INSTITUTE FOR SUSTAINABLE AVIATION

ISAE SUPAERO
Institut Supérieur de l'Aéronautique et de l'Espace

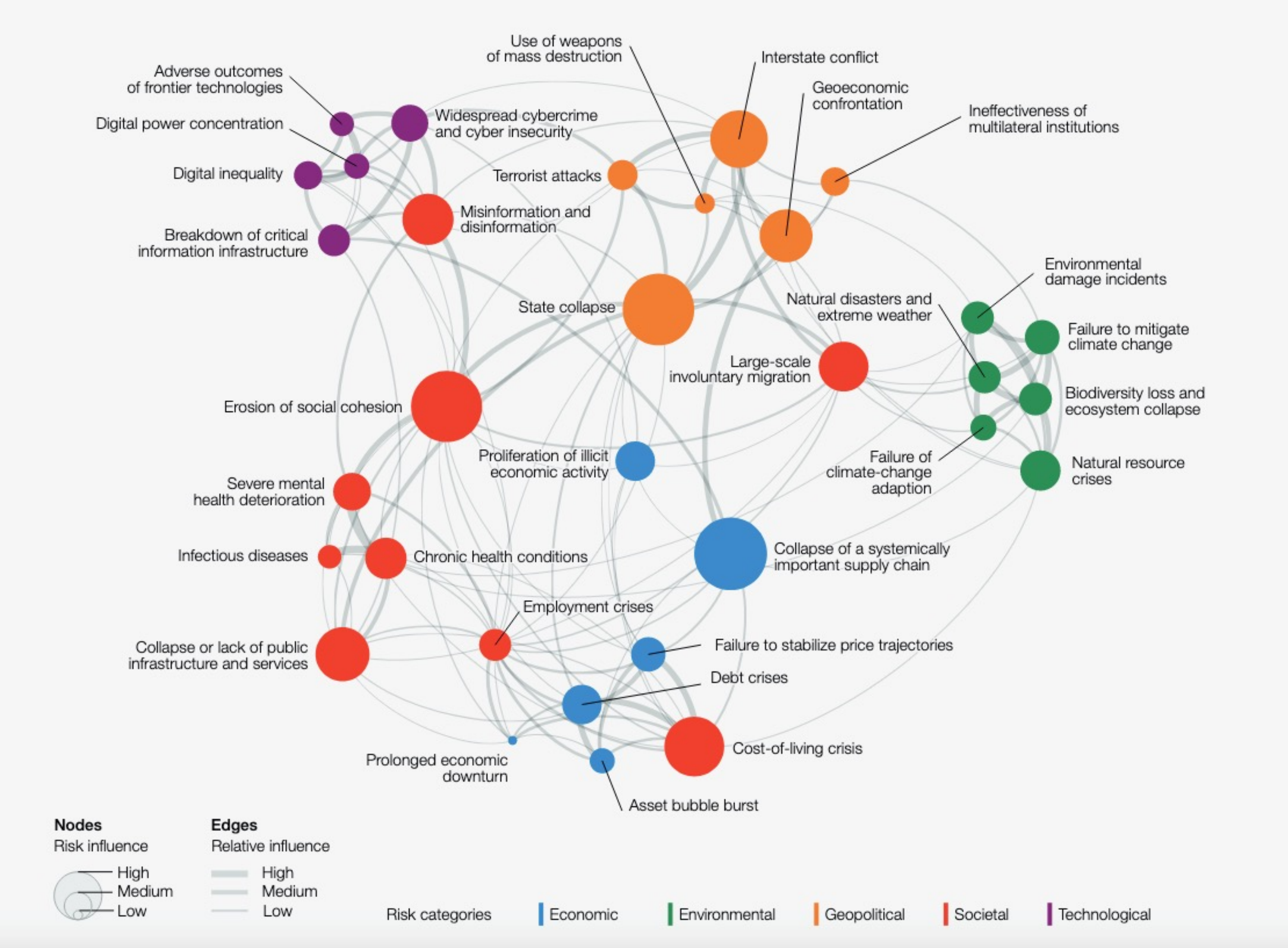
Introduction to Life Cycle Assessment and Eco-Design

Aerospace Summer School

Félix POLLET – Postdoctoral researcher at ISA / ISAE-SUPAERO

July 2024

Global context: the risk of polycrises



Source
World Economic Forum Global Risks.
Perception Survey 2022-2023.

Global risks ranked by severity

over the short & long term

2 years	
1	Cost-of-living crisis
2	Natural disasters and extreme weather events
3	Geoeconomic confrontation
4	Failure to mitigate climate change
5	Erosion of social cohesion and societal polarization
6	Large-scale environmental damage incidents
7	Failure of climate change adaptation
8	Widespread cybercrime and cyber insecurity
9	Natural resource crises
10	Large-scale involuntary migration

10 years	
1	Failure to mitigate climate change
2	Failure of climate-change adaptation
3	Natural disasters and extreme weather events
4	Biodiversity loss and ecosystem collapse
5	Large-scale involuntary migration
6	Natural resource crises
7	Erosion of social cohesion and societal polarization
8	Widespread cybercrime and cyber insecurity
9	Geoeconomic confrontation
10	Large-scale environmental damage incidents

Risk categories | Economic | Environmental | Geopolitical | Societal | Technological

A transition towards more sustainable development is needed...

... As urged by the UN Sustainable Development Goals (SDGs) and the European Green Deal, among others.

The success of this transition depends on our ability to **quantify environmental impacts**, identify hotspots, evaluate strategies, compare alternatives, unveil trade-offs, and monitor evolutions.

Course objectives

- ❑ Understand the basics of Life Cycle Assessment (LCA) and its essential steps

- ❑ Gain insights through applications in aerospace
  - Explore specific case studies of LCA (at the research level)
  - Understand how LCA can be used to improve sustainability and reduce environmental impacts

Course Contents

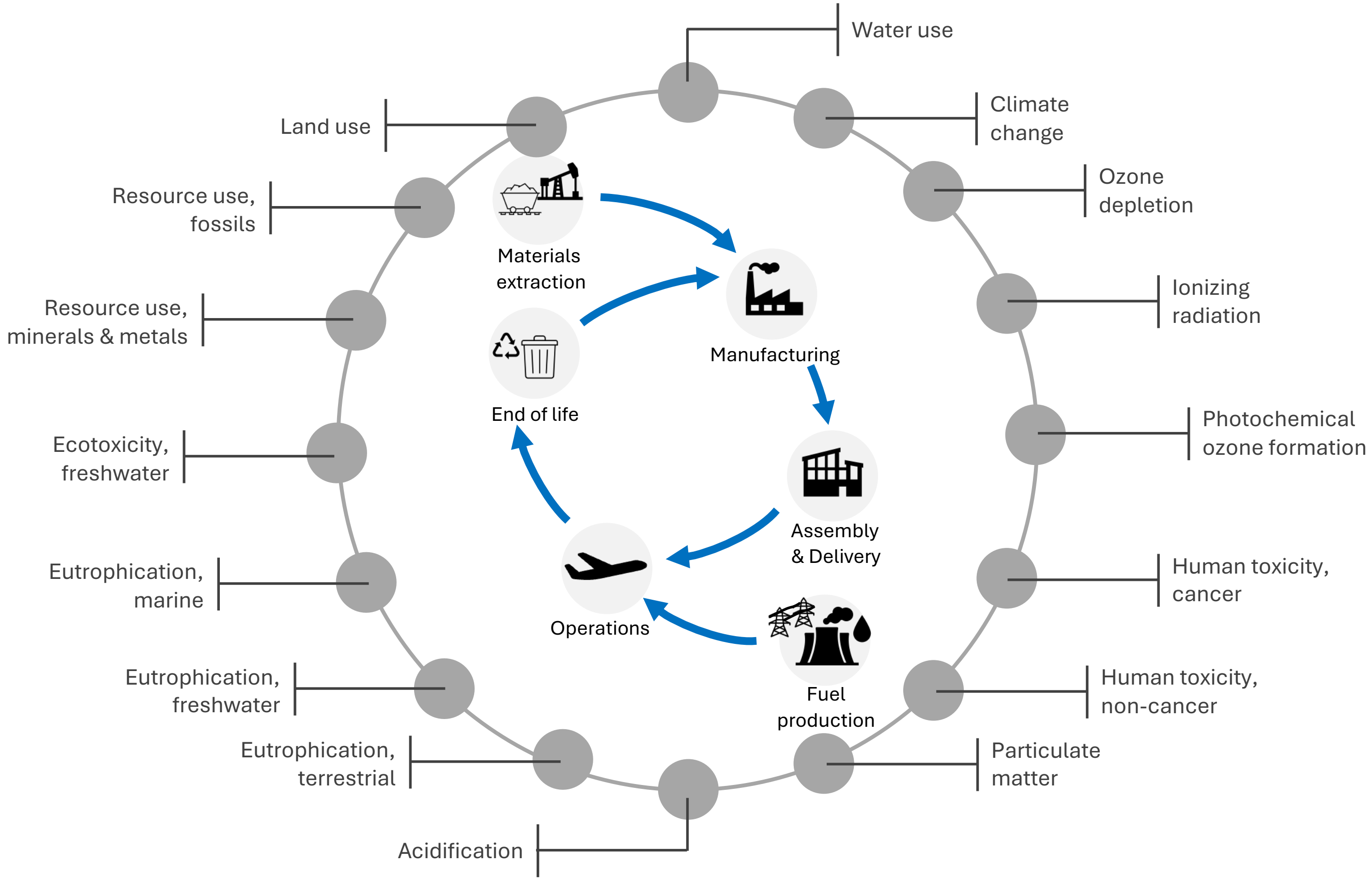
- Introduction
- The 4 steps of LCA
  - Goal and scope definition
  - Inventory
  - Impact assessment
  - Interpretation
- Tools & Databases
- Case studies
  - Eco-design of a drone
  - LCA of an aircraft
  - Sectoral LCA of air transport
- Planetary boundaries
- Conclusion and Q&A

Quizz!

Take your smartphone ☺

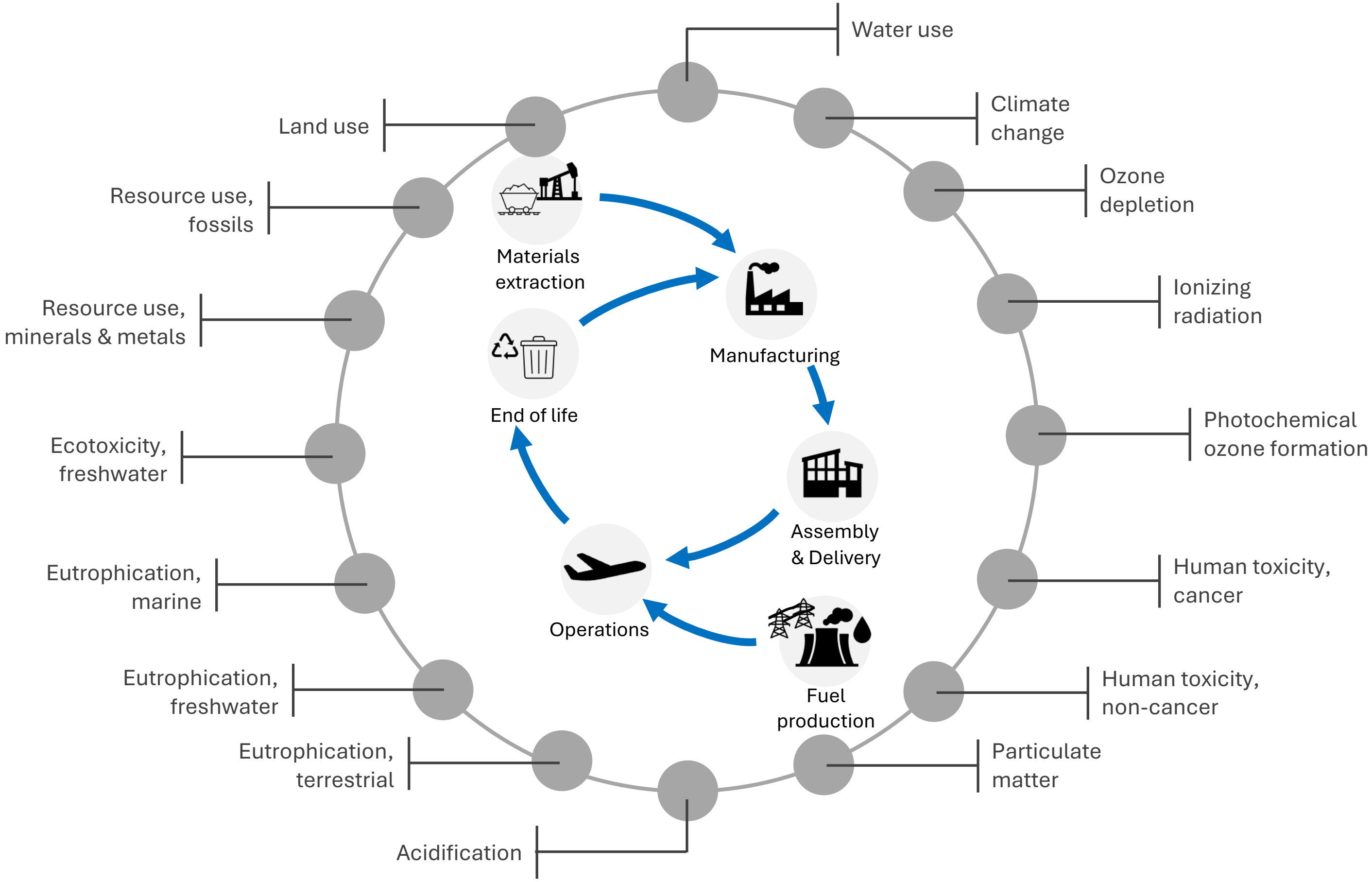
What is Life Cycle Assessment?

Life Cycle Assessment (LCA) is a methodology that allows quantifying the environmental impact**s** of a system throughout its **entire life cycle**

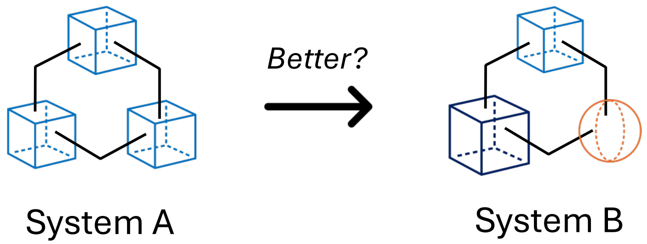


- **Standardised** (ISO 14040 – 14044)
- **Multi-stages** « cradle-to-grave »
- **Multi-criteria** : broader than climate

What is it used for?

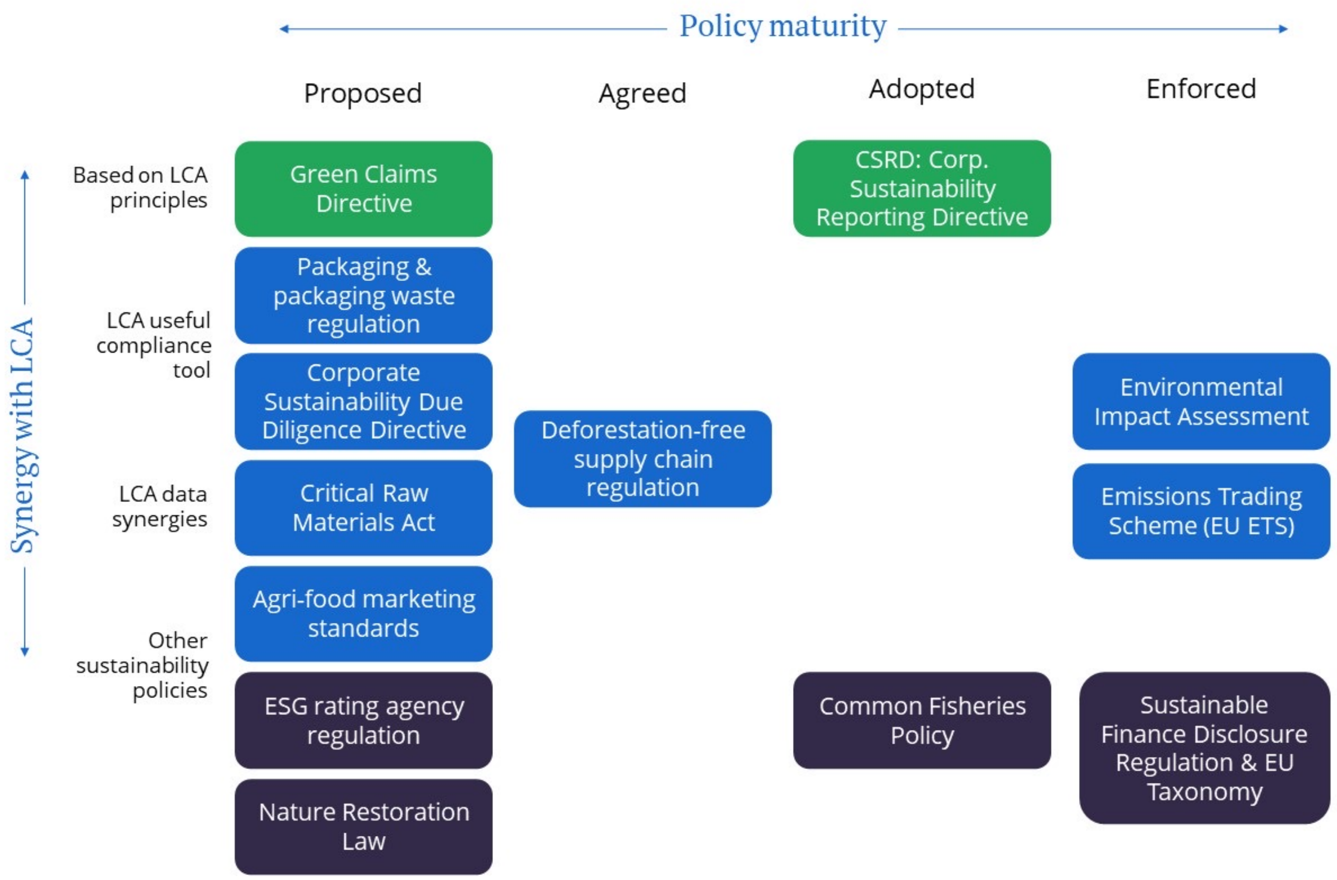


- **Eco-design & decision-making**
  Avoiding « burden-shifting »



- **Reporting**
  → Environmental labels & declarations
  → Comply with regulations

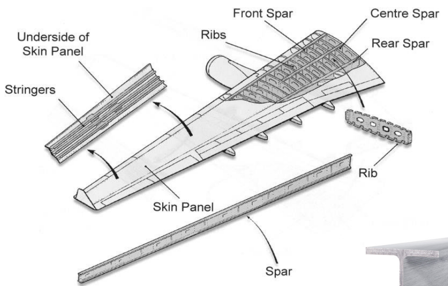
Links with policies and laws in the EU

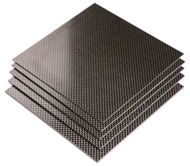


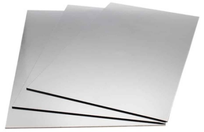
https://pre-sustainability.com/articles/navigating-the-sustainability-reporting-landscape-with-lca/

