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Module 2.2 - LCA: principles and methodology

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Contents

Contents

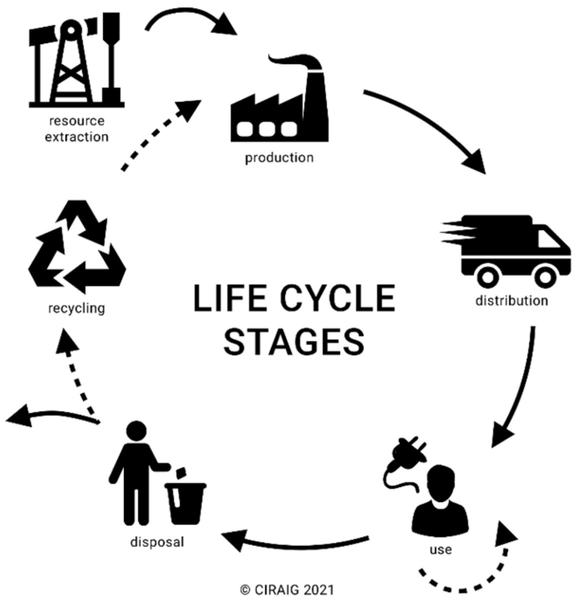
Resources Extraction
Manufacture
Transport
Construction
Use
Recycling

Life Cycle Assessment (LCA) is a tool for evaluating the **environmental impact** of a product, service or system.

Objective 1: Environmental assessment throughout the life cycle

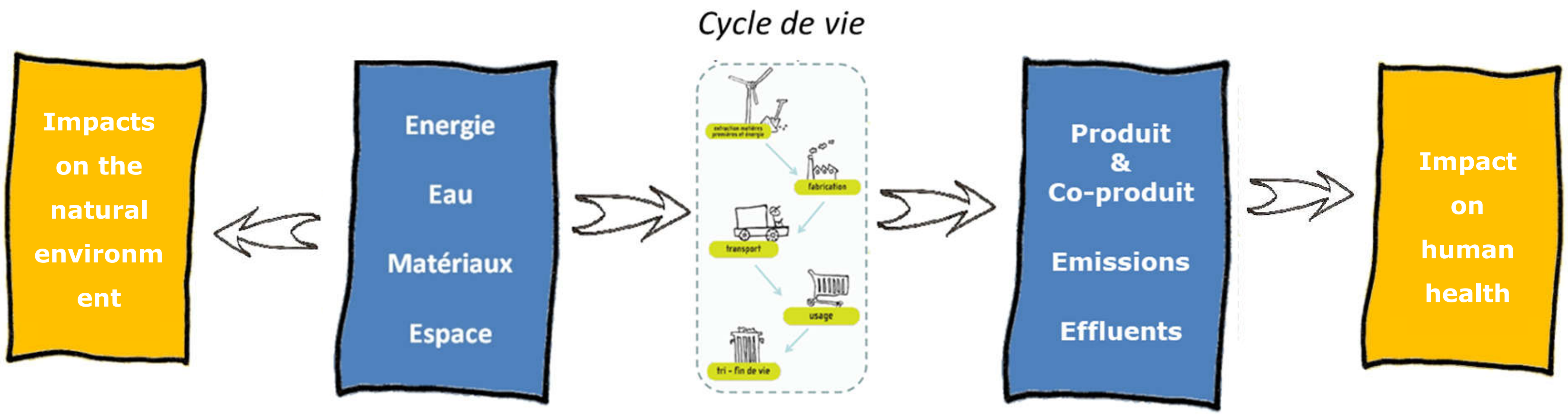
The life cycle of a system is its entire value chain.

This is known as the "cradle to grave" or "cradle to gate" analysis.



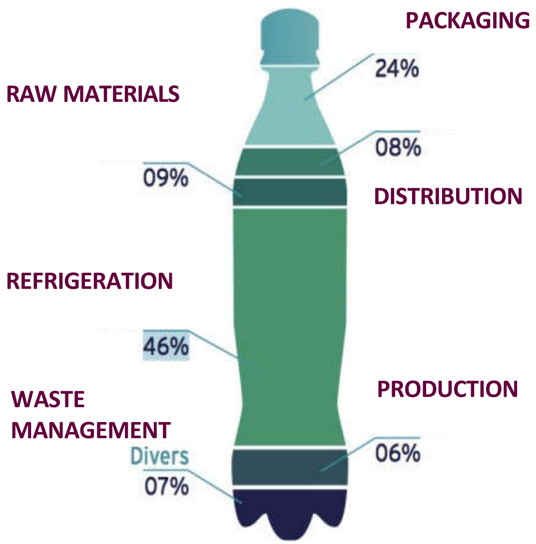
Life Cycle Assessment (LCA) is a tool for evaluating the **environmental impact** of a product, service or system.

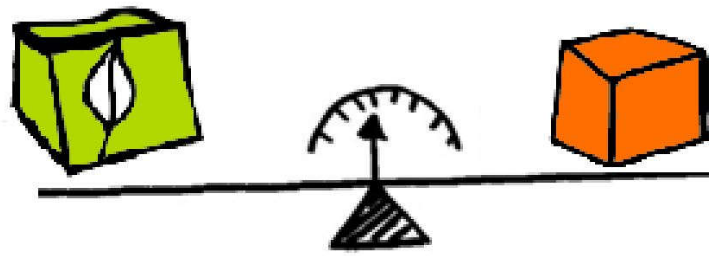
- Account for material and energy flows in and out of the system's life cycle, then characterization of the impacts.



Life Cycle Assessment (LCA) is a tool for evaluating the **environmental impact** of a product, service or system.

Objective 2: Distribute the impacts and prioritize actions contributing to impact reduction. Identify false good actions.

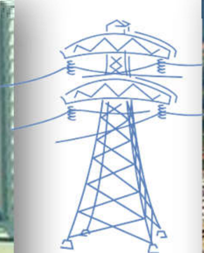




Comparing the impact of different systems (benchmarking)

Life Cycle Assessment (LCA) is a tool for evaluating the **environmental impact** of a product, service or system.

Objective 3: Identify pollution displacements and impact transfers.



Zero emissions?

Emissions "elsewhere"!

To avoid displacing environmental problems

- From one stage of the life cycle to another
- From one geographic region to another
- From one environment to another
- From one generation to the next

Life Cycle Assessment (LCA) is a tool for evaluating the **environmental impact** of a product, service or system.

The specific features and advantages of LCA are :

- Produce **quantified assessments of** a very **large number of pollutants and resources**: mass balances, multi-media models, etc.
- Performs **assessments over the entire cycle**: multi-stage method, applicable at a **global** (regional) **spatial and temporal level.**
- Relates environmental impact to **system function** (unique method in this respect)
- Encompasses the main environmental problems known to date: **multi-criteria approach** (resource extraction, climate change, impact of toxic substances, land use, etc.).
- Focuses on environmental impact: must be **combined with other analyses** (cost, social impact, technical feasibility, economic performance)

Life Cycle Assessment (LCA) is a tool for evaluating the **environmental impact** of a product, service or system.

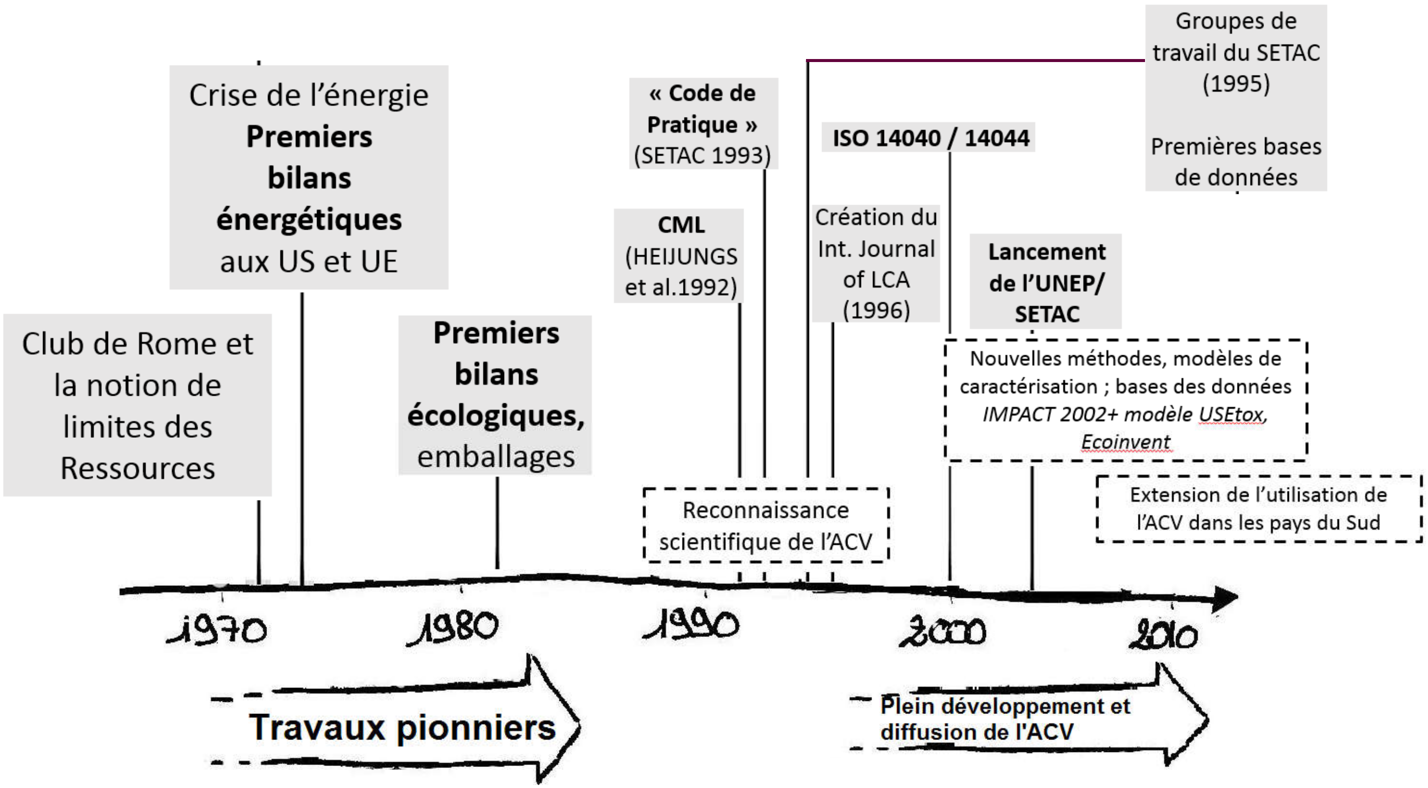
The limitations and drawbacks of LCA are :

- **May be biased:** well identify assumptions and simplifications made during the LCA and define consistency criteria.
- **May lack impartiality:** carry out a critical review by a third party.
- **Can lead to misinterpretation** (by external parts): recall the objectives defined at the outset and clearly state the methodological limits.
- **Does not allow modeling of all decision-support criteria**: flow and environmental impact indicators, but not design and/or management indicators.

Life Cycle Assessment (LCA) is a tool that can be used in a variety of contexts:

- Decision support and corporate strategy
- Research and knowledge contribution
- Eco-design of products (choice of materials, technologies, packaging, end-of-life, etc.)
- Benchmarking (choosing solutions with the least impact)
- Awareness-raising and communication (ecolabels, etc.)

Life Cycle Assessment (LCA) is a scientifically-recognized, internationally-regulated (SETAC & UNEP) and ISO-standardized method.



https://www.eco-conception.fr

Life Cycle Assessment (LCA) is a scientifically-recognized, internationally-regulated (SETAC & UNEP) and ISO-standardized method.

ISO 14040 (2006)
Life cycle assessment
Principles and frameworks

ISO 14044 (2006)
Life cycle assessment
Requirements and guidelines

> Extract from ISO 14040: "***Life cycle assessment takes into*** *consideration the* ***entire life cycle of a product****, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final waste disposal. Through this comprehensive and systematic approach, the shifting of burdens between different life-cycle stages or between particular processes can be identified and avoided."*

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Life Cycle Assessment (LCA) is a scientifically-recognized, internationally-regulated (SETAC & UNEP) and ISO-standardized method.

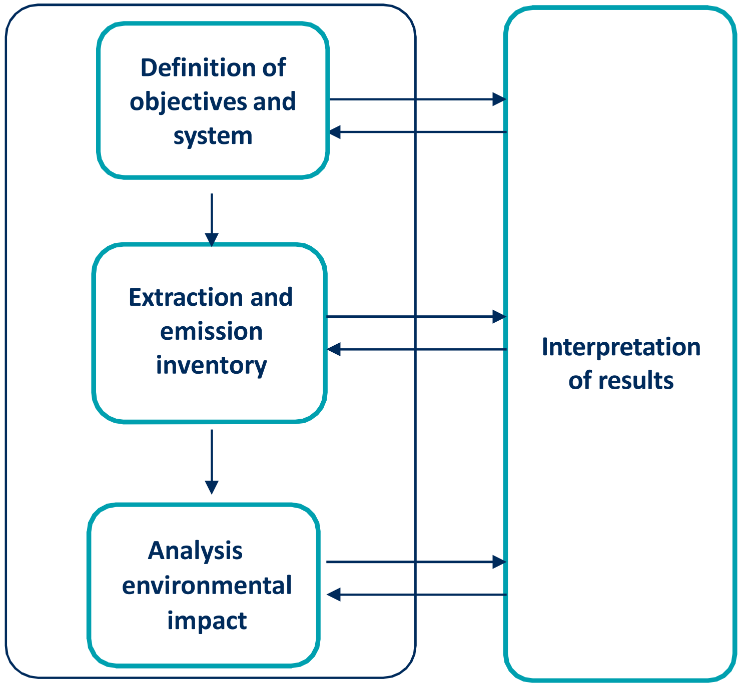
The ISO standard defines the methodology for carrying out a LCA:

4 distinct stages

- Definition of objectives and system
- Inventory: data availability and reliability, allocation issues
- Analysis: different types of characterization, final damage assessment
- Interpretation: sensitivity study and uncertainty analysis

Iterative approach

- Rapid preliminary assessment (screening)
- Detailed analysis: focus on points with the greatest impact



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Contents

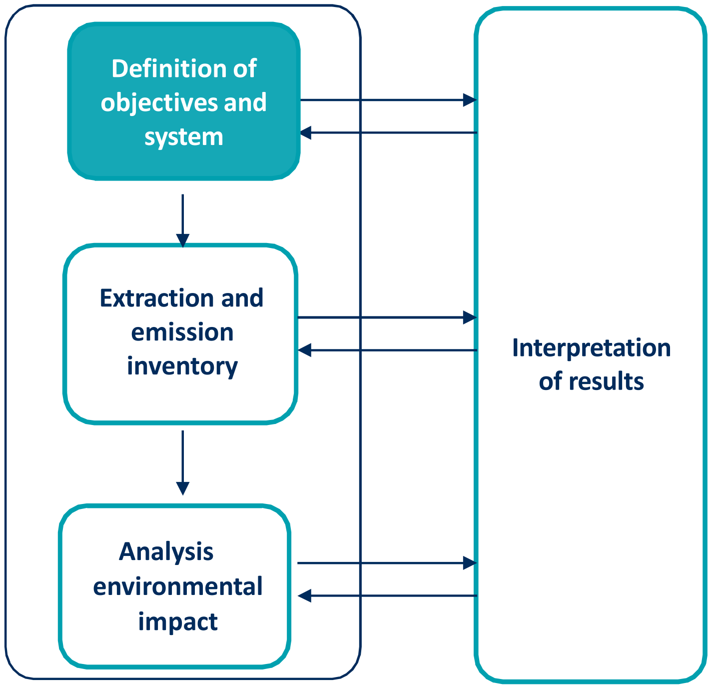
The 1rst step in an LCA is to define the objectives and scope of the study (system).

