including habitat loss, fragmentation, and degradation.
  10. **Human toxicity**: Evaluating impacts on human health through exposure to toxic substances, considering both carcinogenic and non-carcinogenic effects.

- The names of the categories in similar impact areas may differ depending on the life cycle impact analysis (LCIA) method used.
- Impact categories should be chosen based on the goals of the study, stakeholder interests, and relevance to the product or process being analysed.

Data Availability and Resources

- Specify the data needed and their requirements for the study.
- Assess the availability of the data and resources needed to conduct the LCA within the defined scope.
- Consider the time, expertise, and budget required to collect data, perform analyses, and interpret results.
- If certain data are unavailable or uncertain, consider sensitivity analysis or assumptions to address gaps in the data information uncertainty.

State Major Assumptions and Limitations

- Clearly state any assumptions made and limitations of the LCA, including data uncertainties, methodological choices, and constraints imposed by the scope.
- Transparency about assumptions and limitations helps ensure the credibility and reliability of the study results.

Stakeholders Consultation

- Consult with relevant stakeholders, including internal team members, industry experts, regulators, and end-users, to ensure that the scope of the LCA aligns with their interests and concerns.
- Stakeholder engagement can provide valuable insights, improve the relevance of the study, and enhance the credibility of the results.

3.2 Phase 2: Life Cycle Inventory Analysis

- The following steps can be used to conduct a thorough inventory analysis that provides valuable insights into the environmental impacts of a product, service, or process throughout its life cycle.

1. **Identify Life Cycle Stages in the Product System**

    - Break down the life cycle of the product, service, or process into distinct stages.
    - These stages typically include raw material extraction, manufacturing, distribution, use, and disposal.
    - Determine the boundaries of your analysis, including what activities and inputs/outputs will be included in each stage.

2. **Collect Data**

    - Gather data on inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) associated with each stage of the life cycle.
    - This may involve conducting surveys, consulting with experts, reviewing literature, or using databases.
    - Some useful databases:

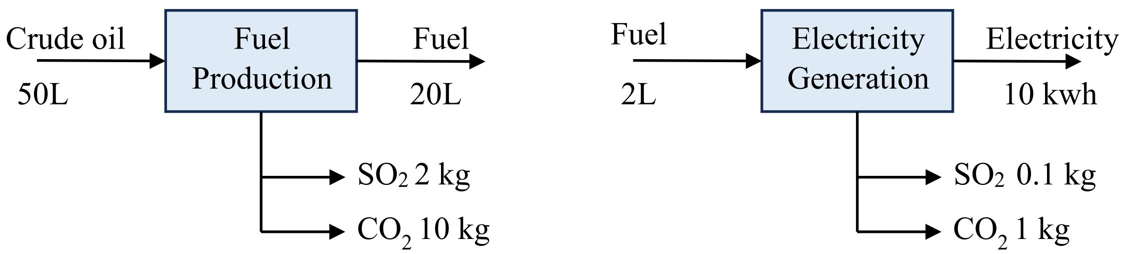
Source	Scale	Features
NEL	Process	Free database for the USA compiled by the National Renewable Energy Laboratory
GREET	Process	Free tool for assessing the life cycle of transportation fuels
Ecoinvent	Process	Commercial and comprehensive database for large number of processes and wide geographical coverage
NEI	Economic sectors	National emissions inventory of air pollutants. Compiled by the US Environmental Protection Agency
TRI	Economic sectors	Toxics release inventory. Compiled by the US Environmental Protection Agency
FAOstat	Nations	Data related to food and agriculture for many countries. Compiled by the Food and Agriculture Organization of the UN.

3. **Quantify Inputs and Outputs**

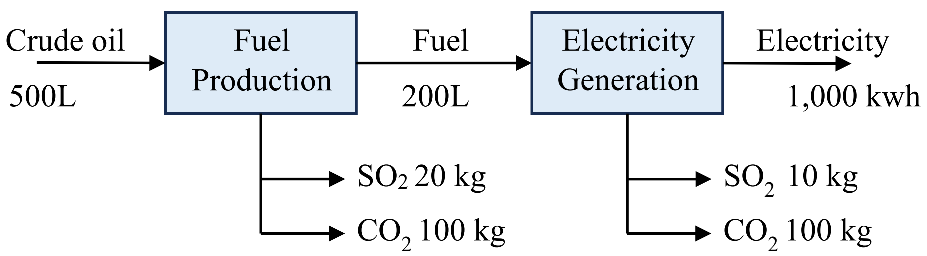
- Convert the collected data into quantitative measures.
- Determine the reference flows for all processes in the product system.
- Express product flows in terms of mass (kg) or volume (m^3), energy consumption in kWh, emissions in kg, etc.
- Ensure consistency in units across different types of inputs and outputs.

Example

- Consider a product system with 2 processes:
  1. 20 L of Fuel is produced from 50 L of Crude oil, emitting 2 kg of SO_2 and 10 kg of CO_2.
  2. 10 kWh of electricity is produced from 2 L of fuel, emitting 0.1 kg of SO_2 and 1 kg of CO_2.



- Let the functional unit be 1,000 kWh of electricity.
- The reference product and elementary flows for the two processes may be computed by finding the scaling factors required to produce the functional unit output.
  1. Scaling factor for Electricity generation = 1,000/10 = 100
  2. Scaling factor for Fuel production = 200/20 = 10



- Product reference flows are:
  1. Crude oil 500 L,
  2. Fuel 200 L
  3. Electricity 1,000 kWh.

- Elementary reference flows are:
    1. Fuel production 20 kg SO_2, 100 kg CO_2
    2. Electricity generation 10 kg SO_2, 100 kg CO_2
- Total inventory:

  SO_2 emissions: 20 + 10 = 30 kg SO_2

  CO_2 emissions: 100 + 100 = 200 kg CO_2

4. Compile Life-Cycle Inventory Tables

- Organize the quantified data into inventory tables
- Systematic organization of the tables with correct ordering of entries and shapes can facilitate matrix multiplications later in impact analysis.
- These inventory tables should provide a comprehensive overview of the inputs and outputs associated with the entire life cycle.

5. Iterative Process

- Life cycle inventory analysis is an iterative process.
- As new data becomes available or as the scope of the analysis evolves, update the inventory accordingly and refine the analysis to improve accuracy and relevance.

3.3 Phase 3: Life Cycle Impact Assessment (LCIA)

3.3.1 Purpose and Structure

- The LCIA phase evaluates the significance of potential environmental impacts using the results of the life cycle inventory (LCI) analysis of the previous phase.

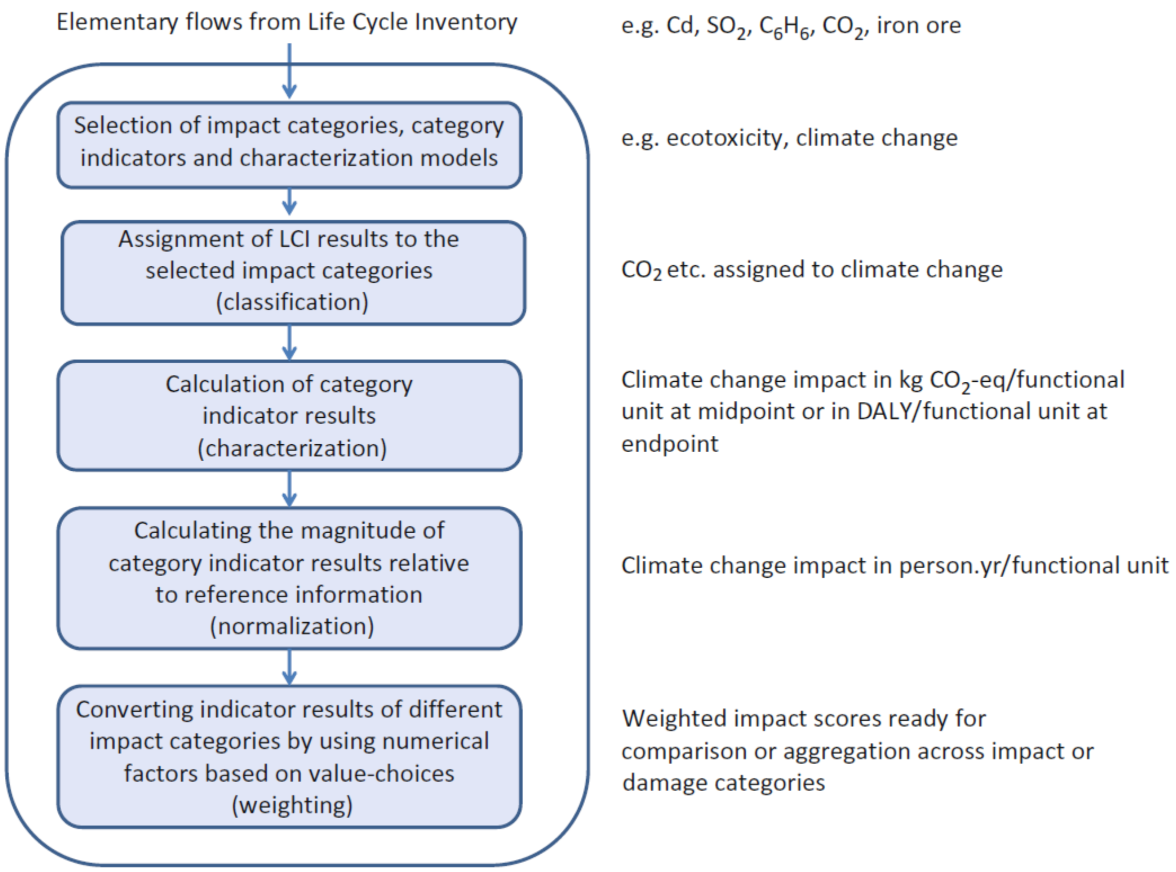
- This process involves associating inventory data with specific environmental impacts and attempting to understand those impacts and translating them into environmental impact scores.

- Ultimately, the results should lead to an understanding of the product's potential impacts in the following three areas of protection:

  1. Human health
  2. Ecosystem quality
  3. Resource scarcity

- The level of detail, choice of impacts evaluated, and methodologies used depends on the goal and scope of the study.

- The LCIA phase comprises three compulsory and two optional steps:



3.3.2 Impact Categories and Category Indicators

- ISO only describes the procedure and does not specify a specific list of impact categories, methodologies, or models for conducting LCIA.

- Organizations are free to conduct this phase of the assessment in accordance with the goal of the study.

Selection of Impact Categories

- The LCI results from the previous phase are to be mapped into contributions to relevant impact categories.

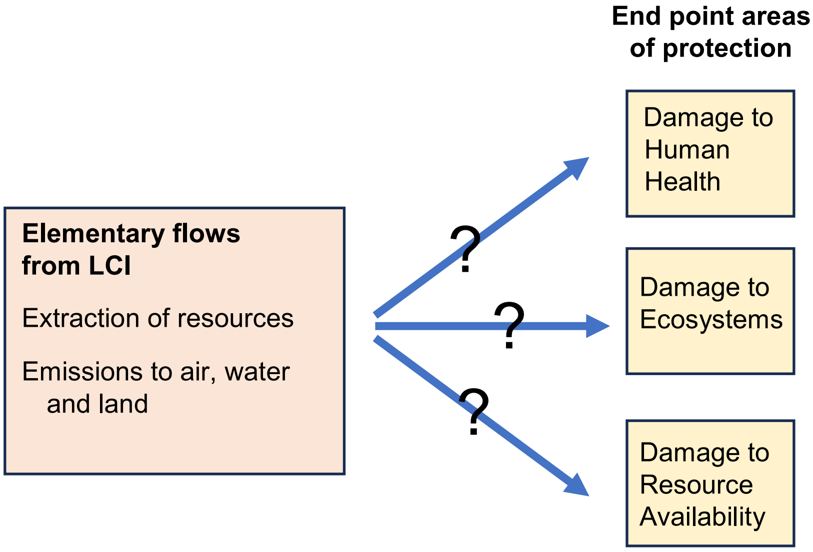
- There are different ways of defining impact categories.

Midpoint verse Endpoint Indicators

- Direct characterization from the product's life cycle elementary flows directly to the end point areas of protection is highly complex and difficult to achieve scientifically.

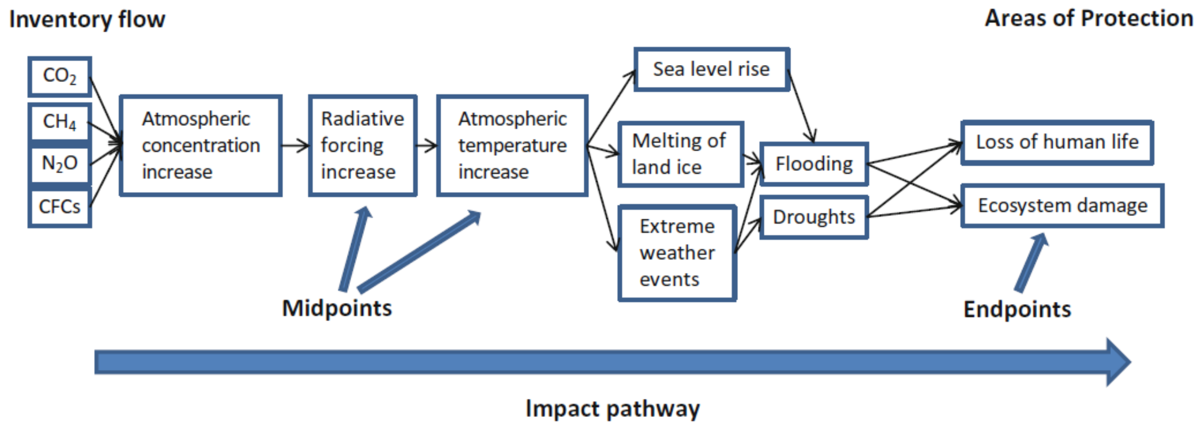
- Sustainable development must aim to protect the following 3 main areas:
  1. Human Health
  2. The Ecosystem
  3. Earth Resources

- Direct characterization from the elementary flows of a product system to the end point areas of protection is difficult to achieve both scientifically and accurately.



- However, the ultimate impacts on areas of protection can be studied scientifically through various indirect impact pathways.

- For example, a simplified impact pathway for global warming connecting elementary flows from the life cycle inventory to the areas of protection is shown below:



Midpoint Indicators

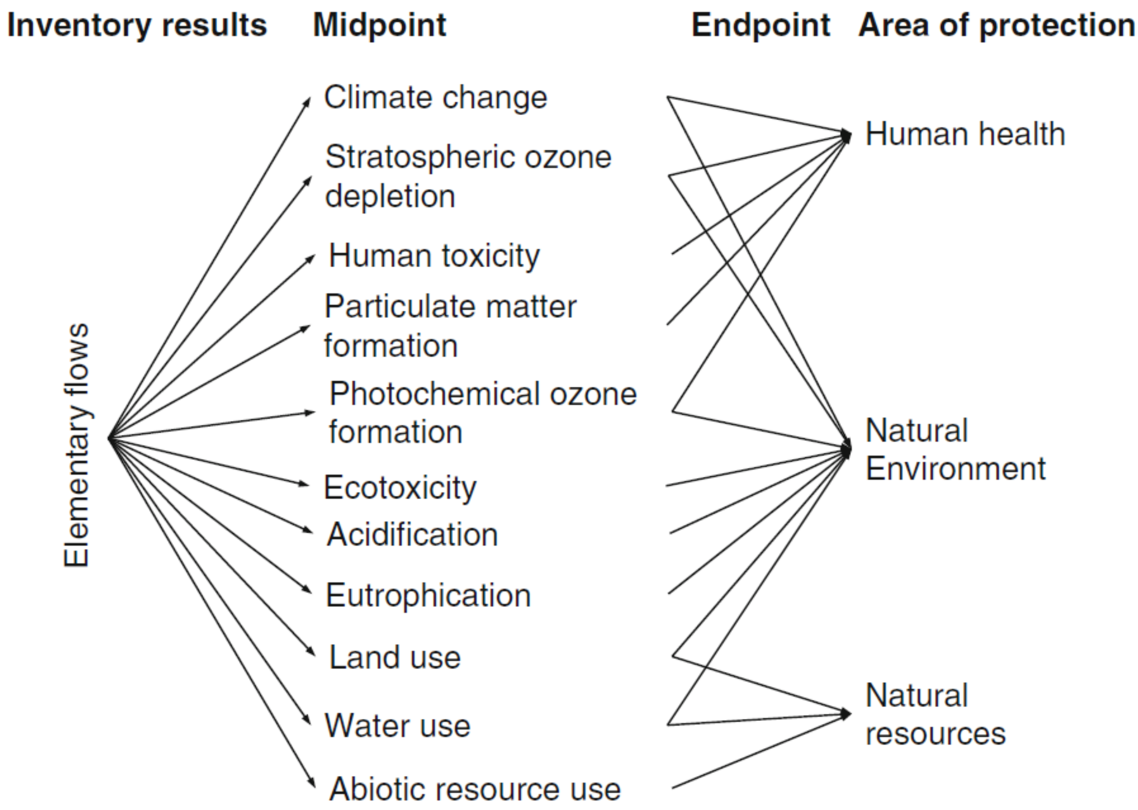
- An indicator that is chosen to represent an impact category can be located anywhere along the impact pathway linking inventory data through consecutive environmental impacts to the damage that they cause on the areas of protection.