Possible levels of application

- Sector
- Product portfolio
- Product
- Subsystem
- Component
- Material



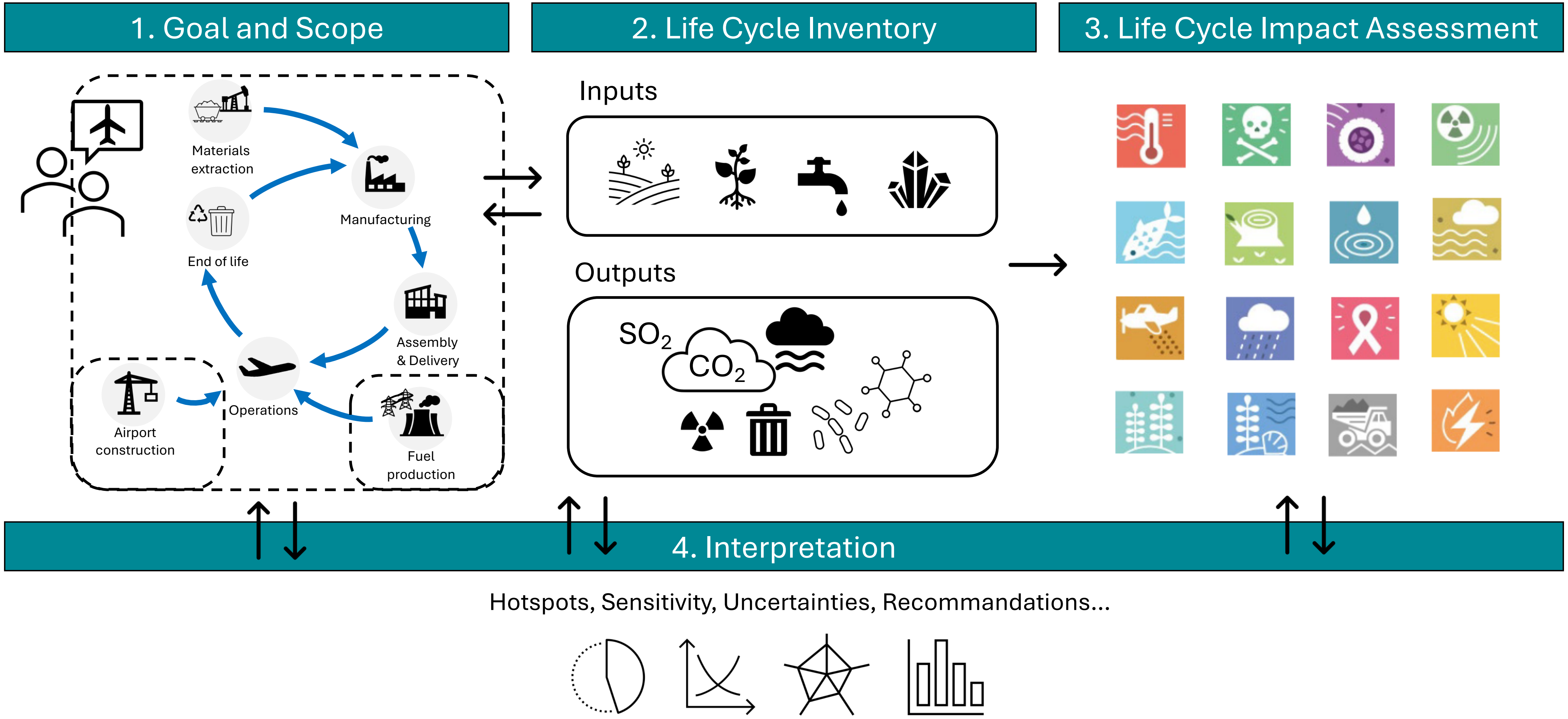




Course Contents

- Introduction
- The 4 steps of LCA
  - Goal and scope definition
  - Inventory
  - Impact assessment
  - Interpretation
- Tools & Databases
- Case studies
  - Eco-design of a drone
  - LCA of passenger aircraft
  - Sectoral LCA of air transport
- Planetary boundaries
- Conclusion and Q&A

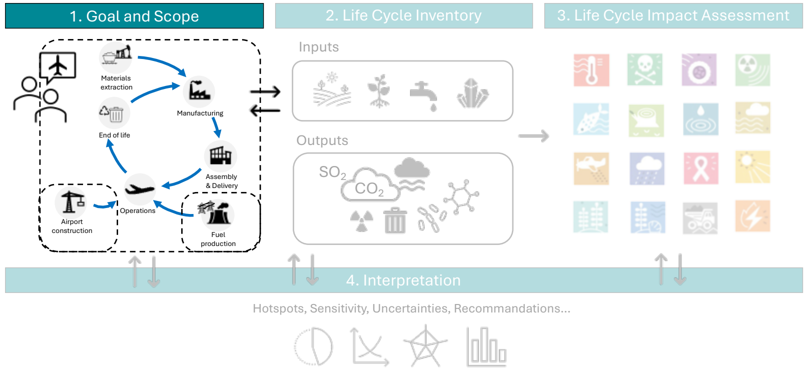
Methodology ISO 14040 / 14044



The first step of LCA consists of defining the **goal**, that is:

- What is the intended application
- What are the reasons for carrying out the study
- Who is the intended audience
- Whether the results are for internal use only or to be disclosed to the public

<u>Example</u>: « Compare several coffee machines to inform the customer on its choice. »



The **scope** of the study shall also be defined:

- The product system to be studied. *E.g. a Moka (Italian) coffee maker in aluminum (200 mL / 7 oz.)*
- The functions of the studied product or service. *E.g. to prepare coffee*
- **The Functional Unit**
- **The System Boundaries**
- The deliverable : ISO report, slides…
- Etc…

Functional Unit

The Functional Unit (FU) enables to quantify the identified functions (performance) of the product.
It serves as a scaling factor for measuring the environmental footprint and allows comparisons between different products that serve the same function.

Example for a coffee machine:
"The product must enable the filling of a ***cup of coffee of 80 ml (2.7 oz), 4 times a day****,*
with a concentration of ***25% caffeine****,*
for ***3 years****. »*

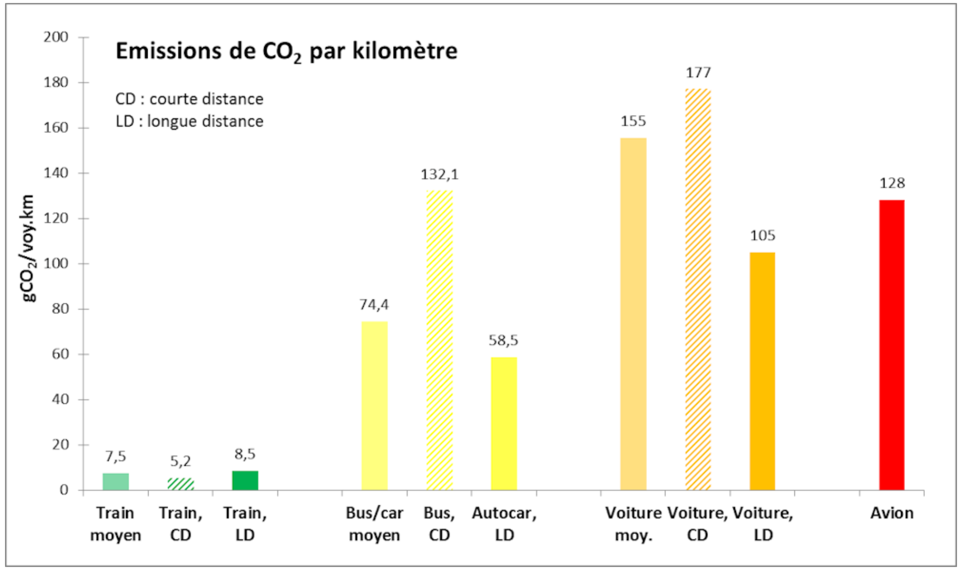
What?
How much?
How well?
How long?

Functional Unit

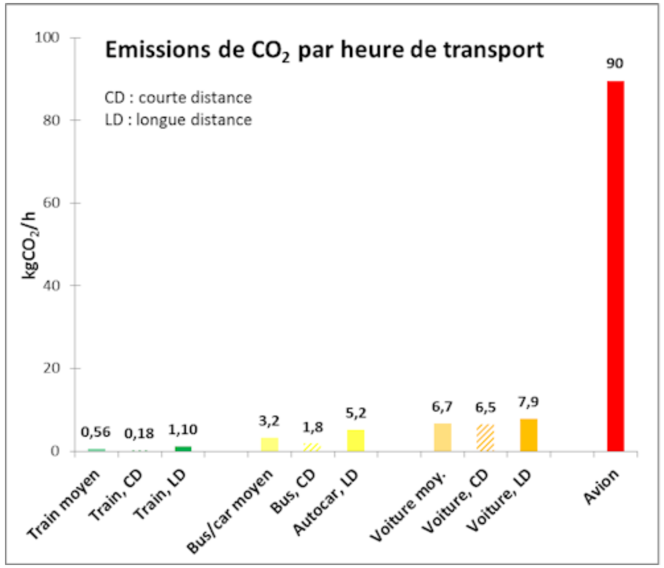
⚠ Importance of the functional unit choice

Comparison of transportation modes [1]

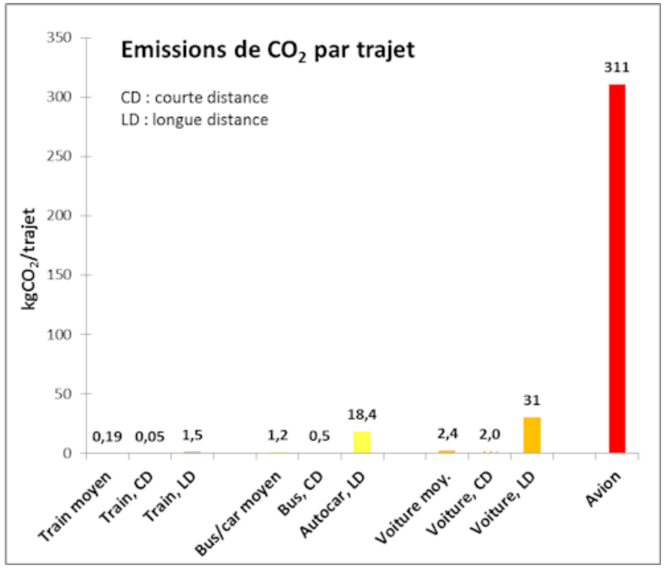
CO_2 emissions expressed per **pax.km**



per **pax.hour**



per **average trip**

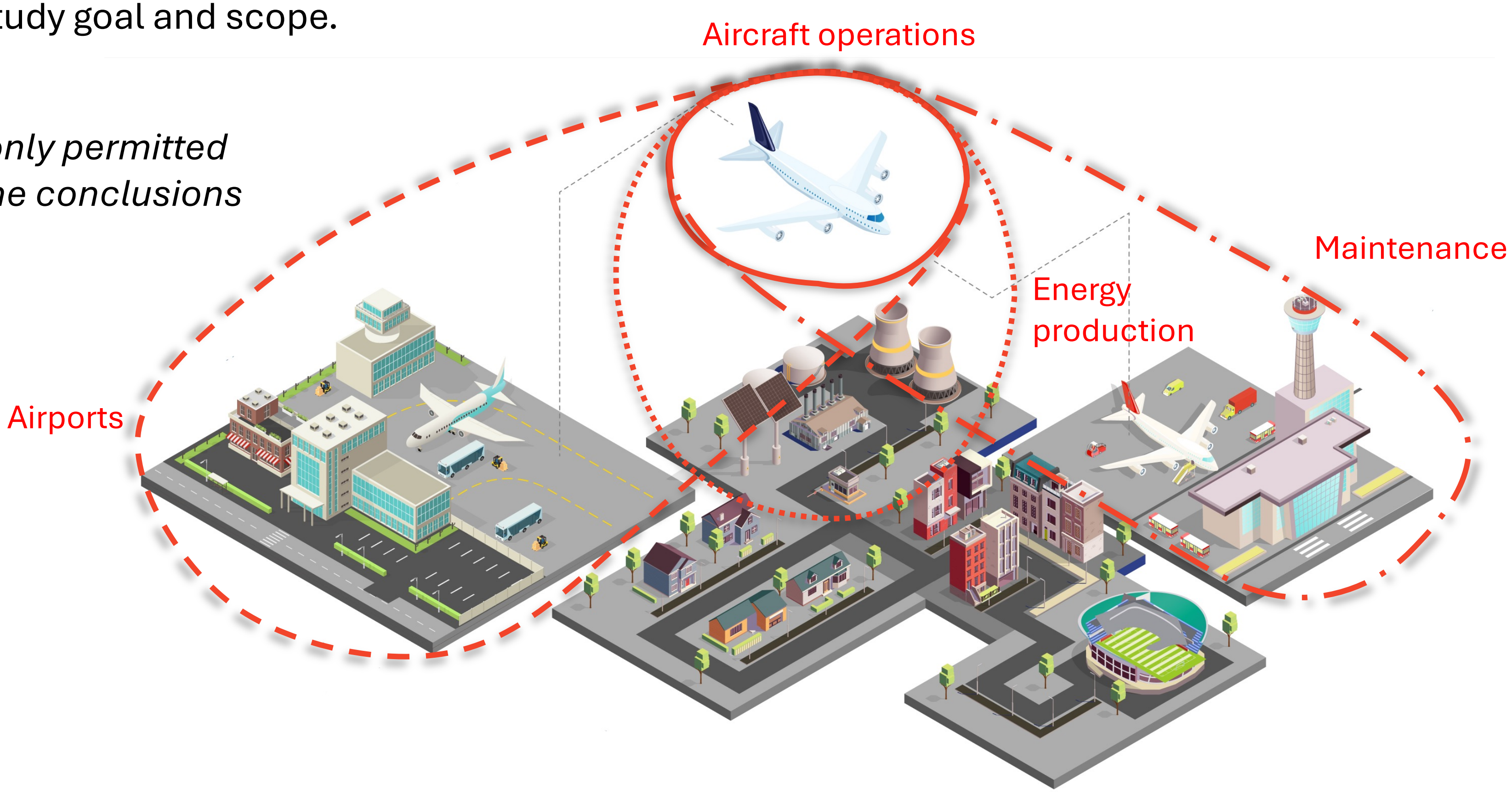


[1] Aurélien Bigo's thesis, 2020

System boundaries

What elements are to be included in the system ?
It is not pre-defined. It depends on the study goal and scope.

⚠ *The deletion of life-cycle stages is only permitted if it does not significantly change the conclusions of the study.*



The **inventory analysis** involves the **collection of data** and calculations to quantify the inputs and outputs of the product or system across its life cycle.

- The data can be **primary** (directly measured) or **secondary** (scientific literature, reports, databases)

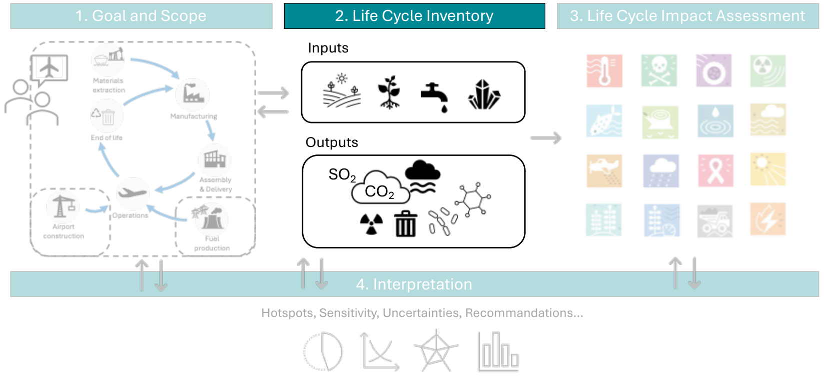
- The resulting **Life Cycle Inventory** (LCI) is a collection of physical flows

Emissions
to air, water, soil…

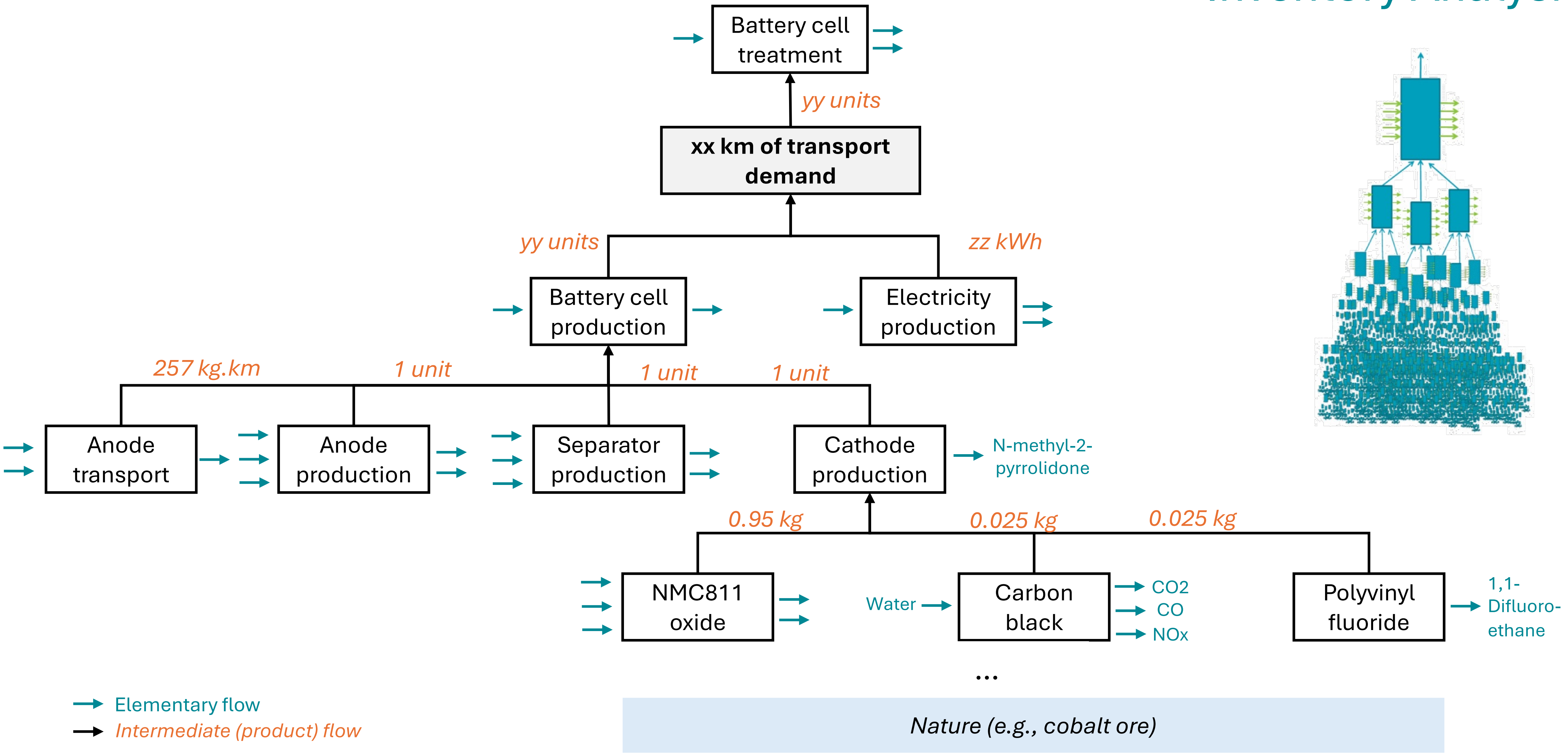
Extractions
fossil, water, minerals…

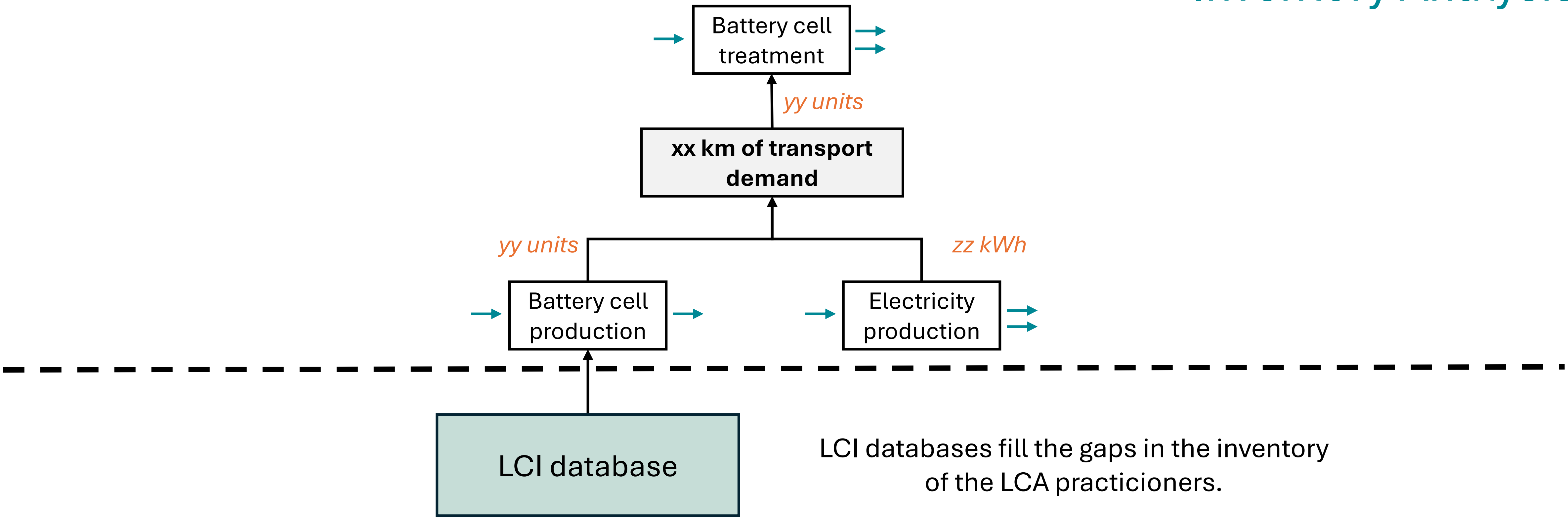
Radioactive

Other
releases



Inventory Analysis





LCI databases fill the gaps in the inventory of the LCA practicioners.

xx km of transport demand

↓

Life Cycle Inventory

Inputs
from environment

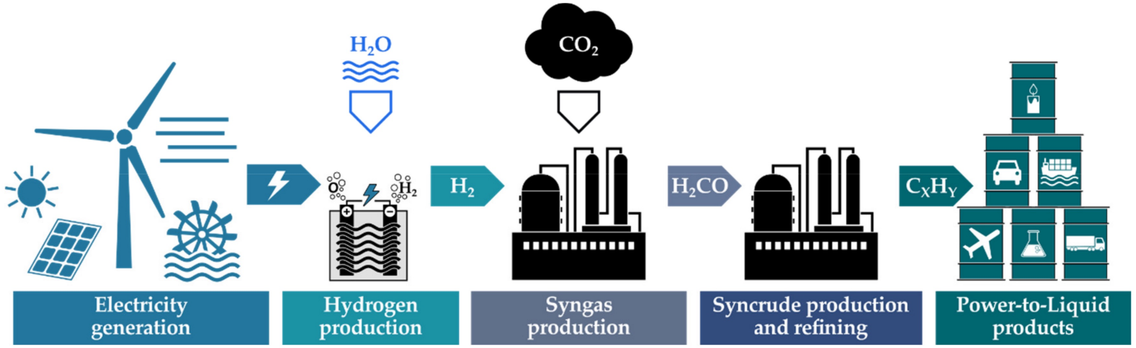
Exchange Name	Compartment	Amount	Unit
Aluminium	natural resource, in ground	2.7337e-1	kg
Anhydrite	natural resource, in ground	8.3908e-7	kg
Antimony	natural resource, in ground	6.9531e-8	kg
Arsenic	natural resource, in ground	1.7427e-4	kg
Barium	natural resource, in ground	1.6098e-2	kg
Basalt	natural resource, in ground	6.6040e-3	kg

...