Objectives

- Type of application (regulatory, info., R&D, etc.)
- Reasons for the study
- Target audience (consumer, business, policy makers, etc.)
- Stakeholders (agent, executor, auditor, etc.)

Scope of study

- Product system
- Function, functional unit and reference flow
- Description, flow chart and scenarios
- Boundary and cut-off rules
- Allocation rules, database used, characterization method and types of impact, requirements, assumptions, choice of values, type of critical review



The 1[rst] step in an LCA is to define the objectives and scope of the study (system).

Function of the system studied

- Appropriate choice of main function (consideration of possible secondary functions)
- The same main function is essential for comparing different systems

Functional unit

- Quantity quantifying the system function = provided service
- Measurable and quantifiable quantity, with a well-defined unit
- Quantity to which all flows and impacts will be reported

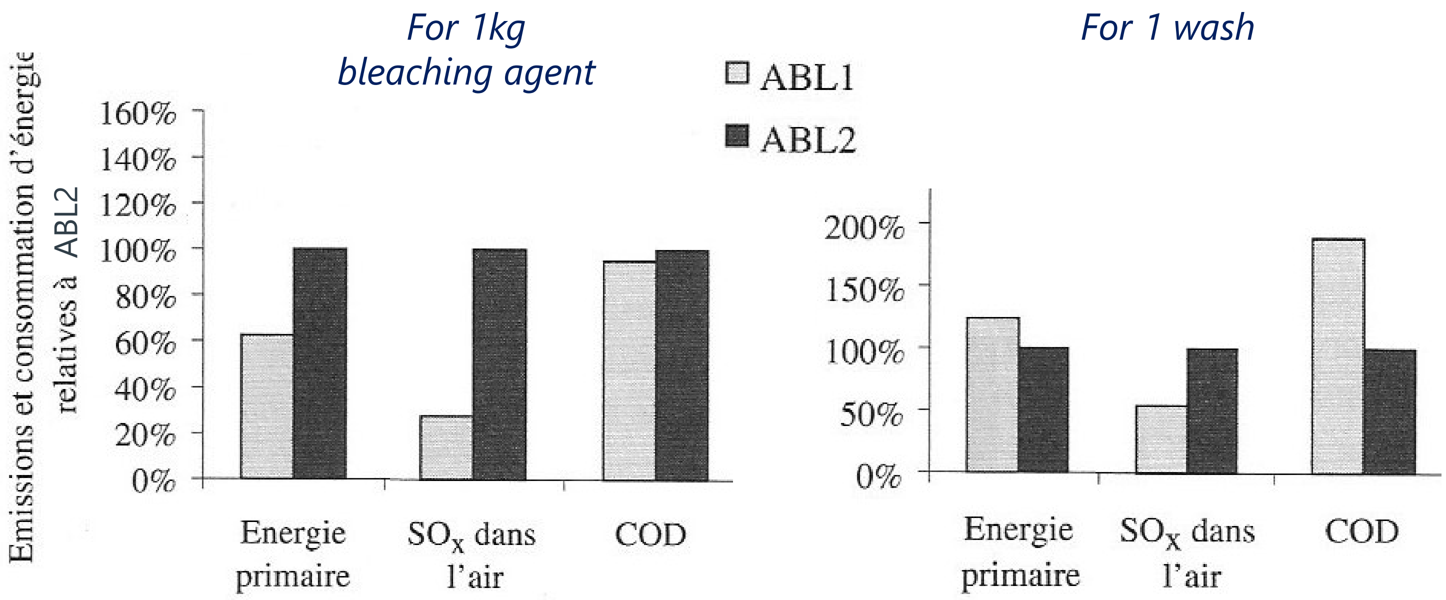
Reference flow

- Quantity of products required to perform the function according to the chosen functional unit
- Specific to each scenario considered for the same system

System	Function	Functional unit	Reference flow	Key parameters
Shoe	*Wear shoes in good condition*	*1 pair of shoes in good condition for 1 year*	*1 pair of shoes **in good condition** for 1 year*	*Quality and durability*
			*2 pairs of **low-quality** shoes for 6 months*	
Paint	*Use paint to paint a wall*	*100 m^2 of painted wall for 20 years*	*30 kg **long-lasting** paint (over 20 years)*	*Quantity applied per m^2 and service life*
			*2 * 25 kg **short-term** paint (over 2*10 years)*	

Illustration of the importance of choosing the right functional unit

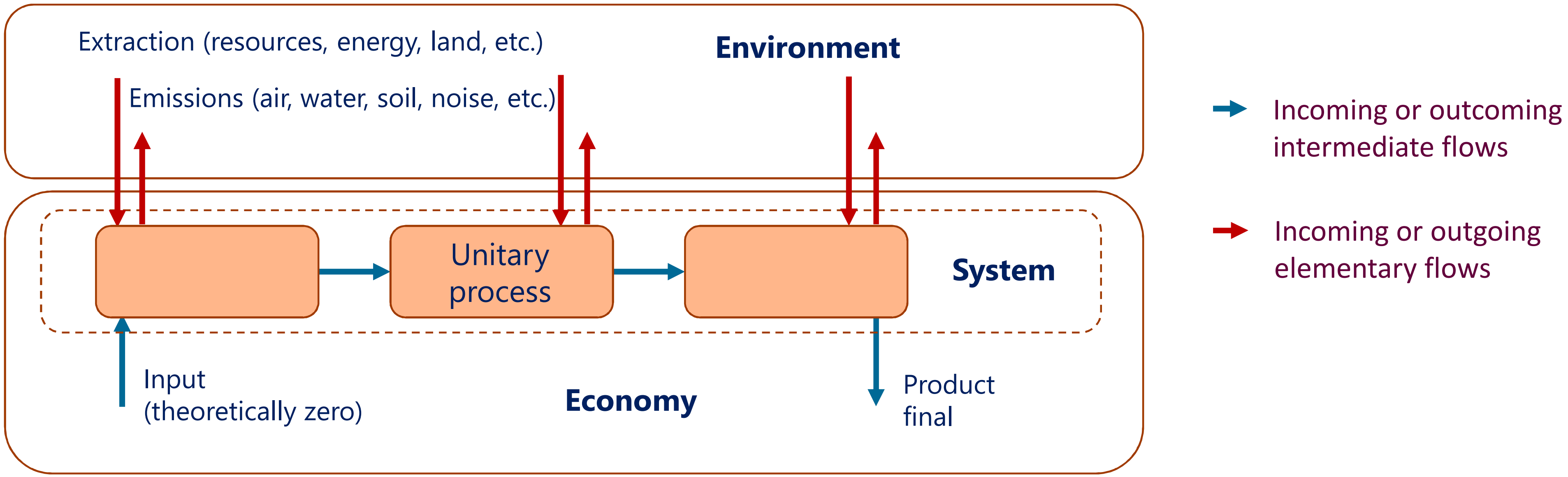
Comparison of environmental burdens related to two laundry bleach additives for two different functional units: 1 kg of agent or 1 wash.



Bretz 1994; O. Jolliet et al 2010

System description

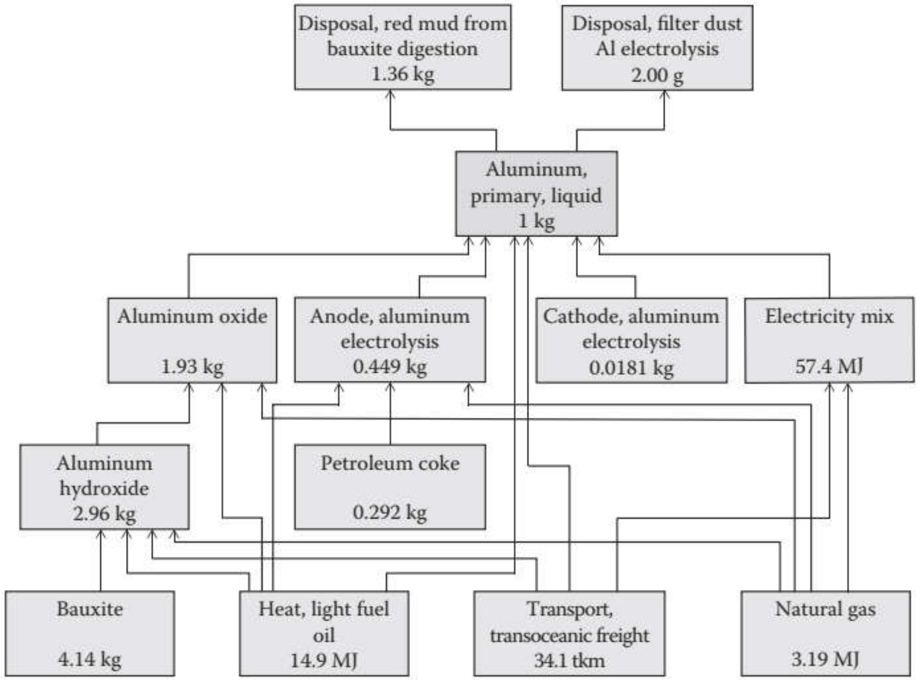
- Lifecycle modeling (systems approach)
- Definition of unit processes (flow chart), elementary flows and intermediate flows between processes
- Description of scenarios envisaged, choice of system limits (cut-off rules)



System description – Flow chart

- The flow chart describes the system's unit processes and the flows linking them.
- System diagram for a clear overview.

Flow chart of the manufacturing of liquid primary aluminium at plant (from Ecoinvent 2.2)



- Total intermediate outflows are shown for each process.
- The chart is built from the reference flow associated with the functional unit (e.g. 1kg of liquid aluminum).
- The extent to which the system can be described in terms of several processes depends on the purpose of the study and the existing characterization of certain processes in databases (e.g. electricity mix).

System description - System limits

- It is technically impossible to take all processes into account, and exclusion choices are necessary.
- Inclusion and exclusion criteria are grouped together in **cut-off rules** defined by the ISO standard.

ISO 14044 cut-off criteria :
"specification of the quantity of material or energy flows or level of environmental significance associated with elementary processes to be excluded from a study."

System exclusion for processes contributing less than :

1. x % of input mass (mass share)
2. x % of energy consumed (energy or economic share)
3. x % of pollutant emissions (contribution to environmental impact)

This choice requires a prior idea of the orders of magnitude of the various contributions (role of screening). The value of x depends on the number of processes (1 to 5%).

Example of LCA of 1[rst] generation biofuels *(based on ADEME 2010 report)*

- Unprecedented **expertise** at national level to update and deepen energy and GHG assessments already carried out
- **Decision-making support for the implementation of** public policies development of alternative energies
- **Produced by** Bio Intelligence Service on **behalf of** the French government (MEEDDM, MAAP), ADEME and FranceAgriMer
- **Support from** a technical committee: manufacturers, institutes, research centers, environmental associations
- Carried out on **various biofuels** consumed in France:

bio Intelligence Service

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MINISTÈRE DE L'ALIMENTATION DE L'AGRICULTURE ET DE LA PÊCHE

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
Ministère de l'Écologie, du Développement durable et de l'Énergie

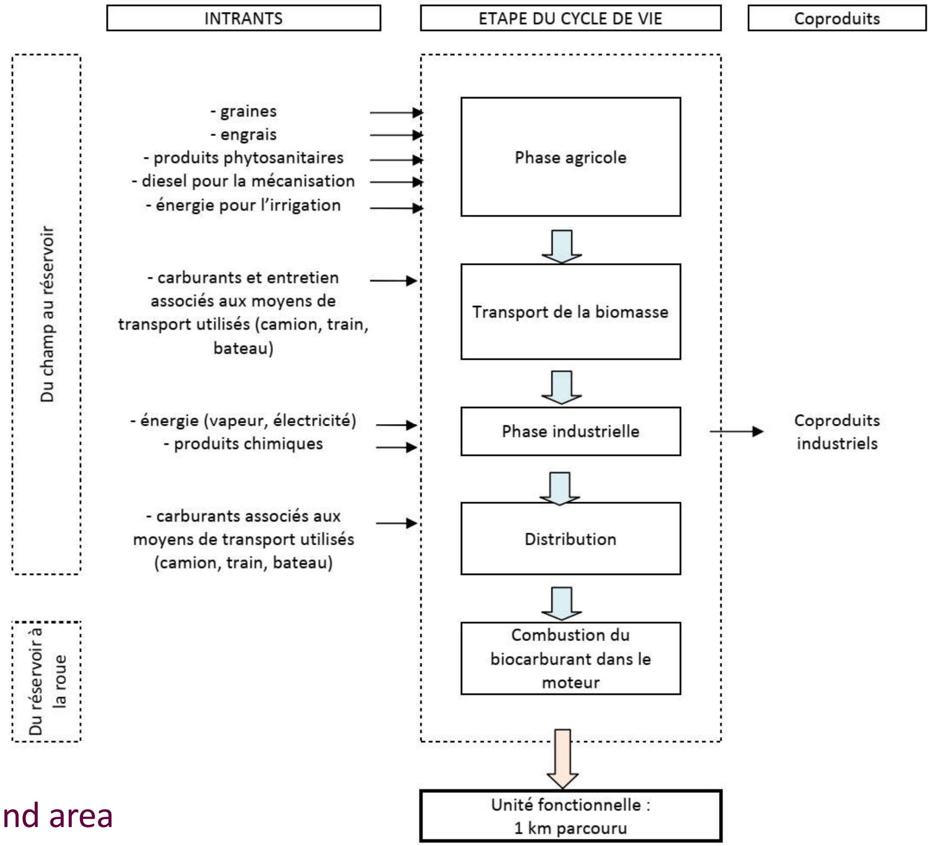
FranceAgriMer
ÉTABLISSEMENT NATIONAL DES PRODUITS DE L'AGRICULTURE ET DE LA MER