- Midpoint indicators are located somewhere along the impact pathway, ideally at the point after which the mechanism is identical for all flows assigned to that impact category.

- With this location of the midpoint indicator, the flows will have different midpoint characterization factors, while their mid-to-endpoint characterization factor is the same.

- Characterization at the endpoint level requires modelling of the whole impact pathway to the point where the impacted entities are the areas of protection.

- Endpoint characterization modelling is sometimes also referred to as ‘damage modelling’.


Inventory results
Midpoint
Endpoint
Area of protection
Elementary flows
Climate change
Stratospheric ozone depletion
Human toxicity
Particulate matter formation
Photochemical ozone formation
Ecotoxicity
Acidification
Eutrophication
Land use
Water use
Abiotic resource use
Human health
Natural Environment
Natural resources

3.3.3 Characterization Models

CML-IA baseline model

- Developed in the mid-1990s by the Institute of Environmental Sciences (CML) at Leiden University as part of efforts to standardize Life Cycle Impact Assessment (LCIA) practices in Europe.

- Established a set of impact assessment methods and characterization factors to standardize impact assessment practices, providing a consistent and widely accepted framework for calculating environmental impacts.

- The baseline version includes a core set of impact categories and midpoint indicators that are commonly used and well-established in environmental research.

- CML-IA baseline impact categories are:

	Impact Category	Abbreviation	Unit	Description
1	Global Warming Potential (100 years)	GWP100	kg CO_2-eq	Contribution to climate change from greenhouse gas emissions.
2	Ozone Layer Depletion Potential	ODP	kg CFC-11-eq	Depletion of stratospheric ozone by halogenated substances.
3	Human Toxicity Potential	HTP	kg 1,4-DB-eq	Harm to human health from chemical emissions.
4	Freshwater Aquatic Ecotoxicity Potential	FAETP	kg 1,4-DB-eq	Toxic effects on freshwater organisms.
5	Marine Aquatic Ecotoxicity Potential	MAETP	kg 1,4-DB-eq	Toxic effects on marine organisms.
6	Terrestrial Ecotoxicity Potential	TETP	kg 1,4-DB-eq	Toxic effects on terrestrial organisms.
7	Photochemical Oxidant Formation Potential	POFP	kg ethene-eq	Formation of ground-level ozone (smog).
8	Acidification Potential	AP	kg SO_2-eq	Acidification of soils and water by airborne substances.
9	Eutrophication Potential	EP	kg PO_4^{3-}-eq	Nutrient enrichment causing excessive biomass growth (e.g., algae).
10	Abiotic Depletion Potential (Elements)	ADP-elements	kg Sb-eq	Depletion of mineral resources.
11	Abiotic Depletion Potential (Fossil Fuels)	ADP-fossil	MJ	Depletion of fossil fuel energy resources.

- CML method has been updated several times and the latest version is reported in *CML 2001 – A Baseline for LCIA* by Guinée et al. (2002).

- CML IA is superseded by ReCiPe.

Eco-indicator 99 method

- The **Eco-indicator 99 (EI99)** method is an **LCIA methodology** developed by **PRé Consultants** (Netherlands) in 1999.

- The purpose is to translate environmental impacts of products and processes into a **single score** reflecting potential damage to human health, ecosystems, and resource availability.

- EI99 provides characterizations for both endpoint and midpoint impact categories:

	Endpoint Category	Description
1	Human Health	Damage caused by diseases, accidents, or chemical exposure (measured in DALYs).
2	Ecosystem Quality	Loss of biodiversity due to acidification, ecotoxicity, or land use.
3	Resource Depletion	Increased energy required to extract future resources (mineral and fossil).

	Midpoint Category	Description
1	Carcinogens	Air, water, and soil emissions causing cancer
2	Respiratory organics	Smog and VOCs impacting respiratory health
3	Respiratory inorganics	PM_{10}, SO_2, NO_x causing respiratory issues
4	Climate change	Greenhouse gas emissions (CO_2, CH_4, etc.)
5	Radiation	Ionizing radiation exposure
6	Ozone layer depletion	Emissions leading to stratospheric ozone damage
7	Ecotoxicity	Toxic effects on ecosystems
8	Acidification/Eutrophication	Soil and water quality degradation
9	Land use	Biodiversity loss and ecosystem disturbance
10	Minerals depletion	Use of non-renewable mineral resources
11	Fossil fuels depletion	Use of coal, oil, gas

- EI99 performs **Damage Assessments** as follows:

  Characterization

  - Converts midpoints to damage in:
    1. DALY (Disability Adjusted Life Years) for Human Health
    2. PDF·m²·yr (Potentially Disappeared Fraction of species per m² per year) for Ecosystems
    3. MJ Surplus Energy for Resources

  Normalization

  - Compares impacts to a reference value (e.g., per capita EU impact in a year).

  Weighting

  - Combines endpoint scores using value choices. EI99 offers three perspectives:
    1. Egalitarian: Precautionary, long-term perspective
    2. Hierarchist (default): Balanced, consensus-based
    3. Individualist: Short-term, optimistic assumptions

  Results

  - A Single Score (Eco-indicator Points) where 1 Pt = 1/1000 of the annual environmental load of one European.

- EI99 is superseded by ReCiPe.

ReCiPe 2016

- The **ReCiPe2016** LCIA method is an evolution of earlier LCIA methodologies, particularly **CML-IA** and **Eco-Indicator 99 (EI99)**.

Year	Method	Type	Key Contribution
1992	CML-IA	Midpoint	Scientific modeling of environmental flows
1999	EcoIndicator99	Endpoint	Value-based impact aggregation
2008	ReCiPe 2008	Midpoint + Endpoint	Integration of CML and EI99 approaches
2016	ReCiPe2016	Midpoint + Endpoint	Updated models, global scope, more precise data

Comparison of ReCiPe 2008 and ReCiPe 2016 Midpoint Categories

Impact Category	ReCiPe 2008	ReCiPe 2016	Notes / Changes
Climate change – Human health	✓	✓	Updated GWP factors (IPCC AR5 in 2016)
Climate change – Ecosystems	✓	✓	Treated separately for better ecosystem impact modeling
Ozone depletion	✓	✓	Refined model, same general approach
Terrestrial acidification	✓	✓	Minor updates to spatial and emission models
Freshwater eutrophication	✓	✓	Improved phosphorus fate model
Marine eutrophication	✓	✓	Nitrogen-based modeling enhanced
Photochemical ozone formation	✓	✓	Renamed from 'Smog formation'
Particulate matter formation	✓	✓	Improved health impact modeling
Ionizing radiation – Human health	✓	✓	Updated with UCL radiation model
Terrestrial ecotoxicity	✓	✓	Updated with USEtox v2.02
Freshwater ecotoxicity	✓	✓	USEtox v2.02 applied
Marine ecotoxicity	✓	✓	Still under discussion; included for completeness
Human toxicity – Cancer effects	✓	✓	Based on updated USEtox model
Human toxicity – Non-cancer effects	✓	✓	Explicitly separated for greater clarity
Land use	✓	✓	Improved biodiversity and soil quality modeling
Mineral resource scarcity	✓ (as depletion)	✓	Renamed from 'Mineral depletion'
Fossil resource scarcity	✓ (as depletion)	✓	Renamed from 'Fossil depletion'
Water consumption	✗	✓	New category using regional scarcity models (e.g., AWARE)

- Overview of the impact categories that are covered in the ReCiPe2016 method and their relation to the areas of protection:

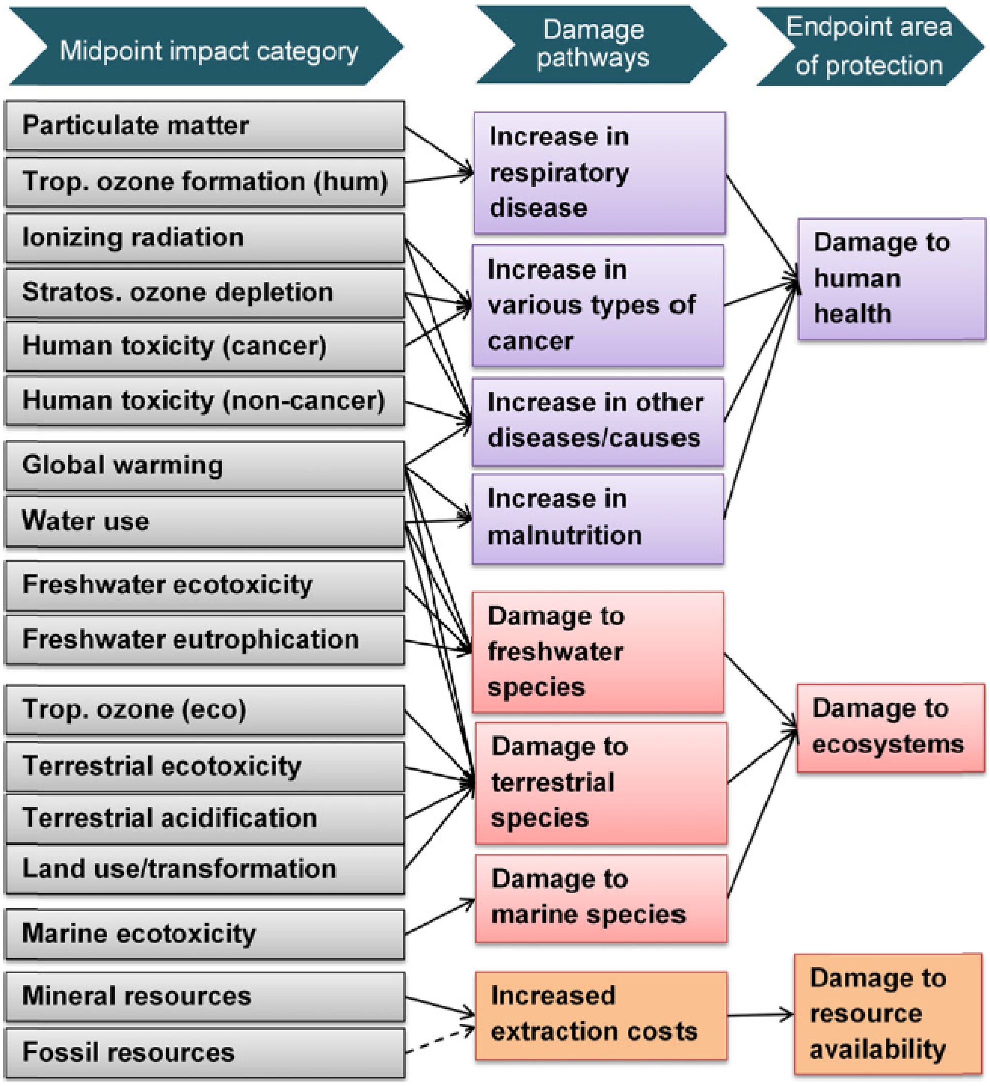


Table 1 Overview of the midpoint impact categories and related indicators

Midpoint impact category	Indicator	CF_m	Unit	Key references
Climate change	Infrared radiative forcing increase	Global warming potential (GWP)	kg CO_2-eq to air	IPCC 2013; Joos et al. 2013
Ozone depletion	Stratospheric ozone decrease	Ozone depletion potential (ODP)	kg CFC-11-eq to air	WMO 2011
Ionising radiation	Absorbed dose increase	Ionising radiation potential (IRP)	kBq Co-60-eq to air	Frischknecht et al. 2000
Fine particulate matter formation	PM2.5 population intake increase	Particulate matter formation potential (PMFP)	kg PM2.5-eq to air	Van Zelm et al. 2016
Photochemical oxidant formation: terrestrial ecosystems	Tropospheric ozone increase	Photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-eq to air	Van Zelm et al. 2016
Photochemical oxidant formation: human health	Tropospheric ozone population intake increase	Photochemical oxidant formation potential: humans (HOFP)	kg NOx-eq to air	Van Zelm et al. 2016
Terrestrial acidification	Proton increase in natural soils	Terrestrial acidification potential (TAP)	kg SO_2-eq to air	Roy et al. 2014
Freshwater eutrophication	Phosphorus increase in freshwater	Freshwater eutrophication potential (FEP)	kg P-eq to freshwater	Helmes et al. 2012
Human toxicity: cancer	Risk increase of cancer disease incidence	Human toxicity potential (HTPc)	kg 1,4-DCB-eq to urban air	Van Zelm et al. 2009
Human toxicity: non-cancer	Risk increase of non-cancer disease incidence	Human toxicity potential (HTPnc)	kg 1,4-DCB-eq to urban air	Van Zelm et al. 2009
Terrestrial ecotoxicity	Hazard-weighted increase in natural soils	Terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-eq to industrial soil	Van Zelm et al. 2009
Freshwater ecotoxicity	Hazard-weighted increase in freshwaters	Freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-eq to freshwater	Van Zelm et al. 2009
Marine ecotoxicity	Hazard-weighted increase in marine water	Marine ecotoxicity potential (METP)	kg 1,4-DCB-eq to marine water	Van Zelm et al. 2009
Land use	Occupation and time-integrated land transformation	Agricultural land occupation potential (LOP)	$m^2 \times$ yr annual cropland-eq	De Baan et al. 2013; Curran et al. 2014
Water use	Increase of water consumed	Water consumption potential (WCP)	m^3 water-eq consumed	Döll and Siebert 2002; Hoekstra and Mekonnen 2012
Mineral resource scarcity	Increase of ore extracted	Surplus ore potential (SOP)	kg Cu-eq	Vieira et al. 2016a
Fossil resource scarcity	Upper heating value	Fossil fuel potential (FFP)	kg oil-eq	Jungbluth and Frischknecht 2010

3.3.4 Classification

- Classification is the first quantitative element of LCIA
- The life cycle inventory results are organized such that they map into the frameworks of the relevant impact category frameworks chosen for the study.
- Classification involves copying your inventory items into a number of different piles, where each pile is associated with one of the impact categories used by the selected LCIA methods.

Example

- If a study has selected climate change as an impact category, then the *carbon dioxide* (CO_2) emissions from the LCI would be classified into that pile since it is a greenhouse gas.
- In addition, Methane (CH_4) and Nitrous oxide (N_2O) are also relevant and would also be classified into the pile for climate change.
- The following is a simplified list of substances relevant to climate change.

Climate Change Characterization Factors (CML 2016 - GWP100)

Greenhouse Gas	GWP100 (kg CO_2-eq/kg)
Carbon dioxide (CO_2)	1.0
Methane (CH_4), fossil	28.0
Methane (CH_4), biogenic	28.0
Nitrous oxide (N_2O)	265.0
Hydrofluorocarbons (HFCs)	12 – 14,800
Perfluorocarbons (PFCs)	7,000 – 12,000
Sulfur hexafluoride (SF_6)	23,500
Carbon monoxide (CO)	1.57
Non-methane volatile organic compounds (NMVOCs)	1.57

- The following is a simplified list of substances relevant to acidification potential.