Outputs
to environment

Exchange Name	Compartment	Amount	Unit
Cadmium II	air, lower stratosphere + upper troposphere	6.3736e-15	kg
Carbon dioxide, fossil	air, lower stratosphere + upper troposphere	1.9846e-6	kg
Carbon monoxide, fossil	air, lower stratosphere + upper troposphere	1.3141e-9	kg
Chromium III	air, lower stratosphere + upper troposphere	3.1864e-14	kg
Copper ion	air, lower stratosphere + upper troposphere	1.0720e-12	kg

An example of methodological issue: multi-functional products



The electricity generation, water consumption, and facilities are known without distinction for the entire process.

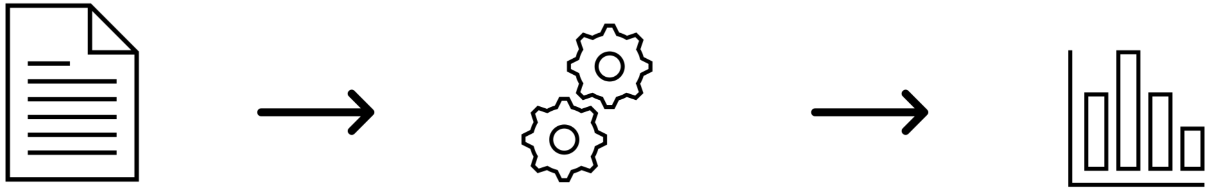
How to distribute the amounts between the co-products (kerosene, diesel, naphtha, lubricating oil) ?

	Energy allocation	Economic allocation
Naphtha	24%	7%
Kerosene	18%	6%
Diesel	37%	16%
Lubricating oil	21%	71%

[1] R. Sacchi et al., *How to make climate-neutral aviation fly*, Nature Communications, 2023
[2] C. Giesen et al., *Energy and climate impacts of producing synthetic hydrocarbon fuels from CO2*, Environmental Science & Technology, 2014

The **impact assessment** translates the inventory into environmental impacts.

⚠ *The physical flows collected in the inventory do no represent impacts in themselves.*



Inventory | LCIA methods | Environmental impacts

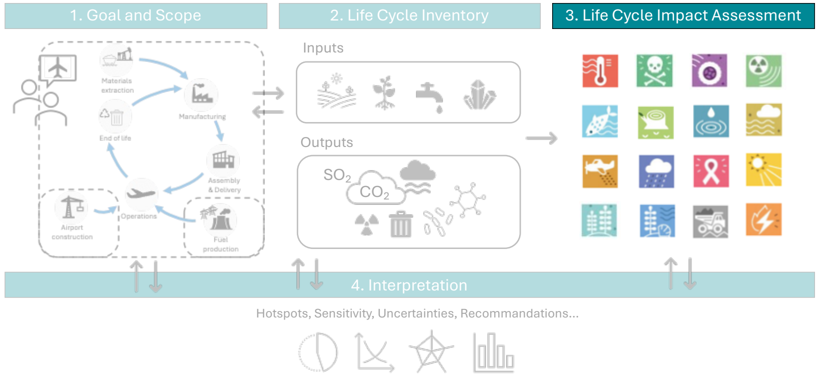
E.g. 0.38 kg CH_4

E.g. GWP-100

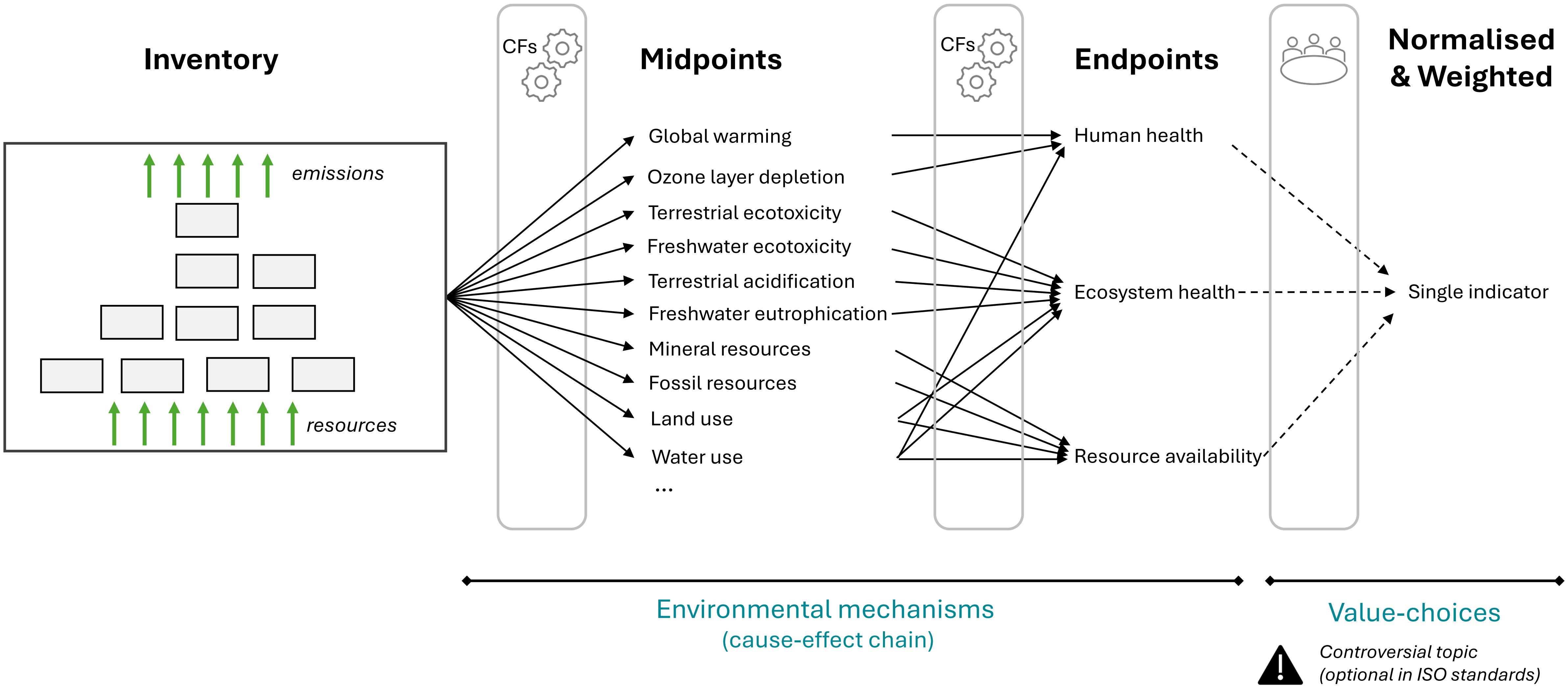
Characterization factors

$$CF_{GWP100,CH_4} = 28.0\ kgCO_{2eq}$$

0.38 x 28 = 10.64 kg CO_{2eq}



Impact assessment



Examples of impacts?

Quizz!

Environmental Footprint methods (midpoint) – European Commission

Impact category	Impact category Indicator (unit of measure)	Description
Climate change, total	Radiative forcing as global warming potential – GWP100 (kg CO_2 eq)	Increase in the average global temperature resulting from greenhouse gas emissions (GHG)
Ozone depletion	Ozone Depletion Potential – ODP (kg CFC-11 eq)	Depletion of the stratospheric ozone layer protecting from hazardous ultraviolet radiation
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	Impact on human health caused by absorbing substances through the air, water, and soil. Direct effects of products on humans are not measured
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	
Particulate matter	Impact on human health (disease incidence)	Impact on human health caused by particulate matter emissions and its precursors (e.g. sulfur and nitrogen oxides)
Ionising radiation, human health	Human exposure efficiency relative to U-235 (kBq U-235 eq)	Impact of exposure to ionising radiations on human health
Photochemical ozone formation, human health	Tropospheric ozone concentration increase (kg NMVOC eq)	Potential of harmful tropospheric ozone formation ("summer smog") from air emissions
Acidification	Accumulated Exceedance – AE (mol H^+ eq)	Acidification from air, water, and soil emissions (primarily sulfur compounds) mainly due to combustion processes in electricity generation, heating, and transport
Eutrophication, terrestrial	Accumulated Exceedance – AE (mol N eq)	Eutrophication and potential impact on ecosystems caused by nitrogen and phosphorous emissions mainly due to fertilizers, combustion, sewage systems
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (kg P eq)	
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (kg N eq)	
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	Impact of toxic substances on freshwater ecosystems
Land use	Soil quality index, representing the aggregated impact of land use on: Biotic production; Erosion resistance; Mechanical filtration; Groundwater replenishment (Dimensionless – pt)	Transformation and use of land for agriculture, roads, housing, mining or other purposes. The impact can include loss of species, organic matter, soil, filtration capacity, permeability
Water use	Weighted user deprivation potential (m^3 world eq)	Depletion of available water depending on local water scarcity and water needs for human activities and ecosystem integrity
Resource use, minerals and metals	Abiotic resource depletion – ADP ultimate reserves (kg Sb eq)	Depletion of non-renewable resources and deprivation for future generations
Resource use, fossils	Abiotic resource depletion, fossil fuels – ADP-fossil (MJ)	

The normalisation step (optional)

Indicators with different units → ***Normalisation*** → Indicators expressed in person equivalent

- kg CO_2 eq
- kg CFC-11 eq
- kBq U-235 eq
- kg NMVOC eq
- Mol H^+ eq
- MJ

÷

Reference system
Annual impact of an average person in the world

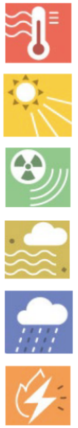
=

- Eq. person
- Eq. person
- Eq. person
- Eq. person
- Eq. person
- Eq. person

The normalisation step enables to better understand the relative magnitude of each impact.

The weighting step (optional)

Indicators expressed in person equivalent —— ***Weighting*** —— ***Aggregation*** ⟶ Single score



Eq. person	x 21.06 %	+
Eq. person	x 6.31 %	+
Eq. person	x 5.01 %	+
Eq. person	x 4.78 %	+
Eq. person	x 6.20 %	+
Eq. person	x 8.32 %	+

xx Points

The weighting step converts the normalised results based on the relative importance of the impact categories. It involves the use of **value choices** (e.g., monetary valuation, experts and citizen panels) and cannot be based on natural science alone.

It may also include an aggregation into a single score.

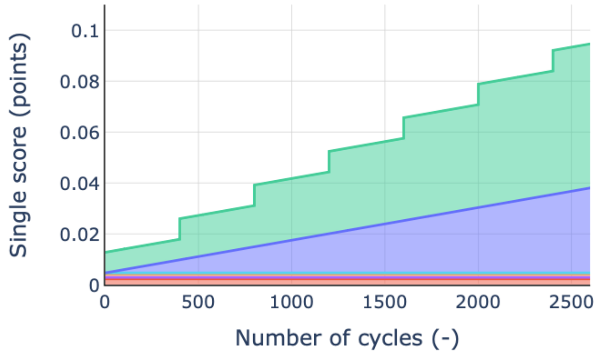
Interpretation

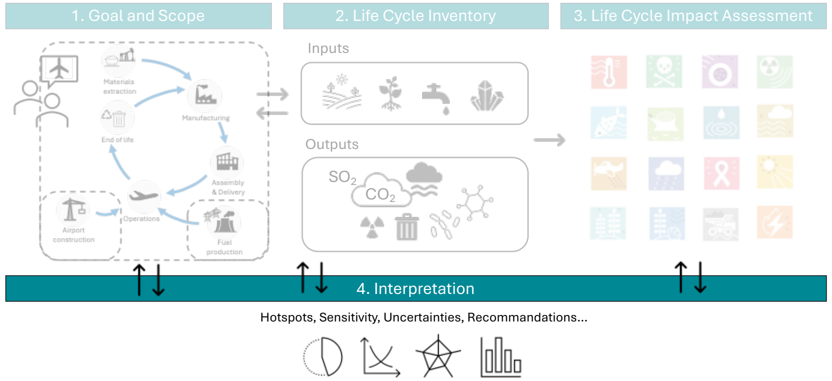
The **interpretation** phase follows the impact assessment to provide a complete and consistent presentation of the results. Interpretation steps include:

- **Completeness check** to ensure that all gathered information and data are sufficient for reaching conclusions

- **Sensitivity analysis** to determine the influence of variations in assumptions, modeling choices and methods
  <u>Examples</u>: What if we use a local supplier? What if we change the electricity mix? If we change the system lifetime?

	Climate	Land use	Water use	...
p_1				
p_2				
p_n				

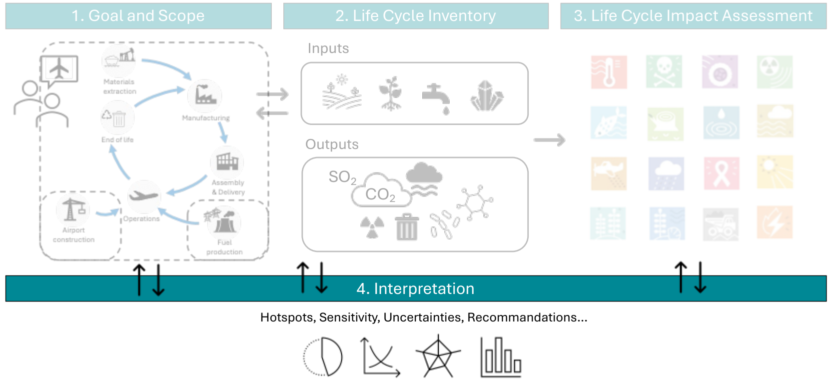


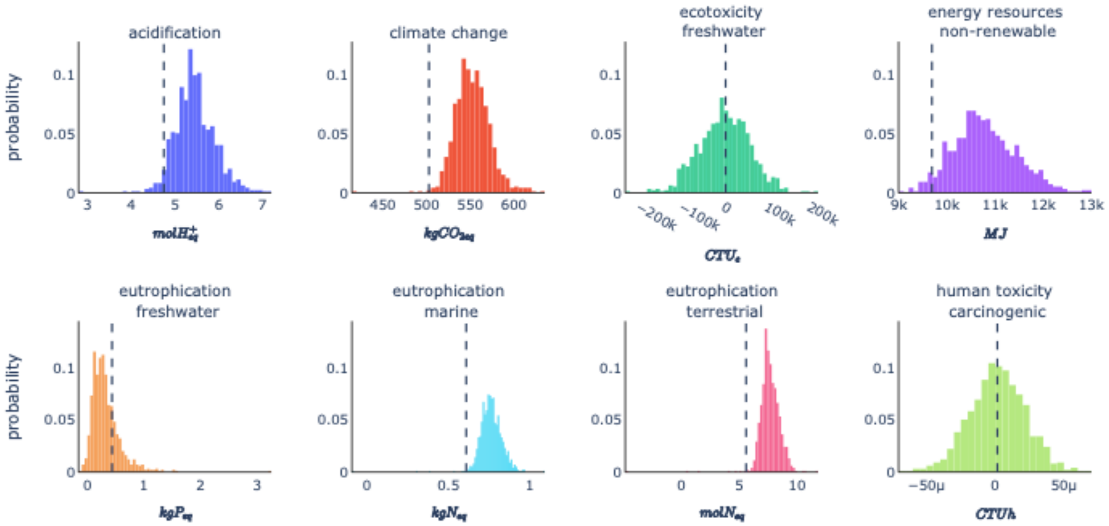


The **interpretation** phase follows the impact assessment to provide a complete and consistent presentation of the results. Interpretation steps include:

- **Uncertainty analysis** to study the influence of discrepancies between the measured/calculated data and their true values.