- ✓ bioethanol from wheat, beet, corn and sugar cane / ETBE
- ✓ biodiesel from rapeseed, sunflower, palm and soybean oils (EMHV), used edible oils (EMHAU) and animal fats (EMGA), pure vegetable oils (HVP)

- **Comparative LCA** with conventional fossil fuels: SP95 petrol and diesel (2009 specifications)

Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*

- **Function:** to move a vehicle
- **Functional unit**: travel 1 km
- The study is of the "**well-to-wheel**" type
  and takes into account fuel combustion in engines.
- Results presented per MJ of fuel consumed
  (by dividing UF by average consumption)
- 5 stages described in **the flow chart** : agricultural production transport, industrial transformation, distribution, combustion
- 5 **impact indicators** monitored: fossil energy consumption, GHG, eutrophication, photochemical pollution, human toxicity
- **Data sources**: Technical institutes, farm networks, production sites (annual data, average statistics, surveys, bibliographical data)



Perimeter enlarged during the sensitivity study to take into account the land area required to maintain the level of food demand (effect of **land use change**).

Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*

The study highlights a number of methodological choices and limitations to LCA, concerning :

- Modeling **N_2O emissions and fertilizer inputs**
- Taking account of direct or indirect **land-use change (CAS)**, more or less pessimistic

Par ha de biocarburant considéré	Ethanol de Canne à Sucre kg CO_2/ha/an	Ester d'Huile de Palme kg CO_2/ha/an	Ester de Soja brésilien kg CO_2/ha/an
Ordre de grandeur maximal	27 000	23 000	32 000
Ordre de grandeur scénarii intermédiaires	10 000	7 000	12 000
Ordre de grandeur scénarii modérés	3 000	1 500	5 000
Scénarii optimistes	-6 000 à -2 000 (valeur utilisée pour le calcul : -4 000)	-10 000 à -2 000 (valeur utilisée pour le calcul : -6 000)	0

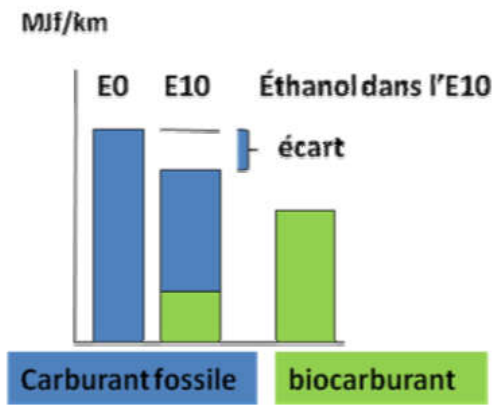
CO_2 emissions for direct CAS (import channels)

Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*

The study highlights a number of methodological choices and limitations to LCA, concerning :

- **Emissions inventories** *(https://www.georisques.gouv.fr/risques/registre-des-emissions-polluantes)*
- The **characterization model** used for eutrophication, photochemical pollution and human toxicity impacts

- **Modeling the combustion/vehicle stage**
  - ✓ Complex stage to model, often oversimplified
  - ✓ At low levels of biofuel incorporation, a discrepancy in this stage can have a strong impact on the overall balance.
  - ✓ Choice of engine operating cycle (NEDC...)
  - ✓ Choice of engine emission levels (IFP study on fossil fuels, etc.)
  - ✓ Choice of emission management for mixtures



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Contents

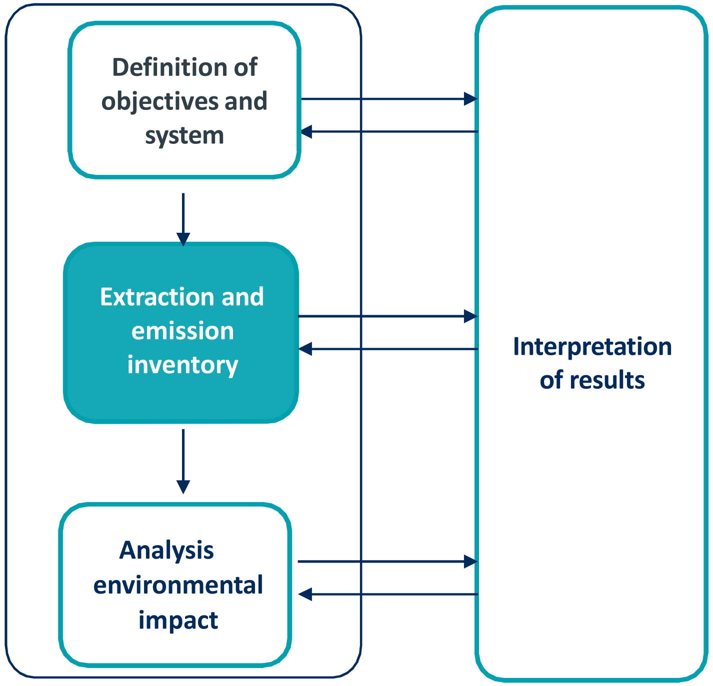
The 2nd step in an LCA is the quantification of the various flows passing through the system by means of an inventory.

Inventory

- **Elementary flows** (incoming and outgoing) between the system and the environment
- Based on the intermediate flows associated with each process
- Uses **emission and extraction factors**

Methodology

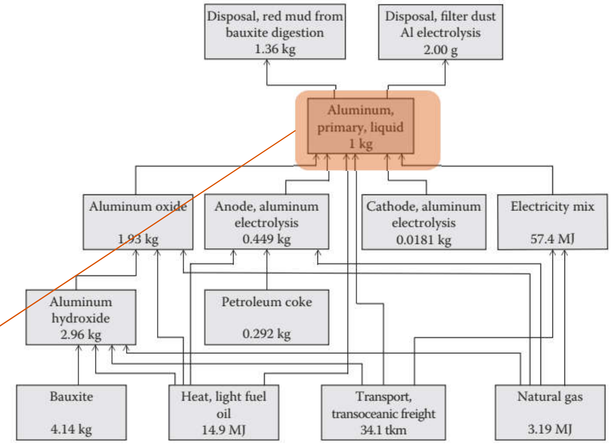
- 2 possible approaches: **by process** or **input-output** (I/O)
- Uses **inventory data** collected in **databases**
- Uses **aggregation** and **allocation principles**

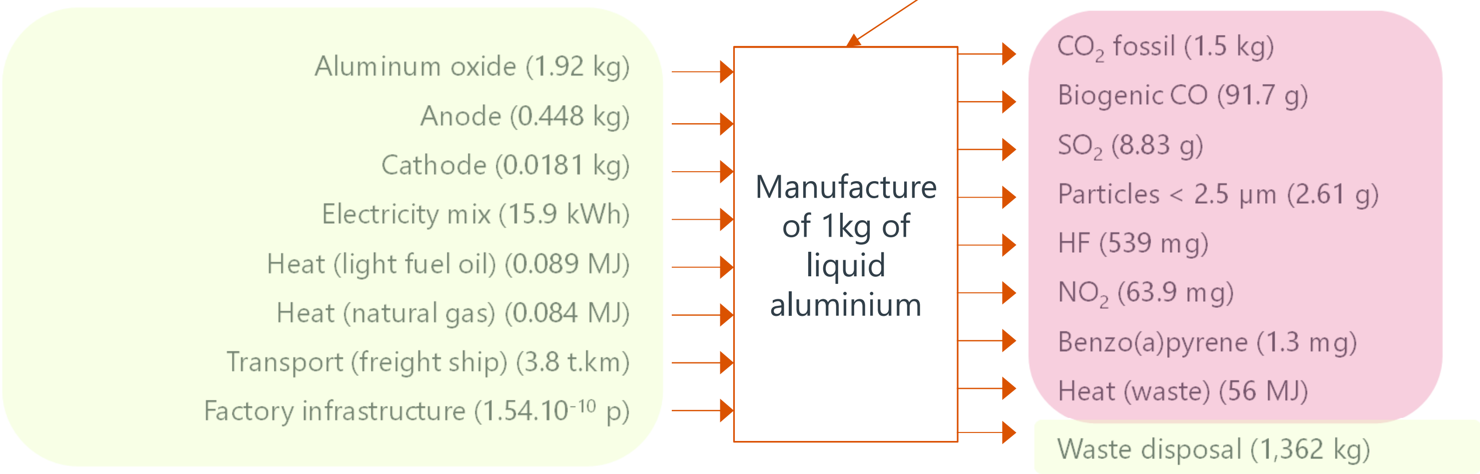


The inventory of emissions and extractions can be carried out using a **process-based approach**.

For each unit process :

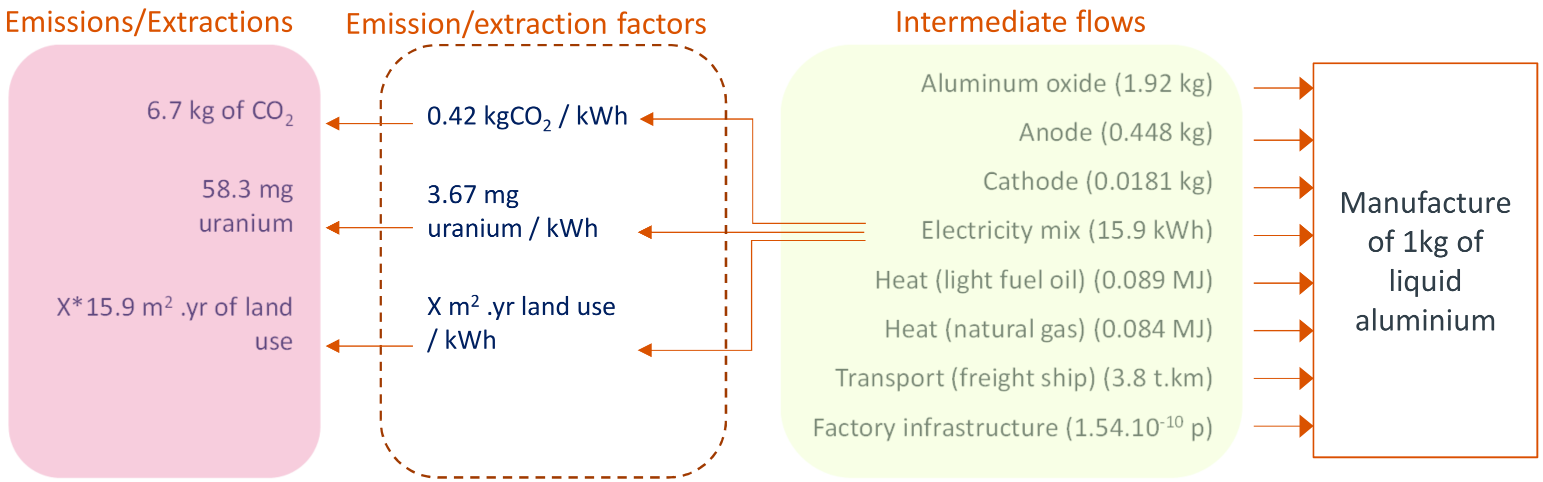
- Identify direct emissions and extractions per unit of outgoing intermediate flow.
- Characterize incoming and outgoing intermediate flows, whose emissions and indirect extractions will then be calculated and added up.





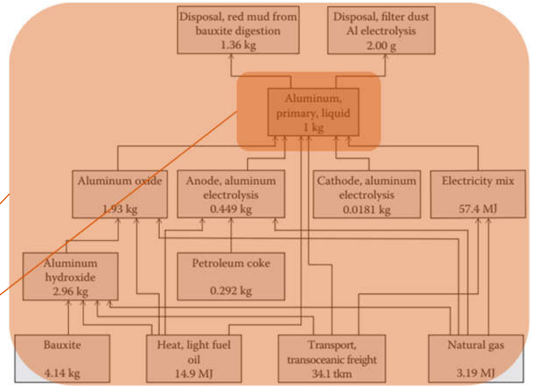
Indirect emissions and extractions

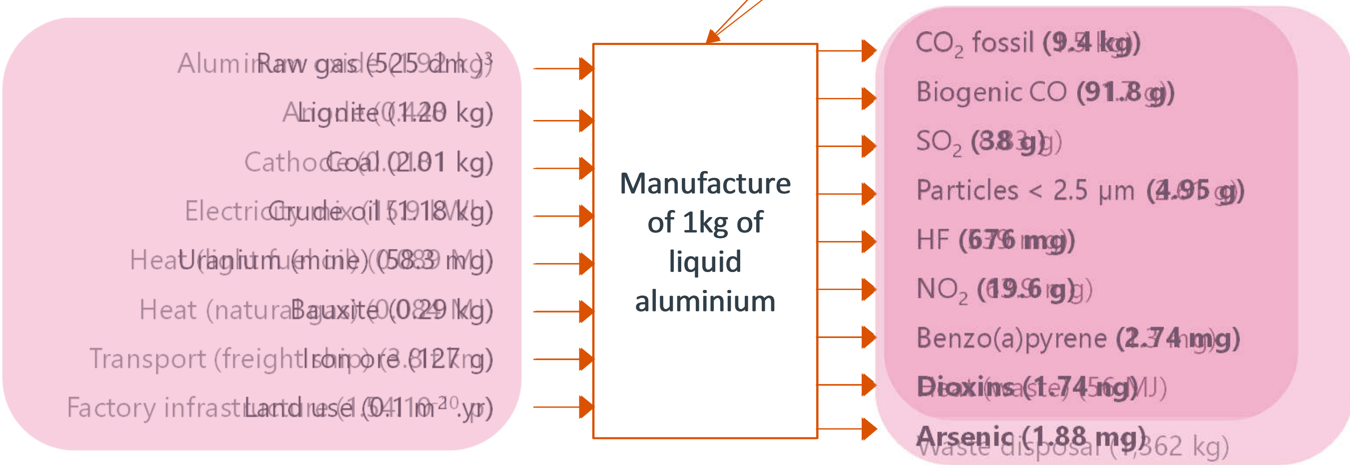
- Are calculated on the basis of previously identified intermediate flows.
- Emissions/extractions are calculated by multiplying intermediate flows with **emission factors** expressed per unit of flow.
- Emission factors are part of **inventory data,** accessible in several ways: database, technological sector (company, trade union,....), in-situ, scientific publications.