Acidification Potential Characterization Factors (CML 2016)

Substance	AP (kg SO_2-eq/kg)
Sulfur dioxide (SO_2)	1.0
Sulfur trioxide (SO_3)	0.77
Hydrogen chloride (HCl)	0.88
Hydrogen fluoride (HF)	1.60
Ammonia (NH_3)	1.88
Nitrogen oxides (NOx as NO_2)	0.70
Nitric acid (HNO_3)	0.50
Hydrochloric acid (HCl)	0.88
Hydrosulfuric acid (H_2S)	1.20

- The following is a simplified list of substances relevant to Freshwater Ecotoxicity

Freshwater Ecotoxicity Characterization Factors (CML 2016)

Substance	FAETP (kg DCB-eq/kg)
Zinc	3.20
Nickel	59.0
Cadmium	2,600.0
Mercury	18,000.0
Copper	14.0
Lead	42.0
Arsenic	610.0
Chromium (VI)	320.0
Silver	160.0
Cyanide	1.10

3.3.5 Characterization

- The purpose of characterization is to apply scientific knowledge of relative impacts such that all classified elementary flows for an impact can be converted into common units for comparison.

- This is done by the quantitative transformation of each set of classified inventory flows for an impact category via **characterization factors** (also called equivalency factors) to create the category's impact indicators.

- The equation is

  Characterized flow = flow * characterization factor

Example

- Suppose the inventory flows are:
  CO_2 20 kg
  CH_4 5 kg

- Under the impact category, Climate Change, the characterization factor for CO_2 is

  = 1 (kg CO_2 eq / kg CO_2)

- Then the characterized flow for CO_2 inventory flow under Climate Change is

  = 20 kg CO_2 × 1 (kg CO_2 eq / kg CO_2)
  = 20 kg CO_2 eq

- Under the impact category, Climate Change, the characterization factor for CH_4 is

  = 28 (kg CH_4 eq / kg CH_4)

- Then the characterized flow for CH_4 inventory flow under Climate Change is

  = 5 kg CH_4 × 28 (kg CO_2 eq / kg CH_4)
  = 140 kg CO_2 eq

Impact Category Indicator

- The Impact Category Indicator can be computed by adding up the characterized flows of all the relevant elementary flows, as they are all in the same unit.

Example

- If CO_2 and CH_4 were the only elementary flows, then the impact indicator for Climate Change is
  = 20 kg CO_2 eq + 140 kg CO_2 eq
  = 160 kg CO_2 eq

3.3.6 Normalization (Optional)

- Normalize the impact scores to facilitate comparison between different impact categories or between different products, services, or processes.

- Normalization involves expressing impact scores relative to a reference value, such as per unit of functional output (e.g., per kilogram of product, per megajoule of energy) or per capita.

3.3.7 Weighting (Optional)

- Optionally, apply weighting factors to the normalized impact scores to reflect the relative importance of different impact categories based on stakeholder preferences or policy priorities.

- Weighting allows you to aggregate the impacts into a single score or indicator that represents overall environmental performance.

- However, weighting is a subjective process and should be used with caution. Proper use of MCDM methods can avoid this problem.

3.4 Phase 4: Interpretation

1. **Review the Results**

   - Start by reviewing the quantitative results of the LCA, including the environmental impacts assessed in different impact categories (e.g., global warming potential, acidification, eutrophication) and their magnitudes across various life cycle stages.

2. **Identify Hotspots**

   - Identify hotspots where the largest environmental impacts occur.
   - These hotspots may represent specific processes, materials, or life cycle stages that contribute disproportionately to overall environmental burdens.
   - Focus on addressing hotspots to achieve the greatest environmental improvements.

3. **Compare Alternatives**

   - If comparing multiple products, services, or processes, compare their environmental performance across different impact categories and life cycle stages.
   - Identify areas of relative strength and weakness for each alternative to inform decision-making and prioritize areas for improvement.

4. **Consider Trade-offs**

   - Recognize that environmental improvements in one impact category or life cycle stage may lead to trade-offs in others.
   - For example, reducing greenhouse gas emissions may increase water consumption or toxicity.
   - Consider trade-offs carefully and strive for holistic solutions that minimize overall environmental impacts.

5. **Contextualize Results**

   - Consider the context in which the LCA results are interpreted.
   - Consider factors such as the scale of production, geographic location, technological advancements, regulatory requirements, and stakeholder preferences.
   - Contextualization ensures that the interpretation is relevant and actionable.

6. **Sensitivity Analysis**

- Assess the sensitivity of the results to uncertainties or variations in individual input parameters via one-way sensitivity analysis.

- Identify key parameters that have the greatest influence on the outcomes and explore alternative scenarios or assumptions to understand their implications.

- Two-way sensitivity analysis can also be performed if the impacts of some parameters on the inventory results are not independent.

- Sensitivity analysis enhances the robustness and reliability of the interpretation.

7. **Engage Stakeholders**

- Involve relevant stakeholders, including internal team members, industry partners, regulators, and consumers, in the interpretation process.

- Seek input and feedback to ensure that the interpretation reflects diverse perspectives and priorities.

- Stakeholder engagement fosters buy-in and support for implementing LCA recommendations.

8. **Set Priorities for Improvement**

- Based on the interpretation of the LCA results, prioritize areas for improvement that offer the greatest potential for environmental benefits and align with organizational goals and objectives.

- Develop action plans and strategies to address identified hotspots and capitalize on opportunities for innovation and optimization.

9. **Document Findings and Recommendations**

- Document the interpretation of LCA results, including key findings, insights, recommendations, and decision-making criteria.

- Communicate the implications of the LCA to stakeholders through reports, presentations, and discussions, ensuring transparency and accountability.

4 Strengths, Limitations and Applications of LCA

4.1 Strengths and Features

- LCA provides a comprehensive, holistic analysis leading to solutions for reducing impacts in an absolute and not a relative way. It models cause-effect relationships in the environment and thus helps to understand the environmental consequences of human actions.

- LCA has four features:
  1. it takes a life cycle perspective (Cradle-to-Grave)
  2. it can cover a broad range of environmental issues
  3. is quantitative
  4. is science-based

- Although LCA is primarily quantitative, qualitative aspects can be taken into account to provide a more complete picture of the environmental impacts involved.

- The life cycle perspective avoids shifting the environmental problem of a product from one stage to another stage in the product's life cycle.

- LCA is now a highly regarded framework for assessing the potential environmental impacts of products. It assesses quantitatively the environmental impacts of goods and processes from cradle to grave.

- LCA can play a useful role in both public and private environmental management of products. The main applications of LCA are

  1. Analysing the root problems related to a particular product.
  2. Comparing improvement variants of a given product.
  3. Development of new products.
  4. Comparison between existing products.
  5. Comparison between the existing and the new product under development.

4.2 Limitations

- The holistic nature of LCA is both a major strength and, at the same time, a limitation. The broad scope of analysing the complete life cycle of a product can only be achieved at the expense of simplifying other aspects.

- LCA does not provide the framework to adequately address localised impacts. It focuses on the impacts on the environment outside the system boundary.

- LCA takes a steady-state view of the system. It does not consider the transient states or the system dynamics.

- LCA focuses on the physical characteristics of industrial activities and other economic processes. It does not include market mechanisms or secondary effects on technological development.

- LCA assumes and models all processes as linear in behaviour, both in the economy and in the environment. It assumes constant returns to scale on all processes and ignores any economies of scale.

- LCA focuses mainly on the environmental aspects of products, and says nothing about their economic, social and other characteristics. The “potential impacts” are not specified in time and space and are often related to an arbitrarily defined functional unit.

- LCA is highly dependent on data. It can be limited by the availability of up-to-date, accurate data at the correct level of detail.

- LCA cannot replace the entire decision-making process. It is a very useful analytical tool that provides information for decision support. It may be necessary to combine LCA with other methodologies:

- Other methodologies that can be used together with LCA:
    - Life Cycle Costing (LCC)
    - Multiple Criteria Decision Making (MCDM)
    - Multiple Objective Optimization (MOP)
    - Data Envelopment Analysis (DEA)
    - Environmental Input-Output Analysis (EIOA)

4.3 Applications

- Here are some applications of LCA at different levels with different goals and objectives.

1	Global exploration of options	LCA is performed to get a first impression of the environmental effect of certain options.
2	Company internal innovation	LCA is performed to assess the environmental impact of company internal product improvements, product development and technical innovations.
3	Sector-driven innovation	Similar to the above, except that it is sector-oriented in a formal organization representing a group of companies.
4	Strategic planning	LCA is performed to assess the environmental impact of strategic scenarios.
5	Comparison	LCA is performed to assess whether a product or system meets certain environmental standards or whether it is environmentally sounder than another product or system.
6	Comparative assertion disclosed to the public	LCA aims to provide an environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function.

Source: Handbook on life cycle assessment.

LCA as a Decision Support Tool

- LCA allows companies and organizations to make informed decisions to minimize environmental impacts, optimize resource efficiency, and reduce the carbon footprint of their products or activities.

- LCA provides an important and effective decision-support tool, among other things, that allows:

  1. Companies to benchmark and optimize the environmental performance of products.

  2. Authorities to design and implement policies for sustainable consumption and production.

  3. Stakeholders to compare all major environmental impacts caused by products, processes, or services and decide between sustainable alternatives.

- However, it should also be emphasized that LCA provides only one perspective and can be used with other factors such as life cycle cost (LCC) and technical performance data to select a product or process that represents the best trade-offs between the major factors.

5 Case Studies

5.1 Case Study 1: LCA study of a 1-Liter Polyethylene Plastic Bottle

- This study evaluates the environmental impacts associated with the production, use, and disposal of a 1-liter polyethylene (PE) plastic bottle.
- The analysis follows the ISO 14040 and ISO 14044 standards and uses the CML-IA methodology to assess various environmental impacts.

Phase 1: <u>Goal and Scope Definition</u>

Goal and Objectives

- To assess the environmental impacts of producing, using, and disposing of a 1-liter Polyethylene bottle filled with drinking water.
- The study also aims to identify hotspots in the life cycle and suggest improvements for reducing environmental impacts.

Functional Unit

- One 1-liter Polyethylene Plastic bottle filled with drinking water.

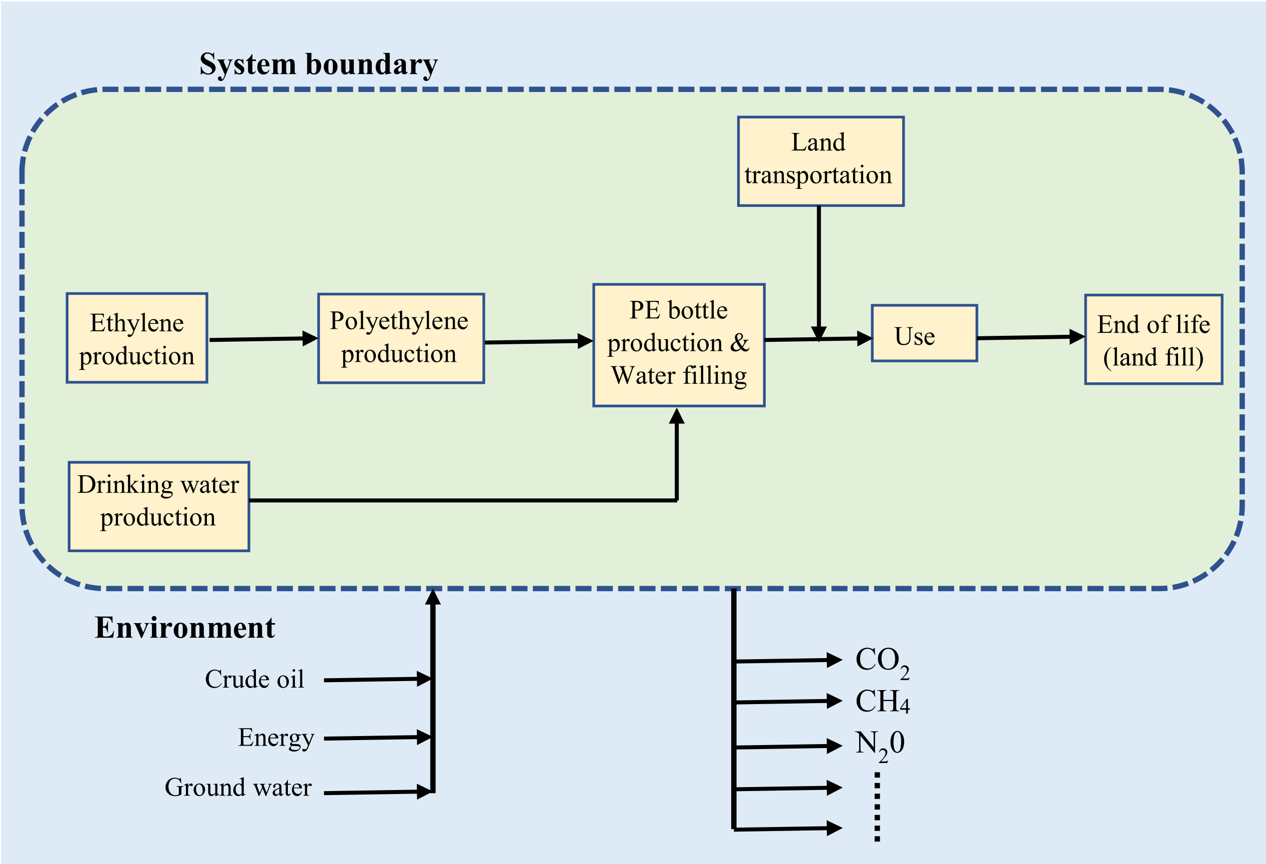
System Boundaries

- The following life cycle stages will be included:

  1. Production of Ethylene from petroleum
  2. Production of Polyethylene from ethylene
  3. Production of Drinking water
  4. Production of PE Bottles and water filling
  5. Transportation to retailers
  6. Usage
  7. End-of-Life (land fill)

- The environmental impact during the usage of the bottles by the user will be excluded.
- The product will be land transported 1,000 km to retail stores.

Product System Diagram



Phase 2: Life Cycle Inventory (LCI) Analysis

Unit Processes Data

Ethylene Production

	Input	Unit	Quantity
1	Crude oil	kg	1.450E+00
2	Energy	MJ	3.126E+01
3	Ground water	Kg	0
	Output		
P1	**Ethene (ethylene)**	kg	1
1	Carbon dioxide	kg	1.157E+00
2	Methane	kg	7.513E-03
3	Nitrogen dioxide	kg	2.119E-03
4	Nitrogen monoxide	kg	1.527E-11
5	Sulfur dioxide	kg	2.514E-03
6	VOC to air	kg	1.637E-06
7	VOC to water, fresh	kg	1.025E-07

Polyethylene Granulates Production

	Input	Unit	Quantity
P1	Ethene (ethylene)	kg	8.500E-01
1	Crude oil	kg	0
2	Energy	MJ	2.740E+01
3	Ground water	Kg	0
	Output		
P2	**Polyethylene granulates**	kg	1
1	Carbon dioxide	kg	1.567E+00
2	Methane	kg	1.420E-02
3	Nitrogen dioxide	kg	3.230E-03
4	Nitrogen monoxide	kg	0.000E+00
5	Sulfur dioxide	kg	4.077E-03
6	VOC to air	kg	1.464E-04
7	VOC to water, fresh	kg	9.948E-06

Drinking water production

	Input	Unit	Quantity
1	Crude oil	kg	0
2	Energy	MJ	1.302E-02
3	Ground water	kg	1.020E+00
	Output		
P3	Water, drinking	kg	1.000
1	Carbon dioxide	kg	5.549E-04
2	Methane	kg	6.089E-07
3	Nitrogen dioxide	kg	1.124E-06
4	Nitrogen monoxide	kg	6.264E-16
5	Sulfur dioxide	kg	6.046E-07
6	VOC to air	kg	4.700E-10
7	VOC to water, fresh	kg	1.943E-12

Bottle production + Water filling

	Input	Unit	Quantity
P3	Drinking Water	kg	1
P2	Polyethylene granulates	kg	4.000E-02
1	Crude oil	kg	0
2	Energy	MJ	3.000E+00
3	Ground water	Kg	0
	Output		
P4	Bottled water, at factory	item	1
1	Carbon dioxide	kg	9.000E-02
2	Methane	kg	5.000E-09
3	Nitrogen dioxide	kg	3.000E-09
4	Nitrogen monoxide	kg	5.000E-09
5	Sulfur dioxide	kg	8.000E-09
6	VOC to air	kg	2.000E-07
7	VOC to water, fresh	kg	2.000E-08

Land Transportation to Retailers

	Input	Unit	Quantity
1	Crude oil	kg	3.180E-02
2	Energy	MJ	8.702E-01
3	Ground water	Kg	0
	Output		
P5	**Land transport**	t*km	1
1	Carbon dioxide	kg	6.396E-02
2	Methane	kg	6.249E-05
3	Nitrogen dioxide	kg	5.387E-04
4	Nitrogen monoxide	kg	1.390E-13
5	Sulfur dioxide	kg	3.415E-05
6	VOC to air	kg	1.223E-08
7	VOC to water, fresh	kg	1.351E-09

Landfill of Plastic Wastes

	Input	Unit	Quantity
1	Crude oil	kg	0
2	Energy	MJ	5.606E-01
3	Ground water	Kg	0
	Output		
P6	**Landfill of plastic waste**	kg	1
1	Carbon dioxide	kg	6.102E-02
2	Methane	kg	3.562E-04
3	Nitrogen dioxide	kg	1.531E-04
4	Nitrogen monoxide	kg	3.855E-13
5	Sulfur dioxide	kg	1.301E-04
6	VOC to air	kg	2.544E-05
7	VOC to water, fresh	kg	1.378E-09

Computation of Product Reference Flows

Functional Unit = 1 one-liter PE bottle filled with drinking water.