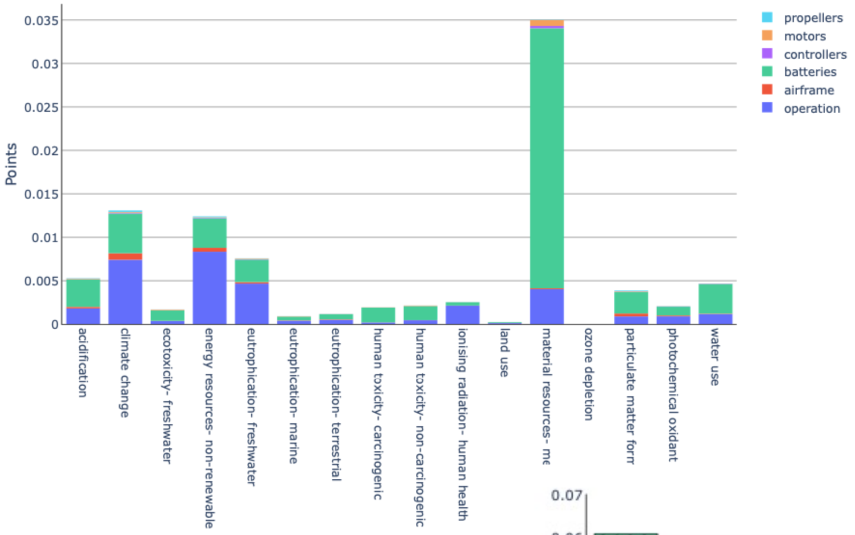
  Examples:
  - LCI data : Kerosene consumption = 40.1 $\pm$ 3.8 kg CO_2 / pax.km
  - LCIA method : 1 kg CH_4 = 25-30 kg CO_2 eq

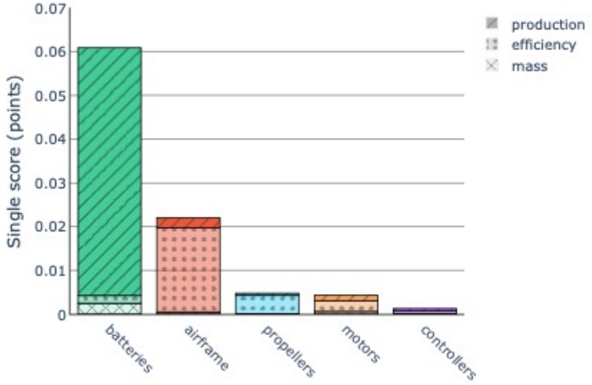


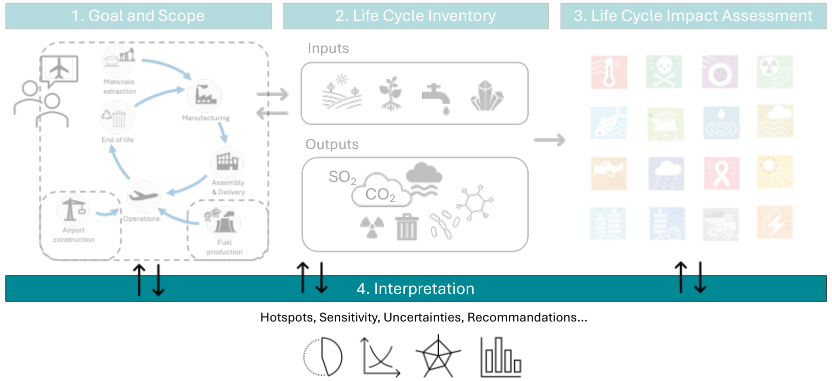


The **interpretation** phase follows the impact assessment to provide a complete and consistent presentation of the results. Interpretation steps include:

- **Hotspot** (or contribution) analysis to identify:
  - The most relevant impact categories,
  - Life cycle stages (e.g. extraction, use),
  - And elementary flow (e.g. CO_2)







Course Contents

- Introduction
- The 4 steps of LCA
  - Goal and scope definition
  - Inventory
  - Impact assessment
  - Interpretation
- Tools & Databases
- Case studies
  - Eco-design of a drone
  - LCA of passenger aircraft
  - Sectoral LCA of air transport
- Planetary boundaries
- Conclusion and Q&A

A range of tools… for various publics

	Spreadsheet	LCA software	LCA through programming
Ease-of-use	●●●●○	●●○○○	●○○○○
Functionalities & Versatility	●○○○○	●●●○○	●●●●●
Possibility of doing a full LCA	●○○○○	●●●●●	●●●●●
Calculation speed	●●●●●	●●○○○	●●●●○
Examples	X	SimaPro, openLCA, thinkstep GaBi	Brightway *Open-source software package written in Python*

Professional databases

Expensive but exhaustive and regularly updated

ecoinvent

thinkstep GaBi

Free databases

BASE Empreinte®

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

ADEME
AGENCE DE LA TRANSITION ÉCOLOGIQUE

Official French database

Product Environmental Footprint

European Commission

European Commision initiative

Sector-specific databases

AGRIBALYSE

carbonminds

ecosystem
recycler c'est protéger

WORLD FOOD LCA DATABASE

agri footprint
understanding the impact of food

PLASTICS EUROPE

& many more...

Course Contents

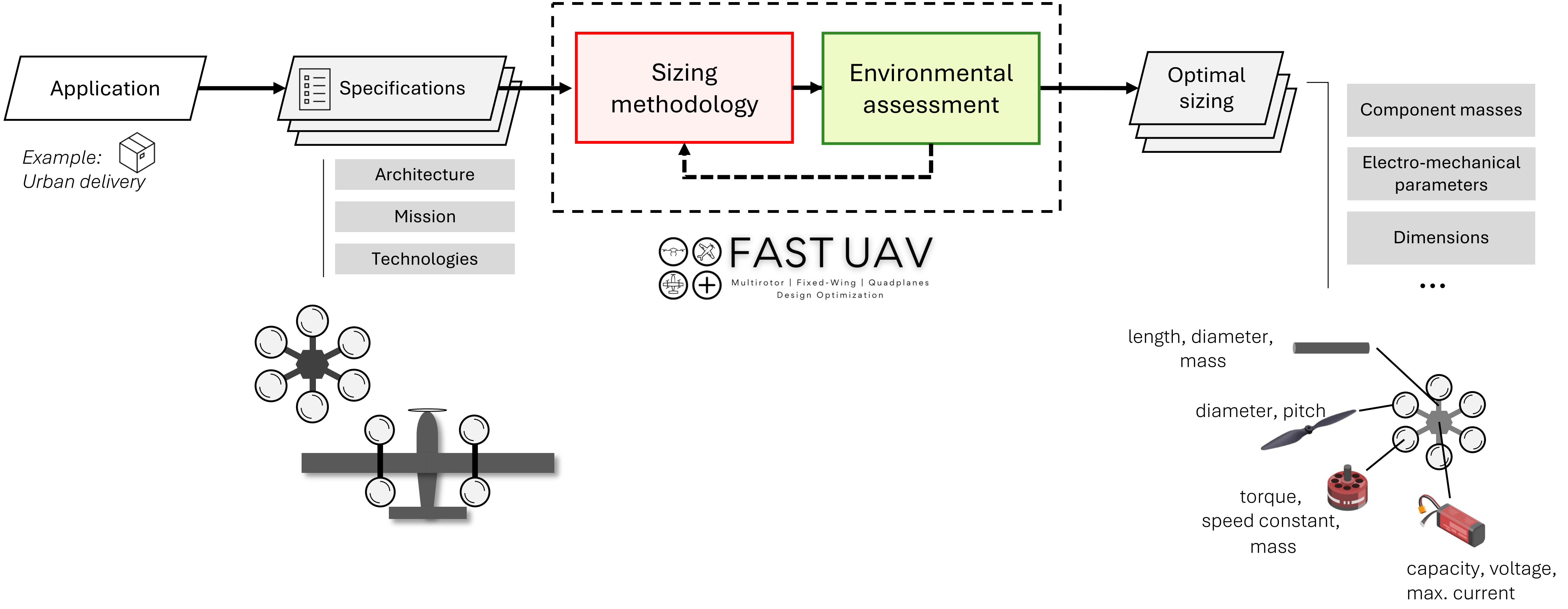
- Introduction
- The 4 steps of LCA
  - Goal and scope definition
  - Inventory
  - Impact assessment
  - Interpretation
- Tools & Databases
- Case studies
  - Eco-design of a drone
  - LCA of passenger aircraft
  - Sectoral LCA of air transport
- Planetary boundaries
- Conclusion and Q&A

Case study

Eco-design of a drone

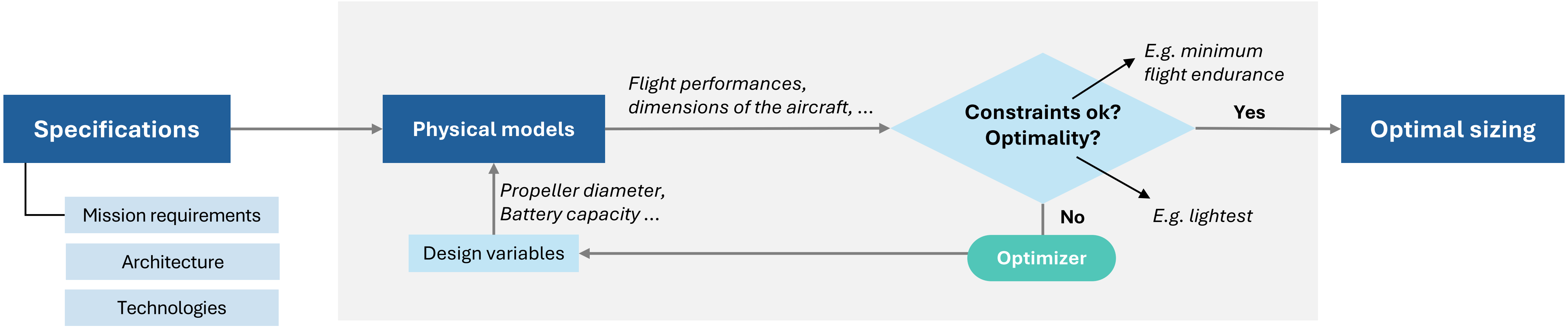
F. Pollet’ s thesis, 2024

Case study – Eco-design of a drone



Case study – Eco-design of a drone

Sizing methodology



Case study – Eco-design of a drone

Environmental assessment

LCA of background

Propeller [1 kg]: 83.2 kg CO2-eq; 2.5 x 10^{-4} kg Sb-eq; …

Battery [1 kg]: 14.8 kg CO2-eq; 2.1 x 10^{-3} kg Sb-eq; …

…

Electricity [1 kWh]: 0.55 kg CO2-eq; …

ecoinvent

LCI database version 3.9.0

Parametric LCA model

$$f_{climate}(P_i) = 83.2 \times m_{propellers} + \ldots + 0.55 \times E_{missions}$$

16 impact categories [1]

+ Partial derivatives for improved numerical resolutions

$$\frac{\partial f_{climate}}{\partial m_{propellers}}(P_i) = 83.2$$

…

$$\frac{\partial f_{climate}}{\partial E_{mission}}(P_i) = 0.55$$

Brightway

MINES ParisTech

LCA Algebraic

Open-source software tools for LCA calculation

Component masses, mission energy

Sizing methodology

$m_{propellers} = 0.08\ kg$

$m_{batteries} = 1.69\ kg$

…

Impacts evaluation

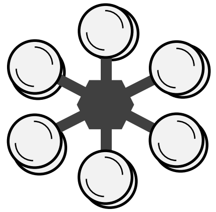
Optimization

objective or constraints

[1] European Commission, Product Environmental Footprint methods, 2021

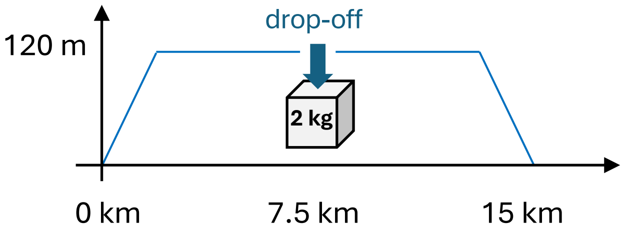
Case study – Eco-design of a drone

Architecture



Hexacopter with coaxial rotors

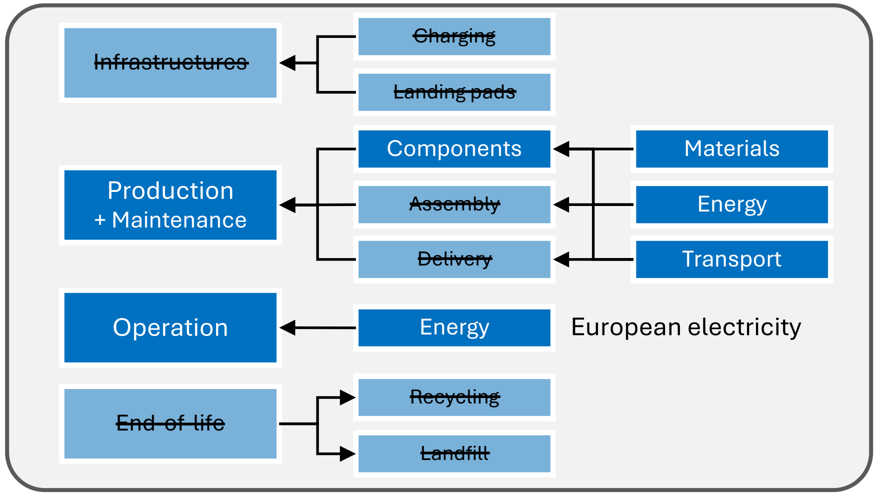
Mission
& usage



5 deliveries/day
260 days/year
2 years

2600 missions

Boundaries
of LCA study



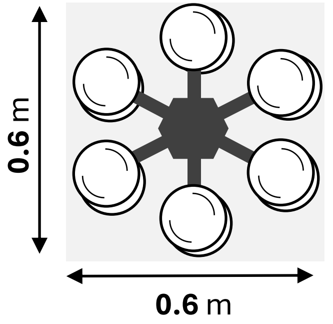
Research questions

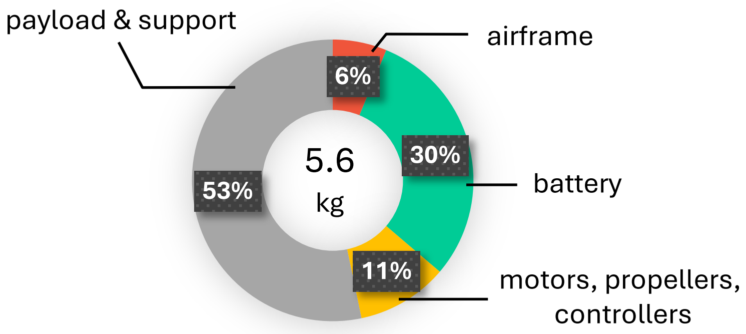
1. Critical environmental impacts and main contributors?
2. Design implications of mitigating these environmental impacts?

Case study – Eco-design of a drone

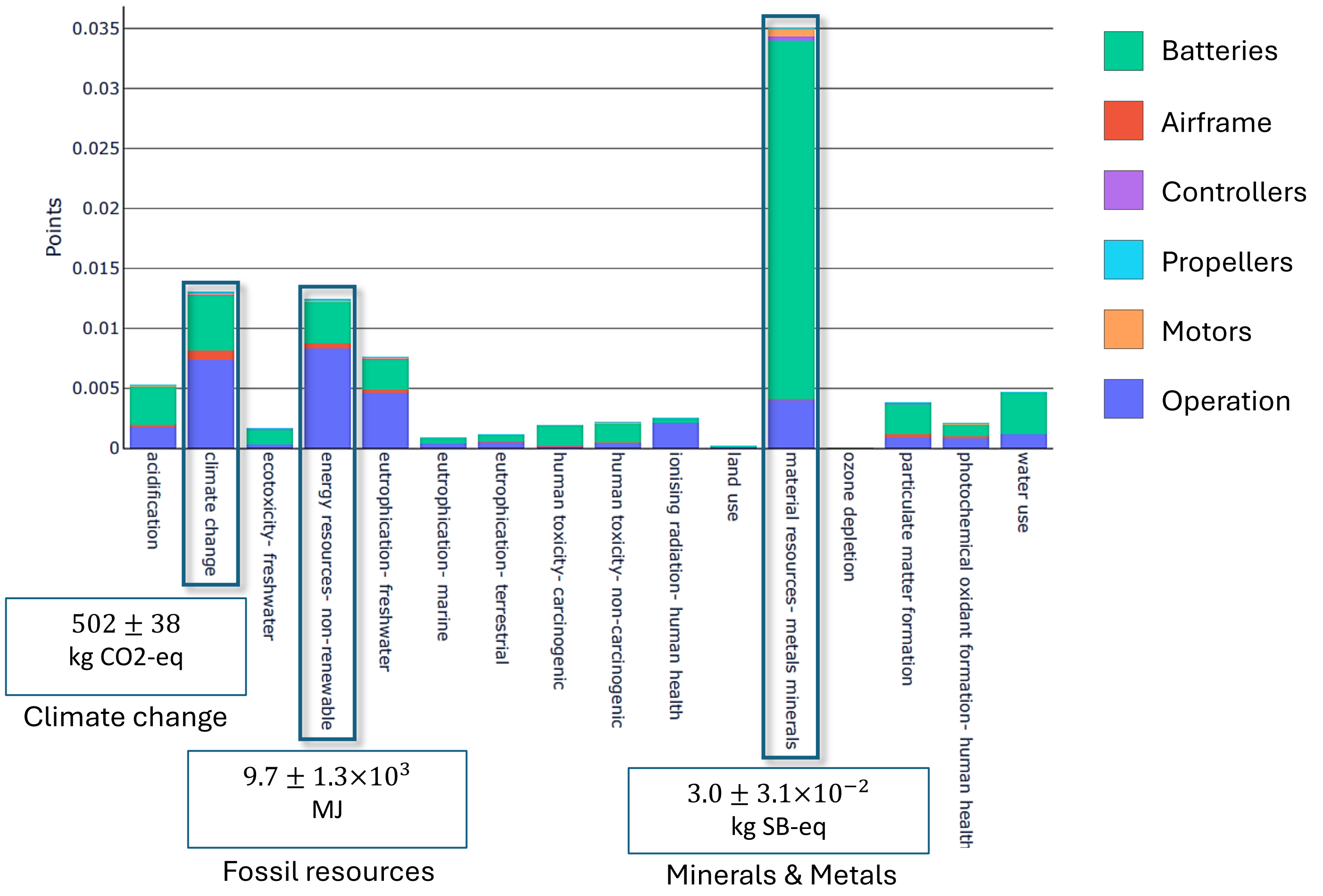
LCA results for the reference drone

Sizing results
(lightest design that meets
the requirements)



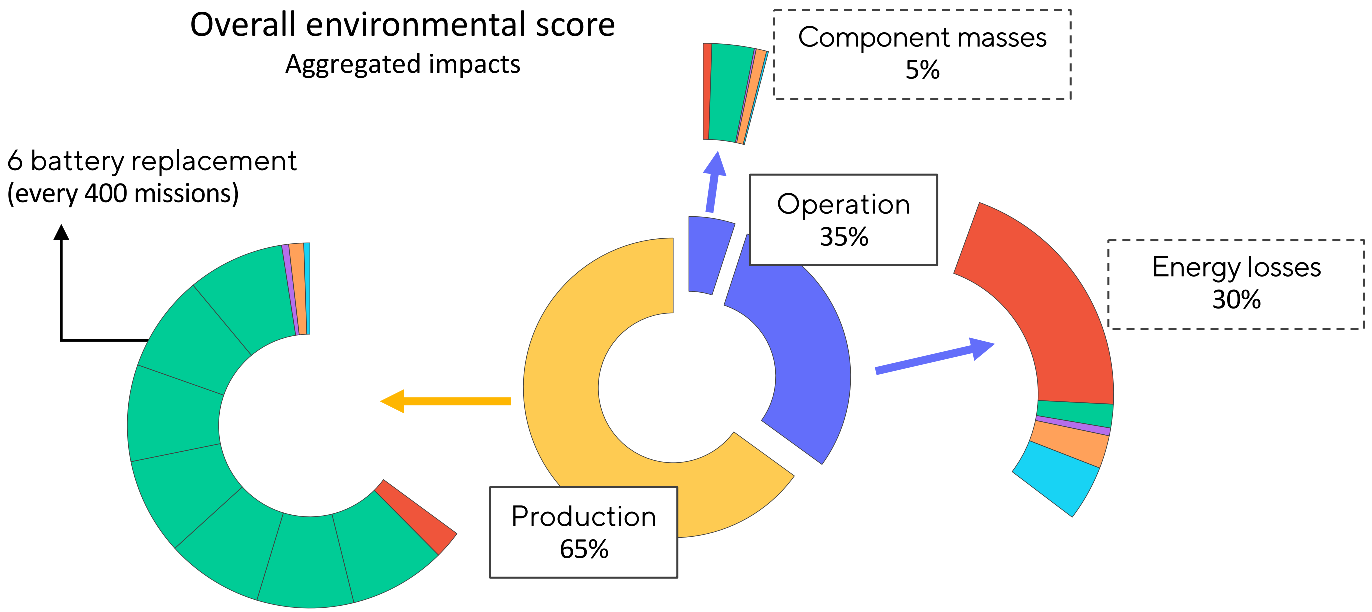


Environmental impacts
Normalized and weighted scores



Case study – Eco-design of a drone

Hotspot analysis



Taylor expansion

$$S_{operation} = S_0 + \sum_i \left.\frac{\partial S}{\partial m_i}\right|_0 \Delta m_i + \sum_i \left.\frac{\partial S}{\partial \eta_i}\right|_0 \Delta \eta_i + \frac{1}{2}\sum_i \left.\frac{\partial^2 S}{\partial m_i^2}\right|_0 \Delta m_i^2 + \frac{1}{2}\sum_i \left.\frac{\partial^2 S}{\partial \eta_i^2}\right|_0 \Delta \eta_i^2 + \ldots$$