The inventory of emissions and extractions can be carried out using a **process-based approach**.

- All emissions/extractions are calculated for the various unit processes.
- Emissions/extractions of the same substance are added up over the whole system. This is called **aggregation**.
- The different modes, locations and times of emission of the same substance are not considered in this inventory phase.





Inventory databases

- Facilitate the painstaking task of retrieving inventory data (reliability, clarity, updating, etc.)
- Ensure data quality, availability and harmonization.
- List processes linked to energy, materials, chemicals, waste treatment, transport, industrial and agricultural activities, food, etc.
- Characterized by geographical and/or sectoral specificities.
- Paid or free access

ecoinvent
European Commission
AGRIBALYSE®
FEDERAL LCA COMMONS
IDEA Inventory Database for Environmental Analysis
thinkstep GaBi

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Non-renewable primary energy demand and CO_2 emission factors *(extracted from Ecoinvent database)*

	Nomenclature Ecoinvent	Primary ENR (MJ/unit) Cumulative Energy Demand	CO2 emitted (g/unit) IPCC 2013	CO2/ENR ratio (gCO2/MJ)
Energy				
1 kWh electricity (mix) - Europe	*market group for electricity, low voltage - RER*	8,8	360	41
1 kWh electricity (mix) - France	*market for electricity, low voltage - FR*	12	78	7
1 kWh electricity (mix) - Poland	*market for electricity, low voltage - PL*	12,3	972	79
1 kWh electricity (mix) - China	*market for electricity, low voltage - CN-CSG*	7,5	600	80
1 kWh of photovoltaic electricity - China	*electricity production, photovoltaic, 580 kWp ground installation, multi-Si - CN-SC*	1	68	68
1 kWh of wood heating - World	*heat production, hardwood chips from forest, at furnace 1000kW - RoW*	0,4	27	68
1 kWh of light oil heating - Europe	*heat production, light fuel oil, at boiler 100kW condensing, non modulating - Europe*	4,5	306	68
1 kWh gas heating - Europe	*heat production, natural gas, at boiler condensing modulating > 100kW - Europe*	4,5	220	49
Transport				
1 t.km by truck > 32 t Euro 6	*transport, freight, lorry > 32 metric ton, EURO6 - RER*	1,5	84	56
1 pers.km by high-speed train - France	*transport, passenger train, high-speed - FR*	1,1	16	15
1 pers.km by plane (intercontinental flight)	*transport, passenger, aircraft, intercontinental - RER*	1,6	106	66
1 km in a Euro 5 city gasoline car	*transport, passenger car, medium size, petrol, EURO 5 - RER*	4,8	320	67
Material				
1 kg low-alloy steel - Europe	*steel production, converter, low-alloyed - RER*	23	1 860	81
1 kg primary aluminum ingot - Europe	*aluminium production, primary, ingot - IAI area, EU27 & EFTA*	114	6 190	54
1 kg primary copper - Europe	*copper production, primary - RER*	22	1 400	64
1kg fiberglass - Europe	*glass fibre production - RER*	36	1 840	51
1 kg HDPE polyethylene - Europe	*polyethylene production, high density, granulate - RER*	76	1 560	21
1 kg bleached pulp - Europe	*sulfate pulp production, from hardwood, bleached - RER*	4,5	266	59
1 m3 of concrete - World	*market for concrete, 20MPa - GLO*	1 663	230 700	139
1 m3 demineralized water - Europe	*water production, deionised - RER*	6	360	60
End of life				
Landfilling 1kg of scrap - Europe	*treatment of scrap steel, inert material landfill - Europe without Switzerland*	0,156	5	32
1kg of aluminium sent to landfill - World	*treatment of waste aluminium, sanitary landfill - RoW*	0,59	35	59
Incineration of 1kg of polypropylene - World	*treatment of waste polypropylene, municipal incineration - RoW*	0,27	2550	9444

Inventory data

- The data inventoried have a **spatial, temporal and technological scope/representativeness**. They can be **specific** or **averaged**.
- The data is **aggregated to varying degrees,** with more or less information on unit processes.
- Data are characterized by their **source** (scientific publication, production site, etc.).
- The types and **classification** of incoming and outgoing elementary flows may differ from one base to another.
- These may include the **quality of the data**, any **shortcomings** from which they may suffer, and any **controls** they may be subject to.
- Data quality covers probability, reliability, completeness, geographical, temporal and technological correlations.
- General information on the data can be accessed via **online platforms**:

Global LCA Data Access

openLCA nexus

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Example of inventory data from the GaBi database (Sphera)

Bioethanol from sugar beet, at filling station

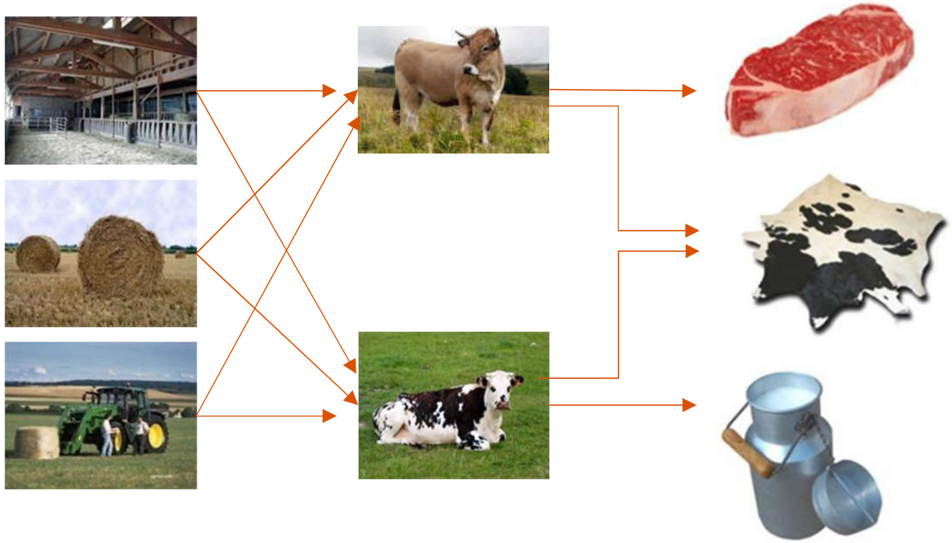
Process data set: Bioethanol from sugar beet, at filling station; from sugar beet; production mix, at filling station; 0.79 g/cm3, 46.07 g/mol (en)	
Table of Contents: Process information - Modelling and validation - Administrative information - Inputs and Outputs	
Process information	
Key Data Set Information	
Location	EU-28
Geographical representativeness description	The data set represents the national / regional production mix including domestic production. Imports are not considered.
Reference year	2020
Name	Base name; Treatment, standards, routes; Mix and location types; Quantitative product or process properties Bioethanol from sugar beet, at filling station; from sugar beet; production mix, at filling station; 0.79 g/cm3, 46.07 g/mol
Use advice for data set	The data set can be used for all LCA studies where the specific product is needed. Combination with individual unit processes using this commodity enables the generation of user-specific (product) LCAs.
Technical purpose of product or process	Supply of 1 kg bioethanol at filling station for road transportation and other consumers.
Classification	Class name / Hierarchy level Energy carriers and technologies / Renewable fuels
General comment on data set	The data set covers all relevant process steps and technologies over the supply chain of the represented cradle to gate inventory. This includes the cultivation of the crop, the transportation from the field to the ethanol production plant, the ethanol production, the transportation and distribution to the depot and to the filling station. The inventory is based on literature data.
	Copyright? Yes — Owner of data set (contact data set) Sphera Solutions GmbH
Quantitative reference	
Reference flow(s)	Ethanol from sugar beet - 1.0 kg (Mass)
Time representativeness	
Data set valid until:	2023
Time representativeness description	annual average
Geographical representativeness	
Technological representativeness	
Technology	Foreground system: The largest sugar beet (Beta vulgaris L.) producers in Europe are France, Germany and Poland. These countries produce more than 50% of the total amount of

Allocation principles when modeling a multi-product system.

- Necessary when a system is multi-product and the study concerns only one of the products.
- Involves **distributing environmental burdens and the use of raw materials** between the product under study and secondary products.
- There are different types of secondary products depending on their economic value.

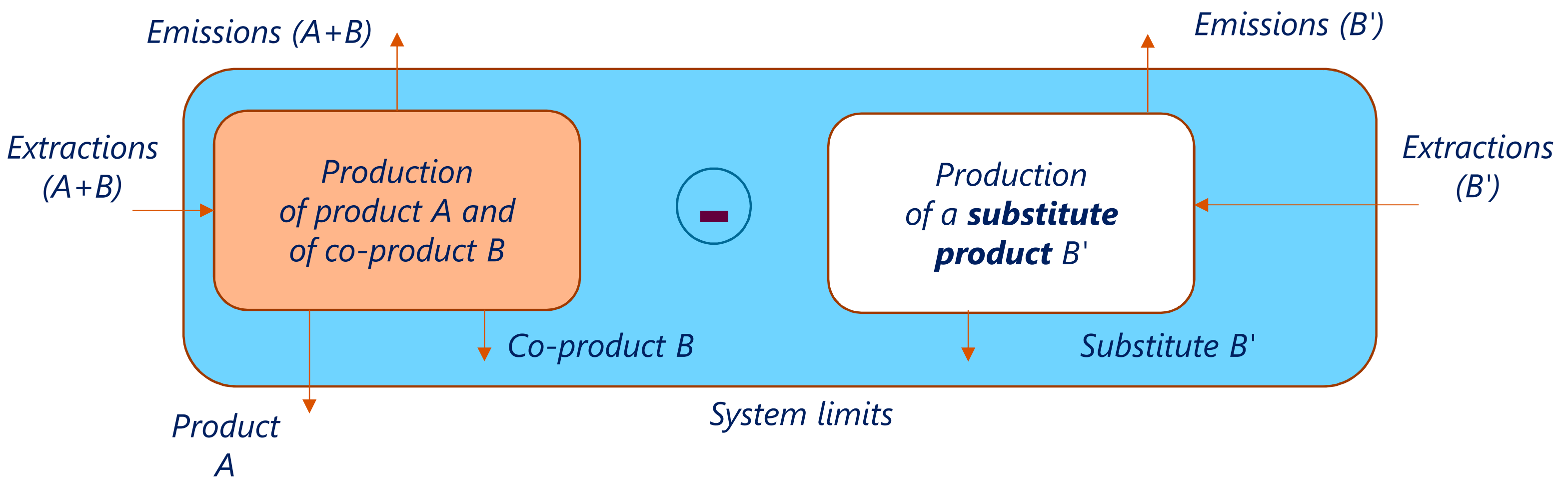
Example of co-products:

For a yogourt LCA, what emissions and extractions associated with raising a cow should be allocated to milk?



Allocation principles when modeling a multi-product system.

- 1rst method (priority): **System extension and substitution of co-products**



- 2nd method: **Physical allocation (according to physical property or marginal variation)**

  Mass is commonly used, although it is not very representative of a cause-and-effect relationship.

- 3rd method: **Economic allocation (based on market value of co-products)**

Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*

- **Sources of** emission/extraction **factors**: ECOINVENT, IFP, REP, BIO
- **Life Cycle Inventories (LCI)**: fertilizers, seeds, drying, transport, etc.
- Biofuel chains generate **valuable co-products**:
  - ✓ Fertilizers
  - ✓ Animal feed
  - ✓ Industry
  - ✓ Energy

Allocation methods

Les coproduits sont…	La méthode recommandée est…
…épandus	la substitution
… utilisés en alimentation animale	le prorata énergétique entre coproduits d'une étape
…utilisés dans l'industrie	
…utilisés à des fins énergétiques	la substitution

Example for the wheat bioethanol sector: co-produced wheat grains can be considered as substitutes for soybean meal.
(sensitivity analysis)

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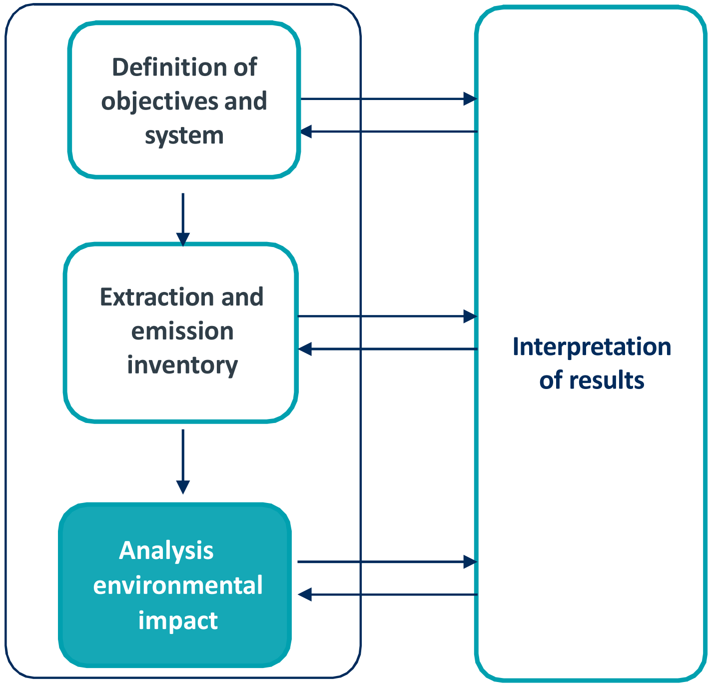
The 3rd step in an LCA is the characterization of the impacts associated with the emissions/extractions in the inventory.