1 PE bottle weights **0.040 kg**

Polyethylene granulates required = **0.040 kg**

Ethylene required = 0.85 × 0.04 = **0.034 kg**

1 litre drinking water = **1 kg**

Ground water drawn from environment = 1.0196 × 1 = **1.0196 kg**

Transportation distance = 100 km

Mass transported = mass of bottle + mass of water
= 0.040 kg + 1 kg
= 1.040 kg

Transportation required = (1.040 × 10^{-3} ton) × (100 km) = **0.1040 t*km**

Product and Elementary Reference Flows

Ethylene Production

Scaling factor = 0.0340 / 1 = 0.034

	Input	Unit	Unit process flow	Reference flow
1	Crude oil	kg	1.450E+00	4.930E-02
2	Energy	MJ	3.126E+01	1.063E+00
3	Ground water	kg	0	0
	Output			
P1	**Ethene (ethylene)**	kg	1	0.0340
1	Carbon dioxide	kg	1.157E+00	3.933E-02
2	Methane	kg	7.513E-03	2.554E-04
3	Nitrogen dioxide	kg	2.119E-03	7.205E-05
4	Nitrogen monoxide	kg	1.527E-11	5.192E-13
5	Sulfur dioxide	kg	2.514E-03	8.548E-05
6	VOC to air	kg	1.637E-06	5.565E-08
7	VOC to water, fresh	kg	1.025E-07	3.485E-09

Polyethylene Granulate Production

Scaling factor = 0.040 / 1 = 0.040

	Input	Unit	Unit process flow	Reference flow
P1	Ethene (ethylene)	kg	8.500E-01	0.034
1	Crude oil	kg	0	0
2	Energy	MJ	2.740E+01	1.096E+00
3	Ground water	kg	0	0
	Output			
P2	**Polyethylene granulates**	kg	1	0.040
1	Carbon dioxide	kg	1.567E+00	6.267E-02
2	Methane	kg	1.420E-02	5.679E-04
3	Nitrogen dioxide	kg	3.230E-03	1.292E-04
4	Nitrogen monoxide	kg	0.000E+00	0.000E+00
5	Sulfur dioxide	kg	4.077E-03	1.631E-04
6	VOC to air	kg	1.464E-04	5.855E-06
7	VOC to water, fresh	kg	9.948E-06	3.979E-07

Drinking Water Production

Scaling factor = 1 / 1 = 1

	Input	Unit	Unit process flow	Reference flow
1	Crude oil	kg	0	0
2	Energy	MJ	1.302E-02	1.302E-02
3	Ground water	kg	1.020E+00	1.020E+00
	Output			
P3	Water, drinking	kg	1.000	1.000
1	Carbon dioxide	kg	5.549E-04	5.549E-04
2	Methane	kg	6.089E-07	6.089E-07
3	Nitrogen dioxide	kg	1.124E-06	1.124E-06
4	Nitrogen monoxide	kg	6.264E-16	6.264E-16
5	Sulfur dioxide	kg	6.046E-07	6.046E-07
6	VOC to air	kg	4.700E-10	4.700E-10
7	VOC to water, fresh	kg	1.943E-12	1.943E-12

PE Bottle Production + Water Filling

Scaling factor = 1 / 1 = 1

	Input	Unit	Unit process flow	Reference flow
P3	Drinking Water	kg	1	1
P2	Polyethylene granulates	kg	4.000E-02	0.040
1	Crude oil	kg	0	0
2	Energy	MJ	3.000E+00	3.000E+00
3	Ground water	kg	0	0
	Output			
P4	Bottled water, at factory	item	1	1
1	Carbon dioxide	kg	9.000E-02	9.000E-02
2	Methane	kg	5.000E-09	5.000E-09
3	Nitrogen dioxide	kg	3.000E-09	3.000E-09
4	Nitrogen monoxide	kg	5.000E-09	5.000E-09
5	Sulfur dioxide	kg	8.000E-09	8.000E-09
6	VOC to air	kg	2.000E-07	2.000E-07
7	VOC to water, fresh	kg	2.000E-08	2.000E-08

Transportation to Retailers

Scaling factor = 0.10400 / 1 = 0.10400

	Input	Unit	Unit process flow	Reference flow
1	Crude oil	kg	3.180E-02	3.307E-03
2	Energy	MJ	8.702E-01	9.050E-02
3	Ground water	kg	0	0
	Output			
P5	**Land transport**	t*km	1	0.10400
1	Carbon dioxide	kg	6.396E-02	6.652E-03
2	Methane	kg	6.249E-05	6.499E-06
3	Nitrogen dioxide	kg	5.387E-04	5.602E-05
4	Nitrogen monoxide	kg	1.390E-13	1.446E-14
5	Sulfur dioxide	kg	3.415E-05	3.551E-06
6	VOC to air	kg	1.223E-08	1.272E-09
7	VOC to water, fresh	kg	1.351E-09	1.405E-10

Landfill of Plastic Wastes

Scaling factor = 0.040 / 1 = 0.040

	Input	Unit	Unit process flow	Reference flow
1	Crude oil	kg	0	0
2	Energy	MJ	5.606E-01	2.2422E-02
3	Ground water	kg	0	0
	Output			
P6	**Landfill of plastic waste**	kg	1	0.0400
1	Carbon dioxide	kg	6.102E-02	2.441E-03
2	Methane	kg	3.562E-04	1.425E-05
3	Nitrogen dioxide	kg	1.531E-04	6.126E-06
4	Nitrogen monoxide	kg	3.855E-13	1.542E-14
5	Sulfur dioxide	kg	1.301E-04	5.205E-06
6	VOC to air	kg	2.544E-05	1.018E-06
7	VOC to water, fresh	kg	1.378E-09	5.510E-11

Life Cycle Inventory Profile

Elementary flows by life cycle phases

	Elementary flow		Ethylene production	Polyethylene granulate production	Drinking water production	Bottle production + water filling	Transportation to customers	Landfill of plastic wastes
1	Carbon dioxide	kg	3.933E-02	6.267E-02	5.549E-04	9.000E-02	6.652E-03	2.441E-03
2	Methane	kg	2.554E-04	5.679E-04	6.089E-07	5.000E-09	6.499E-06	1.425E-05
3	Nitrogen dioxide	kg	7.205E-05	1.292E-04	1.124E-06	3.000E-09	5.602E-05	6.126E-06
4	Nitrogen monoxide	kg	5.192E-13	0	6.264E-16	5.000E-09	1.446E-14	1.542E-14
5	Sulfur dioxide	kg	8.548E-05	1.631E-04	6.046E-07	8.000E-09	3.551E-06	5.205E-06
6	VOC to air	kg	5.565E-08	5.855E-06	4.700E-10	2.000E-07	1.272E-09	1.018E-06
7	VOC to water, fresh	kg	3.485E-09	3.979E-07	1.943E-12	2.000E-08	1.405E-10	5.510E-11
8	Crude oil	kg	4.930E-02	0	0	0	0.0033072	0
9	Energy	MJ	1.063E+00	1.096E+00	1.302E-02	3.000E+00	9.050E-02	2.242E-02
10	Ground water	kg	0	0	1.020E+00	0	0	0

Total Life Cycle Inventory

	Elementary flow		Life Cycle Inventory
1	Carbon dioxide	kg	2.017E-01
2	Methane	kg	8.447E-04
3	Nitrogen dioxide	kg	2.645E-04
4	Nitrogen monoxide	kg	5.001E-09
5	Sulfur dioxide	kg	2.579E-04
6	VOC to air	kg	7.130E-06
7	VOC to water, fresh	kg	4.216E-07
8	Crude oil	kg	5.261E-02
9	Energy	MJ	5.285E+00
10	Ground water	kg	1.020E+00

Phase 3: Life Cycle Impact Assessment (LCIA)

Characterization Factors Matrix

	Midpoint category		Characterization unit	Carbon dioxide	Methane	Nitrogen dioxide	Nitrogen monoxide	Sulfur dioxide	VOC to air	VOC to water, fresh	Crude oil	Energy	Ground Water
1	Acidification	AP	kg SO_2 eq	0	0	0.7	1.07	1	0	0	0	0	0
2	Climate Change	GWP100	kg CO_2 eq	1	21	0	0	0	0	0	0	0	0
3	Freshwater Ecotoxicity:	FAETP	kg 1,4-DB eq	0	0	0	0	0	0	0.2	0	0	0
4	Marine Aquatic Ecotoxicity	MAETP	kg 1,4-DB eq	0	0	0	0	0	0	0.1	0	0	0
5	Terrestrial Ecotoxicity	TETP	kg 1,4-DB eq	0	0	0	0	0	0	0.3	0	0	0
6	Eutrophication	EP	kg PO_4^{3-} eq	0	0	0.13	0.13	0	0	0	0	0	0
7	Human Toxicity	HTP	kg 1,4-DB eq	0	0	0	0	0.096	0.5	0	0	0	0
8	Ozone Layer Depletion	ODP	kg CFC-11 eq	0	0	0	0	0	0	0	0	0	0
9	Photochemical Oxidant Formation (Smog)	POCP	kg ethylene eq	0	0.006	0	0.027	0	0.5	0	0	0	0
10	Abiotic Resource Depletion (Fossil Fuels)	ADP-f	MJ	0	0	0	0	0	0	0	43.4	1	0
11	Abiotic Resource Depletion (Elements)	ADP-e	kg Sb-Eq	0	0	0	0	0	0	0	0	0	0

Computation of Midpoint Impact Scores

Acidification (AP)

Ethylene production

$$7.205E\text{-}05 \text{ kg } NO_2 \times 0.7 \text{ kg } SO_2 \text{ eq / kg } NO_2$$
$$+ \ 5.192E\text{-}13 \text{ kg NO} \times 1.07 \text{ kg } SO_2 \text{ eq / kg NO}$$
$$+ \ 8.548E\text{-}05 \text{ kg } SO_2 \times 1 \text{ kg } SO_2 \text{ eq / kg } SO_2$$
$$= 1.359E\text{-}04 \text{ kg } SO_2 \text{ eq}$$

Polyethylene granulate production

$$1.292E\text{-}04 \text{ kg } NO_2 \times 0.7 \text{ kg } SO_2 \text{ eq / kg } NO_2$$
$$+ \ 0.000E\text{+}00 \text{ kg NO} \times 1.07 \text{ kg } SO_2 \text{ eq / kg NO}$$
$$+ \ 1.631E\text{-}04 \text{ kg } SO_2 \times 1 \text{ kg } SO_2 \text{ eq / kg } SO_2$$
$$= 2.535E\text{-}04 \text{ kg } SO_2 \text{ eq}$$

Drinking water production

$$1.124E\text{-}06 \text{ kg } NO_2 \times 0.7 \text{ kg } SO_2 \text{ eq / kg } NO_2$$
$$+ \ 6.264E\text{-}16 \text{ kg NO} \times 1.07 \text{ kg } SO_2 \text{ eq / kg NO}$$
$$+ \ 6.046E\text{-}07 \text{ kg } SO_2 \times 1 \text{ kg } SO_2 \text{ eq / kg } SO_2$$
$$= 1.391E\text{-}06 \text{ kg } SO_2 \text{ eq}$$

Bottle production + water filling

$$3.000E\text{-}09 \text{ kg } NO_2 \times 0.7 \text{ kg } SO_2 \text{ eq / kg } NO_2$$
$$+ \ 5.000E\text{-}09 \text{ kg NO} \times 1.07 \text{ kg } SO_2 \text{ eq / kg NO}$$
$$+ \ 8.000E\text{-}09 \text{ kg } SO_2 \times 1 \text{ kg } SO_2 \text{ eq / kg } SO_2$$
$$= 1.545E\text{-}08 \text{ kg } SO_2 \text{ eq}$$

Transportation

$$5.602E\text{-}05 \text{ kg } NO_2 \times 0.7 \text{ kg } SO_2 \text{ eq / kg } NO_2$$
$$+ \ 1.446E\text{-}14 \text{ kg NO} \times 1.07 \text{ kg } SO_2 \text{ eq / kg NO}$$
$$+ \ 3.551E\text{-}06 \text{ kg SO2} \times 1 \text{ kg SO2 eq / kg SO2}$$
$$= 4.276E\text{-}05 \text{ kg } SO_2 \text{ eq}$$

Landfill

$6.126E\text{-}06$ kg NO_2 × 0.7 kg SO_2 eq / kg NO_2

+ $1.542E\text{-}14$ kg NO × 1.07 kg SO_2 eq / kg NO

+ $5.205E\text{-}06$ kg SO2 × 1 kg SO2 eq / kg SO2

= $9.493E\text{-}06$ kg SO_2 eq

Total life cycle impact score:

= $4.431E\text{-}04$ kg SO_2 eq

Climate Change (GWP100)

Ethylene production

$$3.933E\text{-}02 \text{ kg } CO_2 \times 1 \text{ kg } CO_2 \text{ eq / kg } CO_2$$
$$+ \ 2.554E\text{-}04 \text{ kg } CH_4 \times 21 \text{ kg } CO_2 \text{ eq / kg } CH_4$$
$$= 4.470E\text{-}02 \text{ kg } CO_2 \text{ eq}$$

Polyethylene granulate production

$$6.267E\text{-}02 \text{ kg } CO_2 \times 1 \text{ kg } CO_2 \text{ eq / kg } CO_2$$
$$+ 5.679E\text{-}04 \text{ kg } CH_4 \times 21 \text{ kg } CO_2 \text{ eq / kg } CH_4$$
$$= 7.460E\text{-}02 \text{ kg } CO_2 \text{ eq}$$

Drinking water production

$$5.549E\text{-}04 \text{ kg } CO_2 \times 1 \text{ kg } CO_2 \text{ eq / kg } CO_2$$
$$+ 6.089E\text{-}07 \text{ kg } CH_4 \times 21 \text{ kg } CO_2 \text{ eq / kg } CH_4$$
$$= 5.677E\text{-}04 \text{ kg } CO_2 \text{ eq}$$

Bottle production + water filling

$$9.000E\text{-}02 \text{ kg } CO_2 \times 1 \text{ kg } CO_2 \text{ eq / kg } CO_2$$
$$+ 5.000E\text{-}09 \times 21 \text{ kg } CO_2 \text{ eq / kg } CH_4$$
$$= 9.000E\text{-}02 \text{ kg } CO_2 \text{ eq}$$

Transportation

$$6.652E\text{-}03 \text{ kg } CO_2 \times 1 \text{ kg } CO_2 \text{ eq / kg } CO_2$$
$$+ 6.499E\text{-}06 \times 21 \text{ kg } CO_2 \text{ eq / kg } CH_4$$
$$= 6.788E\text{-}03 \text{ kg } CO_2 \text{ eq}$$

Landfill

$$2.441E\text{-}03 \text{ kg } CO_2 \times 1 \text{ kg CO2 eq / kg CO2}$$
$$+ 1.425E\text{-}05 \times 21 \text{ kg } CO_2 \text{ eq / kg } CH_4$$
$$= 2.740E\text{-}03 \text{ kg } CO_2 \text{ eq}$$