Components "imperfections":
Mass $m_i \neq 0$, Efficiency $\eta_i \neq 1$

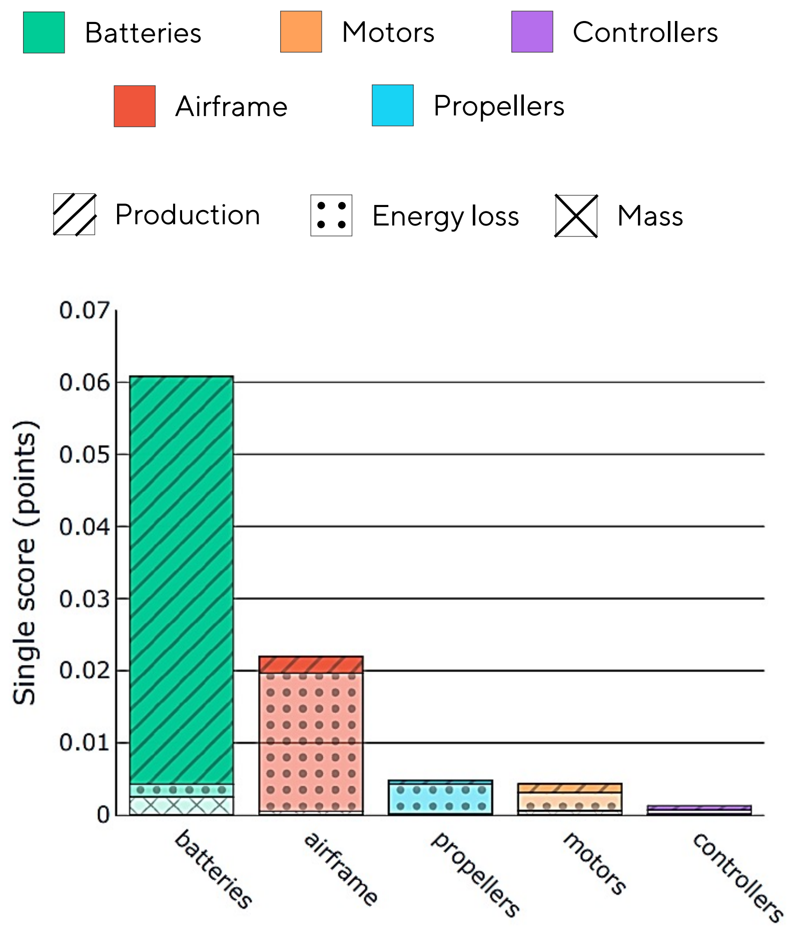
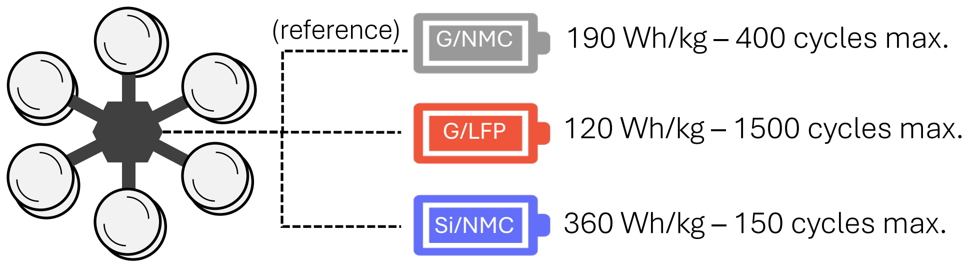


Fig.: Component contributions to the environmental score

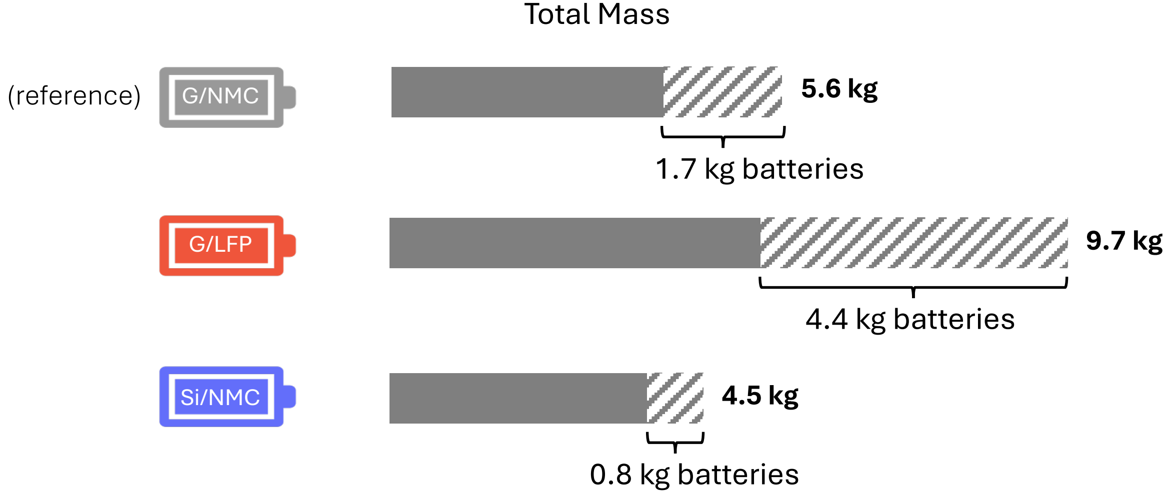
Case study – Eco-design of a drone

Sensitivity to the battery technology

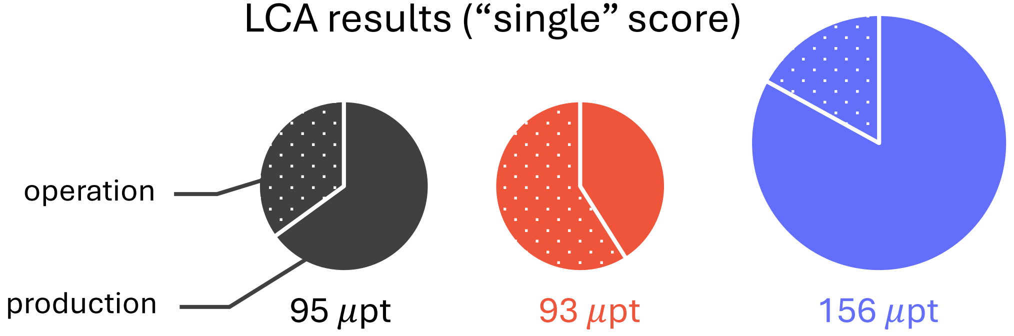
Technology assumptions



Sizing results



LCA results ("single" score)



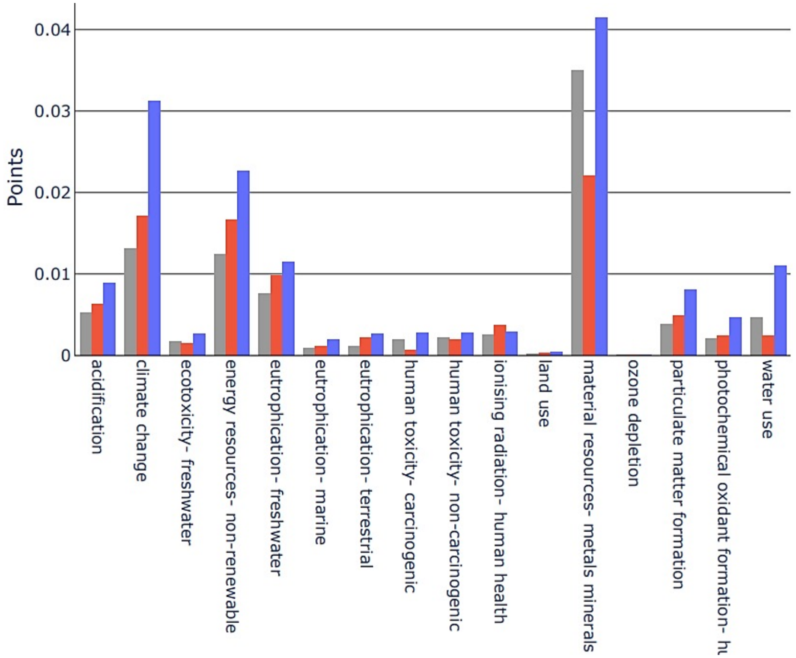
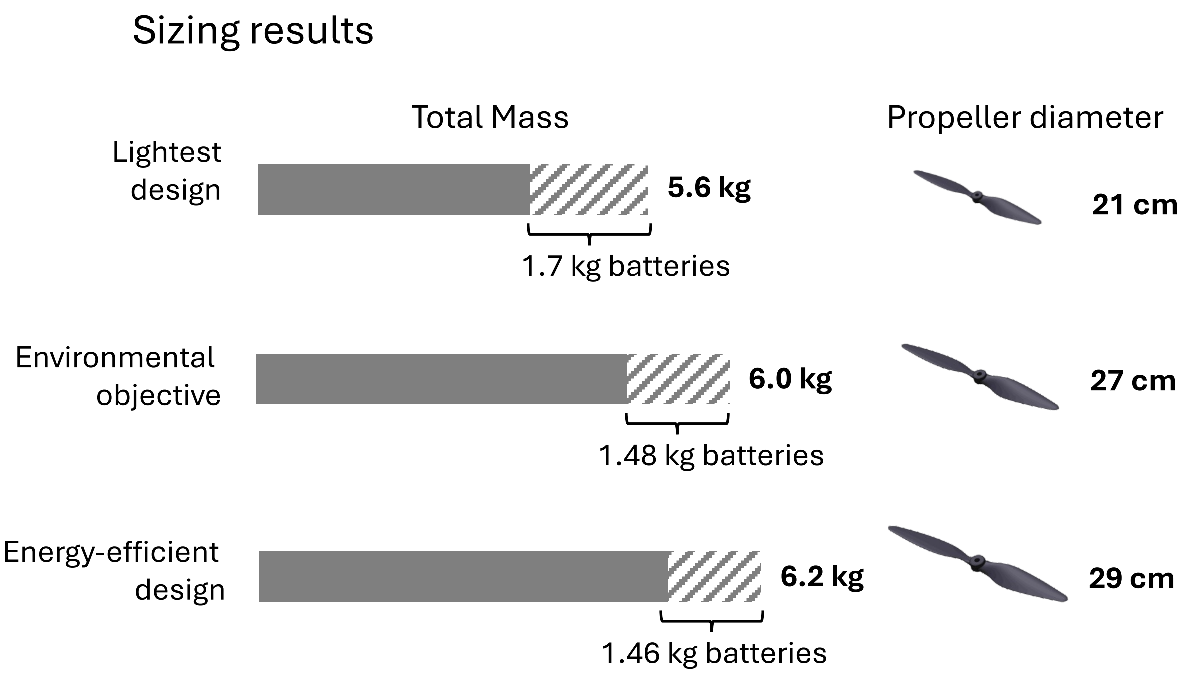


Fig.: Comparison of the environmental impacts for the three UAV designs

Case study – Eco-design of a drone

Sensitivity to the optimality criterion



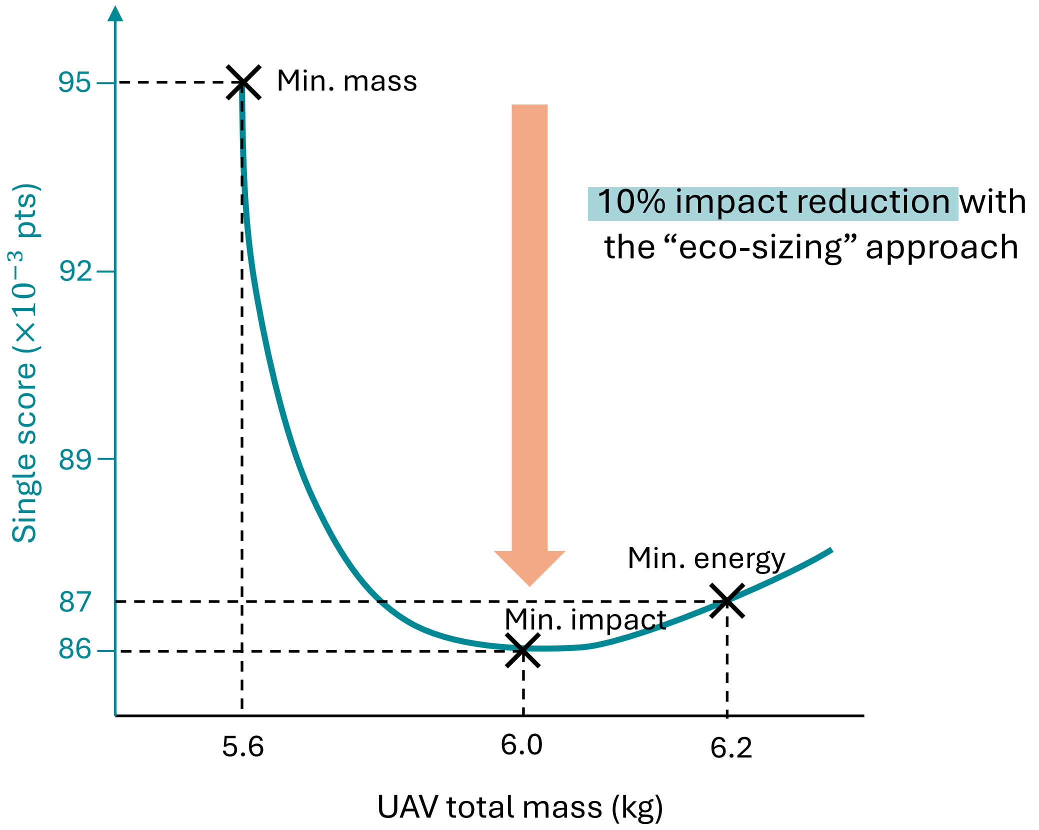
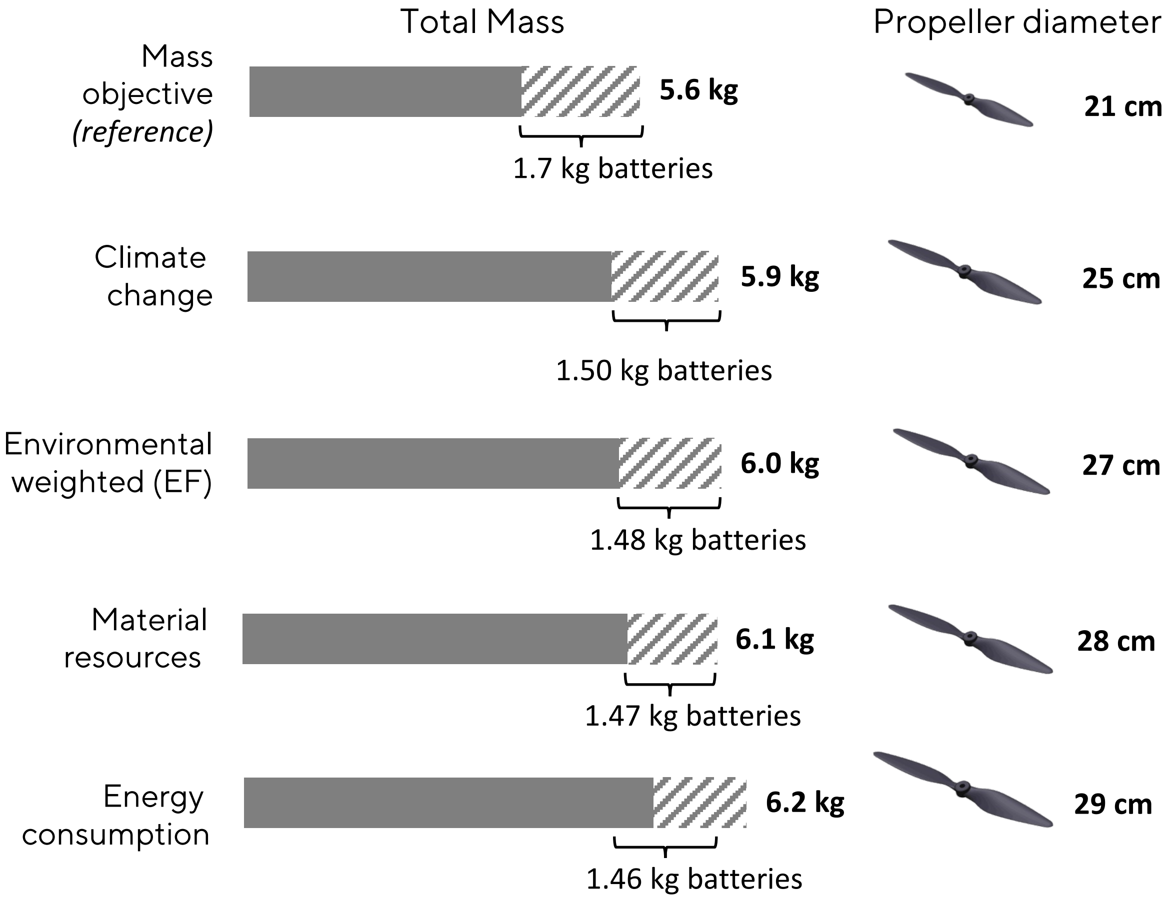


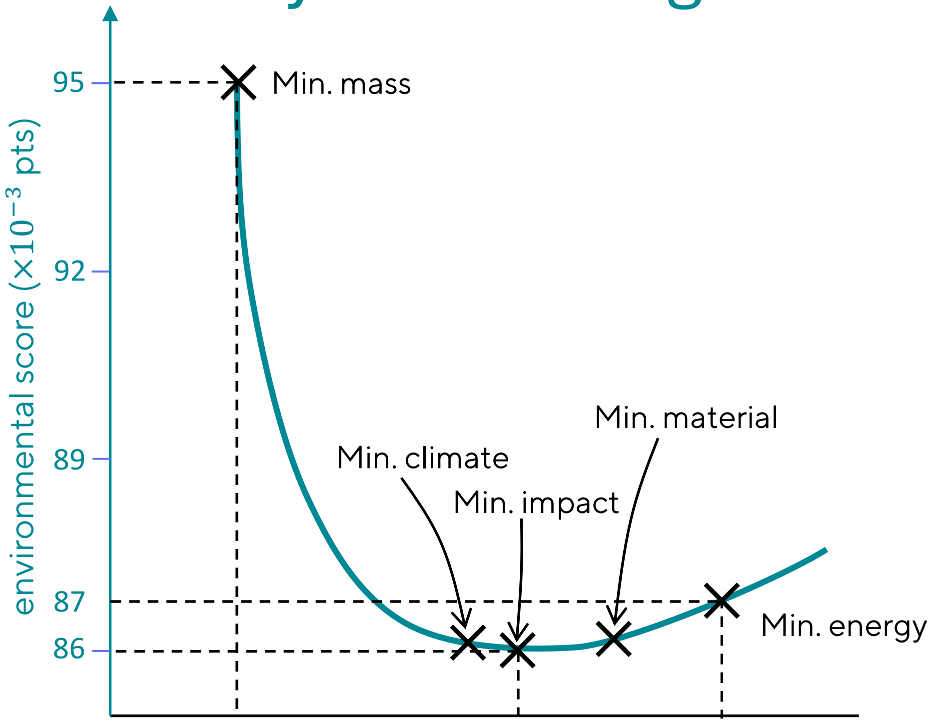
Fig.: Environmental score for different sizing objectives as a function of UAV mass

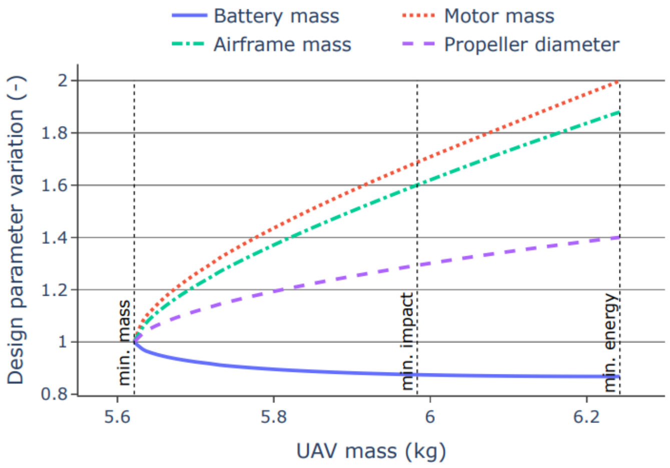
Case study – Eco-design of a drone

Sensitivity to the optimality criterion

Sizing results







Case study

LCA of passenger aircraft

A. Fabre, T. Planès et al., 2022

Case study – LCA of passenger aircraft

Goals

1. Identify the key contributors to the environmental impacts of an aircraft life cycle
2. Explore the potential of biofuels
3. Explore two different aircraft architectures

Scope

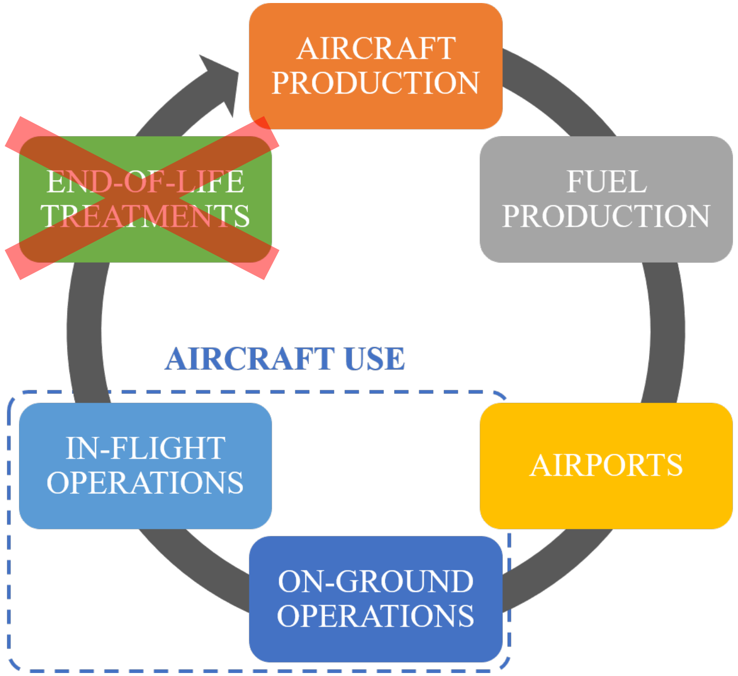
- Functional unit: « Transportation of one passenger over one kilometer » (Revenue Passenger Kilometer - RPK)
  Reference aircraft : A320
  Additional assumptions: 25 years lifetime (32,964 flights), load factor 82.4%, average flight of 1185 km.
- Boundaries: Production of aircraft, airports & fuels. On-ground & in-flight operations. *No end-of-life.*

Data collection

- Data from academic and industrial reports
- EcoInvent database for airports and fuels production

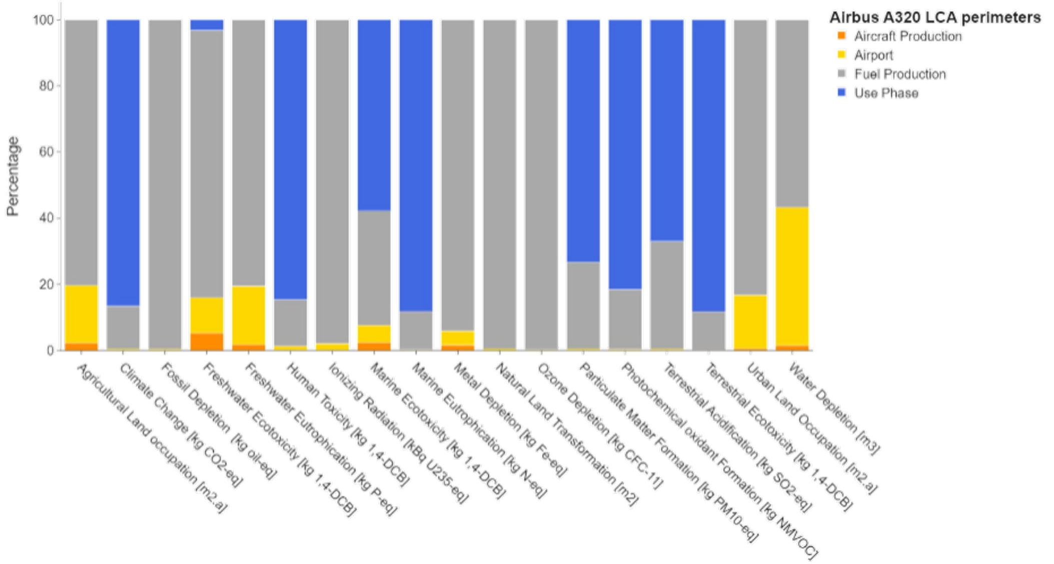
Additional information

- Software tool: OpenLCA
- LCIA methods: ReCiPe 2016



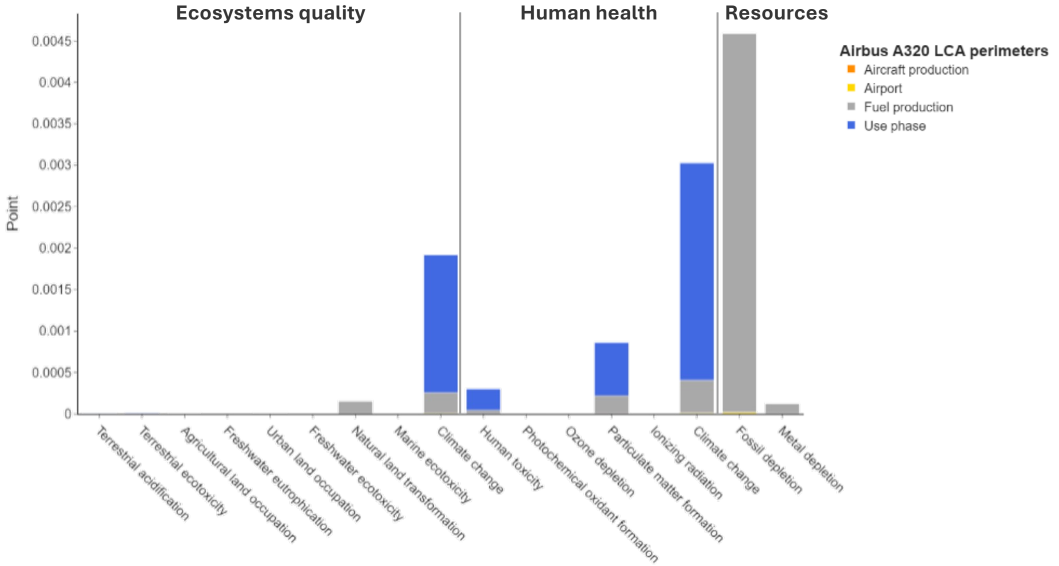
Case study – LCA of passenger aircraft

Midpoint results for an Airbus A320



- ○ Manufacturing negligible
- ○ Airport on water depletion
- ○ Climate change: 109 gCO_2-eq/RPK

Endpoint results for an Airbus A320

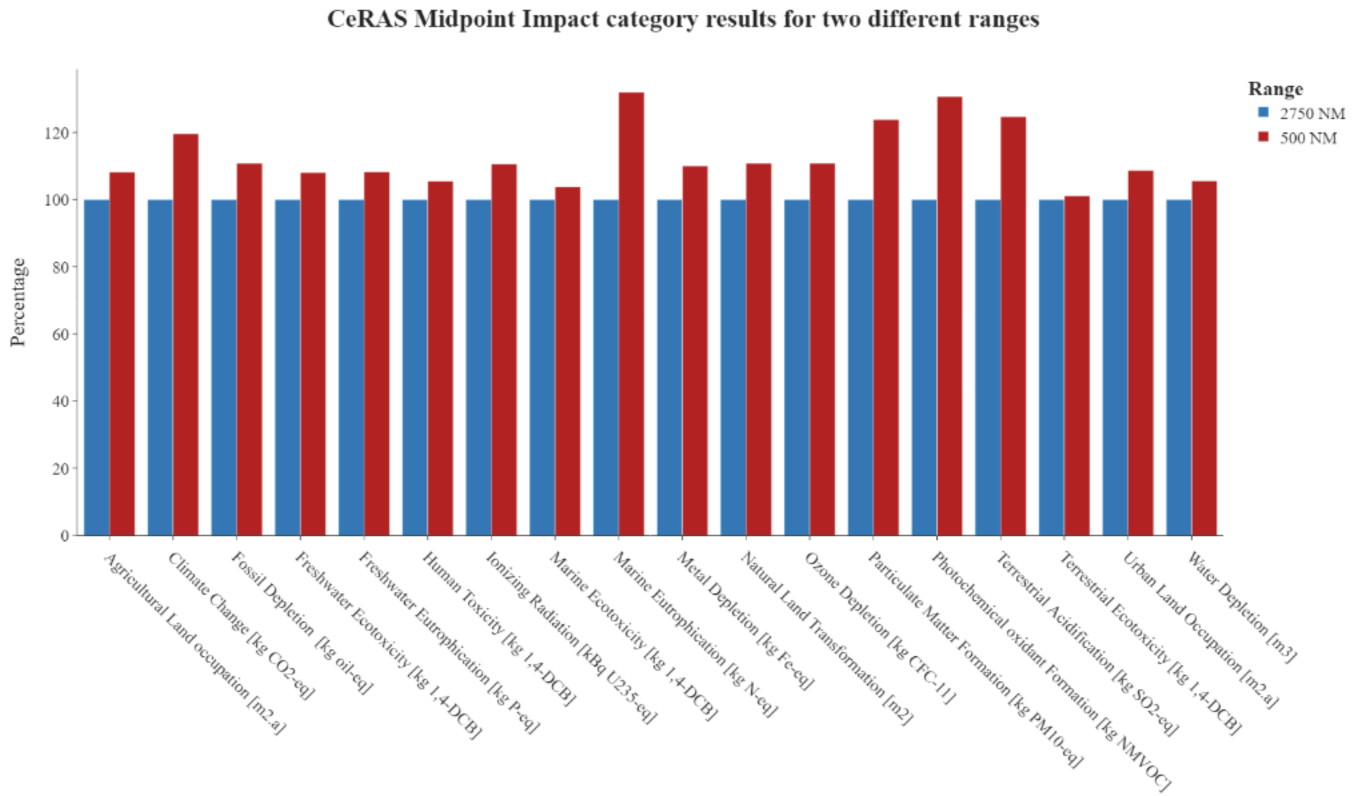


Main contributors to endpoint damages:

- ○ <u>Impact categories</u>: Fossil depletion, Climate change & Particulate matter formation
- ○ <u>Processes</u>: Fuel production and combustion

Case study – LCA of passenger aircraft

Midpoint results for a A320-like aircraft operating at two different ranges



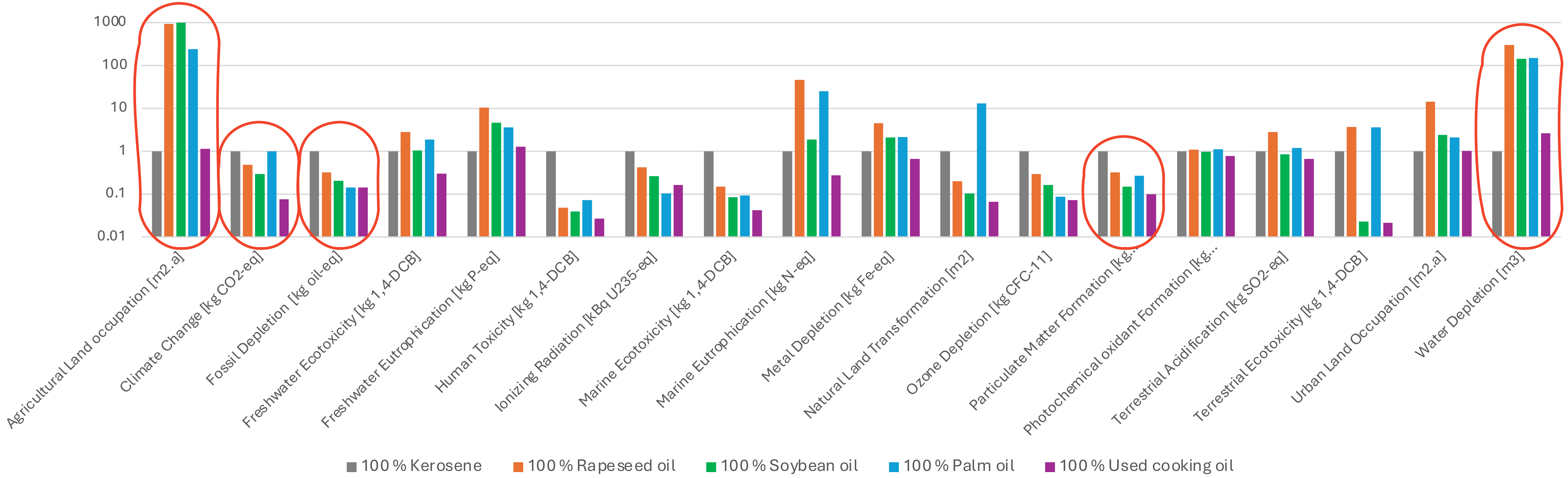
Lower range

=

more impacts ? per kilometer

(relative increase of take-off phases)

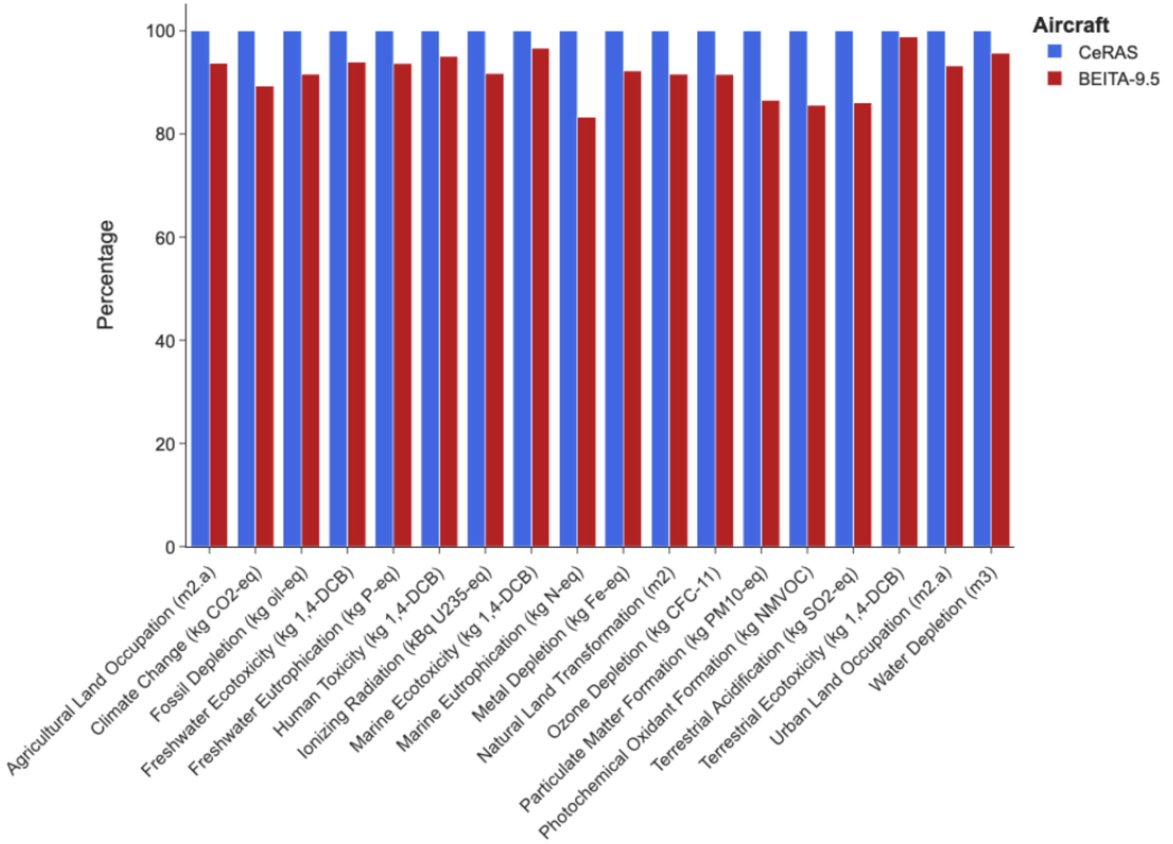
Midpoint results for different fuels – Kerosene and HEFA biofuels, normalized on kerosene impacts



- Not all feedstocks are equal...
- **Palm oil** higher impact on climate change induced by deforestation
- **Used cooking oil** has better potential overall

Case study – LCA of passenger aircraft

Comparison of two aircraft designs on midpoint impacts



Assumptions

- Two aircraft concepts:
  - CeRAS (reference aircraft similar to A320)
  - BEITA architecture :
    - Ultra-High Bypass Ratio (UHBR) Turbofan
    - Electrified Environmental Control System (ECS)
    - Electro-thermal Ice Protection System (IPS)
- Both are sized for a the same mission reqs.: 2500 nm & 150 pax
- ..and evaluated for an operating mission of 800 nm

Results

- 11% impact on climate change with UHBR turbofan & electrified auxiliary systems

Case study

Sectoral & prospective LCA of air transport

Ongoing reasearch at ISA / ISAE-SUPAERO

Case study – Sectoral & Prospective LCA

Previous case study was focused on the impacts of a <u>single aircraft</u> operating at <u>time *t*</u>

↓

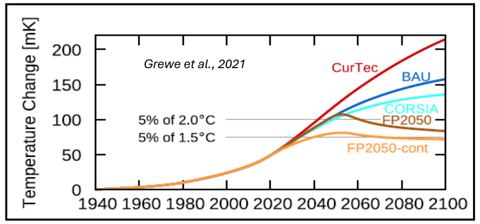
What about the impacts at the sectoral level, i.e. considering a fleet of aircraft?

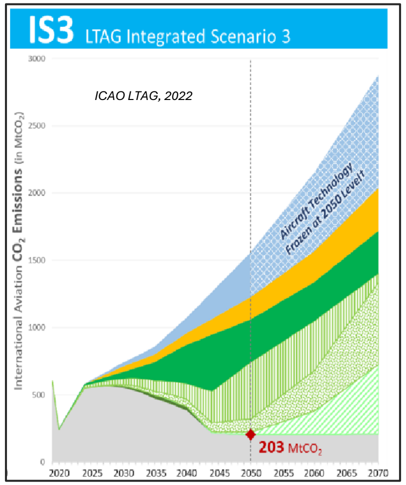
→ **Sectoral LCA**

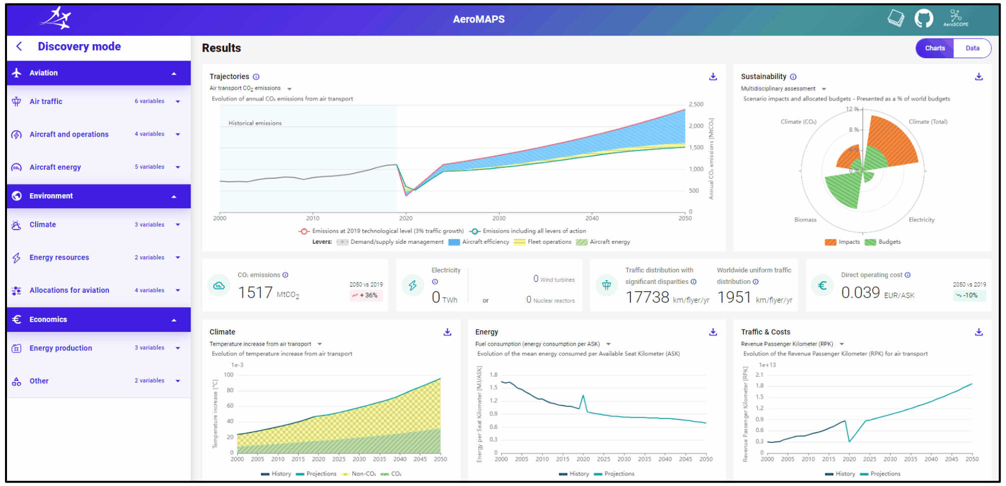
How will these impacts evolve over the next decades?

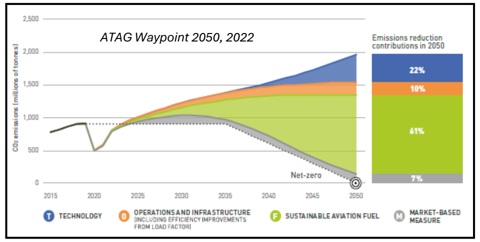
→ **Prospective LCA**

Numerous publications of air transport **prospective** scenarios…



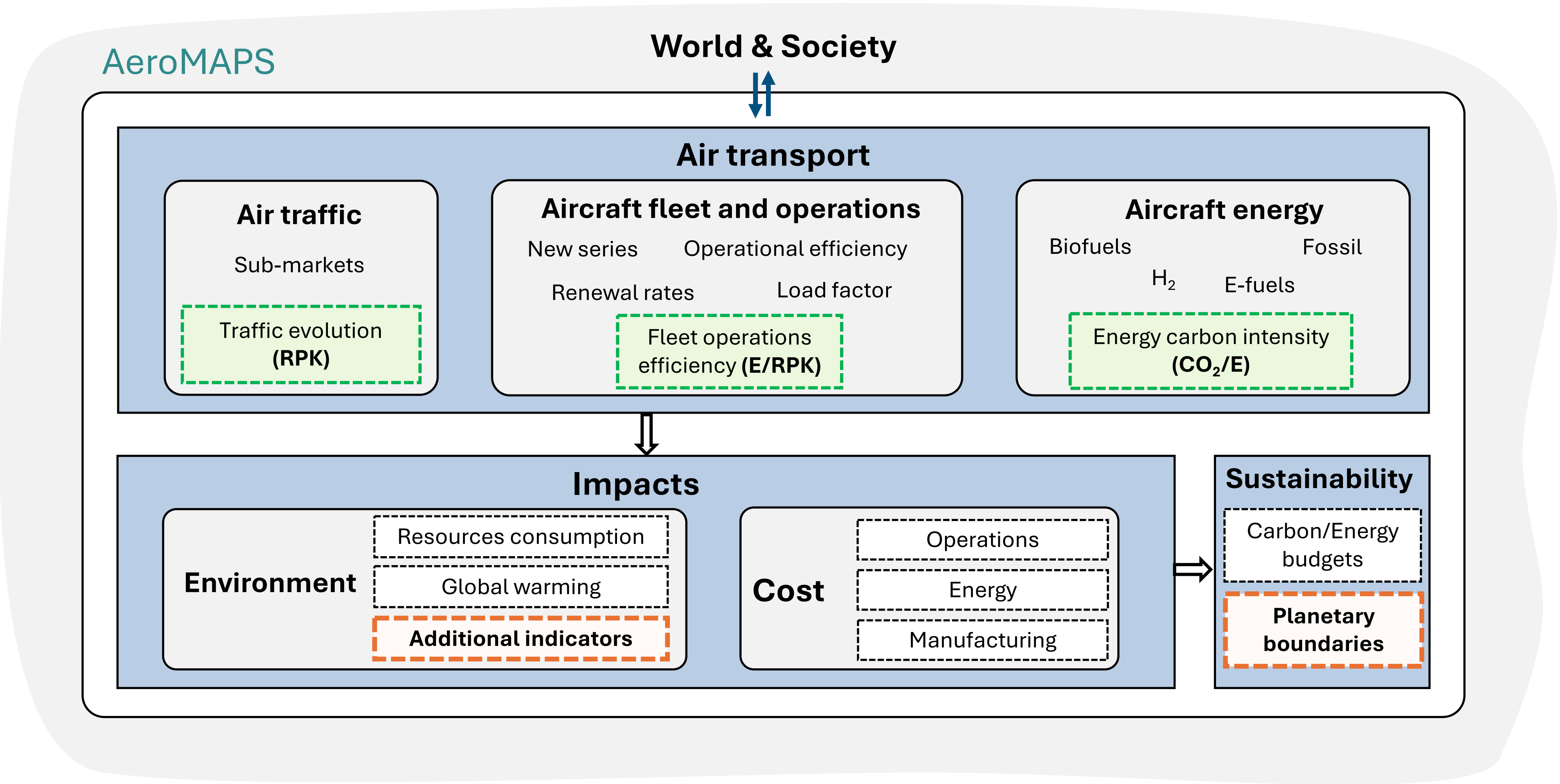






… But focused on climate change. What about other impacts?

Case study – Sectoral & Prospective LCA



Case study – Sectoral & Prospective LCA

Air traffic

+3% per year

Aircraft fleet & operations

New architectures with 20% efficiency gains in 2035

6.1% operational gains 2020 → 2050

82.4 → 85% load factor increase in 2050

Energy mix

Scenario 1 - Fossil

100% fossil kerosene

Scenario 2 - ReFuelEU

	2030	2035	2040	2045	2050	
Fossil	94%	80%	66%	58%	30%	
Biofuels	4.8%	15%	24%	27%	35%	[forest residues]
E-fuels	1.2%	5%	10%	15%	35%	[**grid** electricity]

Scenario 3 – ReFuelEU Solar

ReFuelEU with e-fuels produced from **photovoltaic** electricity

Data collection

- Scientific literature
- EcoInvent data **projected in the future to account for evolutions** in technologies and energy mix supporting the development of aviation

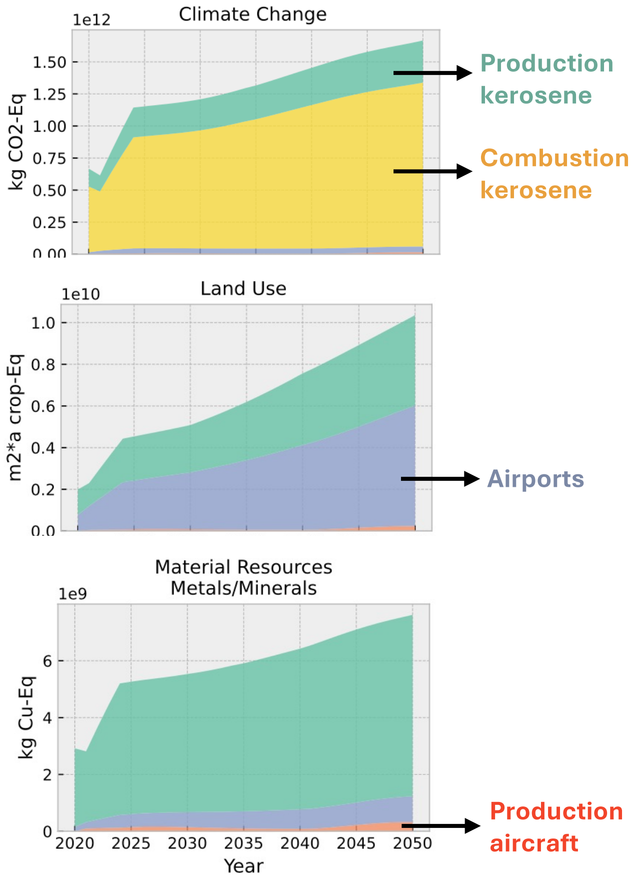
→ Assuming historical trends in human development
→ And no specific climate policies

Environmental indicators

ReCiPe methods
21 impact indicators

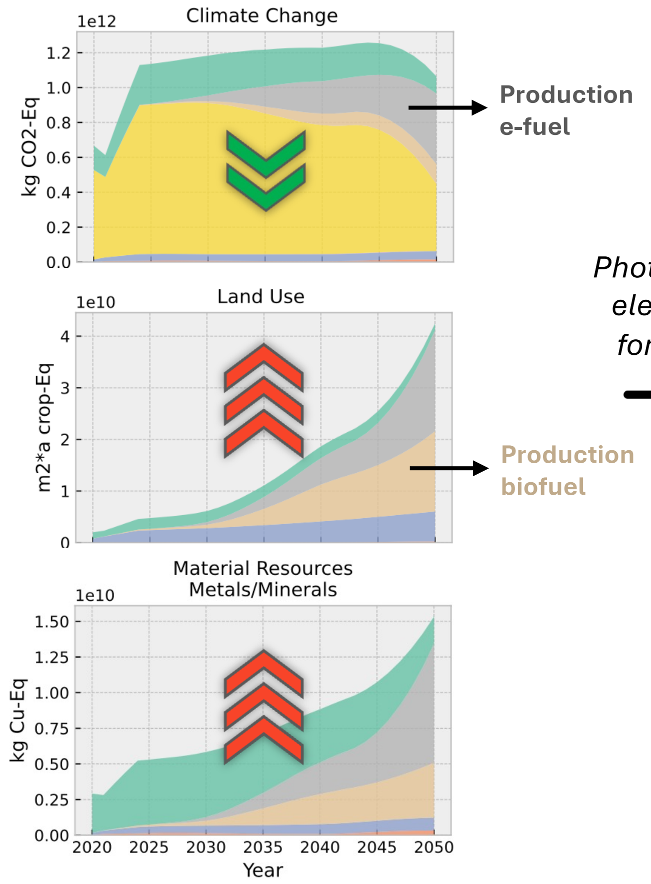
Case study – Sectoral & Prospective LCA

Scenario 1 - Fossil



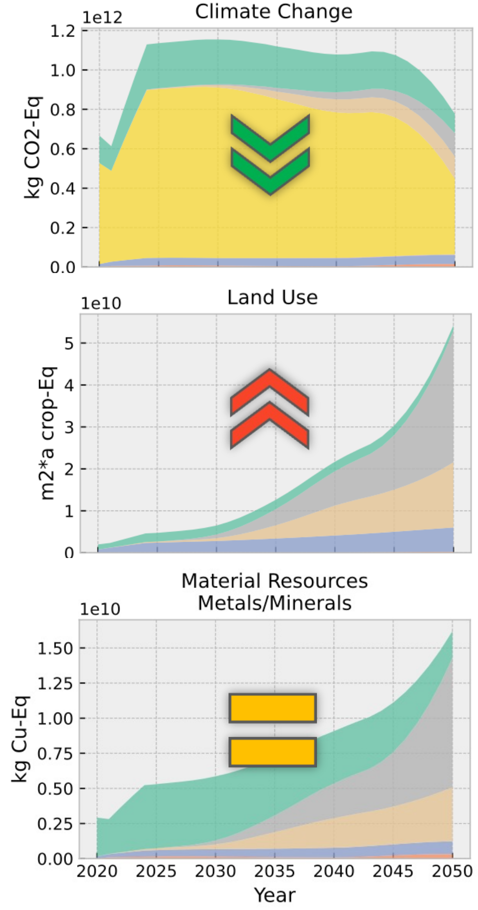
+ Biofuel
+ E-fuel

Scenario 2 – ReFuelEU

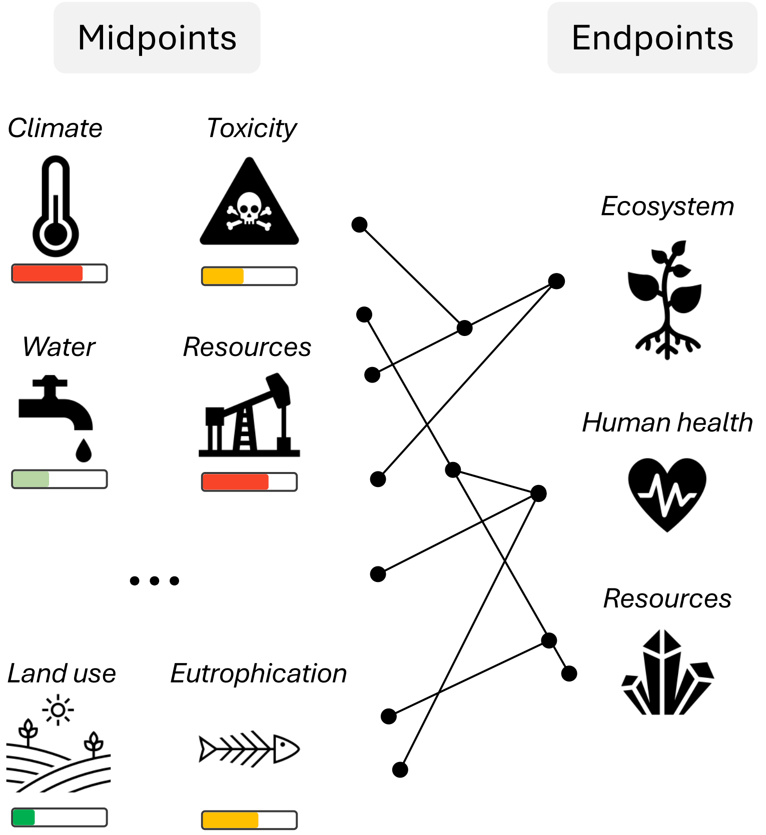


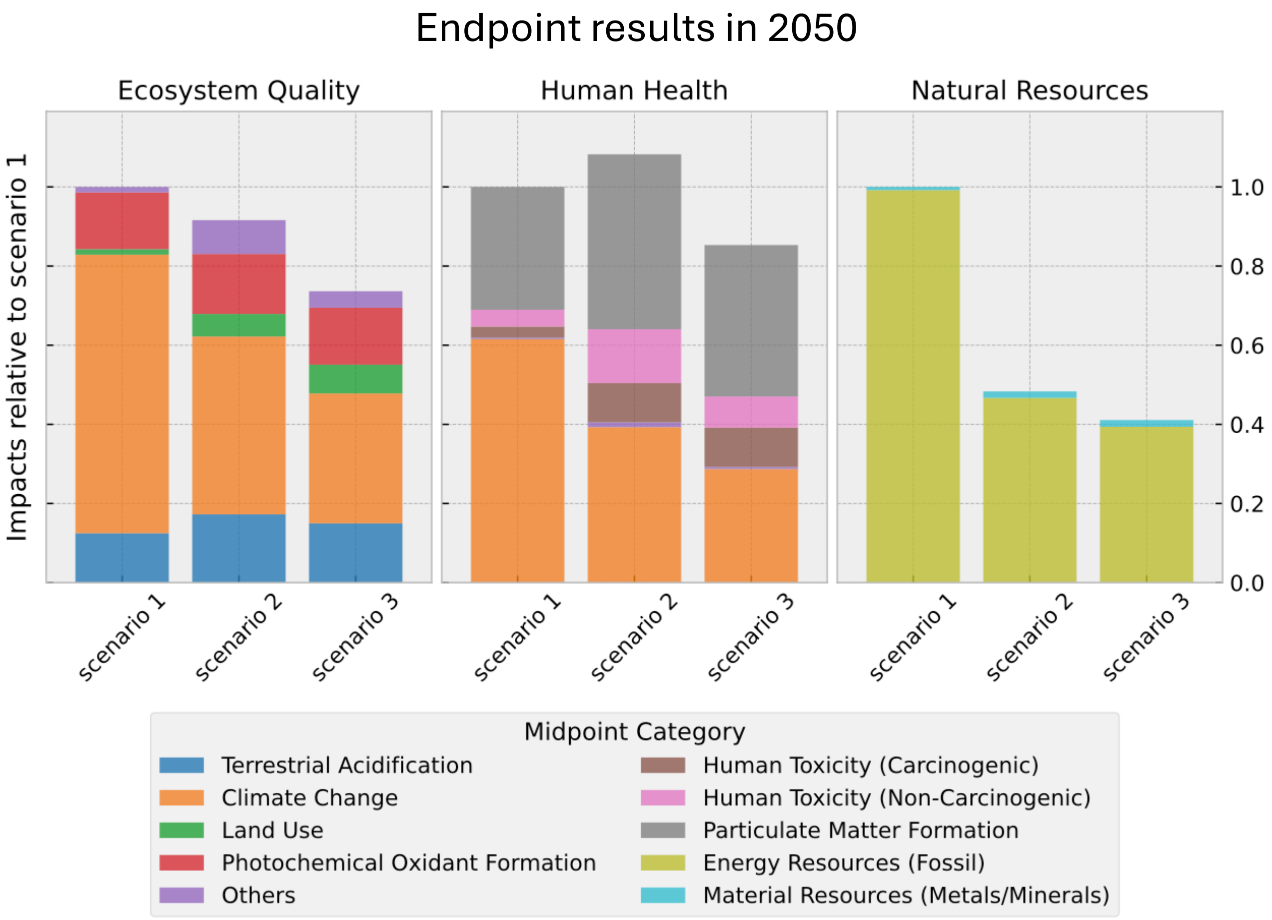
Photovoltaic electricity for e-fuel

Scenario 3 – ReFuelEU Solar



Case study – Sectoral & Prospective LCA





Case study – Sectoral & Prospective LCA

Socio-economic development

Climate policy

	Sustainable development less inequalities, less resource-intensive lifestyles…	**Historical trends** for social, economic, and technology
No climate policy		
RCP 2.6 Paris Agreement +2°C		

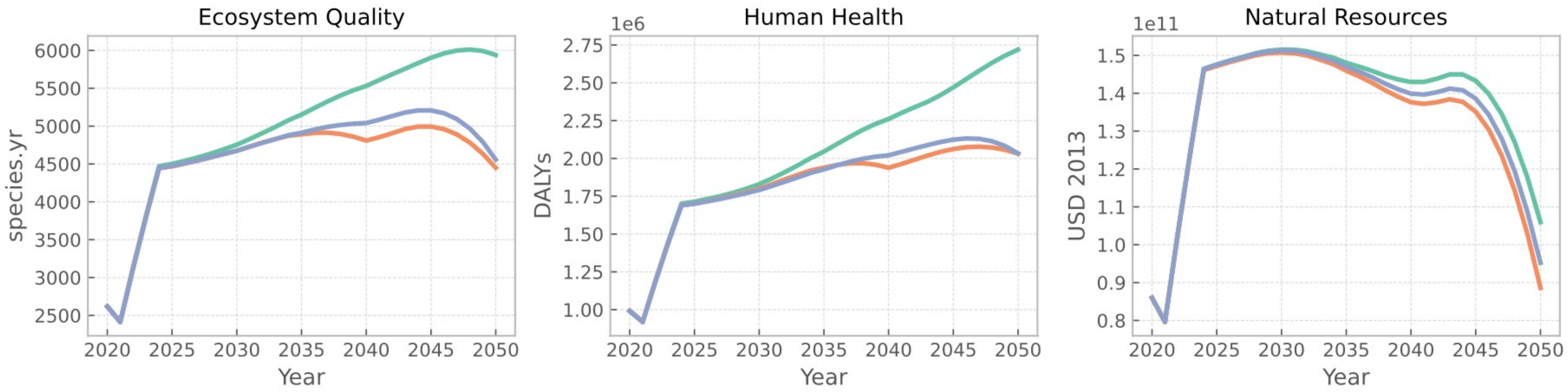


Fig.: Endpoint results for Scenario 2 (ReFuelEU) and different evolutions of human development

Course Contents

- Introduction
- The 4 steps of LCA
  - Goal and scope definition
  - Inventory
  - Impact assessment
  - Interpretation
- Tools & Databases
- Case studies
  - Eco-design of a drone
  - LCA of passenger aircraft
  - Sectoral LCA of air transport
- Planetary boundaries
- Conclusion and Q&A

Absolute Environmental Sustainability Assessment (AESA)

In the introduction of this course, LCA was presented as a systematic and holistic method to estimate the **environmental impacts**, as consequences of **human-driven** environmental pressures.

However, although LCA supports the evaluation of the potential impacts of a product or a system, and a comparison in terms of eco-efficiency, **this is not enough to define how sustainable they are beyond relative terms.**

↓

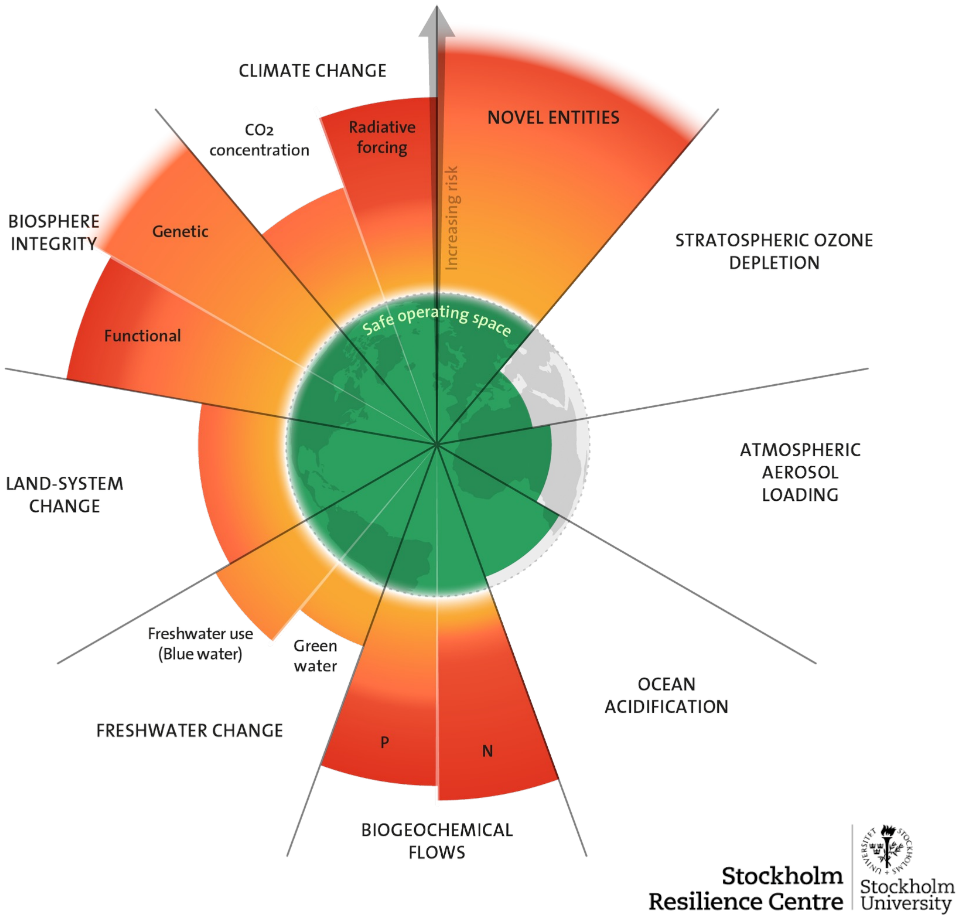
This requires the identification of **absolute sustainability references** against which assessing the impacts.

~~Better~~ Good enough

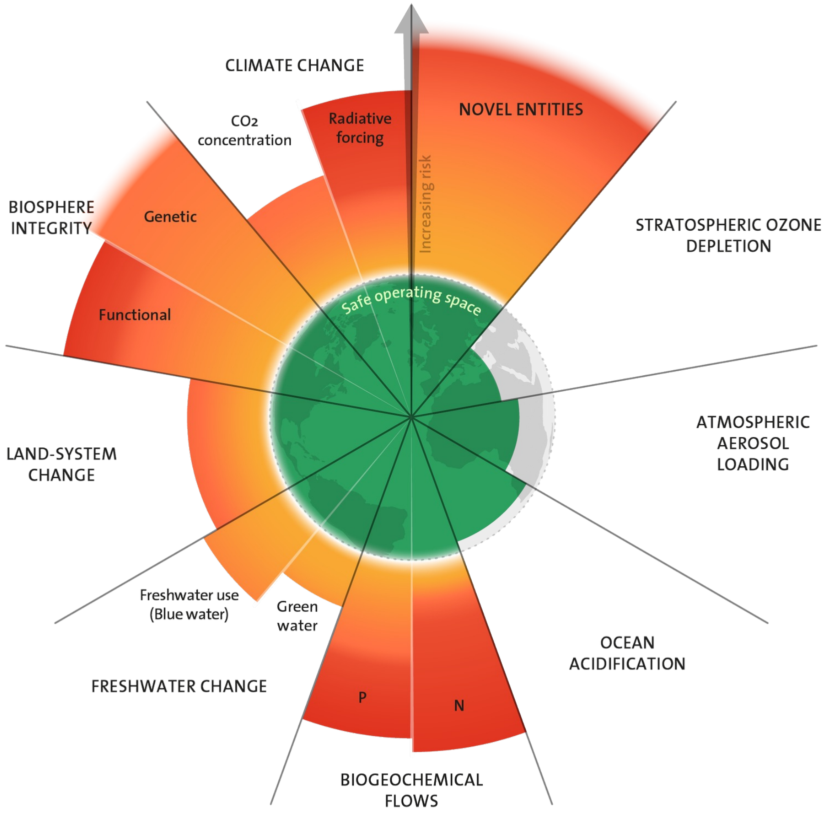
The concept of Planetary Boundaries

Planetary boundaries are a framework to describe thresholds to the impacts of human activities on the Earth system.

Beyond these thresholds, the environment may not be able to self-regulate and Earth system would leave the period of stability of the Holocene, in which human society developed.



Integrating PBs into LCA - (1) through updated LCIA methods



LCIA methods expressing PBs

New impact categories

EF-LCIA impact category	PB-LCIA impact category
Climate change	Climate change – CO2 concentration
	Climate change – Radiative forcing
	Ocean acidification
Ozone depletion	Stratospheric ozone depletion
Land use	Land-system change
Water resource depletion	Freshwater change
Photochemical ozone formation	Atmospheric aerosol loading
Freshwater eutrophication	Biogeochemical flows – P
Marine eutrophication	Biogeochemical flows – N
Acidification, Particulate matter, Human toxicity...	

New characterization factors

	Environmental flow	Emission compartment	Characterization factor	Unit
Climate change – Radiative forcing	CO_2	Air	3.53×10^{-13}	$W\,yr\,m^{-2}\,kg^{-1}$
	CO_2, land transformation	Air	1.18×10^{-15}	$W\,m^{-2}\,kg^{-1}$
	CH_4	Air	1.59×10^{-12}	$W\,yr\,m^{-2}\,kg^{-1}$
	N_2O	Air	4.64×10^{-11}	$W\,yr\,m^{-2}\,kg^{-1}$
	CO	Air	2.74×10^{-13}	$W\,yr\,m^{-2}\,kg^{-1}$
	NMVOC, hydrocarbons	Air	1.06×10^{-12}	$W\,yr\,m^{-2}\,kg^{-1}$
Stratospheric ozone depletion	CFC-11	Air	7.85×10^{-9}	$DU\,yr\,kg^{-1}$
	CFC-12	Air	7.34×10^{-9}	$DU\,yr\,kg^{-1}$
	CFC-113	Air	4.91×10^{-9}	$DU\,yr\,kg^{-1}$
	Halon- 1211	Air	5.16×10^{-8}	$DU\,yr\,kg^{-1}$
	Halon-1301	Air	1.15×10^{-7}	$DU\,yr\,kg^{-1}$
	CFC-10, Carbon Tetrachloride	Air	5.74×10^{-9}	$DU\,yr\,kg^{-1}$
	HCFC-140, 1,1,1-Trichloroethane	Air	1.32×10^{-9}	$DU\,yr\,kg^{-1}$

[1] Ryberg et al., 2018

Integrating PBs into LCA - (2) through normalisation of the results

Sustainable Development Goals

3 GOOD HEALTH AND WELL-BEING

6 CLEAN WATER AND SANITATION

13 CLIMATE ACTION

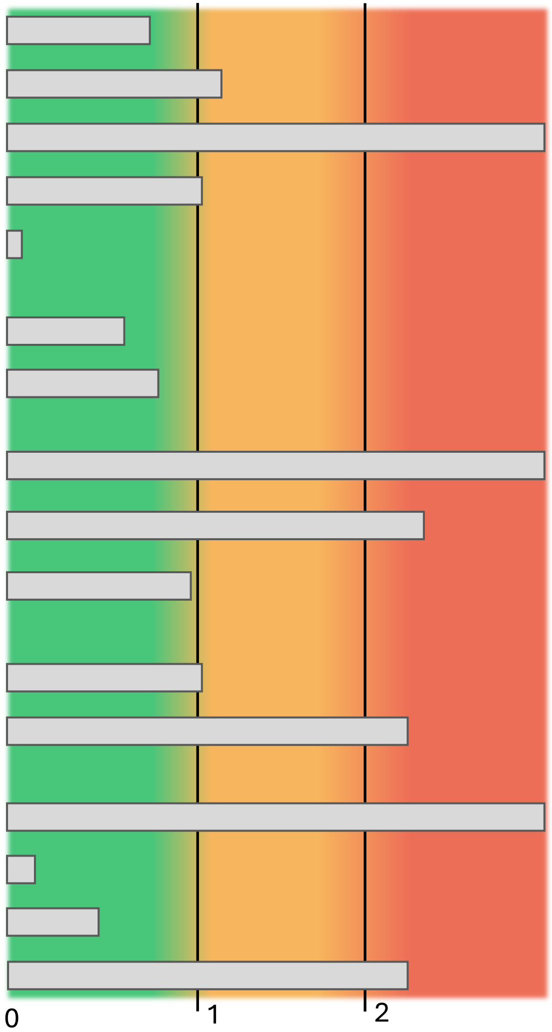
14 LIFE BELOW WATER

15 LIFE ON LAND

LCA impact categories
(Environmental Footprint method)

- Human toxicity, cancer
- Human toxicity, non cancer
- Particulate matter
- Photochemical ozone formation
- Ionising radiation
- Water use
- Ecotoxicity, freshwater
- Climate change
- Resource use, fossil
- Ozone depletion
- Eutrophication, marine
- Eutrophication, freshwater
- Land use
- Eutrophication, terrestrial
- Acidification
- Resource use, minerals and metals

LCIA results normalised against PBs

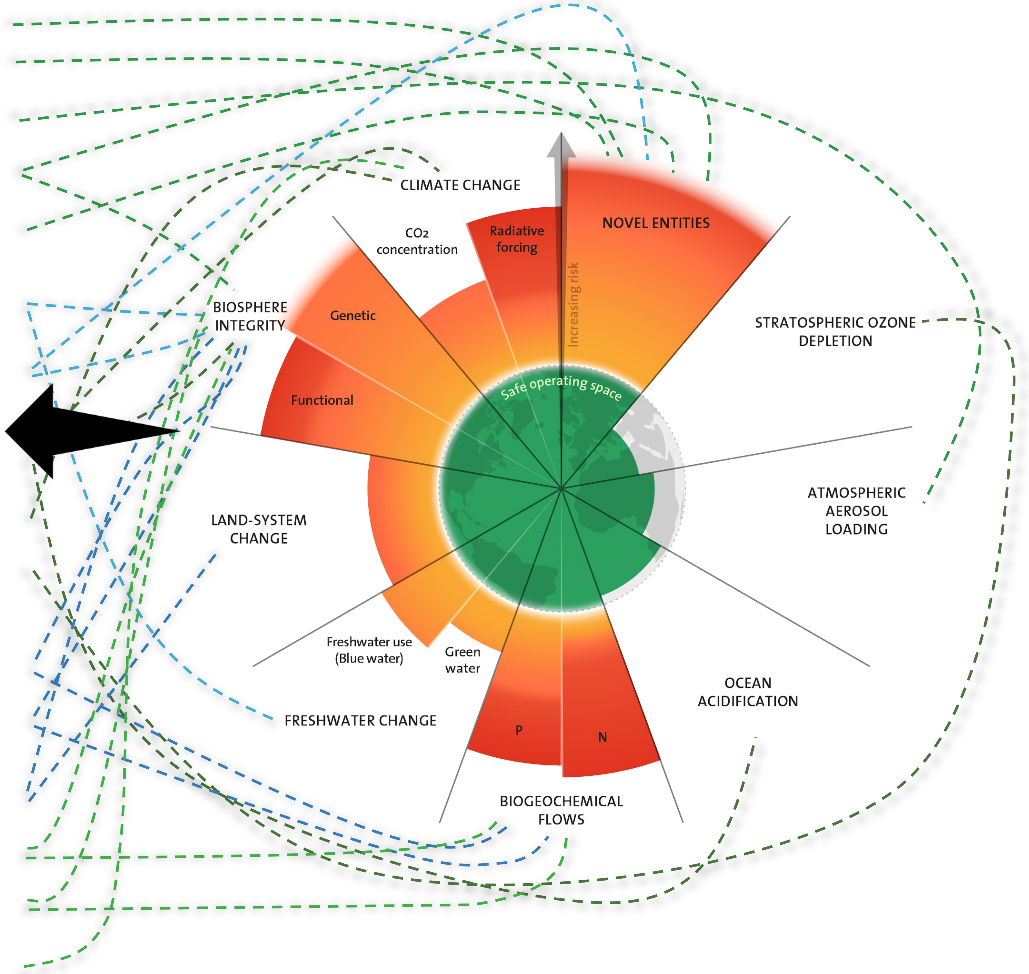


Safe Operating Space

Uncertainty area

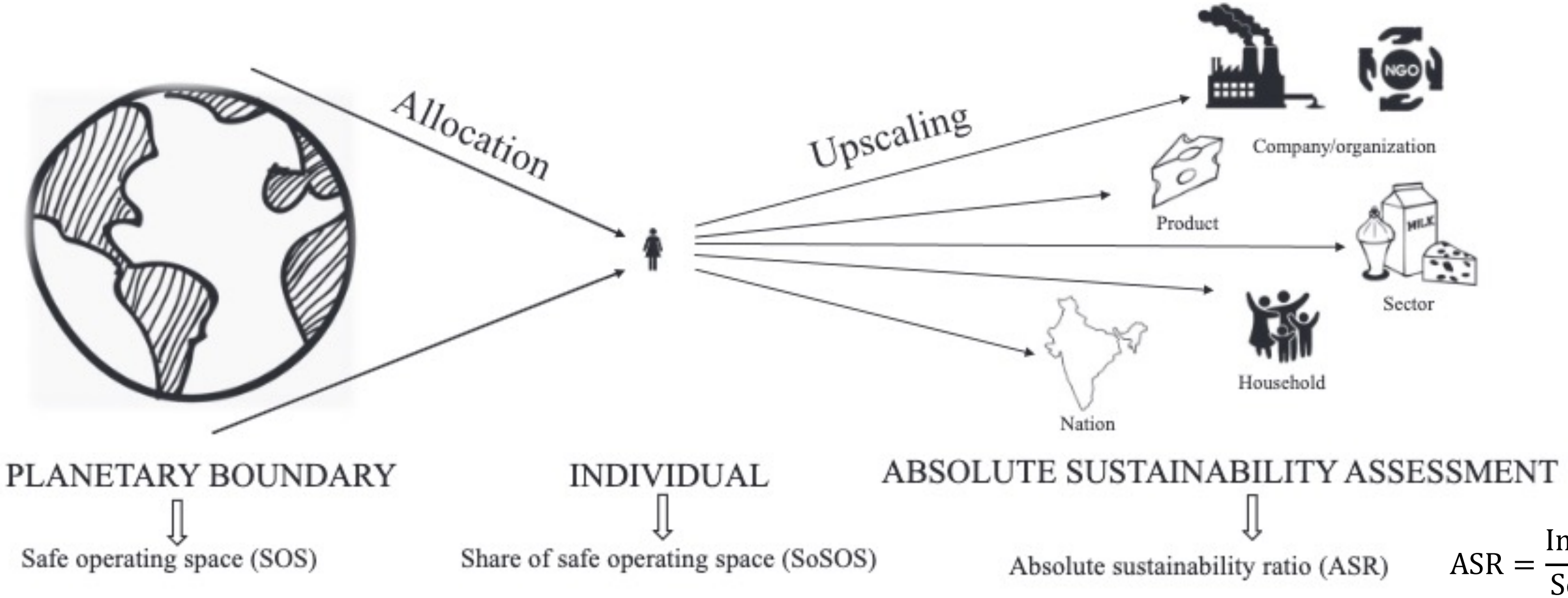
High risk

Planetary Boundaries



[1] Sala et al., 2020

Whatever the approach chosen, a **budget** must be **allocated** to the system (product, service, industry, country) that is assessed.



$$ASR = \frac{Impact_s}{SoSOS_s}$$

Equal per capita $SoSOS_{ind}(t) = \frac{SOS_{PB}}{Pop_{World}(t)}$

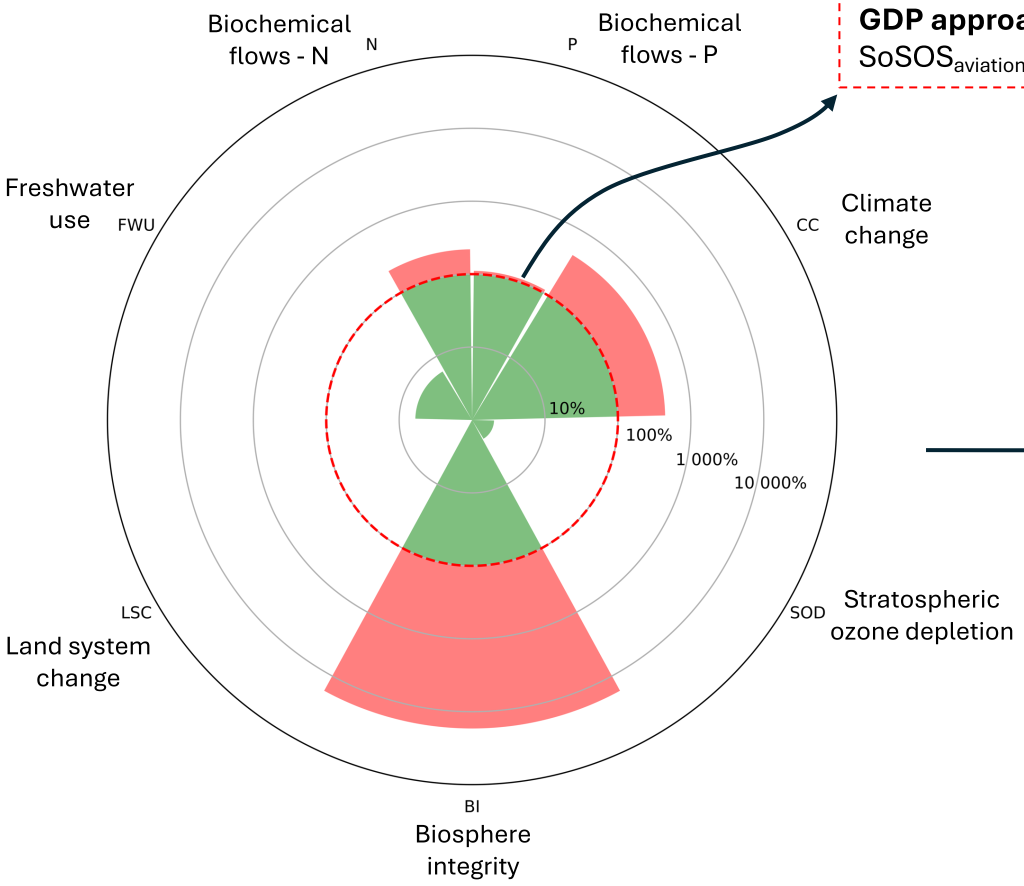
Grandfathering $SoSOS_{ind}(t) = \frac{SOS_{PB}}{Impact_{PB}(t)} \times \frac{Impact_{PB,local}(t)}{Pop_{local}(t)}$

Ability to pay $SoSOS_{ind}(t) = \frac{SOS_{PB}}{Pop_{World}(t)} \times \frac{(GDP/cap)_{World}(t)}{(GDP/cap)_{local}(t)} \cdot \alpha$

Final consumption expanditure $SoSOS_s(t) = SoSOS_{ind}(t) \cdot Pop_{local}(t) \cdot FCE_{local,k}(t)$

[1] Hjalsted et al., 2021

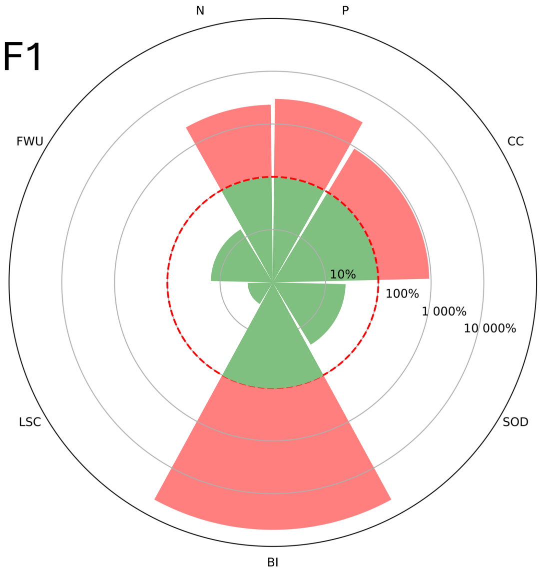
Current aviation



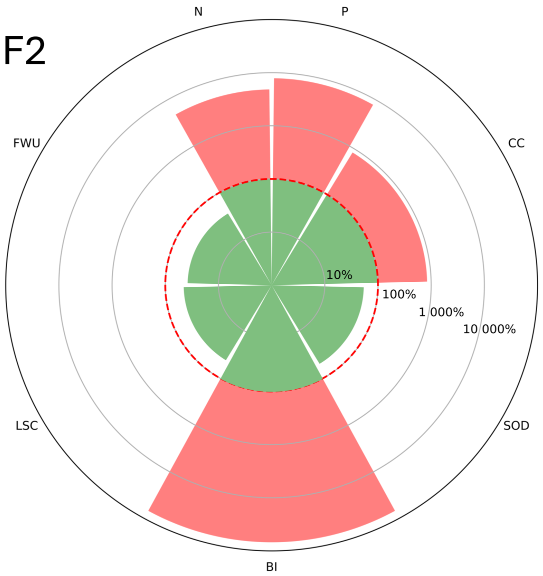
GDP approach
$SoSOS_{aviation}$ = 2.9% of PBs

2050 scenarios

ICAO-F1



ICAO-F2



Commercial air transport cannot be qualified as absolutely sutainable with a GDP-based sharing principle.

Questions?