Methodology

- **Classification of** inventory flows by impact (intermediate) categories.
- **Midpoint characterization** of impacts according to characterization factors and impact scores.
- **Endpoint characterization** based on characterization factors and damage scores
- Scores **normalized** to reference values, then **weighted** between normalized scores.

Tools

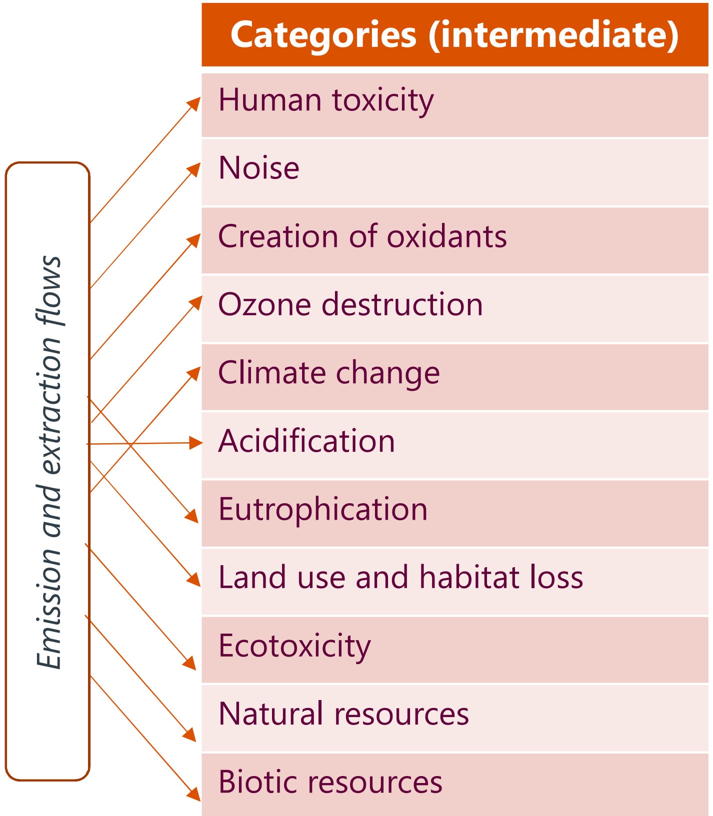
- Various **characterization methods** (impact analysis).



The **classification of** inventory data involves grouping emissions and extractions into different **impact categories**.

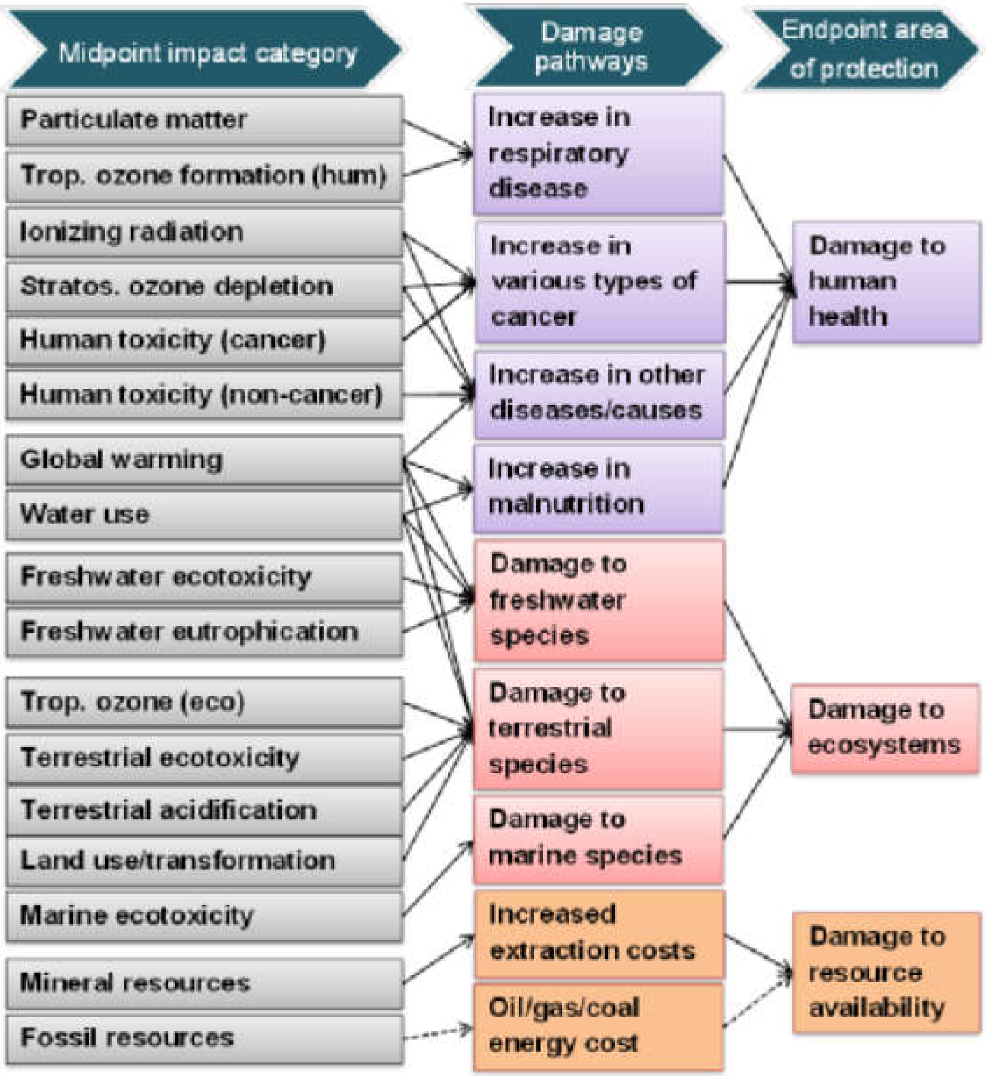
- It allows emissions/extractions to be grouped together on the basis of their capacity to affect the environment.

- The categories correspond to the types of environmental impact.
- The list of categories is generally determined by the choice of analysis method, but can be adjusted.



Classification can be based on **midpoint** or **endpoint impact** categories.

- **Damage categories** consist of a grouping of different types of impact
- The same impact may belong to different damage categories
- Damage represents the ultimate impact on the **three areas to be protected**:
    - Human health
    - Ecosystem quality
    - Resource availability



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Within the same impact/damage category, the significance of the effects of each emission and/or extraction is determined by **characterization factors**.

- Factors are the results of scientific modeling quantifying the effects of a substance (usually in relation to a reference substance).

Example of the climate change impact characterization factor

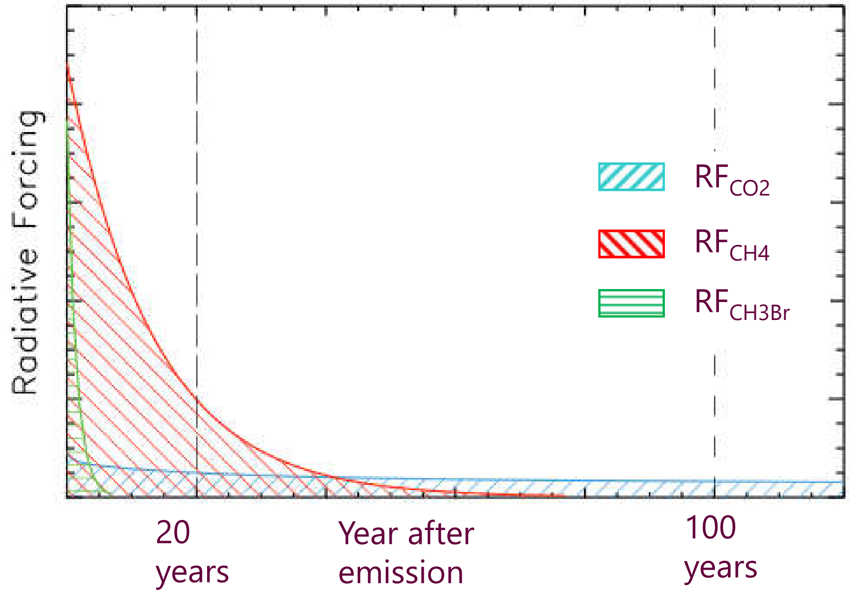
$$GWP = \frac{\int_0^{TH} RF(t)dt}{\int_0^{TH} RF_r(t)dt} = \frac{\int_0^{TH} a.[C(t)]\,dt}{\int_0^{TH} a_r.[C_r(t)]dt}$$

$\int_0^{TH} RF(t)dt$ is the average radiative forcing ($W.m^{-2}$ $.yr.kg$ $)^{-1}$

a is the radiative efficiency of the gas

C(t) is the quantity of gas in the atmosphere

Myhre et al, 2013



Within the same impact/damage category, the significance of the effects of each emission and/or extraction is determined by **characterization factors**.

- Factors are the results of scientific modeling quantifying the effects of a substance (usually in relation to a reference substance).
- Factors may need to take into account the characteristics of the receiving environment, transformation and/or transport processes, etc.

Example of the soil/water acidification impact characterization factor

$$PA = \frac{nb\ mole\ H^{+}/M_{molaire}}{nb\ mole\ H^{+}{}_{ref}/M_{molaire_{ref}}}$$

nb mole H^+ corresponds to the number of H^+ ions available after the formation of acid compounds such as H_2SO_4, HNO_3

compound	reaction equation
SO_2	$SO_2 + H_2O + O_3 \rightarrow 2H^+ + SO_4^{2-} + O_2$
NO	$NO + O_3 + \frac{1}{2}H_2O \rightarrow H^+ + NO_3^- + \frac{3}{4}O_2$
NO_2	$NO_2 + \frac{1}{2}H_2O + \frac{1}{4}O_2 \rightarrow H^+ + NO_3^-$
NO_x^*	-
NH_3	$NH_3 + 2O_2 \rightarrow H^+ + NO_3^- + H_2O$
HCl	$HCl \rightarrow H^+ + Cl^-$
HF	$HF \rightarrow H^+ + F^-$

Within the same impact/damage category, the significance of the effects of each emission and/or extraction is determined by **characterization factors**.

- Factors are the results of scientific modeling quantifying the effects of a substance (usually in relation to a reference substance).
- Factors may need to take into account the characteristics of the receiving environment, transformation and/or transport processes, etc.

Intrant	Nom de l'Inventaire	Source principale		pour 1	Commentaires	Energie primaire non-renouvelable	Emissions de gaz à effet de serre	Oxydation photo-chimique	Toxicité humaine	Eutrophisation
						(MJ)	(kg éq. de CO_2)	(kg éq. de C_2H_4)	(kg éq. 1,4-DB)	(kg éq. de PO_4)
acide chlorhydrique	ICV_acide_chlorydrique_30pourcent_ds_eau	ECOINVENT	Acide chlorhydrique, 30% dans H_2O, à l'usine/RER S	Kg	0	1,87E+01	8,91E-01	2,28E-04	5,91E-01	3,70E-04
engrais CaO	ICV_chaux	ECOINVENT	Chaux de gazéification, stockage régional/CH S	kg		1,85E-01	1,16E-02	5,10E-06	2,16E-03	1,38E-05
B0	ICV_B0	IFP	B0	km	rapport IFP, sur clio III EURO4, GOH, sans FAP	0,00E+00	1,25E-01	3,05E-06	6,87E-01	3,25E-05

For each intermediate impact category, the effects of the various emissions and/or extractions are added together to determine an **intermediate impact score**.

Inventory		Climate change IPCC 2013 100a	Acidification CML 2001
1000g	CO_2	x 1 = 1000	
10g	CH_{4b}	x 28 = 280	
1g	$N O_2$	x 265 = 265	
10g	SO_2		x 1 = 10
2g	NH_3		x 1,88 = 3,76
5g	NO_x		x 0,7 = 3,5

M_s $FI_{s,i}$

$$SI_i = \sum_s FI_{s,i} . M_s$$

Intermediate categories are grouped into **damage** categories using damage characterization factors

- Damage categories qualify the damage caused to different "subjects" to be protected (human health, ecosystems, resources, etc.).
- An impact analysis can be limited to intermediate impact categories, or can focus directly on damage categories.
- The contribution of each impact category is weighted by a **damage characterization factor** (FD).$_{i,d}$
- The sum of the contributions from each intermediate impact category gives the SD **damage characterization score.**$_{d}$

$$SD_d = \sum_i FD_{i,d}.SI_i$$

Following characterization, impact analysis can include two other optional steps: **normalization** and **weighting.**

- Normalization consists of relating intermediate impact scores or damage scores to **reference values** (normalization values).

$$N_i = \frac{SI_i}{VN_i} = \sum_s \frac{FI_{s,i}}{VN_i} . M_s = \sum_s FI^N_{s,i} . M_s$$

VN_i : normalization value for impact category (i)

$FI^N_{s,i}$: standardized impact characterization factor

- The reference value quantifies a **contribution to the global impact** (global, national, regional, etc.).

Example: the normalization value for climate change (IMPACT 2002+ method) = 9950 kgeqCO_2 / European / year.

Following characterization, impact analysis can include two other optional steps: **normalization** and **weighting.**

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10g	SO_2		x 1 = 10
2g	NH_3		x 1,88 = 3,76
5g	NO_x		x 0,7 = 3,5
Impact score		1545g eqCO_2	17.26g eqSO_2
Standardized score		**1.55.10^{-4} europ.an**	**5.3.10^{-4} europ.an**

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Following characterization, impact analysis can include two other optional steps: **normalization** and **weighting.**

- Weighting involves defining the relative importance of standardized damage characterization scores using weighting factors.

$$\mathrm{IP} = \sum_{d} FP_d . N_d$$

- Aggregating the various damage scores by weighting enables us to define a single **total weighted environmental impact score IP**.

- The FP weighting factors_d are determined according to a **judgment of** social, political and ethical **values**:

"How do you assess the value of a lost year of life compared to that of an extinct species?"