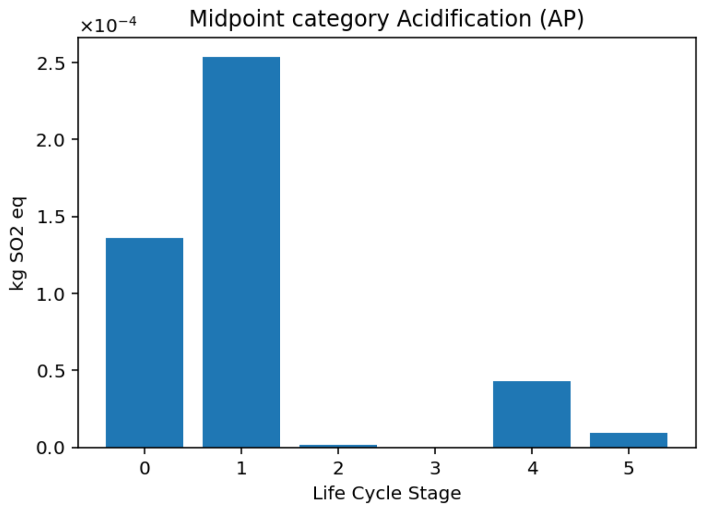
Total impact score

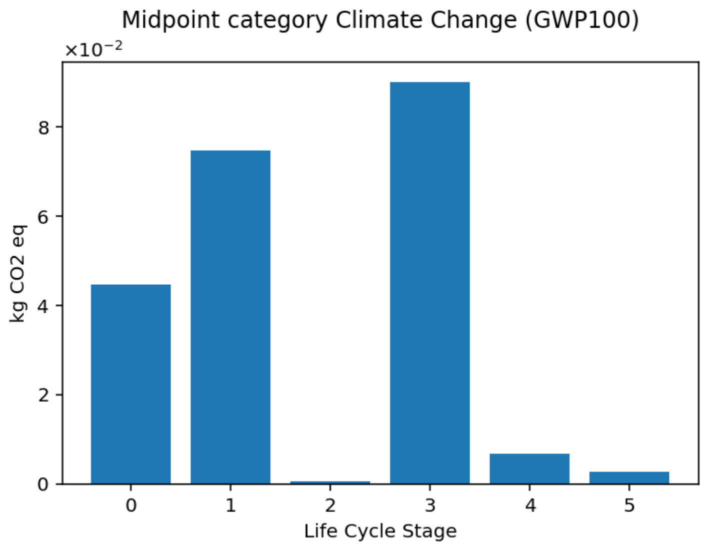
$$= 2.194E\text{-}01 \text{ kg } CO_2 \text{ eq}$$

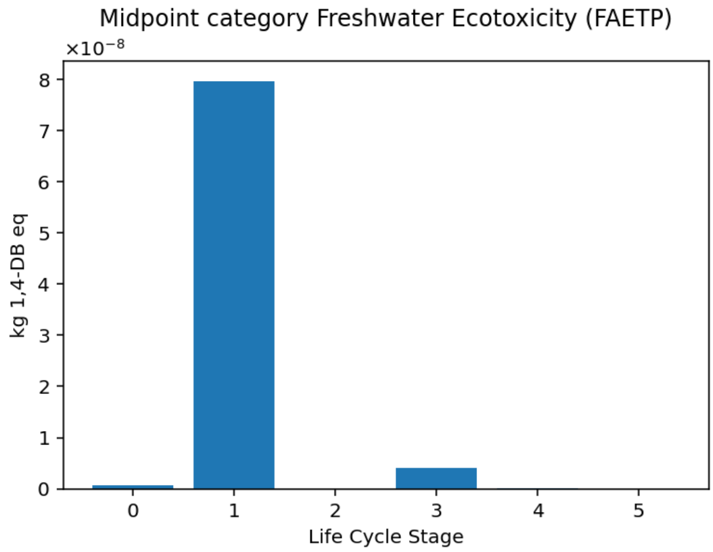
- The scores for the rest of the impact categories are computed and shown in the table below

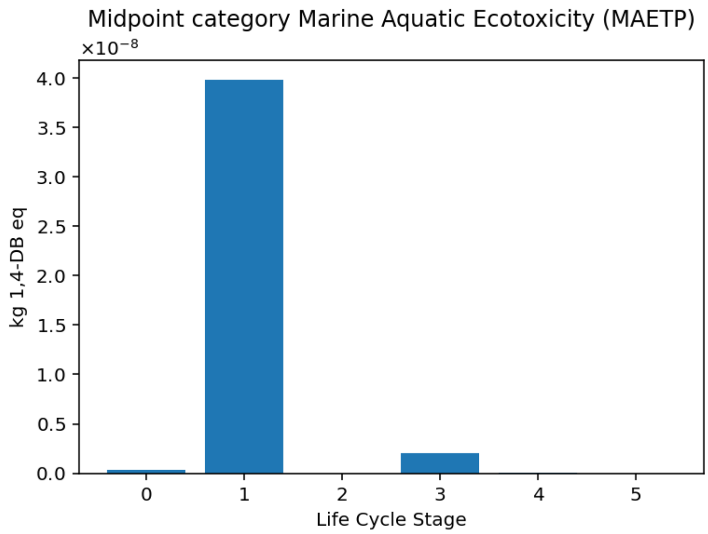
	Midpoint category	Characterization unit		Ethylene production	Polyethylene granulate production	Drinking water production	Bottle production + water filling	Transportation to customers	Landfill of plastic wastes	**LCIA profile**
1	Acidification	AP	kg SO_2 eq	1.359E-04	2.535E-04	1.391E-06	1.545E-08	4.276E-05	9.493E-06	4.431E-04
2	Climate Change	GWP100	kg CO_2 eq	4.470E-02	7.460E-02	5.677E-04	9.000E-02	6.788E-03	2.740E-03	2.194E-01
3	Freshwater Ecotoxicity:	FAETP	kg 1,4-DB eq	6.971E-10	7.958E-08	3.886E-13	4.000E-09	2.810E-11	1.102E-11	8.432E-08
4	Marine Aquatic Ecotoxicity	MAETP	kg 1,4-DB eq	3.485E-10	3.979E-08	1.943E-13	2.000E-09	1.405E-11	5.510E-12	4.216E-08
5	Terrestrial Ecotoxicity	TETP	kg 1,4-DB eq	1.046E-09	1.194E-07	5.829E-13	6.000E-09	4.215E-11	1.653E-11	1.265E-07
6	Eutrophication	EP	kg PO_4^{3-} eq	9.366E-06	1.680E-05	1.461E-07	1.040E-09	7.283E-06	7.963E-07	3.439E-05
7	Human Toxicity	HTP	kg 1,4-DB eq	8.234E-06	1.858E-05	5.827E-08	1.008E-07	3.415E-07	1.008E-06	2.832E-05
8	Ozone Layer Depletion	ODP	kg CFC-11 eq	0	0	0	0	0	0	0
9	Photochemical Oxidant Formation (Smog)	POCP	kg ethylene eq	1.560E-06	6.335E-06	3.889E-09	1.002E-07	3.963E-08	5.943E-07	8.634E-06
10	Abiotic Resource Depletion (Fossil Fuels)	ADP-f	MJ	3.203E+00	1.096E+00	1.302E-02	3.000E+00	2.340E-01	2.242E-02	7.568E+00
11	Abiotic Resource Depletion (Elements)	ADP-e	kg Sb-Eq	0	0	0	0	0	0	0

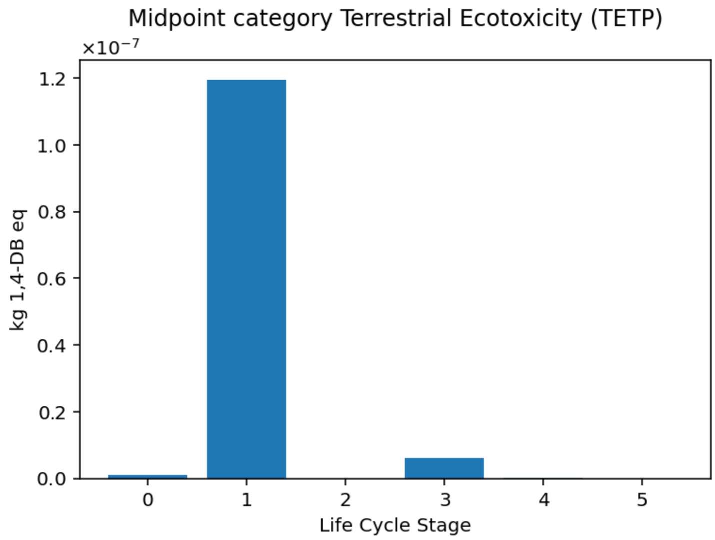
Comparing the impact scores by life cycle phase for each impact category.

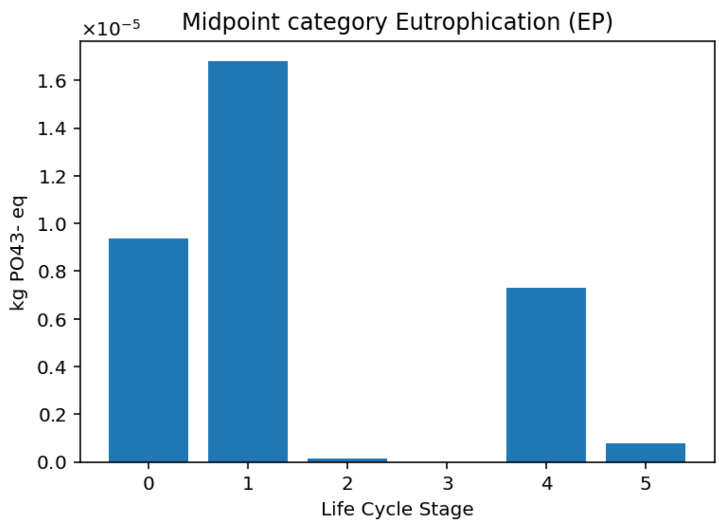


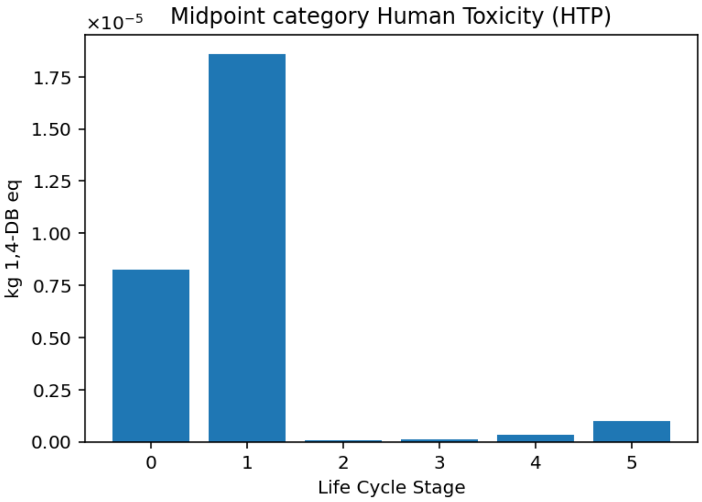


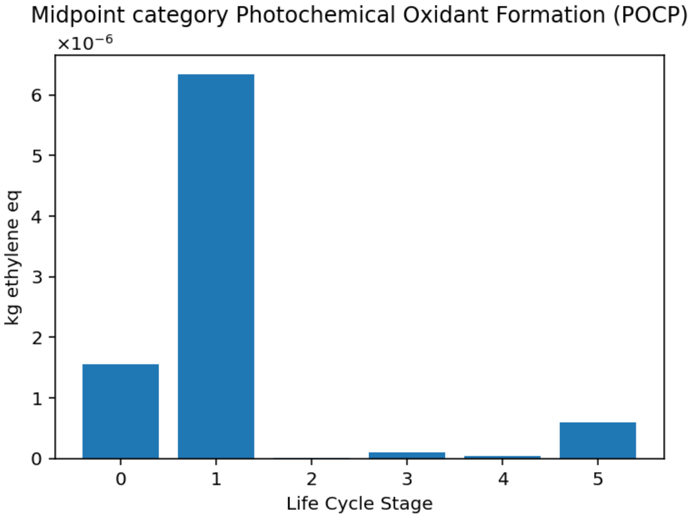


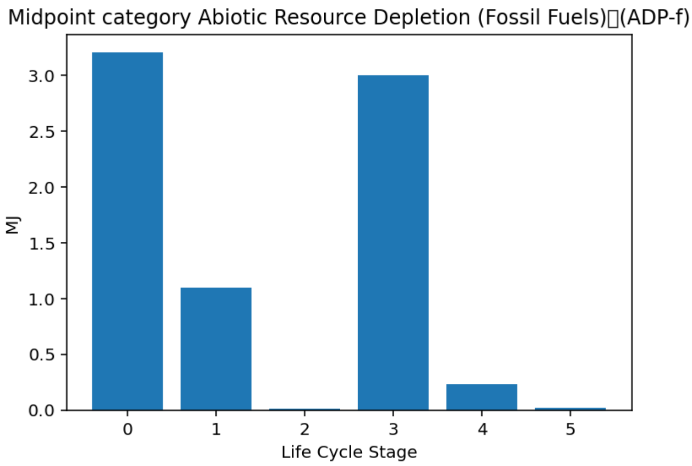

Midpoint category Marine Aquatic Ecotoxicity (MAETP)
×10−8
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
kg 1,4-DB eq
0
1
2
3
4
5
Life Cycle Stage


Midpoint category Terrestrial Ecotoxicity (TETP)
×10−7
1.2
1.0
0.8
0.6
0.4
0.2
0.0
kg 1,4-DB eq
0
1
2
3
4
5
Life Cycle Stage

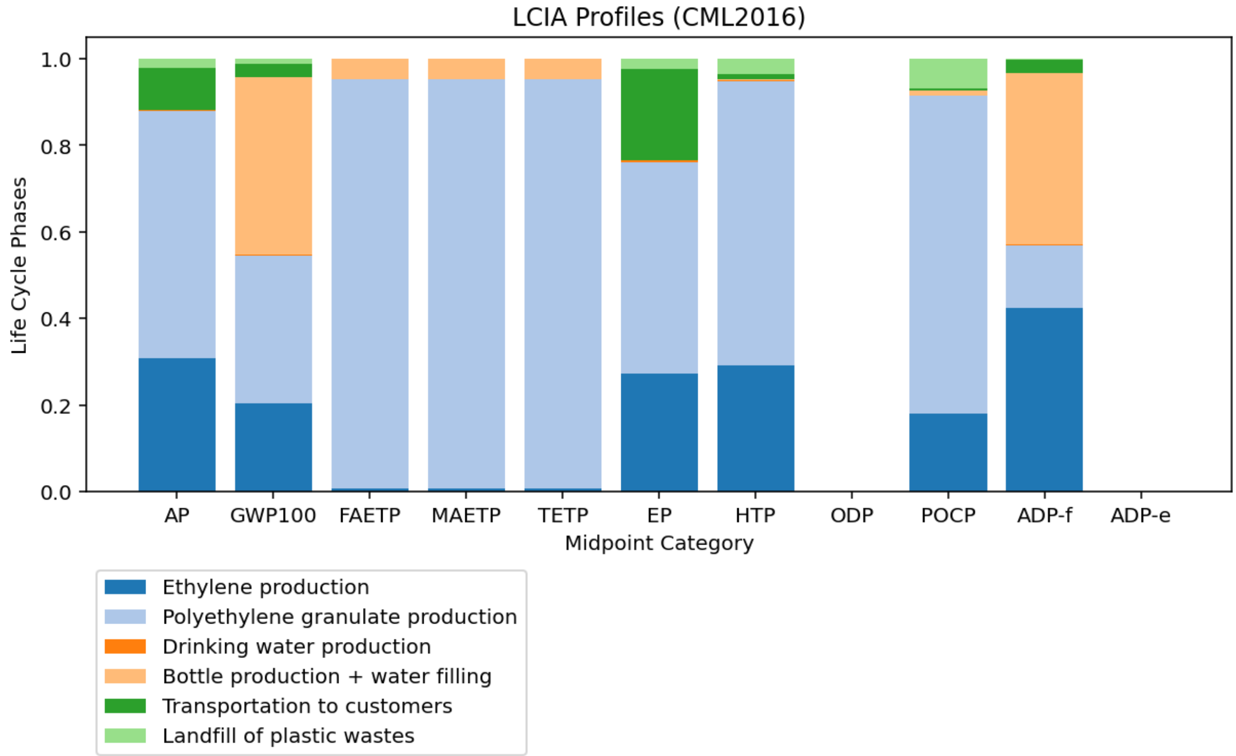

Midpoint category Eutrophication (EP)
×10−5
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
kg PO43- eq
0
1
2
3
4
5
Life Cycle Stage


Midpoint category Human Toxicity (HTP)
×10⁻⁵
kg 1,4-DB eq
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
0 1 2 3 4 5
Life Cycle Stage


Midpoint category Photochemical Oxidant Formation (POCP)
×10⁻⁶
kg ethylene eq
0 1 2 3 4 5 6
0 1 2 3 4 5
Life Cycle Stage


Midpoint category Abiotic Resource Depletion (Fossil Fuels) (ADP-f)
MJ
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0 1 2 3 4 5
Life Cycle Stage

Comparison of relative contributions by life cycle phases for each impact category



Total Impact Score by Category

	Midpoint category		Characterization unit	LCIA profile
1	Acidification	AP	kg SO_2 eq	4.431E-04
2	Climate Change	GWP100	kg CO_2 eq	2.194E-01
3	Freshwater Ecotoxicity:	FAETP	kg 1,4-DB eq	8.432E-08
4	Marine Aquatic Ecotoxicity	MAETP	kg 1,4-DB eq	4.216E-08
5	Terrestrial Ecotoxicity	TETP	kg 1,4-DB eq	1.265E-07
6	Eutrophication	EP	kg PO_4^{3-} eq	3.439E-05
7	Human Toxicity	HTP	kg 1,4-DB eq	2.832E-05
8	Ozone Layer Depletion	ODP	kg CFC-11 eq	0
9	Photochemical Oxidant Formation (Smog)	POCP	kg ethylene eq	8.634E-06
10	Abiotic Resource Depletion (Fossil Fuels)	ADP-f	MJ	7.568E+00
11	Abiotic Resource Depletion (Elements)	ADP-e	kg Sb-Eq	0

Phase 4: Interpretation

Hotspots

1. Acidification Potential

   Ethylene production and Polyethylene production were the largest contributors.

2. Climate Change

   Ethylene production, Polyethylene production and bottle production were the largest contributors.

3. Freshwater Ecotoxicity:

   Polyethylene granulate production is main contributor with some contribution from production of bottles.

4. Marine Aquatic Ecotoxicity

   Polyethylene granulate production is main contributor with some contribution from production of bottles.

5. Terrestrial Ecotoxicity

   Polyethylene granulate production is main contributor with some contribution from production of bottles.

6. Eutrophication

   Polyethylene granulate production is main contributor with some contribution from production of bottles.

7. Human Toxicity

   Ethylene production and Polyethylene production were the largest contributors.

8. Ozone Layer Depletion

   None

9. Photochemical Oxidant Formation (Smog)

   Ethylene production and Polyethylene production were the main contributors with some from landfill.

10. Abiotic Resource Depletion (Fossil Fuels)

    Ethylene production and Polyethylene production were the main contributors with some from landfill.

11. Abiotic Resource Depletion (Elements)

    None.

Limitations

- The product system has been simplified into a few major processes. More details can be included in the study.
- Only CML2016 midpoint indicators were studied.
- The study can be extended to the endpoint areas of protection using ReCiPe.

Conclusion

1. This LCA study provides a detailed analysis of the environmental impacts associated with the life cycle of a 1-liter PE plastic bottle.
2. By identifying the key contributors to environmental impacts, the study offers actionable insights for improving the sustainability of plastic bottle production and usage.

5.2 Case Study 2: Comparative LCA study on using LED and Incandescent Lamps

- This case study shows how to conduct a comparative Life Cycle Assessment (LCA) of using LED and incandescent lamps for home lighting.

- Some of the data used here are only representative values for illustrative purposes only.

Phase 1: Goal and Scope Definition

Goal

- To assess and compare the environmental impact of the LED and incandescent lamps for home lighting based on the LCA methodology. The study aims to identify the most significant environmental aspects of the two kinds of lamps in the production, use and disposal stages.

- The results of this study will inform stakeholders including consumers, manufacturers, and policymakers, about the sustainability of each lighting option, enabling more environmentally conscious decisions.

Functional Unit

- To provide 10,000 hours of 800 lumens of home lighting.

- This ensures that the comparison between the two lamps is based on delivering the same lighting service, allowing for a fair assessment of their environmental impacts over a comparable duration of use.

Lamp Specifications

- The following two lamps will be evaluated:

1. **LED Lamp:**
    - Power: 10W
    - Estimated output: 800 lm
    - Lifespan: 25,000 hours

    - Number of LED lamps needed for 10,000 hours
      = 10,000 hours / 25,000 hours per lamp
      = **0.4 lamps**

2. **Incandescent Lamp:**
    - Power: 60W
    - Estimated output: 800 lm
    - Lifespan: 1,000 hours

    - Number of incandescent lamps needed for 10,000 hours
      = 10,000 hours / 1,000 hours per lamp
      =**10 lamps**

System Boundaries

- Cradle-to-Grave analysis including the following stages:

    1. Raw Material Extraction and Processing: Extraction and processing of raw materials used in manufacturing the lamps.

    2. Manufacturing: Production processes for both LED and incandescent lamps, including energy and material inputs.

    3. Use Phase: Energy consumption during the operation of the lamps for 10,000 hours.

    4. End-of-Life: Disposal, recycling, or landfilling of lamps after their use phase.

Major Assumptions

- Manufacturing energy and materials data are based on industry averages.

- The transportation phase will not be considered.

- End-of-life scenarios assumed:
    - LED lamps: 100% recycled
    - Incandescent lamps: 100% landfilled

Impact Categories

- The following mid-point impact categories from the CML-IA baseline will be assessed and compared for both lamps:

    1. Global Warming Potential (GWP100)

    2. Eutrophication Potential (EP)

    3. Acidification Potential (AP)

    4. Photochemical Ozone Creation Potential (POCP)

    5. Terrestrial Ecotoxicity Potential (TETP)

Additional Impact

- The total energy used throughout the life cycle of the lamps will also be assessed and compared.

Data Sources

- Inventory data are obtained from industry reports, life cycle databases and scientific literature.

- Impact characterization factors from the CML-IA baseline will be used.

Phase 2: **<u>Life Cycle Inventory (LCI)</u>**

LED Lamp

1. Manufacture Unit Process

Inputs	Unit	Quantity
Materials	kg	0.100
Plastic	kg	0.025
Electricity	kWh	8.340
Outputs		
LED (10w) lamp	item	1
CO2	kg	1.8000
CH4	kg	0.0030
NH3	kg	0.0006
SO2	kg	0.0085
NOx	kg	0.0062
PM2.5	kg	0.0011

2. Usage Unit Process

Inputs	Unit	Quantity
LED Lamp	item	1
Electricity	kWh	250
Outputs		
Lights	hours	25000
CO2	kg	118.7500
CH4	kg	0.0250
NH3	kg	0.0050
SO2	kg	0.6000
NOx	kg	0.4750
PM2.5	kg	0.0625

3. End-of-Life (Recycle) Unit Process

Inputs	Unit	Quantity
LED Lamp used	item	1
Electricity	kwh	0.3600000
Outputs		
CO2	kg	0.1710000
CH4	kg	0.0000360
NH3	kg	0.0000072
SO2	kg	0.0008640
NOx	kg	0.0006840
PM2.5	kg	5.00E-06

Computing Reference Flows

- Number of LED lamps = 0.4
- Applying the scaling factor to the unit process flows:

1. Manufacturing

Scaling factor = 0.4

Inputs	Unit	Quantity	Reference flow
Materials	kg	0.100	0.04
Plastic	kg	0.025	0.01
Electricity	kWh	8.340	3.336
Outputs			
LED (10w) lamp	item	1	0.4
CO2	kg	1.8000	7.200E-01
CH4	kg	0.0030	1.200E-03
NH3	kg	0.0006	2.400E-04
SO2	kg	0.0085	3.400E-03
NOx	kg	0.0062	2.480E-03
PM2.5	kg	0.0011	4.400E-04

2. Usage

Scaling factor = 0.4

Inputs	Unit	Quantity	Reference flow
LED Lamp	item	1	0.4
Electricity	kWh	250	100
Outputs			
Lights	hours	25,000	10,000
CO2	kg	118.7500	4.750E+01
CH4	kg	0.0250	1.000E-02
NH3	kg	0.0050	2.000E-03
SO2	kg	0.6000	2.400E-01
NOx	kg	0.4750	1.900E-01
PM2.5	kg	0.0625	2.500E-02

3. End-of-Life (Recycle)

Scaling factor = 0.4

Inputs	Unit	Quantity	Reference flow
LED Lamp used	item	1	0.4
Electricity	kWh	0.3600000	1.440E-01
Outputs			
CO2	kg	0.1710000	6.840E-02
CH4	kg	0.0000360	1.440E-05
NH3	kg	0.0000072	2.880E-06
SO2	kg	0.0008640	3.456E-04
NOx	kg	0.0006840	2.736E-04
PM2.5	kg	5.00E-06	2.000E-06

Summary of Inventory by Life Cycle Phases (LED Lamp)

Elementary flow	Unit	Manufacture	Usage	EOL	LCI
CO2	kg	7.200E-01	4.750E+01	6.840E-02	4.829E+01
CH4	kg	1.200E-03	1.000E-02	1.440E-05	1.121E-02
NH3	kg	2.400E-04	2.000E-03	2.880E-06	2.243E-03
SO2	kg	3.400E-03	2.400E-01	3.456E-04	2.437E-01
NOx	kg	2.480E-03	1.900E-01	2.736E-04	1.928E-01
PM2.5	kg	4.400E-04	2.500E-02	2.000E-06	2.544E-02
Electricity	kWh	3.336E+00	1.000E+02	1.440E-01	1.035E+02

Incandescent Lamp

1. Manufacture Unit Process

Inputs	Unit	Quantity
Materials	kg	0.0060
Plastic	kg	0.0140
Electricity	kWh	1.4
Outputs		
Incandescent lamp	item	1
CO2	kg	0.3000
CH4	kg	0.0005
NH3	kg	0.0001
SO2	kg	0.0012
NOx	kg	0.0008
PM2.5	kg	0.0002

2. Usage Unit Process

Inputs	Unit	Quantity
Incandescent lamp	item	1
Electricity	kWh	60
Outputs		
Lights	hours	1,000
CO2	kg	28.5000
CH4	kg	0.0060
NH3	kg	0.0012
SO2	kg	0.1440
NOx	kg	0.1140
PM2.5	kg	0.0150

3. End-of-Life (Landfill) Unit Process

Inputs	Unit	Quantity
Incandescent lamp used	item	1
Electricity	kWh	0.025
Outputs		
CO2	kg	0.01187500
CH4	kg	0.00000250
NH3	kg	0.00000050
SO2	kg	0.00006000
NOx	kg	0.00004750
PM2.5	kg	0.00000625

Computing Reference Flows for Incandescent lamps

- Number of Incandescent lamps = 10
- Applying the scaling factor to the unit process flows:

1. Manufacturing

Scaling factor = 10

Inputs	**Unit**	**Quantity**	**Reference flow**
Materials	kg	0.0060	0.06
Plastic	kg	0.0140	0.14
Electricity	kWh	1.4	14
Outputs			
Incandescent lamp	item	1	10
CO2	kg	0.3000	3.000E+00
CH4	kg	0.0005	5.000E-03
NH3	kg	0.0001	1.000E-03
SO2	kg	0.0012	1.200E-02
NOx	kg	0.0008	8.000E-03
PM2.5	kg	0.0002	2.000E-03

2. Usage

Scaling factor = 10

Inputs	**Unit**	**Quantity**	**Reference flow**
Incandescent lamp	item	1	10
Electricity	kWh	60	600
Outputs			
Lights	hours	1000	10000
CO2	kg	28.5000	2.850E+02
CH4	kg	0.0060	6.000E-02
NH3	kg	0.0012	1.200E-02
SO2	kg	0.1440	1.440E+00
NOx	kg	0.1140	1.140E+00
PM2.5	kg	0.0150	1.500E-01

3. End-of-Life (Landfill)

Scaling factor = 10

Inputs	Unit	Quantity	Reference flow
Incandescent lamp used	item	1	10
Electricity	kwh	0.025	2.500E-01
Outputs			
CO2	kg	0.01187500	1.188E-01
CH4	kg	0.00000250	2.500E-05
NH3	kg	0.00000050	5.000E-06
SO2	kg	0.00006000	6.000E-04
NOx	kg	0.00004750	4.750E-04
PM2.5	kg	0.00000625	6.250E-05

Summary of Inventory by Life Cycle Phases (Incandescent Lamp)

Elementary flow	Unit	Manufacture	Usage	EOL	LCI
CO2	kg	3.000E+00	2.850E+02	1.188E-01	2.881E+02
CH4	kg	5.000E-03	6.000E-02	2.500E-05	6.503E-02
NH3	kg	1.000E-03	1.200E-02	5.000E-06	1.301E-02
SO2	kg	1.200E-02	1.440E+00	6.000E-04	1.453E+00
NOx	kg	8.000E-03	1.140E+00	4.750E-04	1.148E+00
PM2.5	kg	2.000E-03	1.500E-01	6.250E-05	1.521E-01
Electricity	kWh	1.400E+01	6.000E+02	2.500E-01	6.143E+02

Phase 3: Life Cycle Impact Assessment

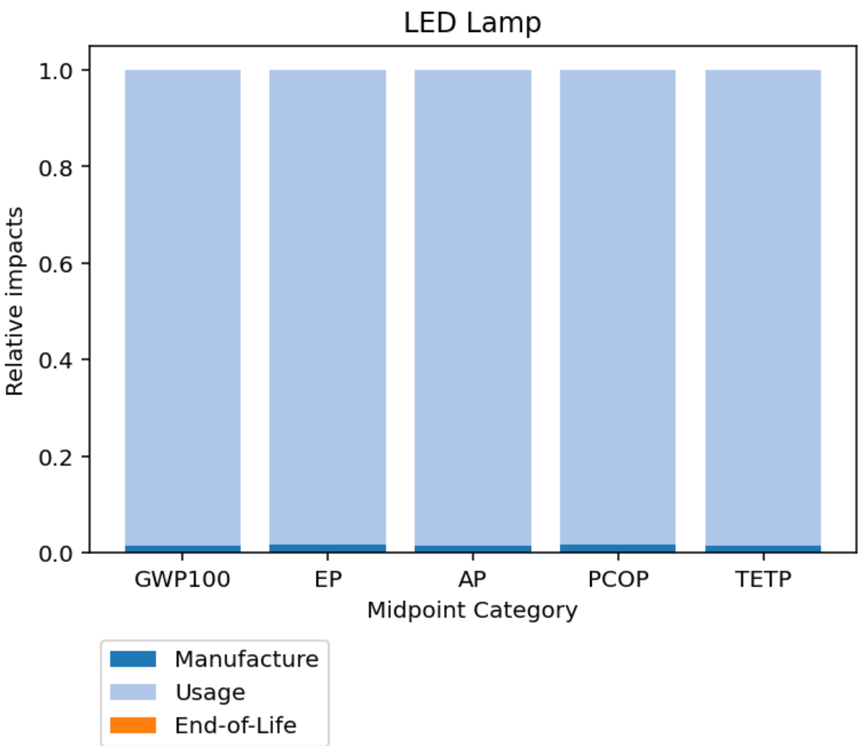
Characterization Factors Matrix

		CO2	CH4	NH3	SO2	NOx	PM2.5
GWP100	kg CO2 eq	1	21				
EP	kg $PO4^{3-}$eq		0.022	0.35		0.13	
AP	kg SO2 eq		0.01	1.88	1	0.7	
PCOP	kg $PO4^{3-}$ eq		0.006			0.017	0.4
TETP	kg 1,4 DCB eq				0.09		

- By applying matrix multiplications, we obtain the impact scores for each category by life cycle phases:

LED Lamp

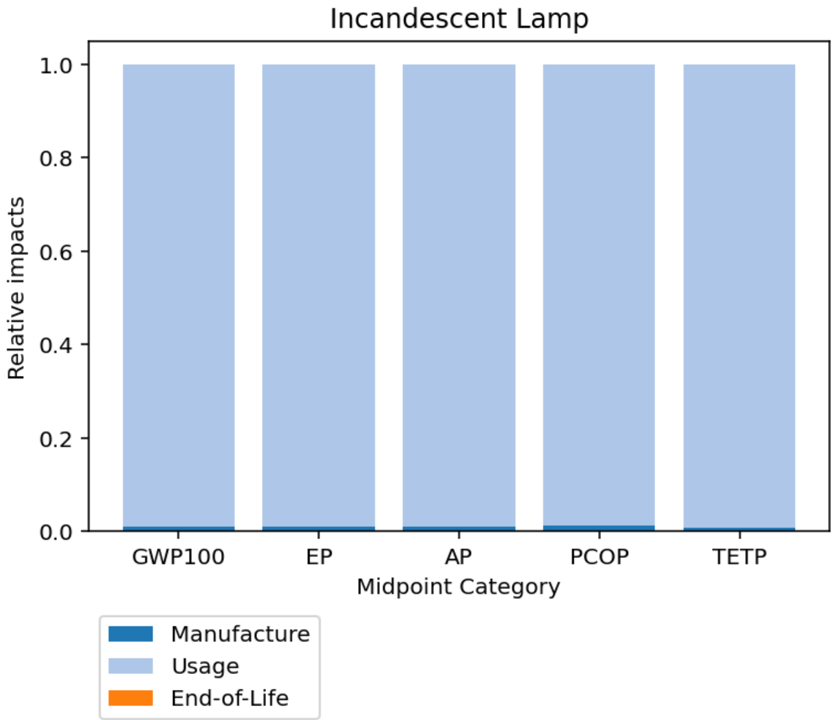
Category	Unit	Manufacture	Usage	End-of-Life	LCI
GWP100	kg CO2 eq	7.452E-01	4.771E+01	6.870E-02	4.852E+01
EP	kg $PO4^{3-}$eq	4.328E-04	2.562E-02	3.689E-05	2.609E-02
AP	kg SO2 eq	5.599E-03	3.769E-01	5.427E-04	3.830E-01
PCOP	kg $PO4^{3-}$ eq	2.254E-04	1.329E-02	5.538E-06	1.352E-02
TETP	kg 1,4 DCB eq	3.060E-04	2.160E-02	3.110E-05	2.194E-02
Energy	kWh	3.336E+00	1.000E+02	1.440E-01	3.336E+00



- We observe that for each impact category, the largest contribution is from the Usage phase.