Following characterization, impact analysis can include two other optional steps: **normalization** and **weighting.**

- Methods for determining weighting factors can be based on :
  - ✓ **Monetarization**, where we estimate what we are willing to pay to avoid damage (*willingness to pay*).
  - ✓ **Surveys** of experts or the general public to determine the perception of the relative importance of damage
  - ✓ **Distance** *to* **a** *target* **value** (political, administrative or environmental)

- Damage weighting remains a debated issue in LCA (industrial applications).

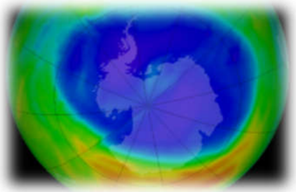
There are many **impact analysis methods** defining impact and damage categories and grouping together characterization factors:

- CML 92 (*Heijungs, 1992*) => CML 2016 => **Dutch LCA Guide** (*Guinée 2001, 2002*)
- Eco Indicator 95 => Eco-indicator 99 (*Goedkoop, 1999*)
- CML 2016 + Eco-indicator 99 => **ReCiPe 2016** (*Goedkoop, 2009*)
- Impact 2002^{+} (*Jolliet, 2003*)
- EDIP97 => EDIP 2003 (*Hauschild, 2004*)
- Impact 2002^{+} + EDIP => **Impact World+.**
- **ILCD LCIA** (*Hauschild, 2010, 2011, 2013*)
- USEtox (*UNEP-SETAC*)
- **IPCC 2021** , LIME , TRACI

The methods are distinguished by the different impact categories covered, different characterization models for a given impact category, different flows, different geographical representativeness, etc.

Tip: use several analysis methods in an LCA and compare results.

Intermediate impact category	Characterization factor and Environmental impact	Unit	Analysis method concerned
Climate change	GWP (global warming potential)		
	Capacity of greenhouse gases (CO_2 , CH_4 , N_2 O,...) to increase the Earth system's radiation balance over a 100-year horizon.	kg CO eq$_2$	Dutch Guide, Impact 2002+, ReCiPe 2008, ILCD LCIA, IPCC 2013
Acidification water/soil	AP (acidification potential)		
	Capacity of emitted gases (SO_2 , NH_3 ,...) to acidify the atmosphere, water and soil (as a result of acid rain).	kg SO eq$_2$	Dutch Guide, Impact 2002+, ReCiPe 2008, ILCD LCIA,...
Photochemical oxidation	POP (photochemical oxidation potential)		
	Capacity of gases (VOC, NOx, etc.) to contribute in the formation of tropospheric ozone (smog).	kg C H eq $_{24}$	Dutch Guide, Impact 2002+, ReCiPe 2008, ILCD LCIA,...

Intermediate impact category	Characterization factor and Environmental impact	Unit	Analysis method concerned
Destruction of the ozone layer	ODP (ozone depletion potential)		
	Capacity of emitted gases to contribute the destruction of the stratospheric ozone layer.	kg CFC-11 eq	Dutch Guide, Impact 2002+, ReCiPe 2008, ILCD LCIA, ...
Eutrophication water	EP (eutrophication potential)		
	Capacity of substances emitted to contribute excess nutrients (N, P, etc.) to water and soil, suffocating living organisms.	kg PO eq$_4^{3-}$ kg P eq kg N eq	Dutch Guide, Impact 2002+, ReCiPe 2008, ILCD LCIA,...
Ecotoxicity water / soil	ETP (ecotoxicity potential)		
	Capacity of substances to pollute water and soil directly (heavy metals, pesticides, herbicides, etc.).	kg 1.4 DB eq kg TEG CTUe (PAF.m^3 .day)	Dutch Guide, Impact 2002+, ReCiPe 2008, ILCD LCIA,...

Intermediate impact category	Characterization factor and Environmental impact	Unit	Analysis method concerned
Human toxicity	HTP (human toxicity potential)		
	Characterizes the danger of a substance to human health, taking into account its toxicity and the potential dose received.	kg 1.4 DB eq kg C H_{23} Cl eq CTUh	Dutch Guide, Impact 2002+, ReCiPe 2008, ILCD LCIA, ...
Resource depletion	DP (depletion potential)		
	Characterizes resource scarcity, taking into account reserves, extraction rates and costs	MJ / kg oil eq kgCu eq / kgSb eq m^3	Dutch Guide, Impact 2002+, ReCiPe 2008, ILCD LCIA,...
Land use	LOP / LTP (land use potential / land transformation)		
	Characterizes areas used for ongoing human activities or areas whose use has changed	m^2 .year m^2 (land) eq kg C deficit	Dutch Guide, Impact 2002+, ReCiPe 2008, ILCD LCIA,...

Damage category	Impacts taken into account	Unit	Analysis method concerned
Human health	HDF (human damage factor)		
	Characterizes impacts on human health, including carcinogenic and non-carcinogenic effects, respiratory effects, ionizing radiation, formation of photo-oxidants and destruction of the stratospheric ozone layer.	DALYs	Impact 2002+, ReCiPe 2008, ILCD LCIA, ...
Natural environment	EDF (Ecotoxicological Damage Factor)		
	Characterizes the loss of ecosystem quality due to aquatic and terrestrial ecotoxicity, terrestrial and aquatic acidification and eutrophication, and land use.	PDF.m^2 .an	Impact 2002+, ReCiPe 2008, ILCD LCIA,...
Natural resources			
	Refers to the additional energy required to continue mining or exploiting fossil fuels.	MJ	Impact 2002+, ReCiPe 2008, ILCD LCIA,...

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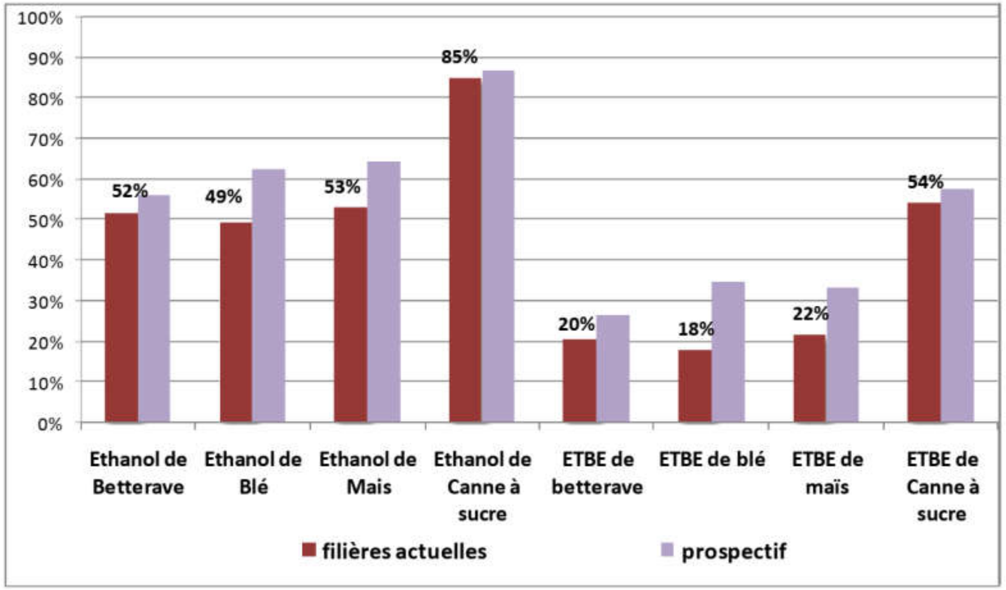
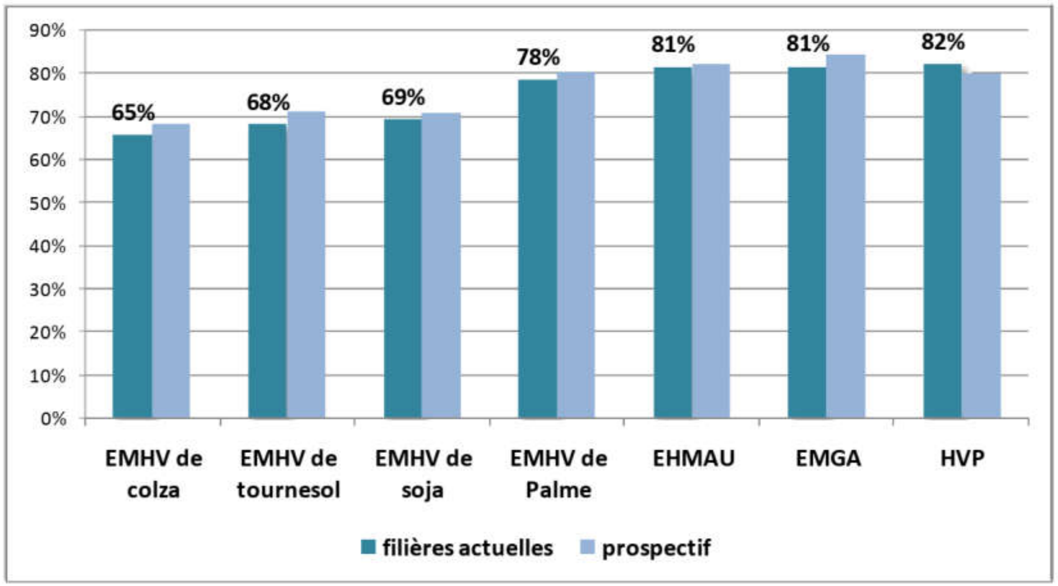
Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*

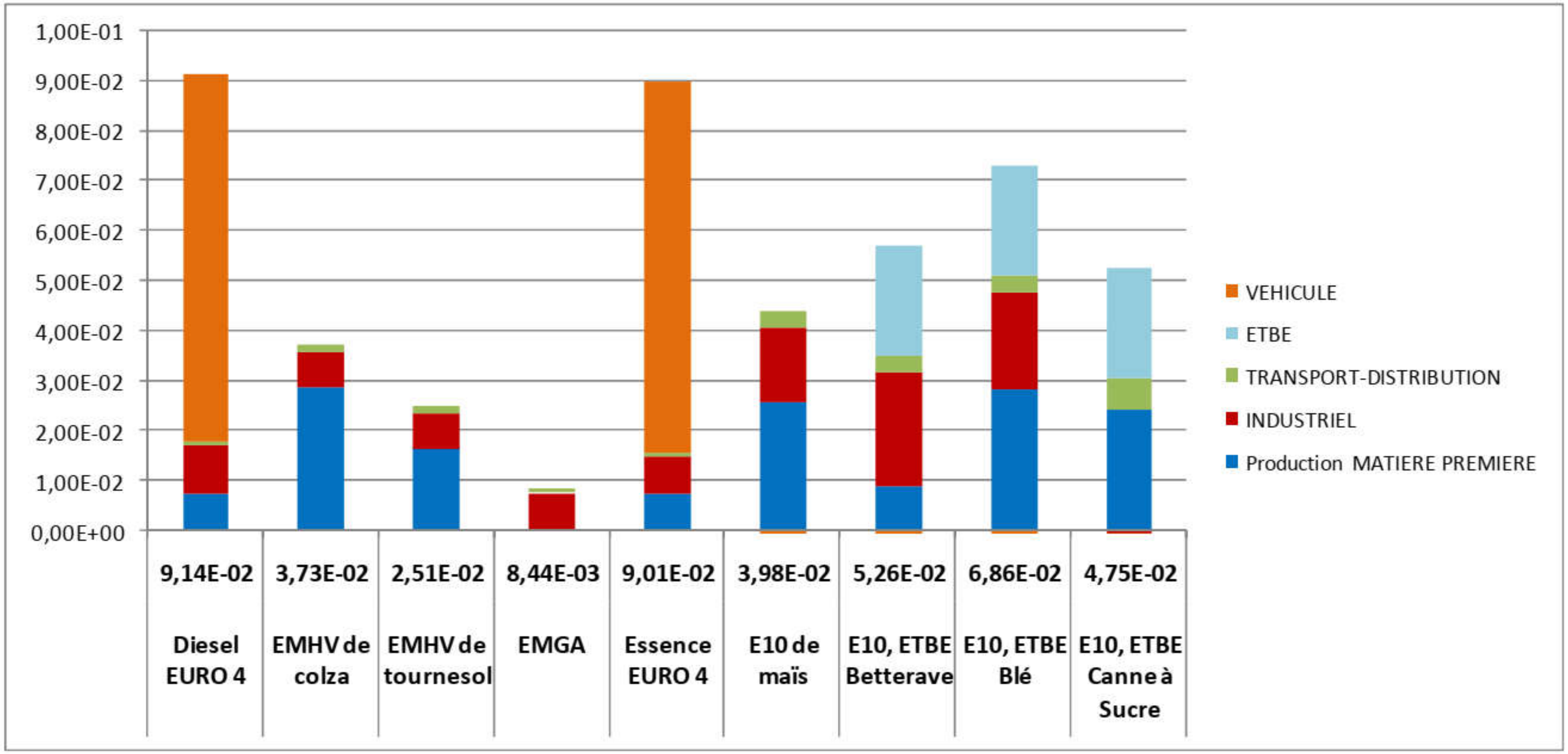
- **Intermediate** impact **characterization** (no final damage characterization)
- Fossil energy consumption deducted from **energy content** of inputs (PCI/kg)
- GHG emissions deduced from IPCC **global warming potentials** (GWP) (AR3)
- **CML** method used for eutrophication, photochemical pollution and human toxicity impacts