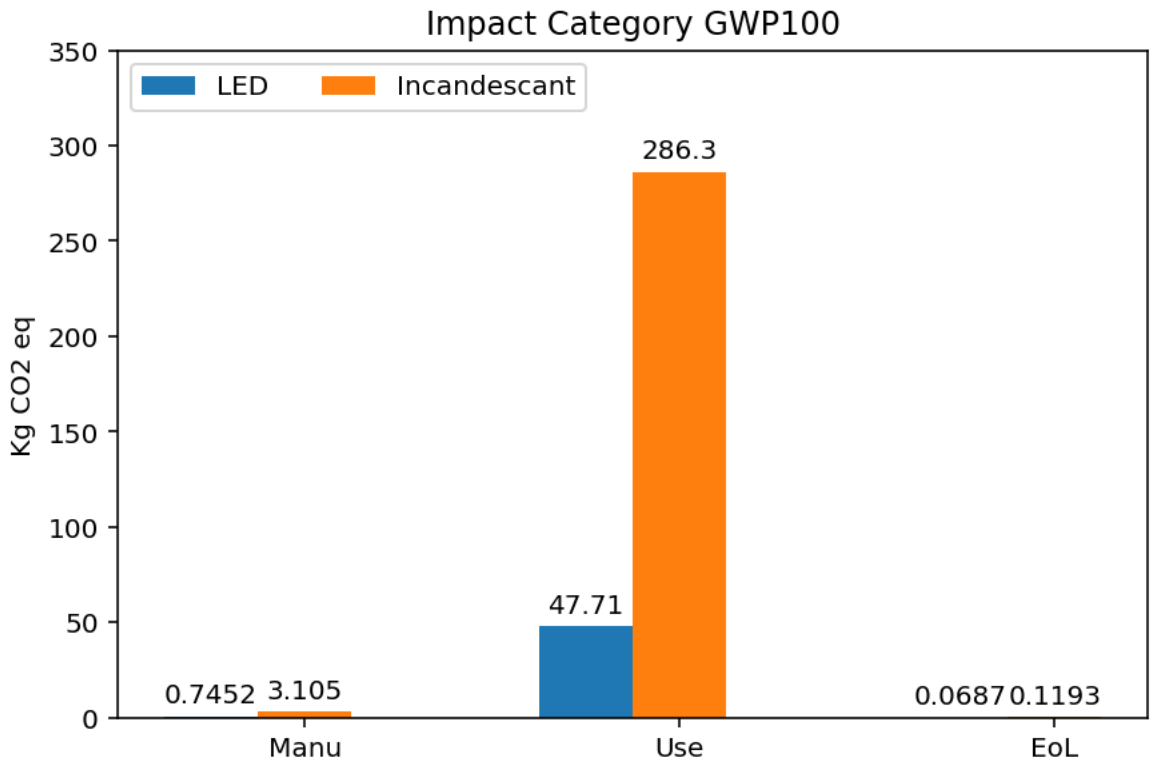
Incandescent Lamp

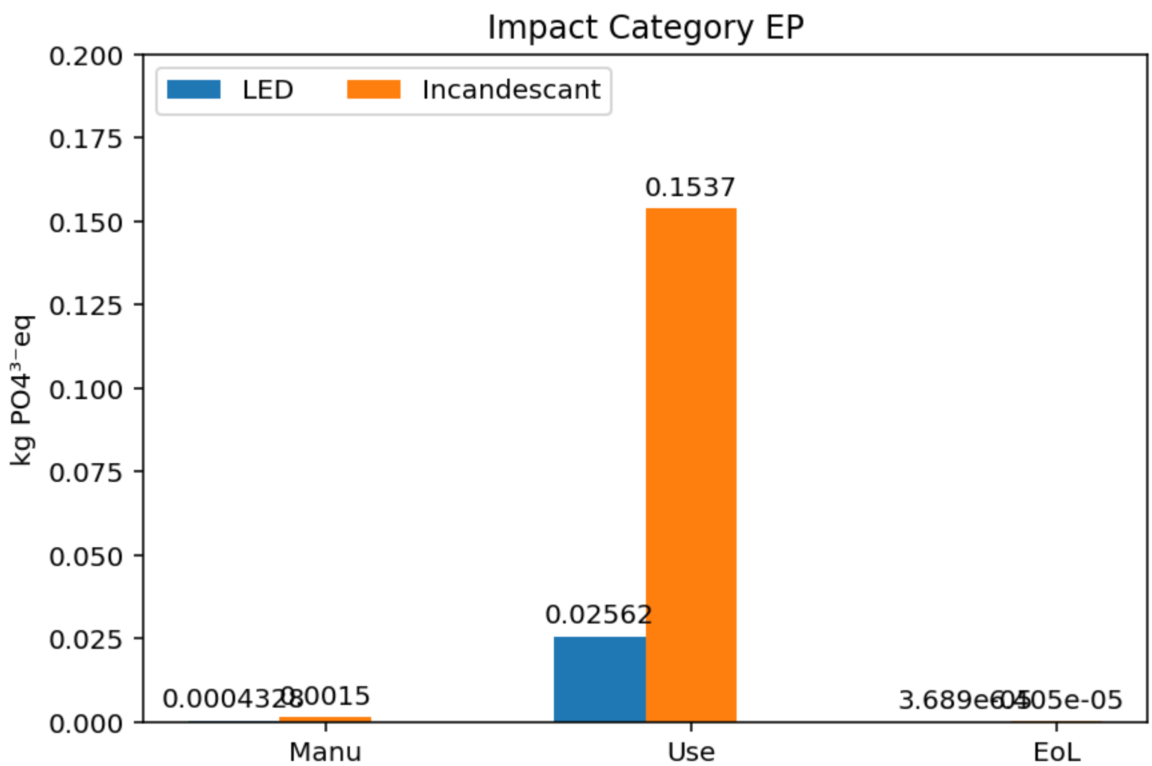
Category	Unit	Manufacture	Usage	End-of-Life	LCI
GWP100	kg CO_2 eq	3.105E+00	2.863E+02	1.193E-01	2.895E+02
EP	kg PO_4^{3-}eq	1.500E-03	1.537E-01	6.405E-05	1.553E-01
AP	kg SO_2 eq	1.953E-02	2.261E+00	9.422E-04	2.282E+00
PCOP	kg PO_4^{3-} eq	9.660E-04	7.974E-02	3.323E-05	8.074E-02
TETP	kg 1,4 DCB eq	1.080E-03	1.296E-01	5.400E-05	1.307E-01
Energy	kWh	1.400E+01	6.000E+02	2.500E-01	6.143E+02

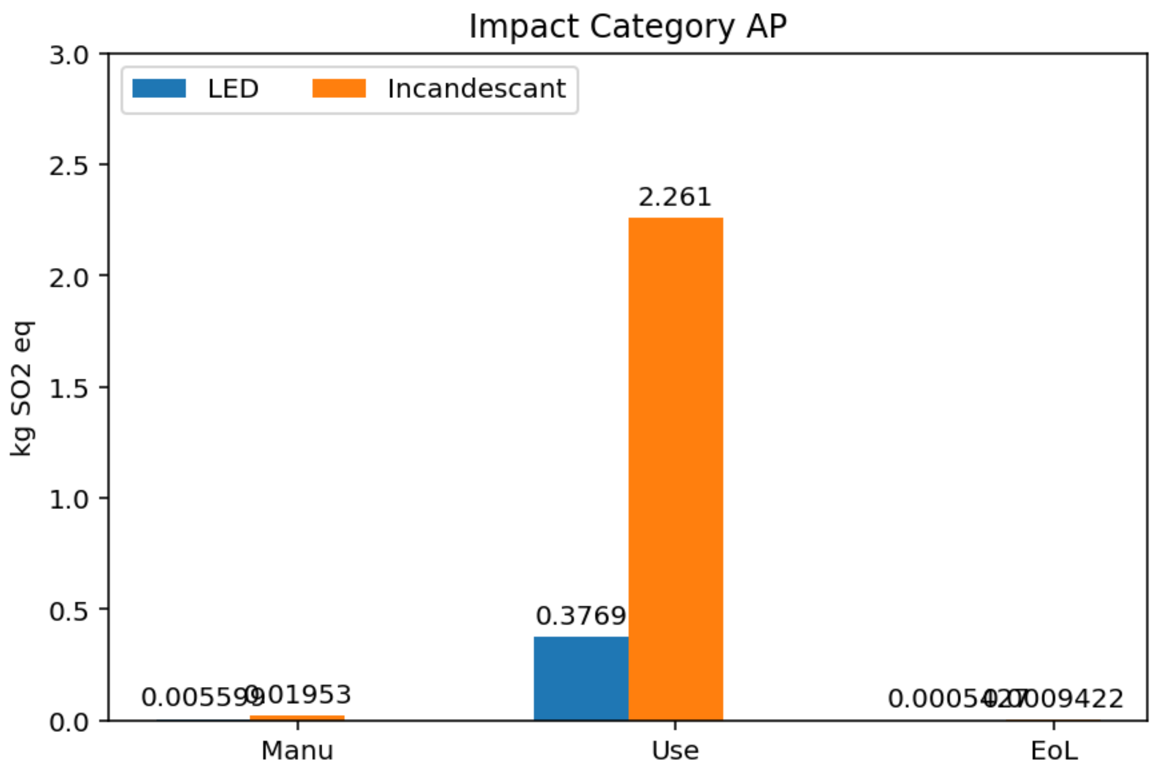


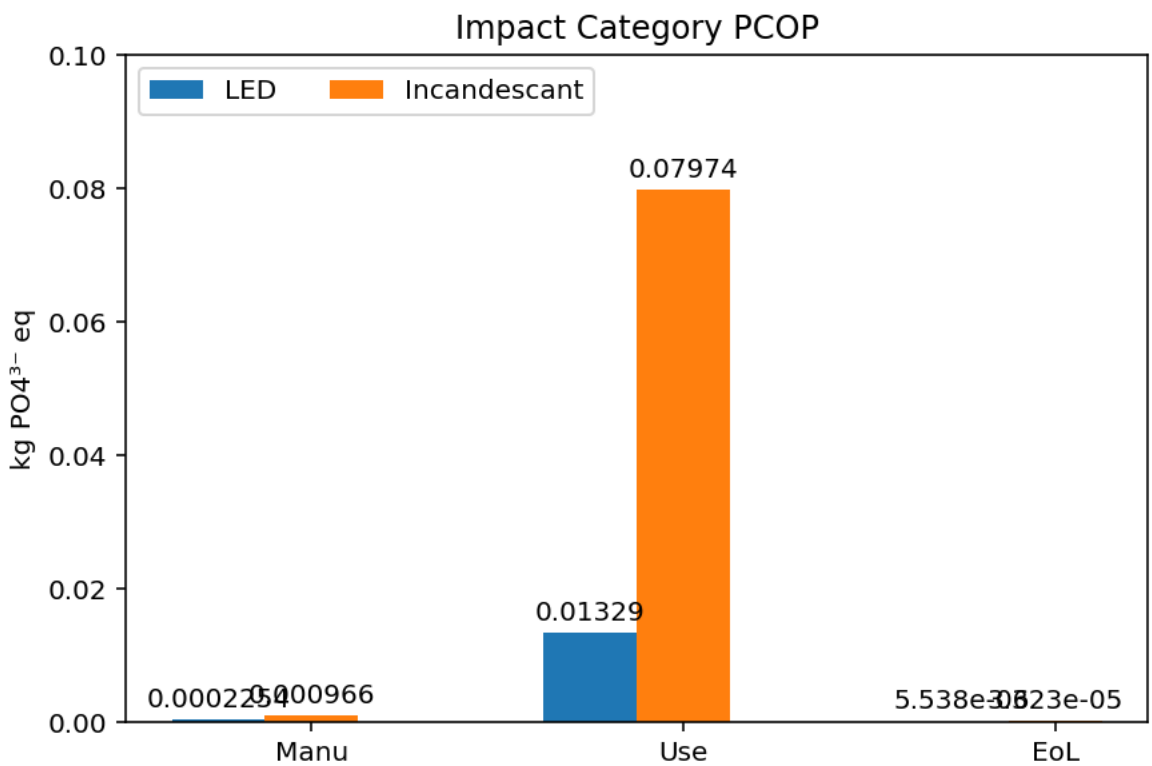
- We observe that for each impact category, the largest contribution is from the Usage phase.

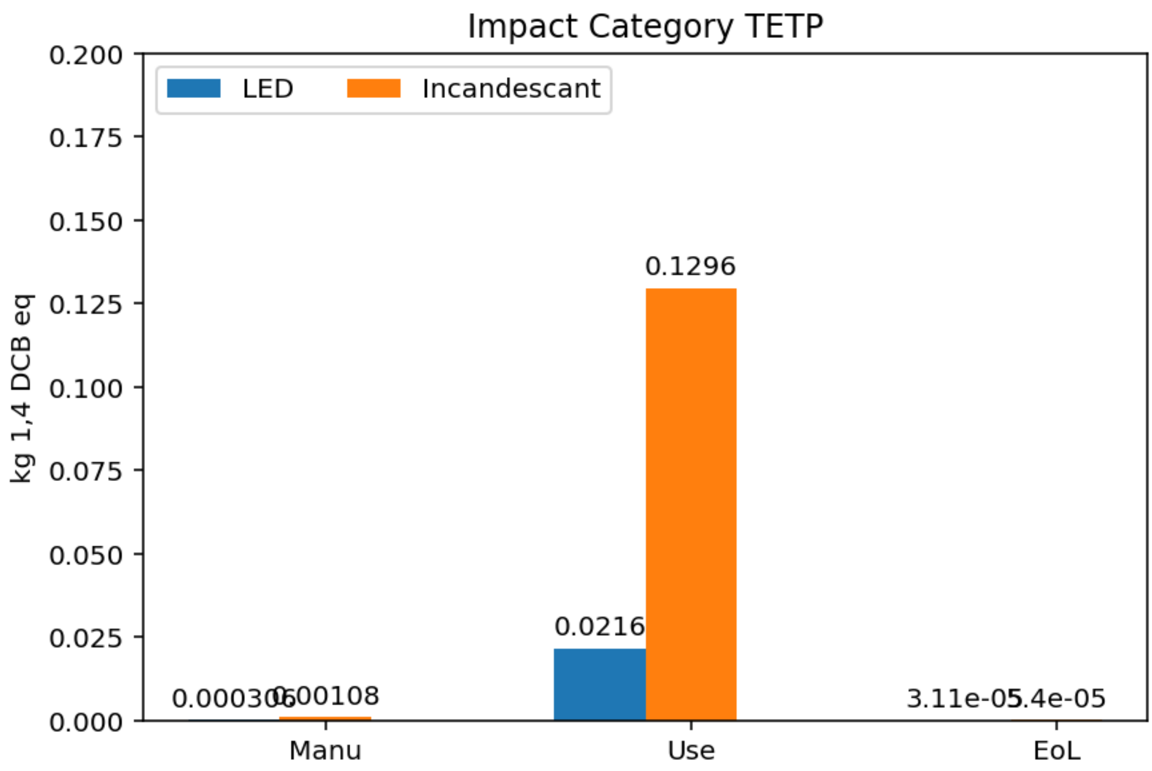
Comparison of LED and Incandescent Lamps by Life Cycle Stages

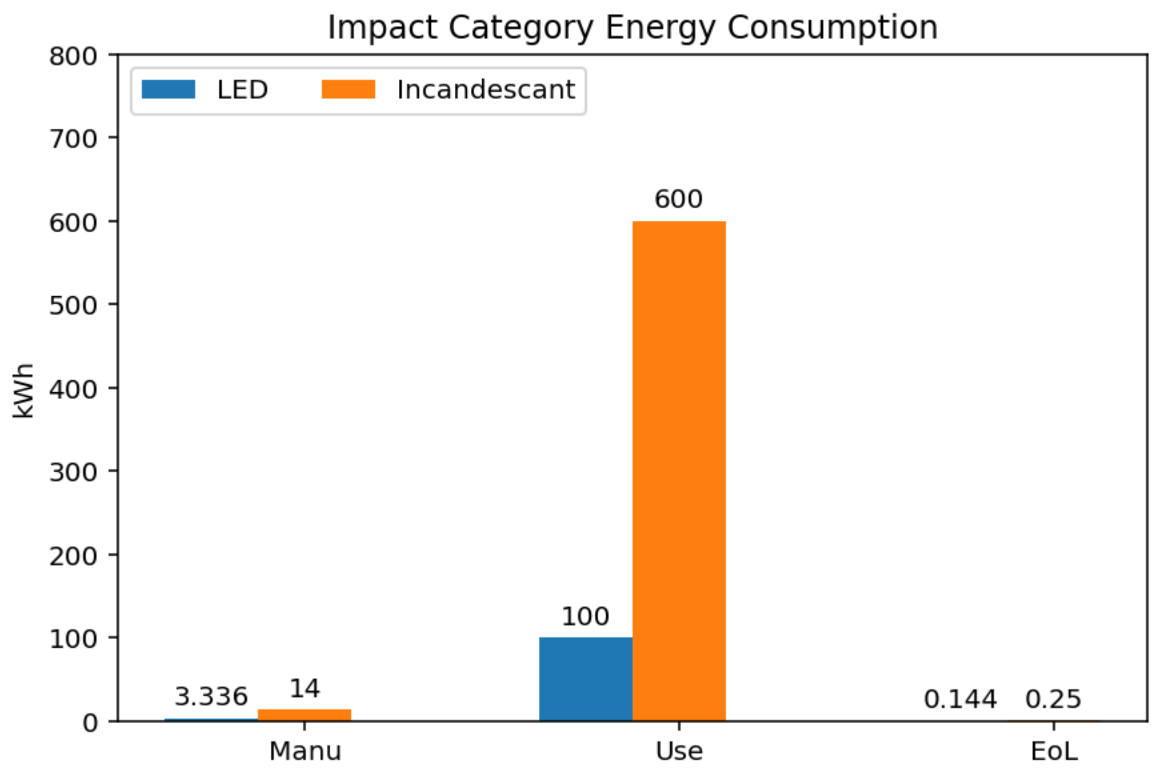





Impact Category AP
LED
Incandescant
kg SO2 eq
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2.261
0.3769
Manu
Use
EoL

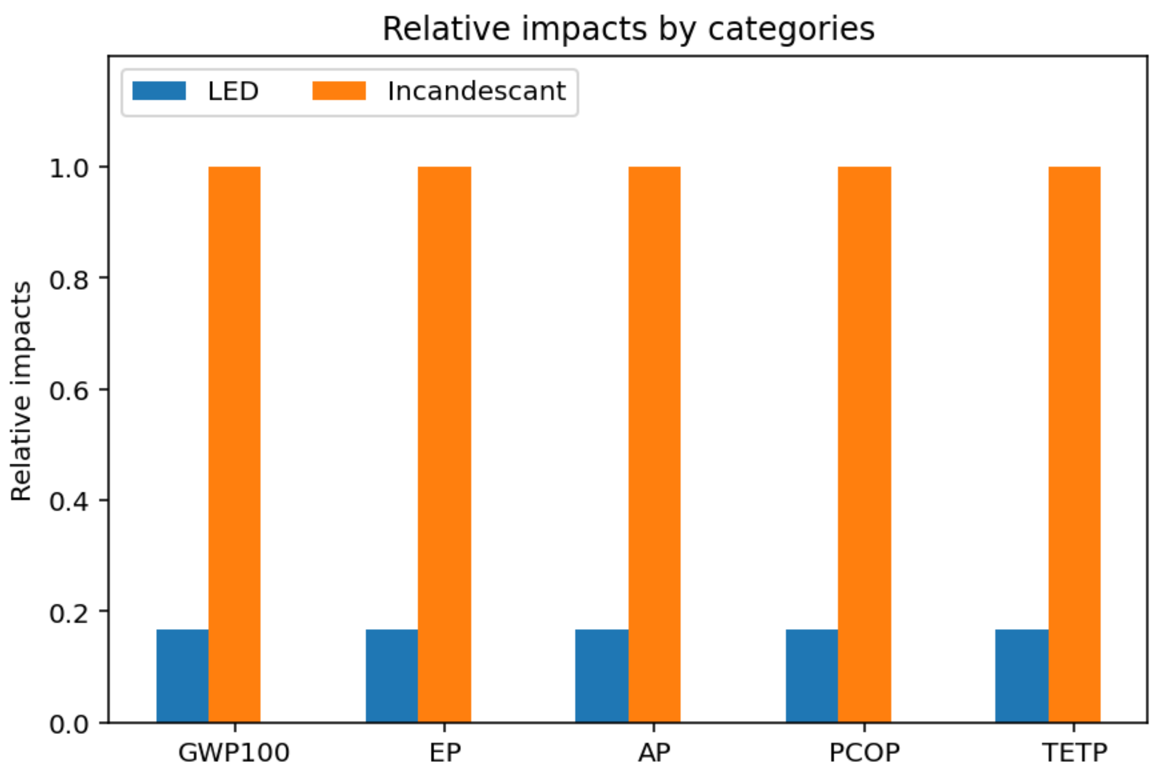

Impact Category PCOP
LED
Incandescant
kg PO4³⁻ eq
0.10
0.08
0.06
0.04
0.02
0.00
0.07974
0.01329
Manu
Use
EoL


Impact Category TETP
LED
Incandescant
kg 1,4 DCB eq
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
0.1296
0.0216
0.000306
0.00108
3.11e-05
5.4e-05
Manu
Use
EoL


Impact Category Energy Consumption
LED
Incandescant
kWh
800
700
600
500
400
300
200
100
0
600
100
3.336
14
0.144
0.25
Manu
Use
EoL

Comparing Total Impact Scores of LED and Incandescent Lamps.

Category	Characterization Unit	LED	Incandescent
GWP100	kg CO_2 eq	48.5239	289.4843
EP	kg PO_4^{3-}eq	0.0261	0.1553
AP	kg SO_2 eq	0.3830	2.2816
PCOP	kg PO_4^{3-} eq	0.0135	0.0807
TETP	kg 1,4 DCB eq	0.0219	0.1307
Energy	kWh	3.336	614.3



Observations

- LED lamps have significantly lower global warming potential and energy consumption across all impact categories, compared to incandescent lamps.

Normalization of Impacts

- Normalization expresses impact results relative to a reference value, such as the total per capita or regional impact in a year.

- This process helps to understand the significance of the results in a broader context.

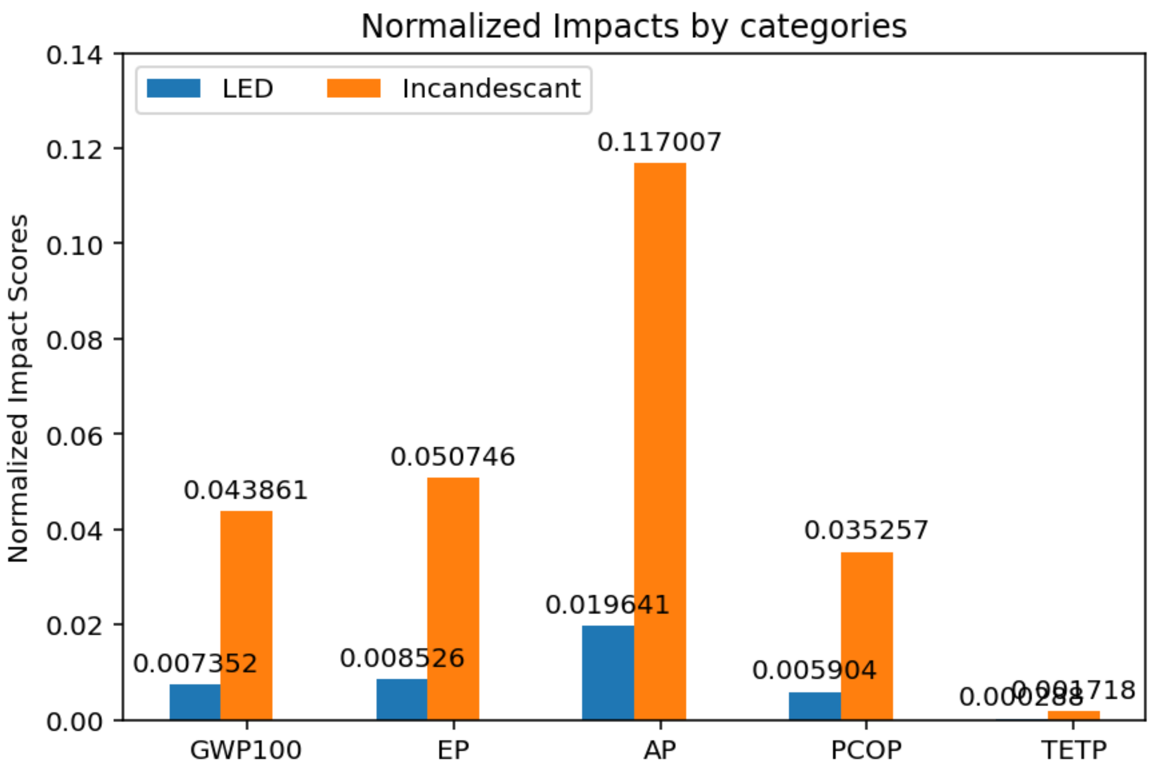
- For CML-IA baseline midpoint categories like GWP100, EP, AP, POCP, and TETP, normalization factors are available from reports and academic literature.

- Here are some normalization values (per person, per year) from Europe (EU-25 or EU-27), global, or world average perspectives.

	Impact Category	Unit	EU-25 (2000)	World (2008–2010 Avg)
1	GWP100	kg CO2-eq	10900	6600
2	EP	kg PO4^3--eq	4.87	3.06
3	AP	kg SO2-eq	27.3	19.5
4	POCP	kg C2H4-eq	3.49	2.29
5	TETP	kg 1,4-DB-eq	89.3	76.1

- Applying normalization of the overall impact scores for LED and incandescent lamps to the world's value:

	Impact Category	Unit	LED	Incandescent
1	GWP100	per person, per year	0.007352	0.043861
2	EP	per person, per year	0.008526	0.050746
3	AP	per person, per year	0.019641	0.117007
4	POCP	per person, per year	0.005904	0.035257
5	TETP	per person, per year	0.000288	0.001718



Summary of Results

LED Lamp

	Category	Absolute value		Normalized value
1	GWP100	48.5239	kg CO2-eq	0.007352
2	EP	0.0261	kg PO4^3--eq	0.008526
3	AP	0.3830	kg SO2-eq	0.019641
4	PCOP	0.0135	kg C2H4-eq	0.005904
5	TETP	0.0219	kg 1,4-DB-eq	0.000288

Incandescent Lamp

	Category	Absolute value		Normalized value
1	GWP100	289.4843	kg CO2-eq	0.043861
2	EP	0.1553	kg PO4^3--eq	0.050746
3	AP	2.2816	kg SO2-eq	0.117007
4	PCOP	0.0807	kg C2H4-eq	0.035257
5	TETP	0.1307	kg 1,4-DB-eq	0.001718

- LED lamps have significantly lower normalized impact values in all categories.

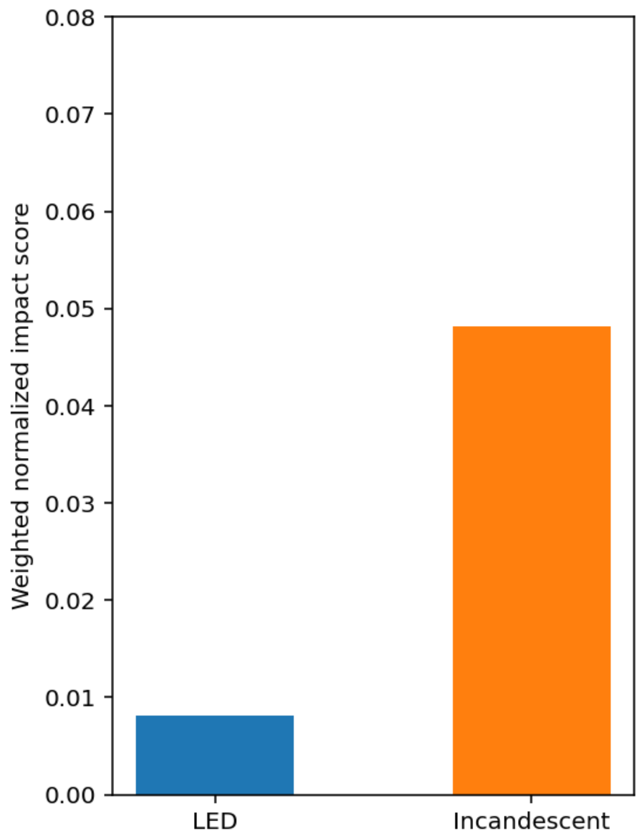
Weighting

- Weighting assigns a relative importance to each normalized impact category based on societal, environmental, or economic considerations.
- The value of the weights should be accessed from stakeholder preferences, policy goals, or expert judgment.
- Multiple Criteria Decision Making (MCDM) methods may be used in this step.
- Suppose that in consultation with the stakeholders and decision makers, the following weights were assessed:

	Category	Weight
1	GWP100	0.4
2	EP	0.3
3	AP	0.1
4	PCOP	0.1
5	TETP	0.1

Weighted Normalized Impact Values

Lamp	Weighted normalized score
LED	0.008082
Incandescent	0.048167



- From the weighted scores, it's clear that the LED lamp has a significantly lower overall environmental impact compared to the incandescent lamp.

Observations

- The normalized and weighted results show that the LED lamp has a significantly lower overall environmental impact compared to the incandescent lamp.
- This conclusion is supported by lower normalized impacts in global warming potential, energy consumption, and other categories.
- The total weighted score for the LED lamp is much lower than that for the incandescent lamp, indicating that LED lamps are more environmentally friendly for home lighting over their life cycle.

Overall Summary

- LED lamps are more environmentally friendly in terms of GWP and energy consumption, despite slightly higher impacts in resource depletion and human toxicity.

- The advantages of reduced energy use and lower GWP make LEDs a better choice for sustainable home lighting.

References

1. Michael Z. Hauschild, Ralph K. Rosenbaum and Stig Irving Olsen (Editors), *Life Cycle Assessment: Theory and Practice*, Springer, 2018.

2. Jingzheng Ren and Sara Toniolo (Editors), *Life cycle sustainability assessment for decision-making: methodologies and case studies*. Elsevier, 2020.

3. Mary Ann Curran (Editor), *Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products*, Wiley, 2012.

4. ISO 14040:2006: Environmental management - Life cycle assessment - Principles and framework.

5. ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines.

6. Jeroen B. Guinée (Editor), *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*, Springer-Verlag, 2002.