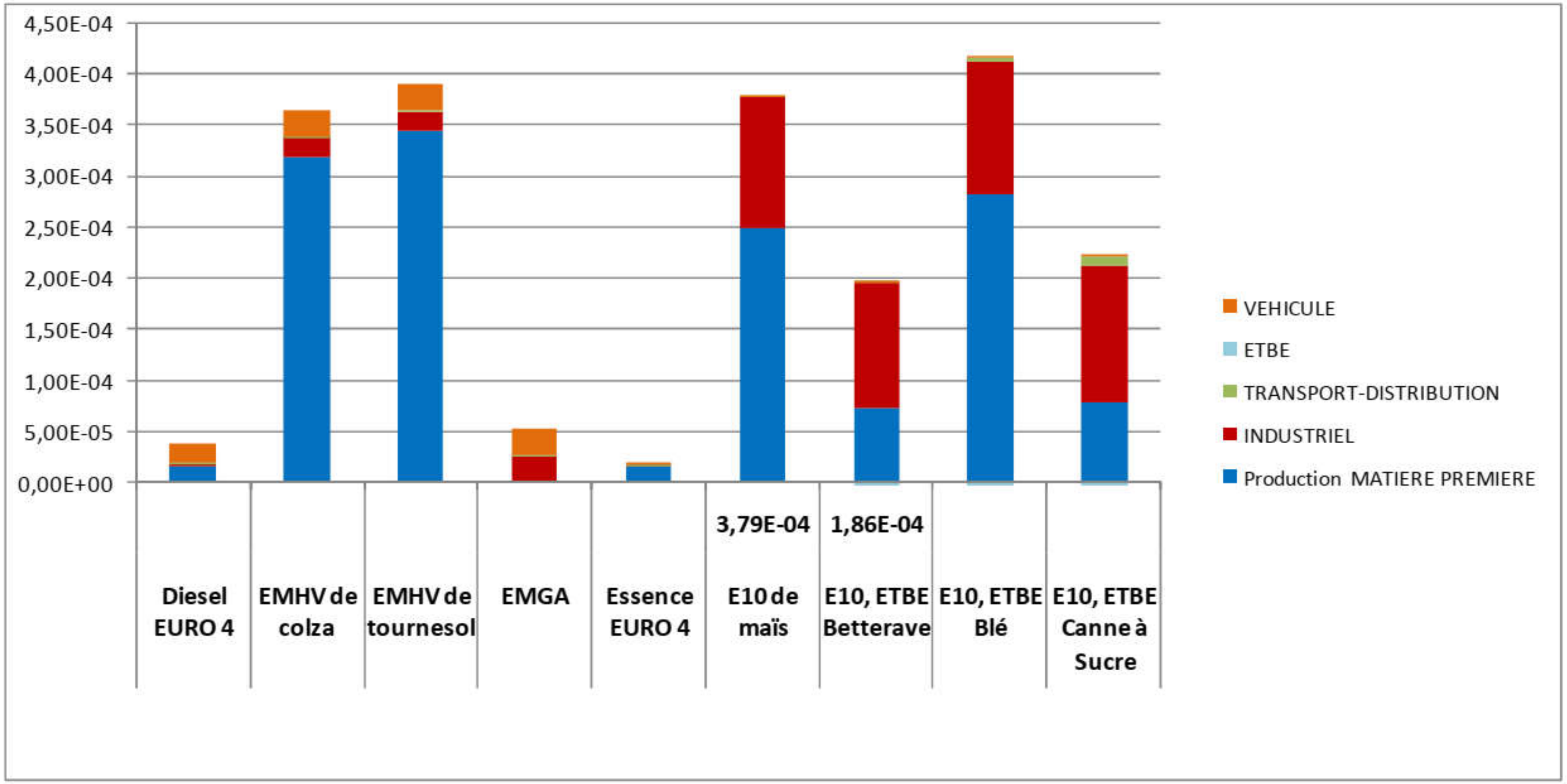
Reduction in energy consumption (in % reduction compared with fossil fuel)

Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*



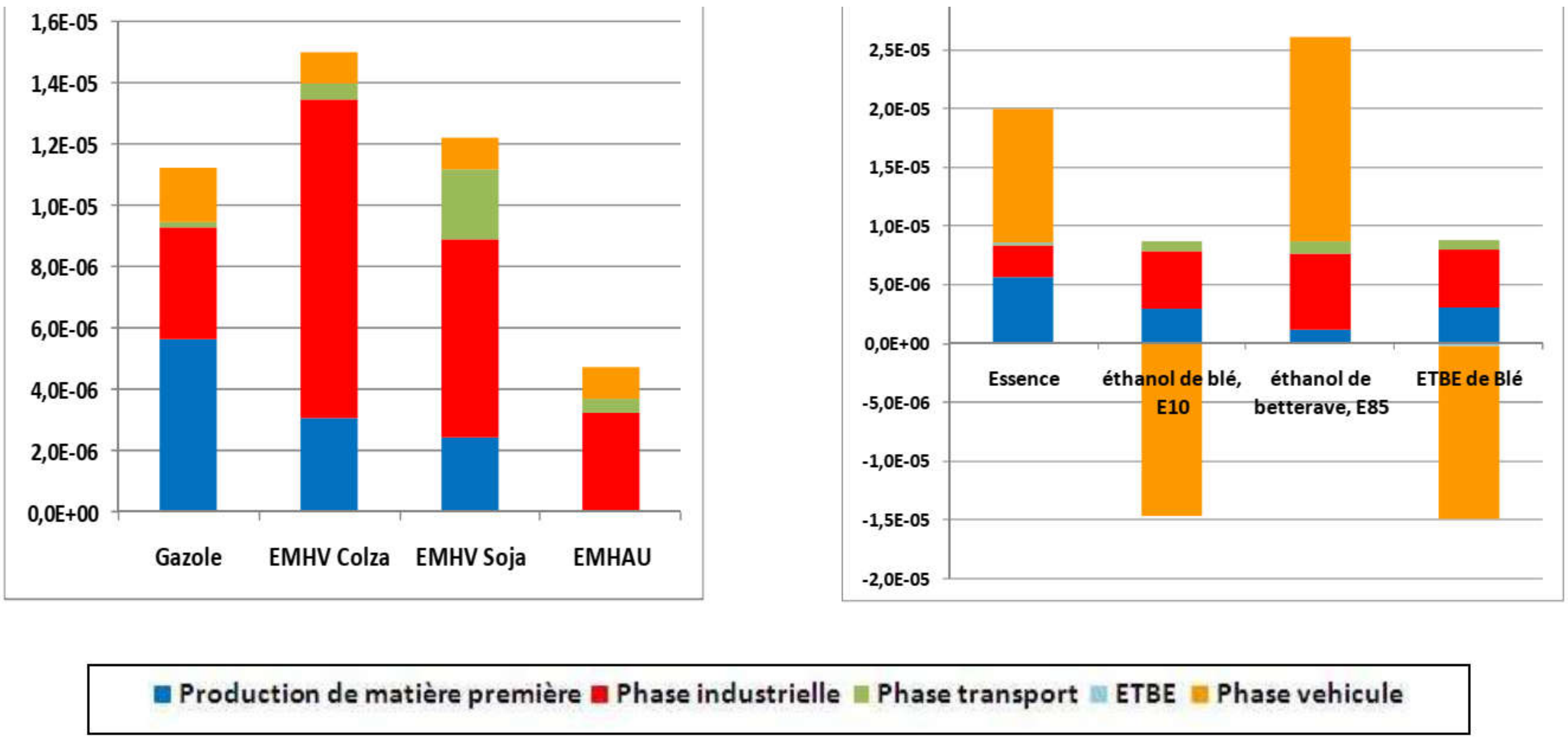
Contribution of life cycle stages to GHG emissions (kg eq CO2 / MJ)

Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*



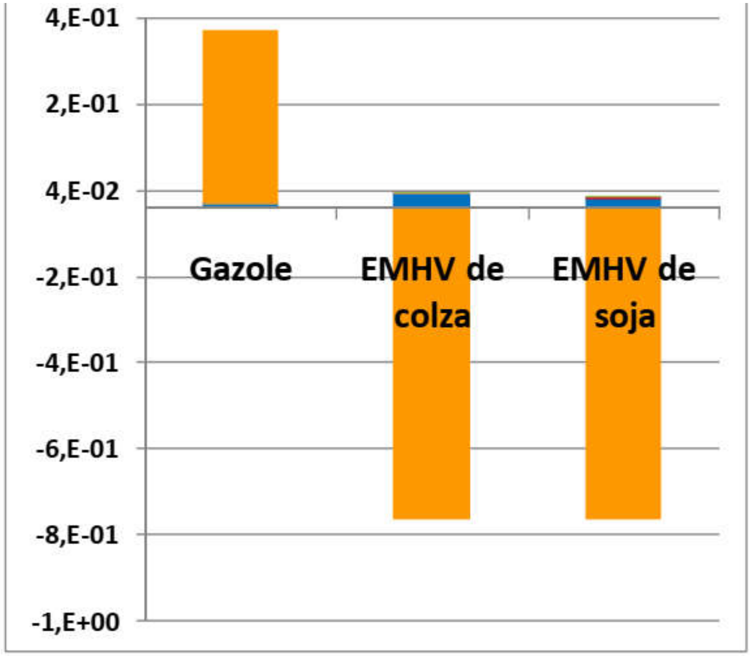
Eutrophication potential of different fuels (kg eq PO_4^{3-} / MJ)

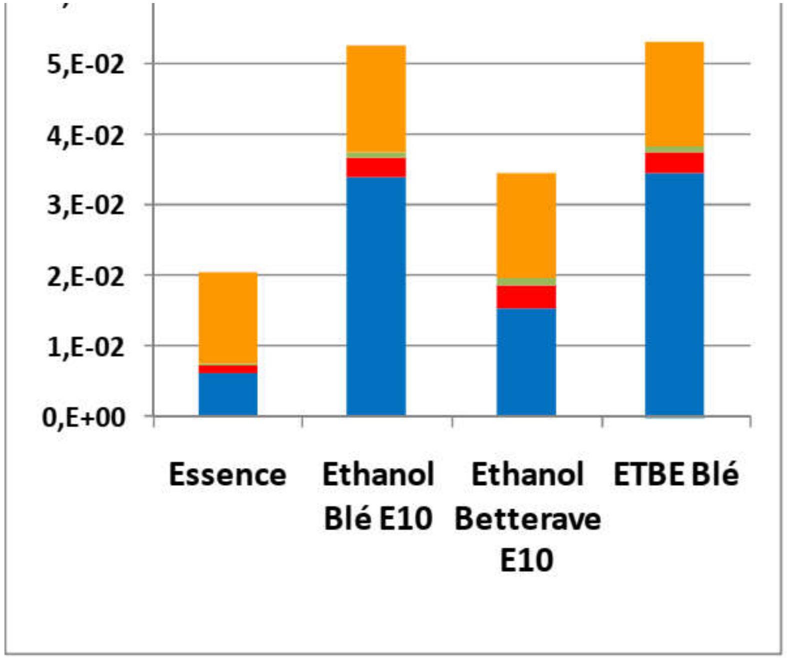
Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*



Photochemical oxidation potential of different fuels (kg eq C_2H_4 / MJ)

Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*





■ Production de matière première ■ Phase industrielle ■ Phase transport ■ ETBE ■ Phase vehicule

Human toxicity potential of different fuels (kg eq 1,4 DB/ MJ)

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Contents

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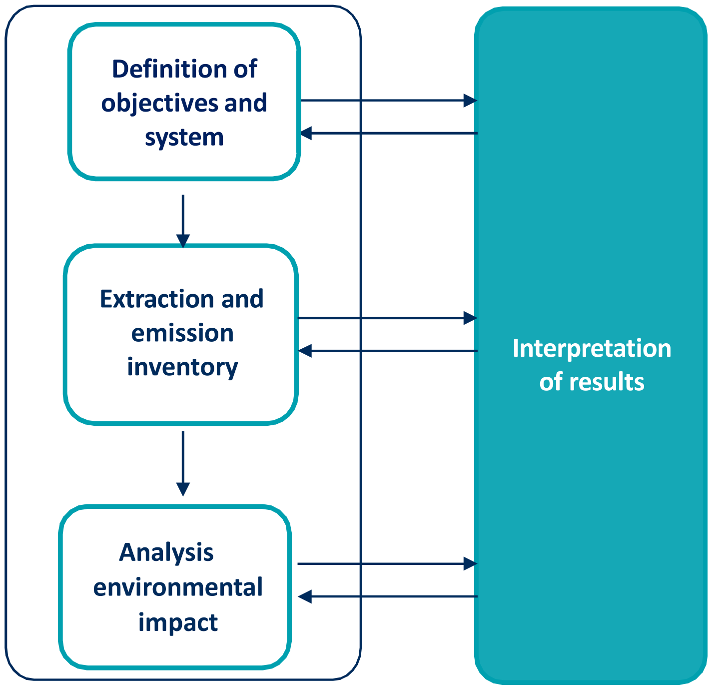
The 4th step in an LCA is the **interpretation of the results**.

Critical analysis of results

- **Identification of** high-impact hotspots.
- **Critical review of** the study's limitations and methodological choices.
- Conclusions and **proposed actions** to reduce impacts (decision support).

Analysis quality and robustness

- **Quality control** and consistency of results (error correction).
- **Sensitivity** analysis
- **Uncertainty** analysis



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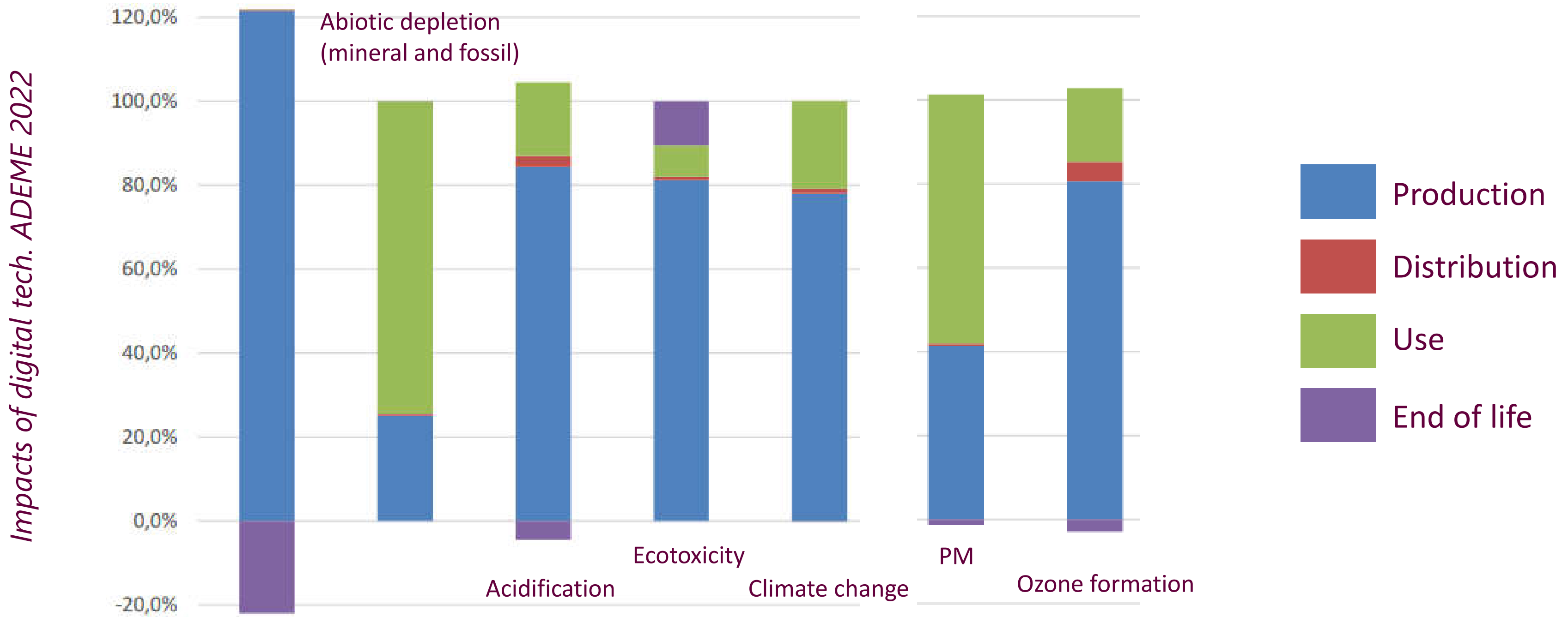
Major impacts can be **identified by** comparing the various stages of the life cycle, the different components of the system under study, or each of the substances emitted or extracted.



IMPORTANT: Impact scores (not standardized) are expressed in their own units and cannot be directly compared with each other. Results should be expressed as **percentages** for a common reading scale.

Interpreting the results requires a **critical review of the previous phases**:
system limits and choices made, emissions inventory and extractions, characterization and choice of methods.

To avoid pitfalls and highlight delicate points, the following questions can be asked:

- ✓ Has each LCA step been interpreted: inventory, characterization, overall impact assessment?
- ✓ Are the differences between scenarios significant (uncertainty analysis)?
- ✓ Do the main conclusions vary depending on the characterization method chosen?
- ✓ What is the quality of the data and the level of certainty of the conclusions reached?
- ✓ What are the key parameters from an environmental point of view (sensitivity study)?

The **critical review** verifies that an LCA meets the methodology, data, interpretation and communication requirements defined by the standard (ISO 14040). It guarantees :

- Methodology (consistency with the standard, allocations, recycling, scientific and technical validity)
- Data used (consistency with objectives, homogeneity)
- Calculations (orders of magnitude, etc.)
- Interpretations (consistency with objectives and limits, unjustified extrapolations, insufficient sensitivity analyses)
- Transparency and overall consistency of the report

There are **2 types of critical review** (mandatory if the LCA is comparative):

(1) critical review by an independent expert

(2) critical review by a committee of at least three experts
(mandatory if LCA results are to be made available to the general public)

LCA **quality control** requires a number of checks on the data, assumptions and choices made.

- ✓ Clarity and transparency of **system modeling:** flow chart identifying each process and scenario in a precise and structured way.
- ✓ Consistency of **units**: g/kg/t; MJ/GJ/kWh; t.km/pers.km/km...
- ✓ Validity of **mass balances**: carbon, nitrogen, phosphorus, heavy metals....
- ✓ Comparison of **inventory results** with other studies.
- ✓ Consistency of **energy consumption and CO_2** emissions: reference flow, electricity mix, materials considered, end-of-life, etc. The ratio gCO_2 /MJ consumed is a good indicator of quality.

The sensitivity study tests the robustness of the results and their sensitivity to the data, assumptions and models used. It is generally based on :

- The **percentage variation in** various model input parameters and its effect on the variation in model results (recycling rate, loading rate, element content, process yield, etc.).
- The variation of certain parameters between **minimum and maximum values** and the achievement of maximum deviations on results.
- **Modification of certain assumptions** and their effect on results (allocation methods and substitution choices, characterization methods, type of materials, choice of geographical origin for certain inputs, etc.).

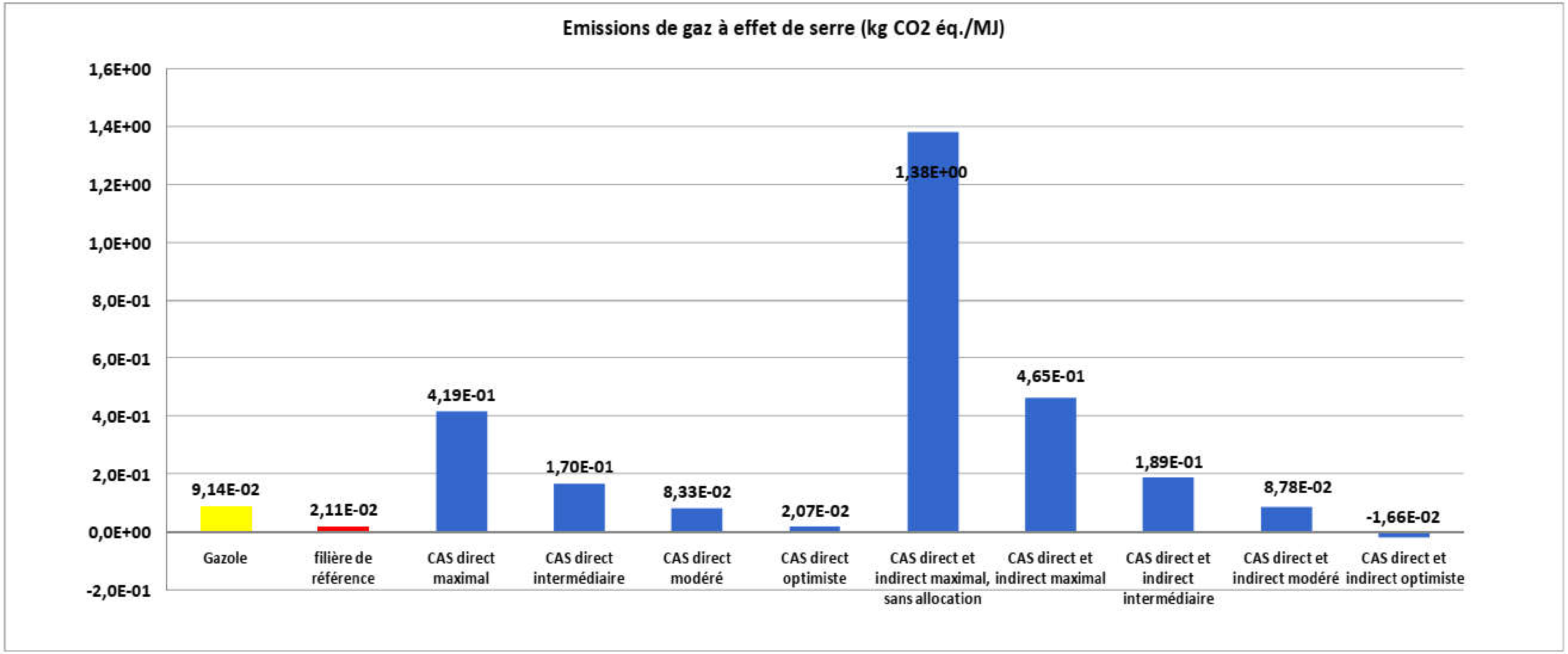
Sensitivity analysis is a mandatory step
for an LCA that must comply with standards 14040 and 14044.

The analysis of uncertainties and their propagation makes it possible to specify the confidence with which results are obtained, and to say at what value a variation on a result can be significant. Uncertainties come into play at several levels of LCA:

- **Uncertainties linked to assumptions and choices made:** functional unit, allocation method, etc.
- **Uncertainties in inventory data:** the impact of these uncertainties on results can be assessed using a Monte-Carlo method.
- **Uncertainties about the model and impact analysis methods:** characterization factors, pollutant transport models, linearity assumptions, threshold effects, etc.
- **Data variability**: spatial, temporal and technological

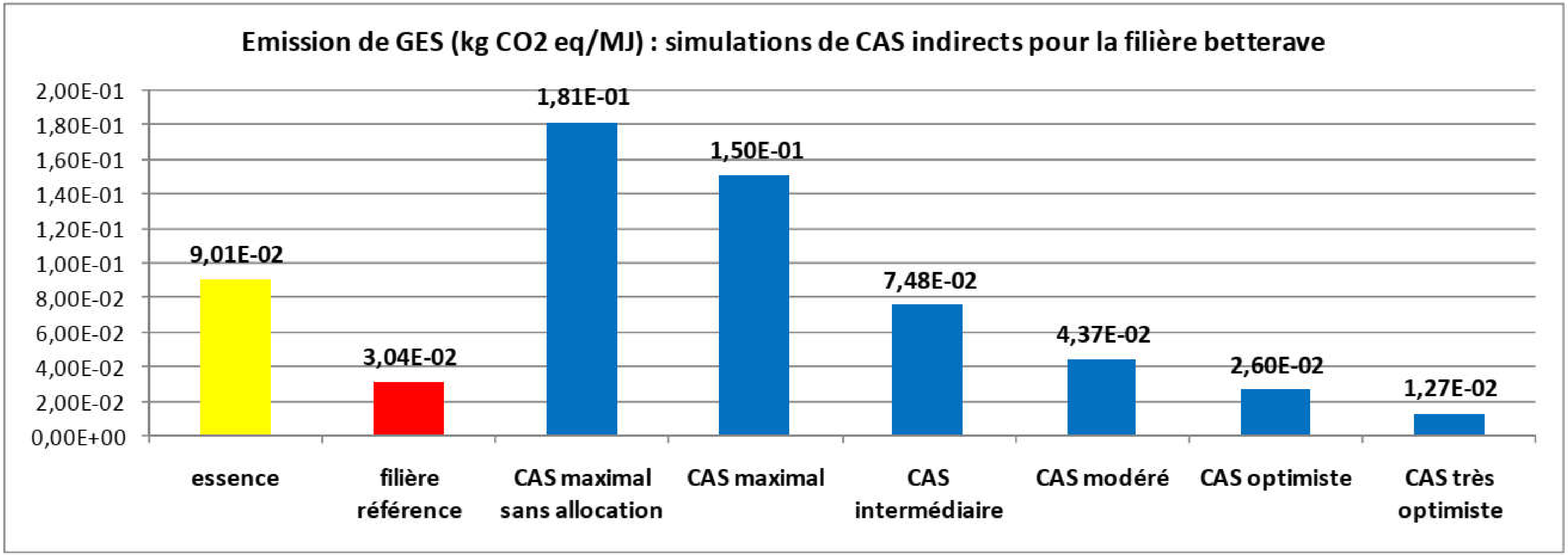
Uncertainty analysis is not a mandatory step in standards 14040 and 14044.

Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*



Sensitivity analysis: Impact on GHG emissions of taking indirect or direct CAS into account for the sojabean sector

Example of LCA of 1rst generation biofuels *(based on ADEME 2010 report)*



Sensitivity analysis: Impact on GHG emissions of taking indirect CAS into account for the beet sector

References

1 General information

2 LCA tools

3 Databases

4 Characterization methods

General information on Life Cycle Assessment

- ***Analyse de Cycle de Vie, comprendre et réaliser un écobilan***
  Olivier Jolliet, Myriam Saadé and Pierre Crettaz, Presses Polytechniques et Universitaires Romandes, 2005
- ***The Life Cycle Assessment of a product or service, applications and practical implementation***
  Laurent Grisel and Philippe Osset, AFNOR, 2008
- ***Life Cycle Assessment (LCA) - A guide to best practice***
  Walter Klöpffer and Birgit Grahl, Wiley-VCH, 2014
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  Helias A. Udo de Haes, Göran Finnveden, Mark Goedkoop and Michael Hauschild, SETAC Press, 2002
- ***Handbook on Life Cycle Assessment - Operational guide to the ISO Standards***
  Jeroen Guinée et al, Kluwer Academic Publishers, 2004
- ***Progress in Life Cycle Assessment 2019***
  Stephan Albrecht et al, Springer, 2021
- ***The International Journal of Life Cycle Assessment*** *(https://link.springer.com/journal/11367)*

LCA tools

- ***SIMAPRO*** *- Pre Sustainability*
  Commercial reference software - https://simapro.com/
- ***GABI*** *- Sphera Solutions*
  Widely used in the manufacturing and industrial sectors - https://sphera.com/
- ***EIME*** *- Bureau Veritas / CODDE*
  Developed for the electronics, telecom and transport industries - https://codde.fr/
- ***ELODIE*** *- CSTB / CYPE*
  Developed to analyze the environmental impact of construction projects - https://info.cype.com
- ***OPENLCA*** *- Green Delta*
  Open Source and performance equivalent to commercial tools - https://www.openlca.org/greendelta/
- ***Product balance*** *- ADEME*
  Simplified awareness-raising tool for non-specialists - https://base-empreinte.ademe.fr/

Databases (listed on OpenLCA Nexus - https://nexus.openlca.org/databases)

- **Ecoinvent** - http://www.ecoinvent.ch
- **European Life Cycle Database (ELCD)** - https://eplca.jrc.ec.europa.eu/ELCD3/
- **Agribalyse** - https://agribalyse.ademe.fr/
- **Agri-footprint** - https://blonksustainability.nl/tag/Databases
- **LCA Commons** - https://www.lcacommons.gov/
- **Carbons Minds** - https://www.carbon-minds.com/
- **Environmental Footprints (EF)** - https://green-business.ec.europa.eu/environmental-footprint-methods_en
- **NEEDS** - https://www.epa.gov/power-sector-modeling/national-electric-energy-data-system-needs
- ...

Impact characterization methods

- **CML 2016 - Dutch LCA Guide** (*Guinea, 2002)*
  https://link.springer.com/book/10.1007/0-306-48055-7
- **Eco-indicator 99** (*Goedkoop, 2001*) - *https://pre-sustainability.com/files/2013/10/EI99_methodology_v3.pdf*
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- **USEtox** (*UNEP-SETAC*) - *https://usetox.org/sites/default/files/assets/USEtox_Documentation.pdf*
- **IPCC 2021 AR6 -** *https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf*