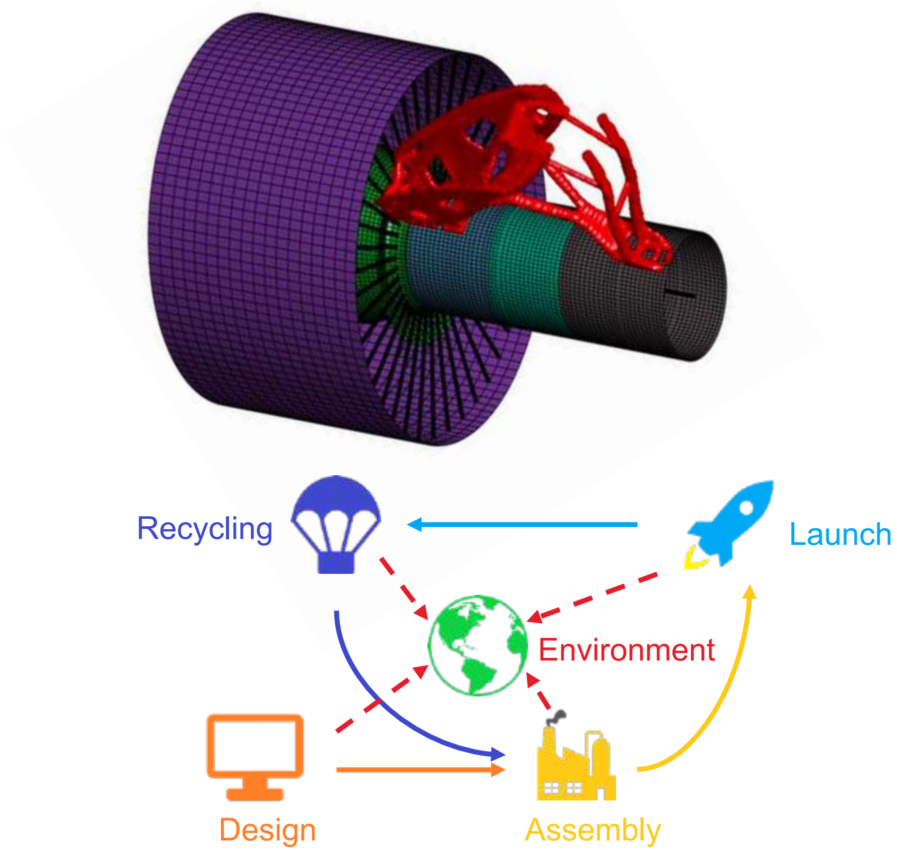
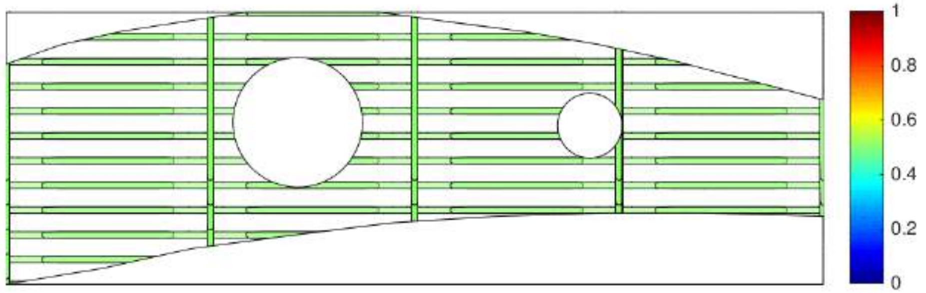
Short Course on Multidisciplinary Design Optimization

Prof. Joseph Morlier

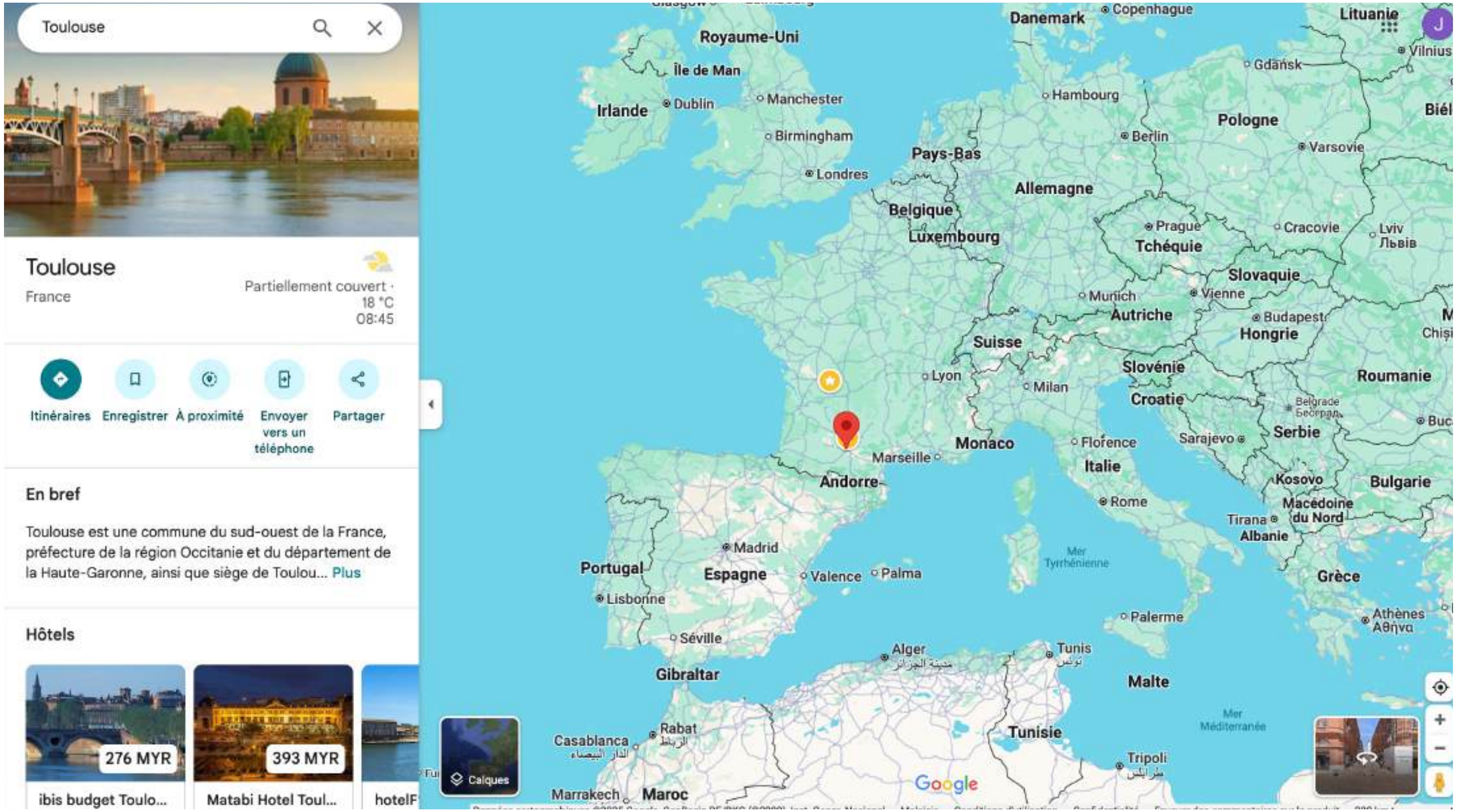
About Me?

- Prof in Structural and Multidisciplinary Optimization





My University



ISAE-SUPAERO’s Key Figures at a Glance

268
PhD students

140
Professors & Researchers

65 M€
Budget

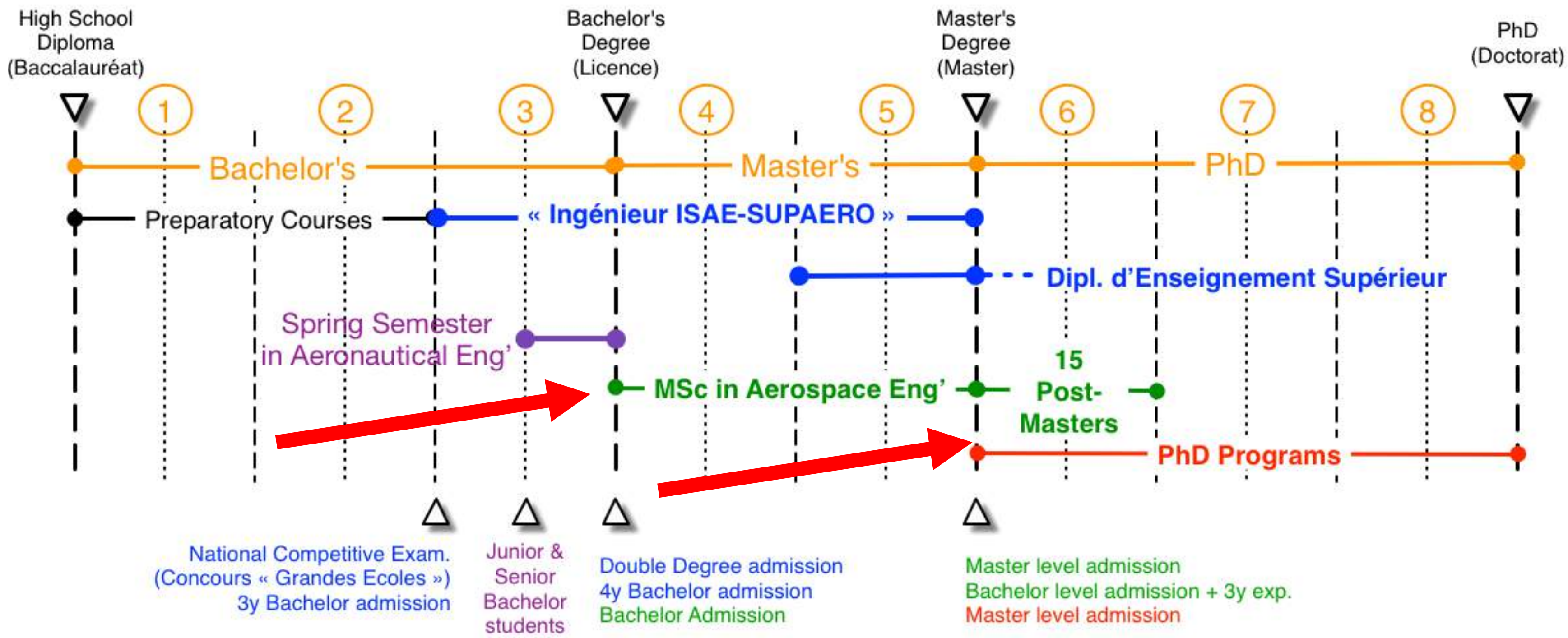
40%
Foreign Students

25000
Alumnis

1 900
Students

> 100
Academic Agreements

SUPAERO’s program



Inside the Aerospace city !

Spring Semester in Aeronautical Engineering

SSAE
SPRIN
AERO
ENGIN

Toulous
January
to May
Undergr
Application de

A worldwide reference in Aerosp
http://www.isae-supaero.fr

Since 1909, some Pioneer Engineers

A few of our Alumni

Sky is Not the Limit

2022 ESA selection

Sophie Adenot, France
SUPAERO 2004

2022 ESA astronaut reserve selection

Anthea Comellini, Italy
SUPAERO 17 PhD 2021

Arnaud Prost, France
SUPAERO 2017

1992 ESA selection

Jean-François Clervoy, France
675 hours in space
SUPAERO 1983

2009 ESA selection

Thomas Pesquet, France
SUPAERO 2001

Samantha Cristoforetti, Italy
Erasmus SUPAERO 2007

Luca Parmitano, Italy
PMP in experimental flight test engineering
SUPAERO 2009

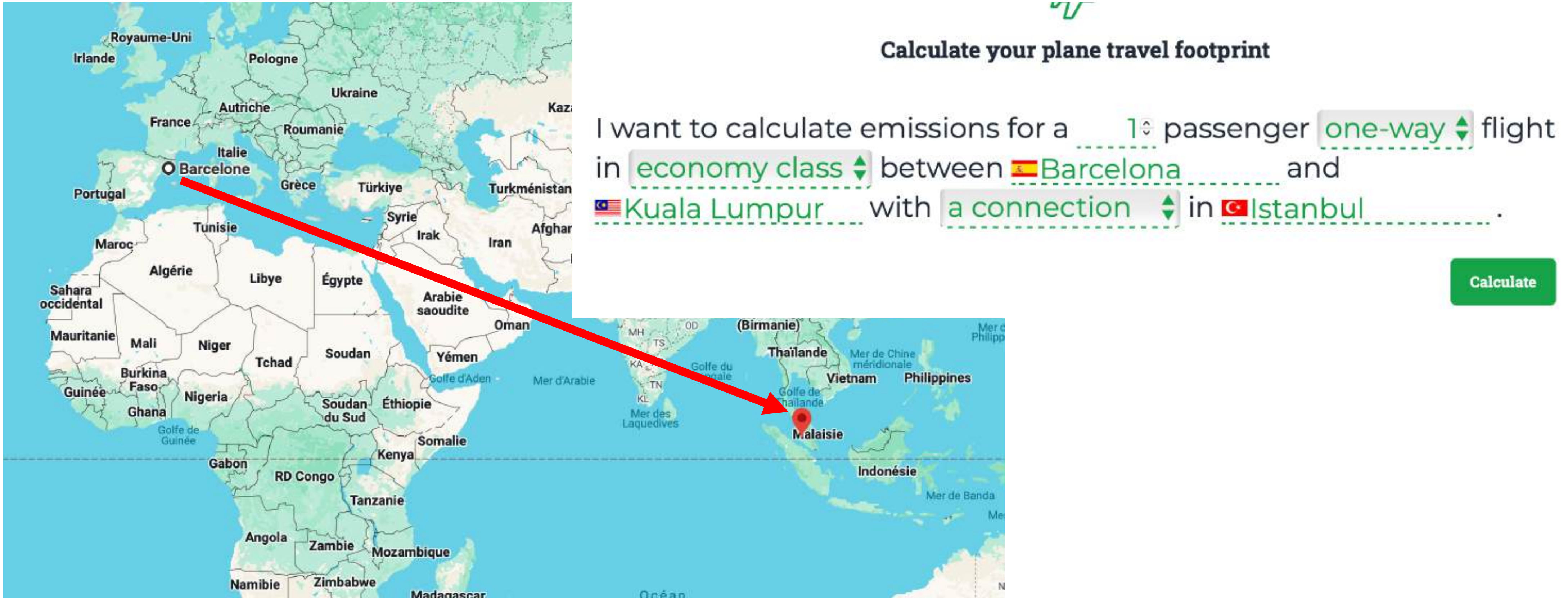
8

Research Experiences

- PhD graduated from Univ. Bordeaux in SHM of civil engineering structures in 2005
- Visiting Postdoc in Beijing (China), LIAMA : Sino French lab on Applied Mathematics (summer 2006)
- Ass. Prof in SUPAERO in 2006 SHM of composites structures
- Full Professor in Structural and Multidisciplinary Design Optimization since 2012

As a visiting Researcher:

- In University of Michigan @MDOlab (summer 2017)
- in TU Delft/polytechnique Montréal/MDOlab (Summer 2022) with **ANR Grant 2021** (French Science Foundation)



You calculated an emission of:

1.7t - 9.9 months*

*Estimation of the carbon dioxide emissions budget for one person, based on the Paris Agreement objective of maintaining global temperature warming "well below" 2°C.

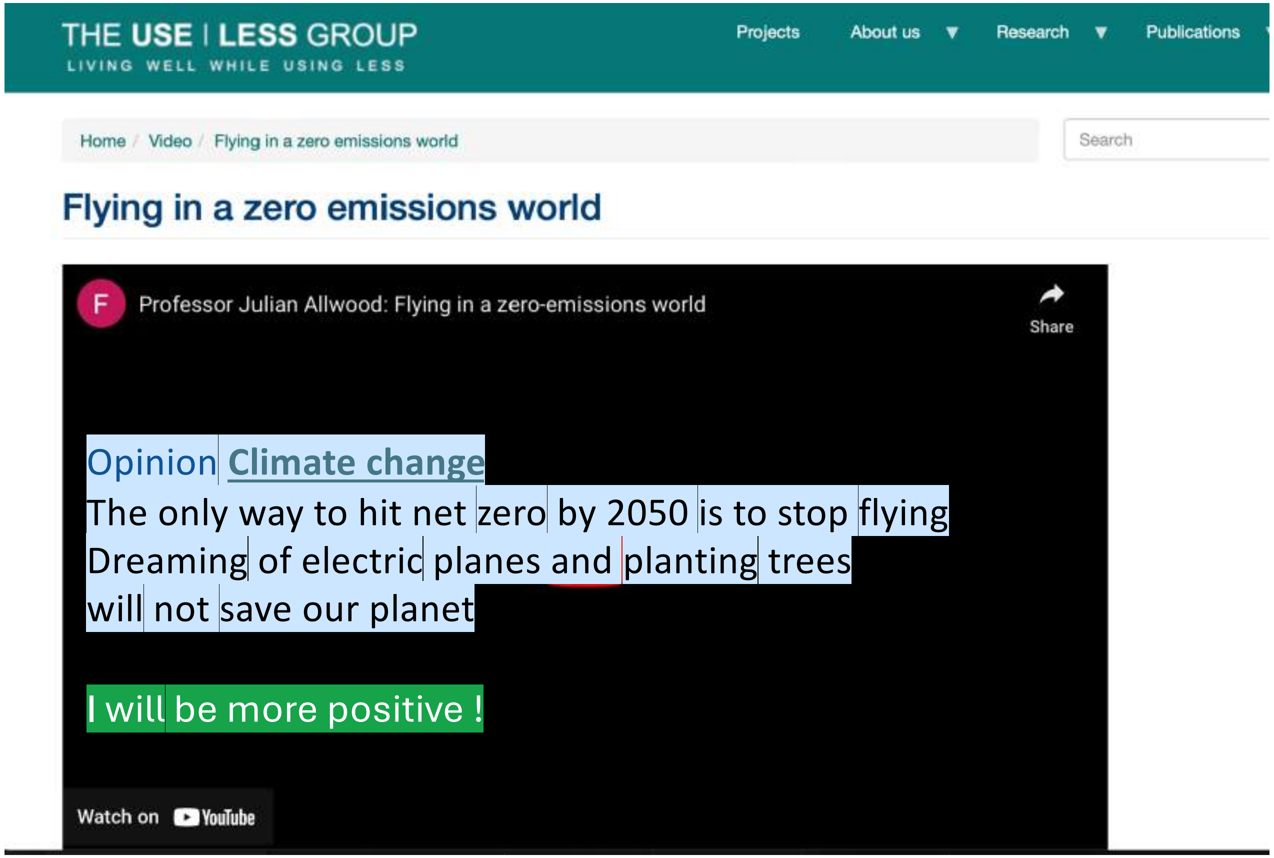
https://curb6.com/calculators/plane

Let's make a pause on my flight

My round trip Flight « costs » me 2*1.7tCO2eq

But I'm here for research and education to promote Sustainable aviation !

"The Most Intelligent Photo Ever Taken": The 1927 Solvay Council Conference, Featuring Einstein, Bohr, Curie, Heisenberg, Schrödinger & More



https://www.uselessgroup.org/publications/video/flying-zero-emissions-world

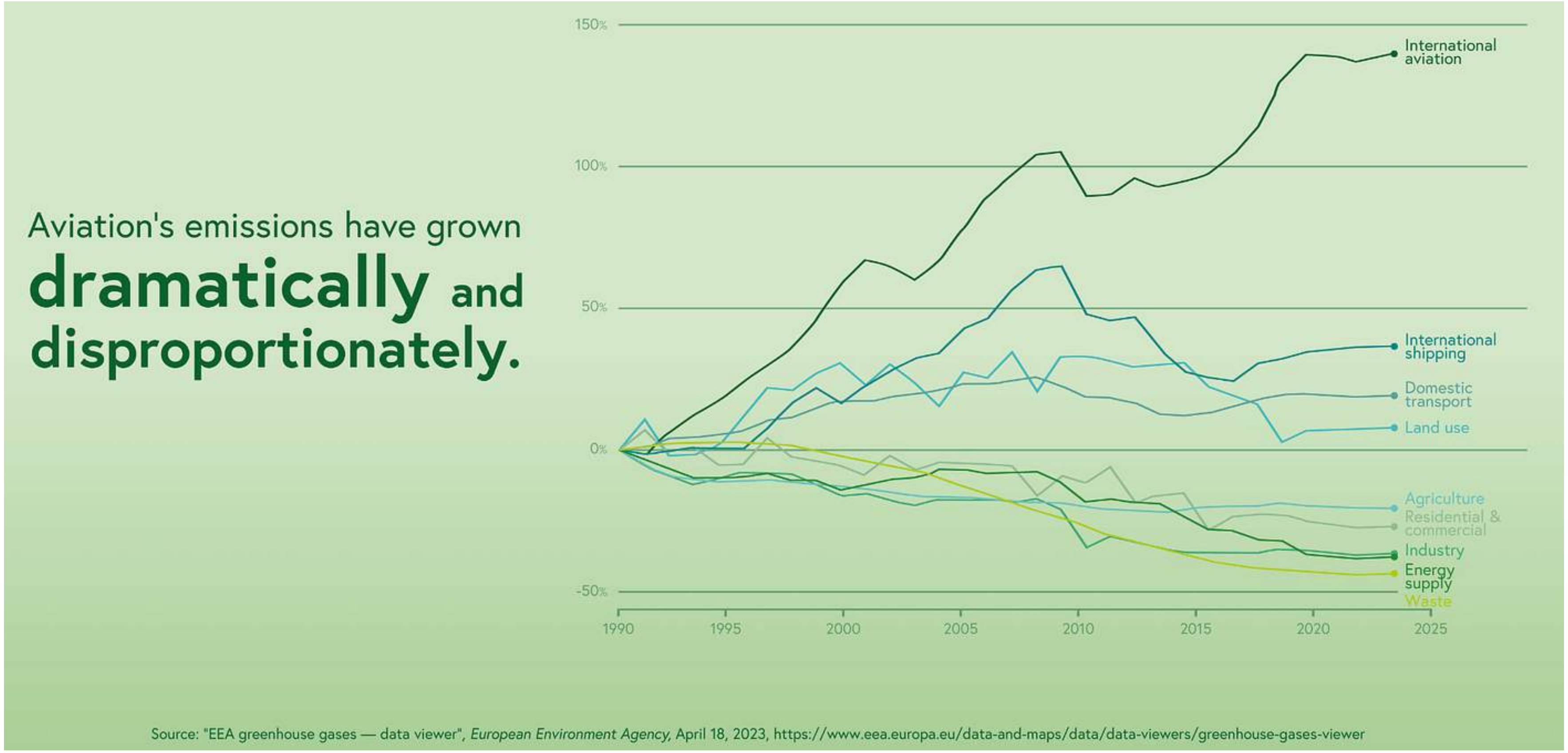
Last year

Undergraduate and Graduate Students from Bandung Institute of Technology and various ASEAN Universities.

https://itb.ac.id/berita/optimasi-desain-rahasia-meningkatkan-efisiensi-dan-keberlanjutan-pesawat-terbang/61111

Sustainable aviation?

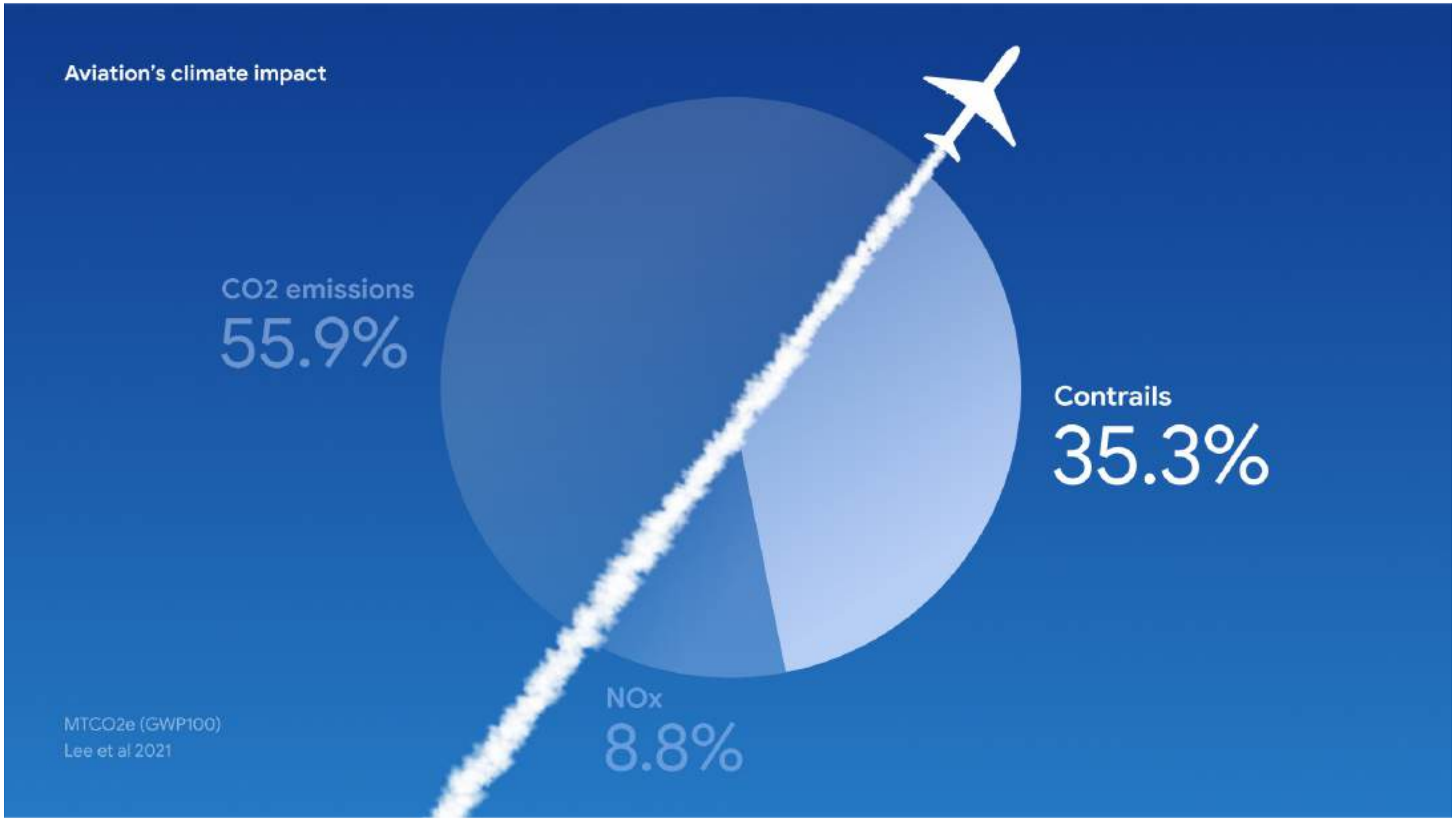
https://green.simpliflying.com/p/understanding-sustainable-aviation



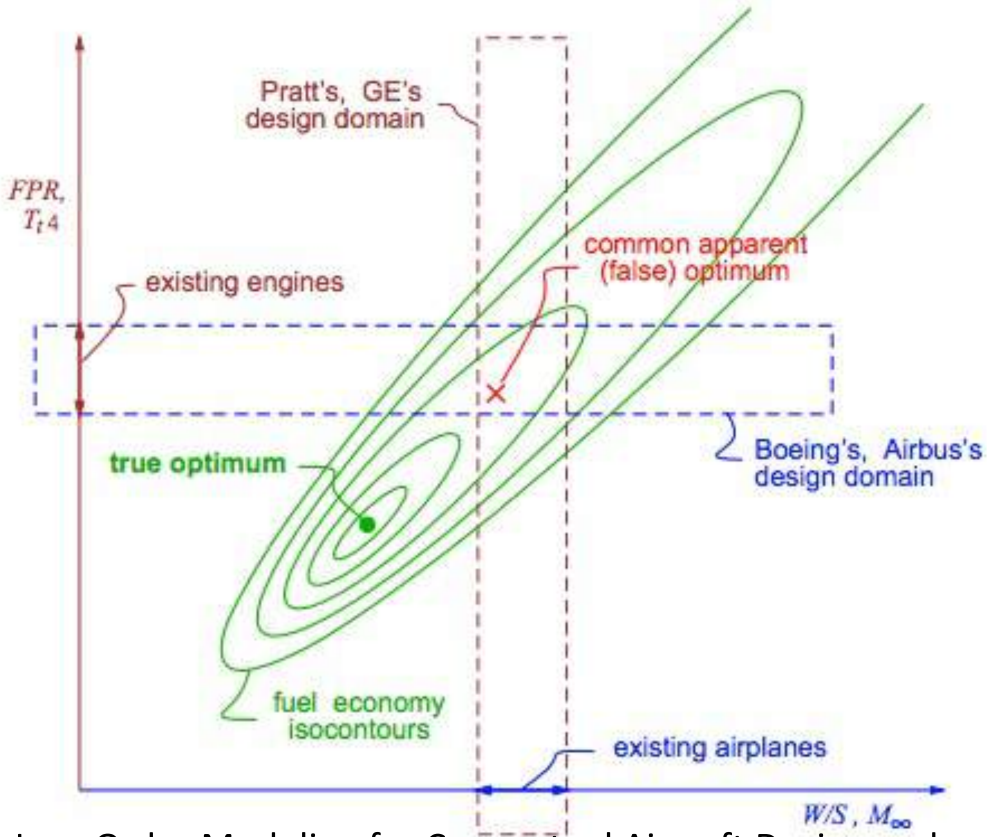
Sustainable aviation?

Sustainable aviation?

Sustainable aviation?



Sustainable Aviation (SA)



Low-Order Modeling for Conceptual Aircraft Design and Development of the D8 Transport Concept
Mark Drela MIT Aero & Astro

Sustainable aviation is a multi-disciplinary field that seeks solutions to improve the environmental and societal impacts of air transportation. It aims to reduce aviation's contribution to climate change through new practices and radical innovation

https://aero.engin.umich.edu/research/research-areas/sustainable-aviation/

Agenda for today

1. Sustainable Aviation (SA) With one eye open / With two eyes open
2. Design Optimization (DO)
3. Combining SA+DO for my research
4. Conclusions

Duration	Description	Agenda
60’	Sustainable aviation with both eyes open	Morning
30’	Design optimization	Morning
30’	Computing Derivatives	Morning
30’	Constrained Gradient-Based Optimization	Afternoon
30’	Multidisciplinary Design Optimization	Afternoon
30’	MultiObjective Optimization	Afternoon
30’	Surrogate-Based Optimization	Afternoon
30’	Research topics and conclusion	Afternoon

Agenda for today

1. Sustainable Aviation (SA) With one eye open / With two eyes open
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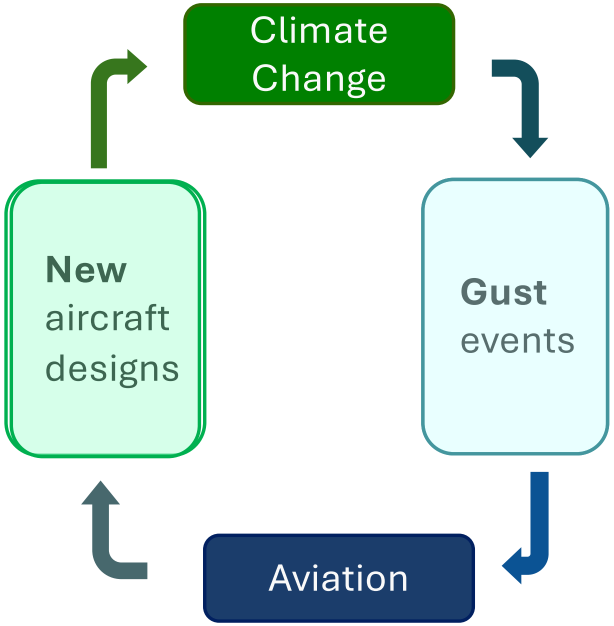
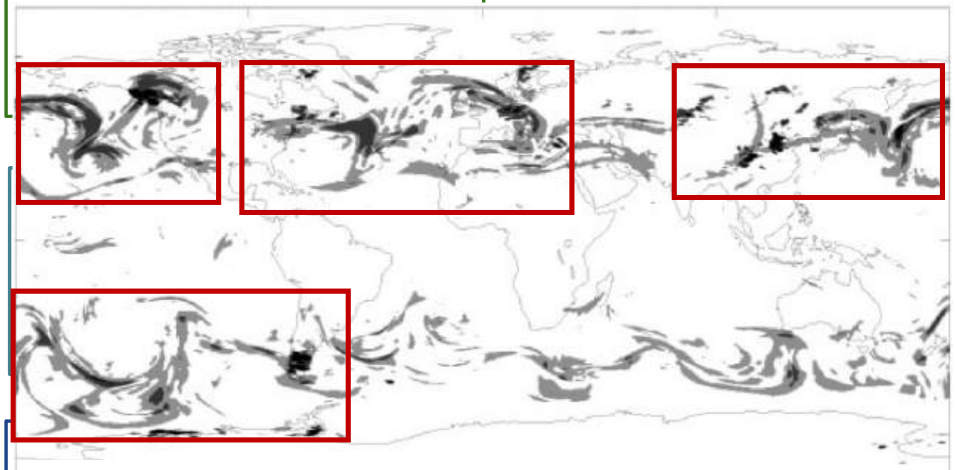
Current situation

- Fuel consumption per passenger per km is comparable to that of a modern car
- The **large distances** and **massive number of passengers** cause significant climate impact
- Aviation currently accounts for **2.5%** of the global CO_2 emission
- This percentage will rise if we do not act
- Furthermore, **non-CO_2 effects** ($NO_x \rightarrow O_3$, contrails) more than double the climate impact

But what are the effect on aviation?

Aviation currently accounts for **2.5%** of the global CO_2 emission





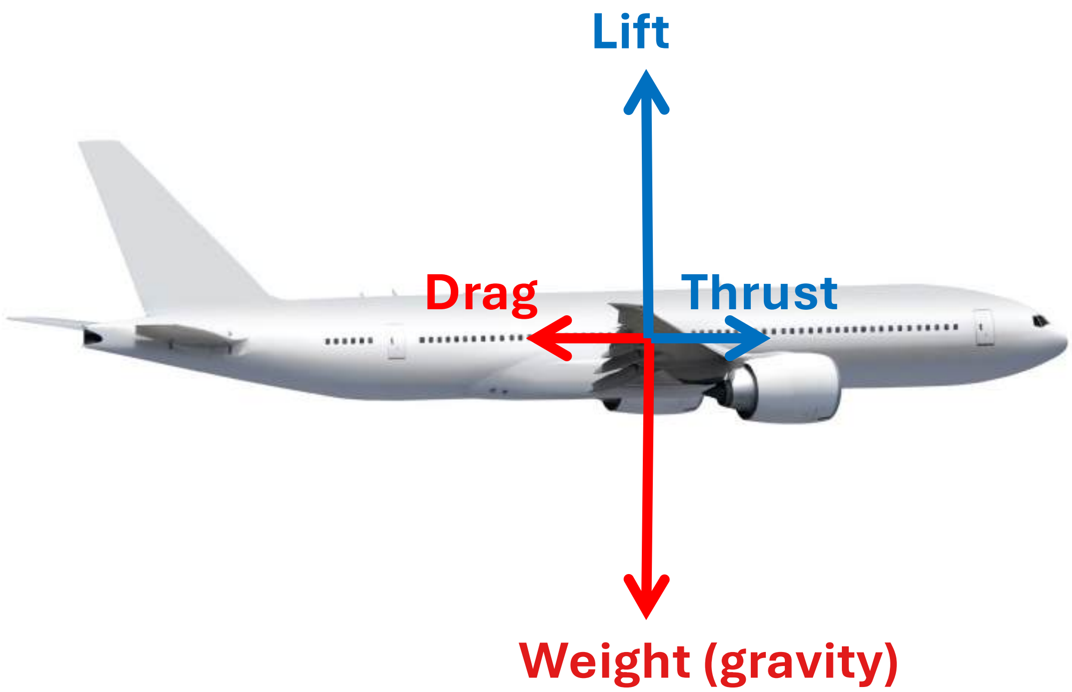
Source:
Gill, Meteorology Applications, 2014.

loads for new **high Aspect Ratio** wings.

Source: Airbus ©

Energy-efficient planes are the key

And weight is a determining factor…



Why?

$$\text{"The rate of aircraft weight reduction"} = \text{"The rate of fuel weight burned"}$$

$$\text{Range} = V t_f = V \times \underbrace{\left(\frac{L}{D}\right)}_{\text{aircraft designer}} \times \underbrace{I_{sp}}_{\text{propulsion system designer}} \times \underbrace{\ln\left(\frac{W_i}{W_f}\right)}_{\text{structural designer}} .$$

Since the endurance/range is defined by *cruise* conditions, the equilibrium steady flight conditions of T=D and L=W

We have to use a holistic approach

All knobs we may turn are interconnected

Reduce ***Emission*** by

- Replace fossil fuels
- Introduce extremely fuel-efficient aircraft (high L/D, **low mass**)
- Using energy efficient and cleaner propulsion systems
- Optimizing cruise altitude/speed (also for non-CO_2 effects!)
- Alternative/intermodality transport

An important figure: the weight !

Weights of commonly known Aircrafts:

Type	MTOW [kg]	MLW [tonnes]
Airbus A380-800	575,000	394
Boeing 747-8F	447,700	346.091

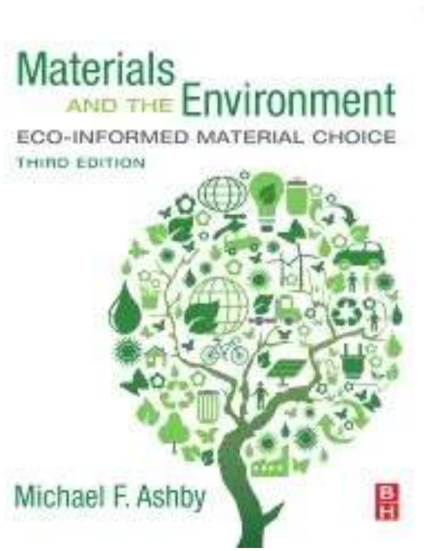
Energy is all

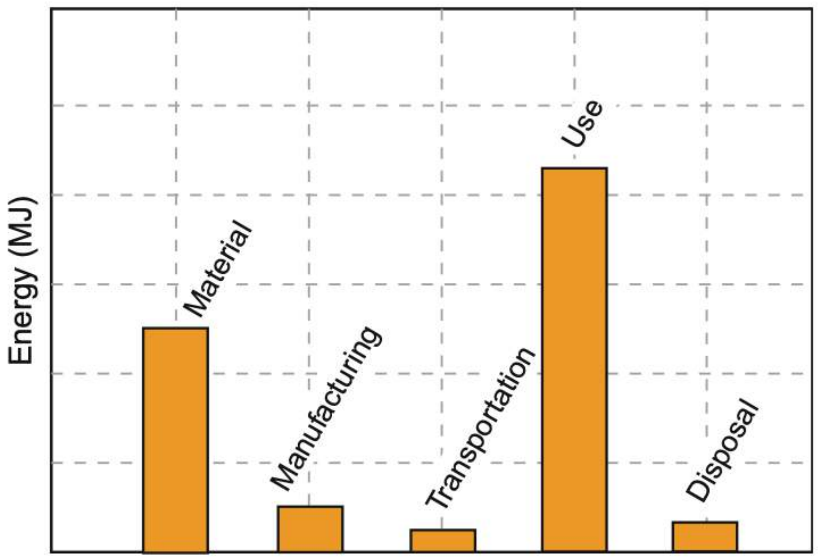
- According to Lee et al. (2021), aviation industry is responsible for only 3.5% of the anthropogenic climate changes with non-CO2 related emissions, namely contrails, presenting a similar impact to the CO2 related ones. Despite this value being smaller than other means of transportation, the energy required to transport a person in the same distance is larger.
- Thus, pressing this industry to find energy and cost efficient solutions.

Transportation Vehicles	MJ/(PAX.km)
Buses	0.15 - 0.49
Electric and Hybrid Cars	0.31 - 0.45
High Speed Trains	0.35 - 0.64
Diesel Cars	0.65 - 1.05
Petrol Cars	0.79 - 1.6
Aircraft	1.11 - 1.62

JD.S. Lee, et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018", *Atmospheric Environment*, Vol. 244, 117834, 2021, https://doi.org/10.1016/j.atmosenv.2020.117834
J.-H. Zheng, et al., "A universal mass-based index defining energy efficiency of different modes of passenger transport", *International Journal of Lightweight Materials and Manufacture*, Vol. 4, No. 4, pp. 423-433, 2021, https://doi.org/10.1016/j.ijlmm.2021.06.004

Environnemental Footprint

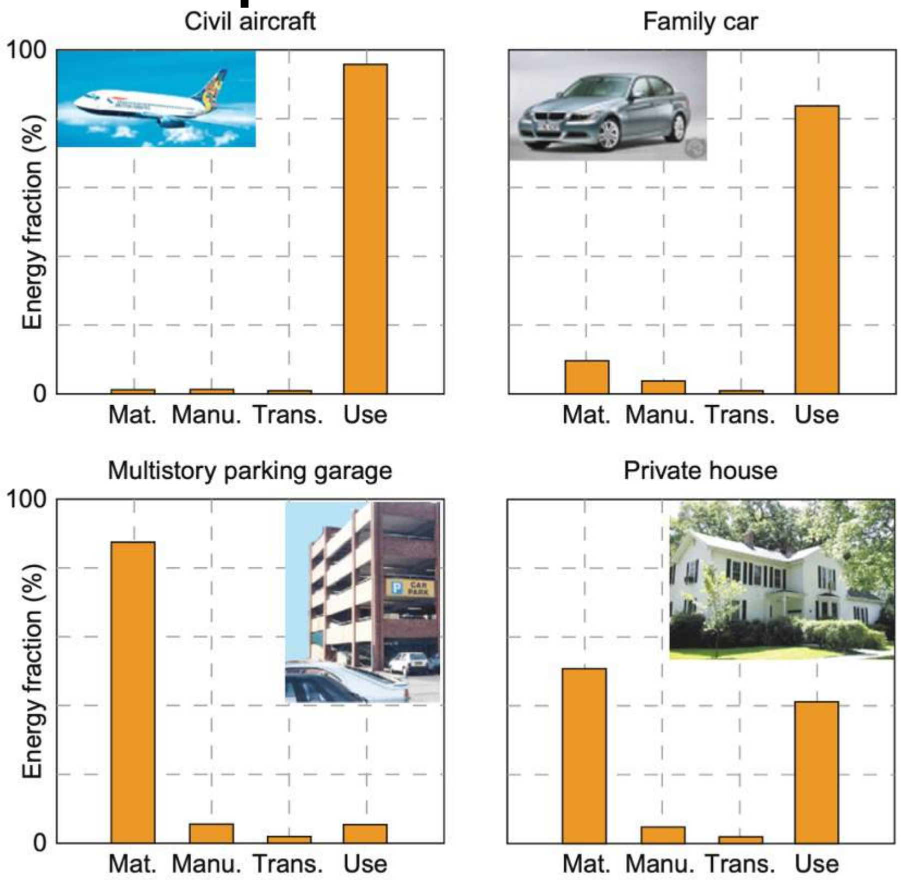




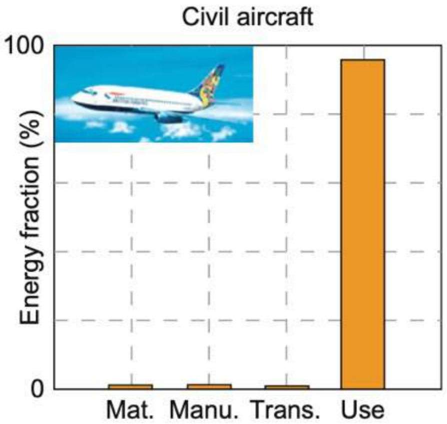
$\propto CO_2$

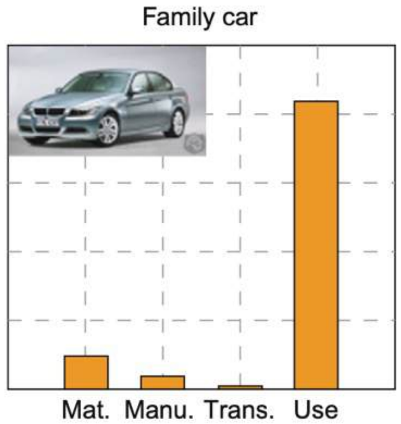
Breakdown of energy into that associated with each life phase

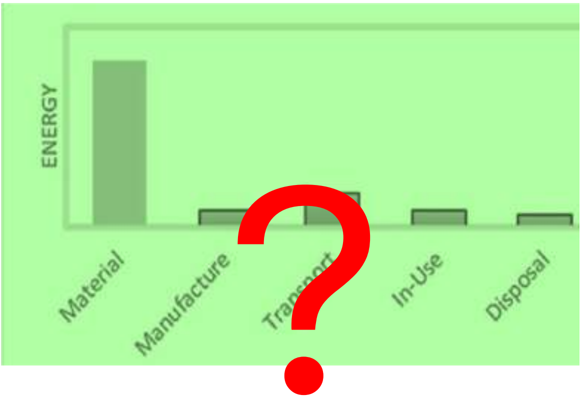
Different products ... different impacts

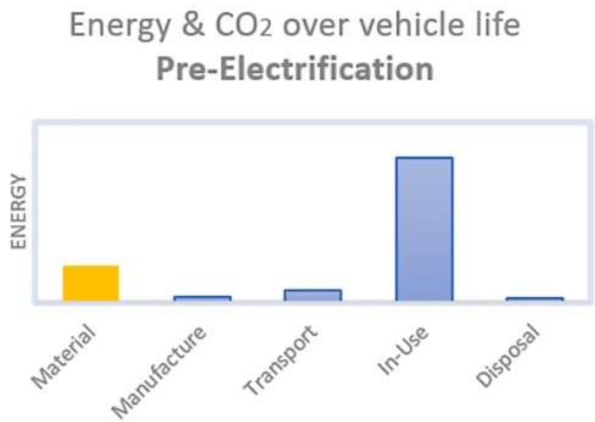


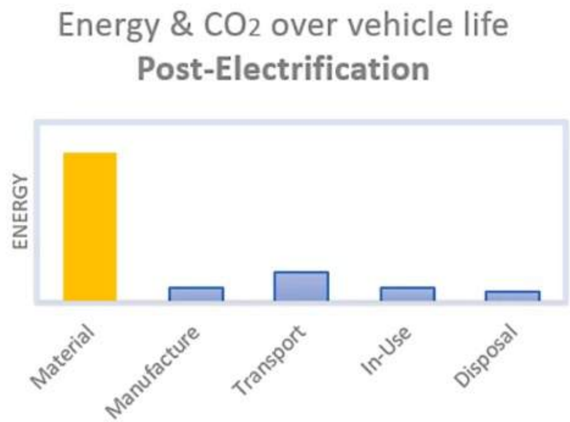
Electrification example (from automotive)







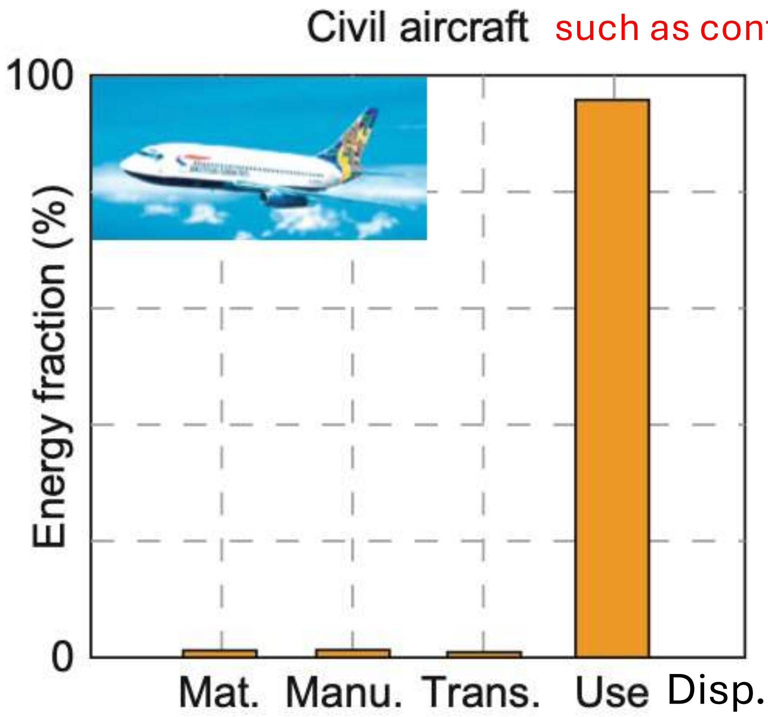




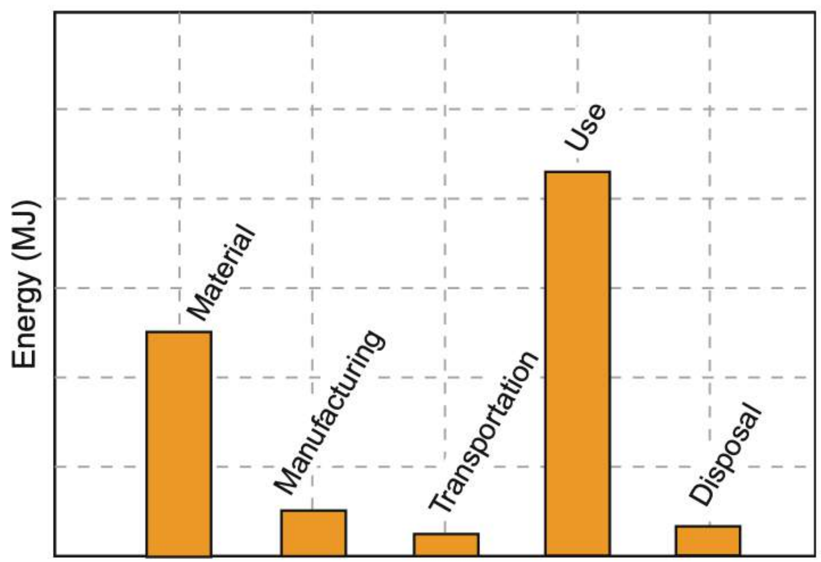
https://www.ansys.com/blog/the-impact-of-materials-on-sustainability-part-2

Energy ∝ CO_2 footprint

Fuel burn
+ non CO_2
such as contrails



Future Sustainable Air vehicule

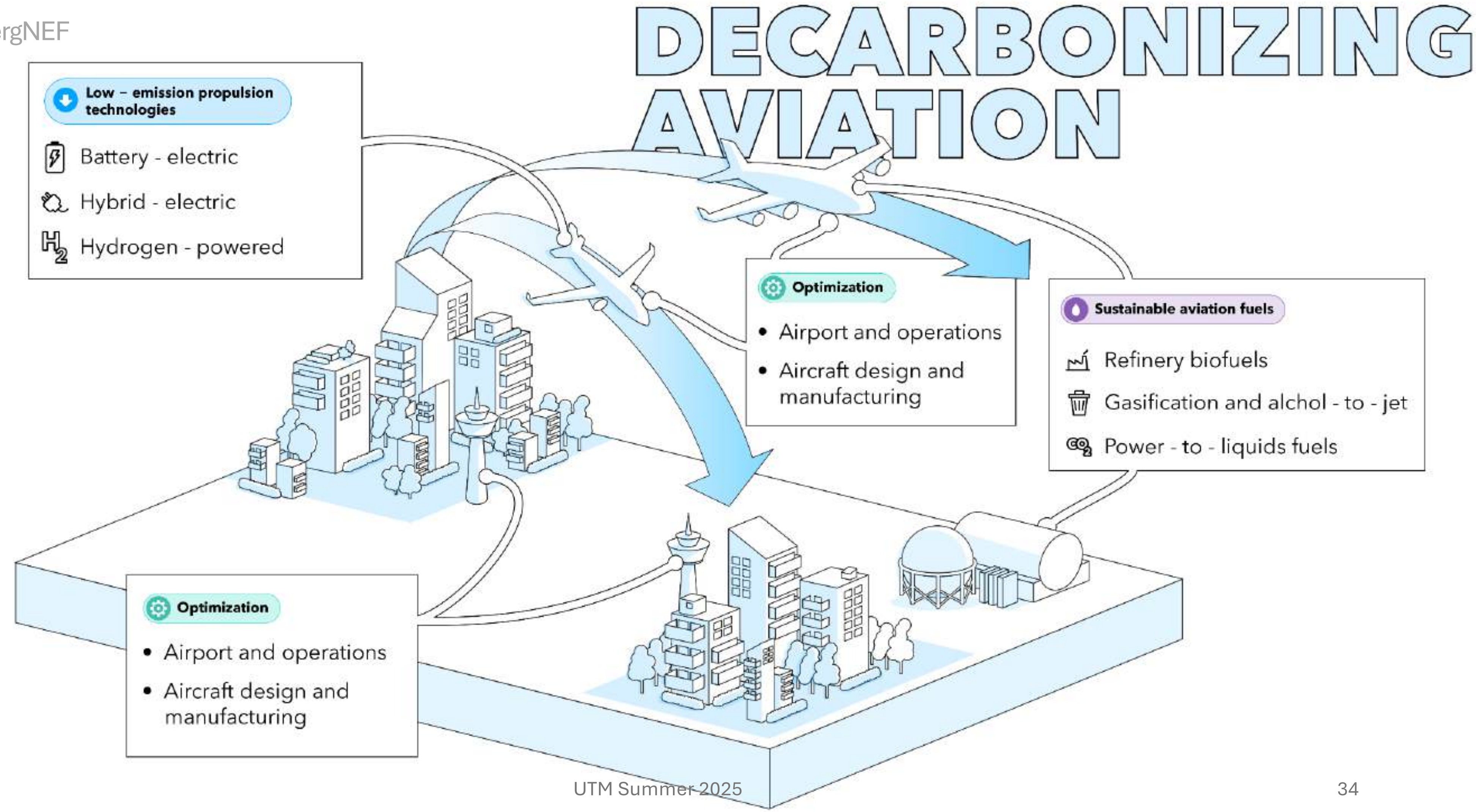


Breakdown of energy into that associated with each life phase

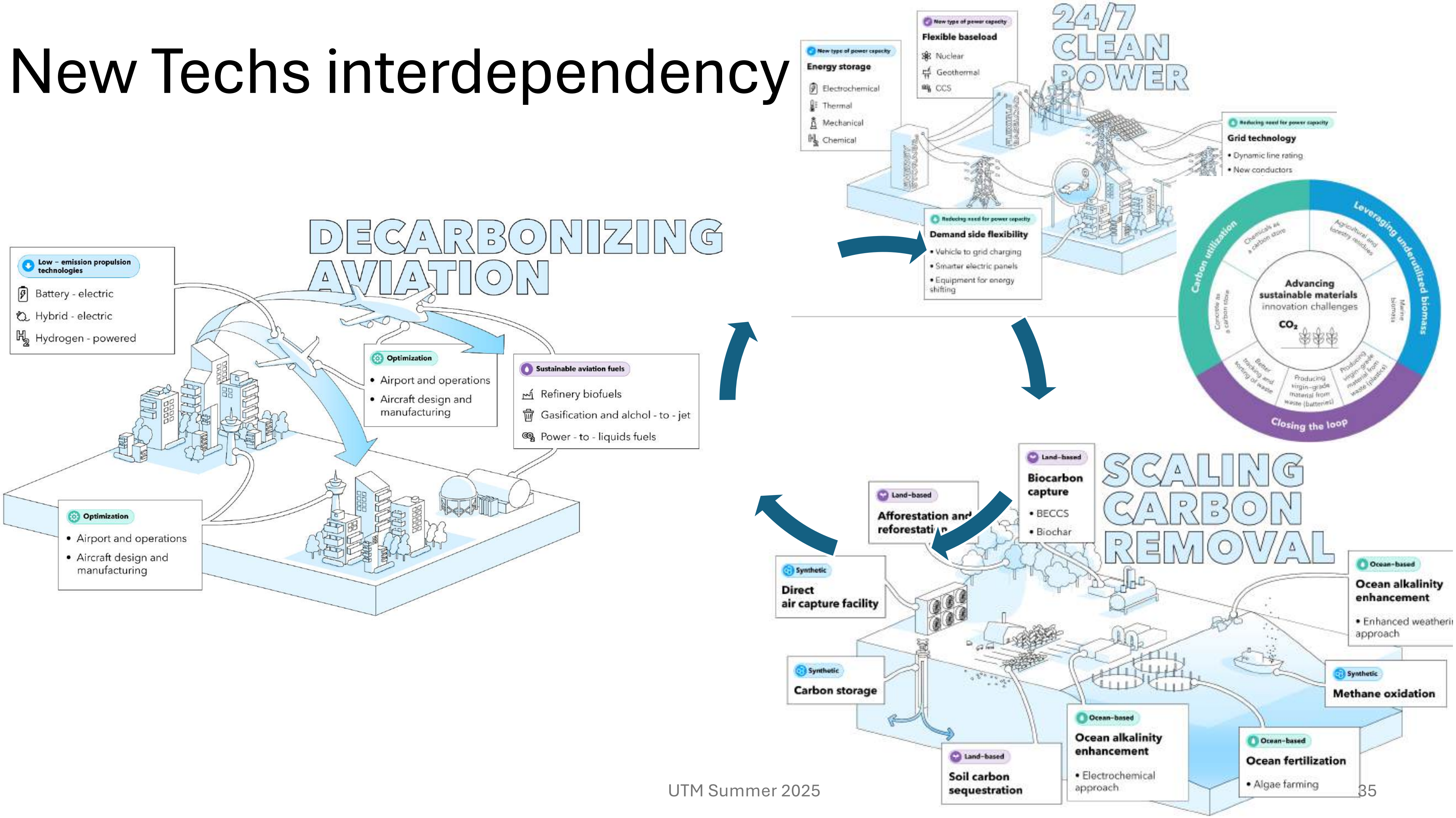
Hydrogen, SAF, Electric/Hybrid Propulsion…

Overview

from BloombergNEF



New Techs interdependency

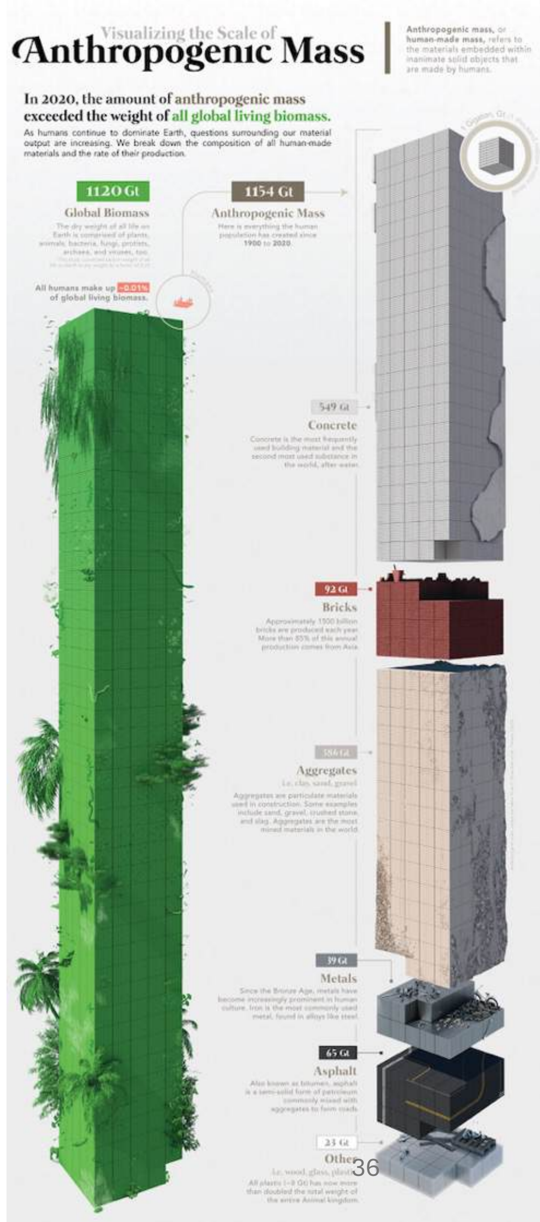


An important figure

Massive Demand in Energy and Materials

In 2020, the amount of anthropogenic mass exceeded for the first time the dry weight of all life on Earth

Over the past century Anthropogenic mass has increased rapidly, doubling approximately every 20 years. The collective mass of these materials has gone from 3% of the world's biomass in 1900 to being on par with it today [1]

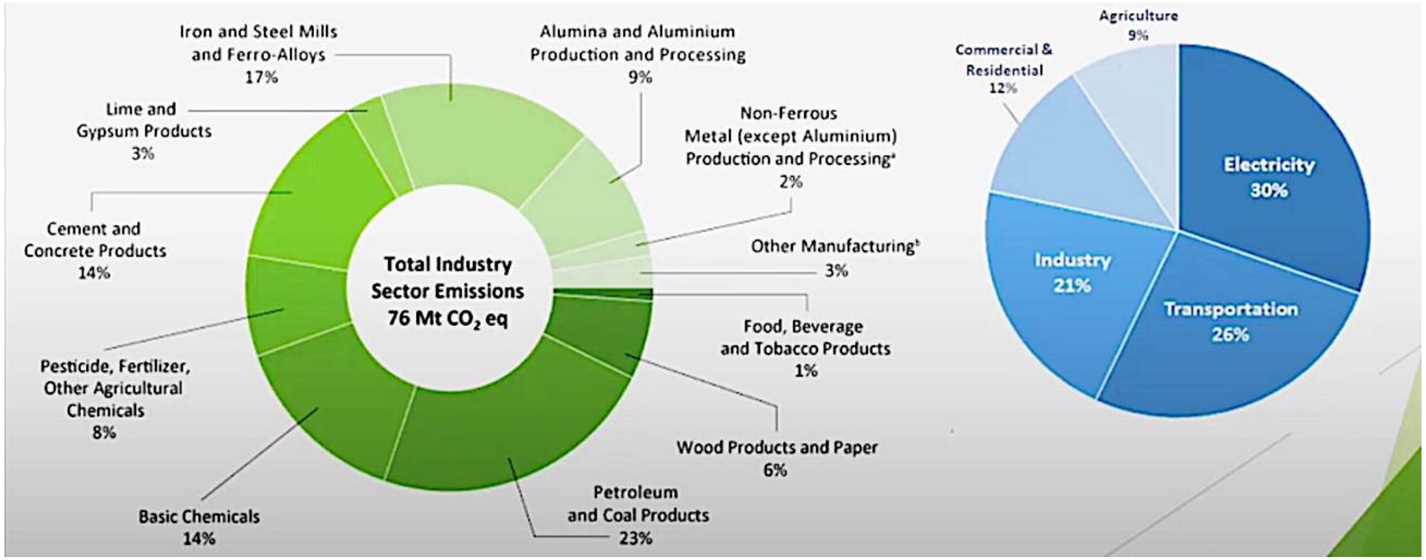


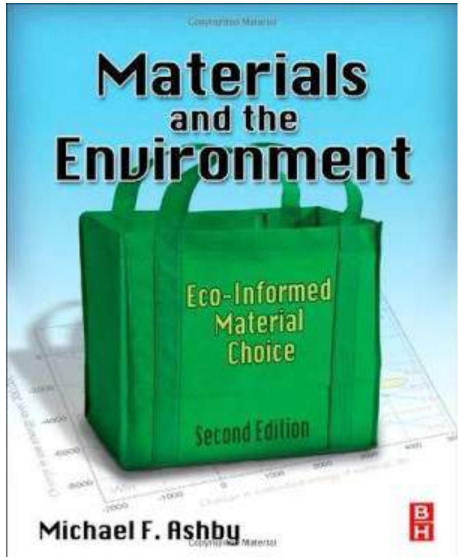
Materials and Energy ressources are linked and limited…

#Structural materials used in a massive way → huge environmental impact

#The essential technologies for the transition, in particular green energy, will translate into considerable demand for metals that have become strategic.

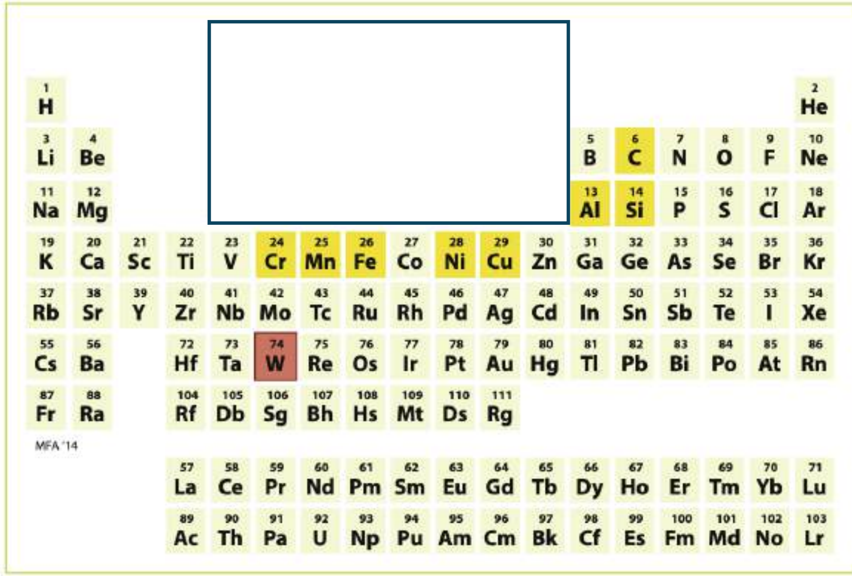
#In anticipation of 2050, the total tonnage of concrete, steel, aluminum etc… necessary for the development of these energies will be 2 to 8 times the world production of 2010. !!!

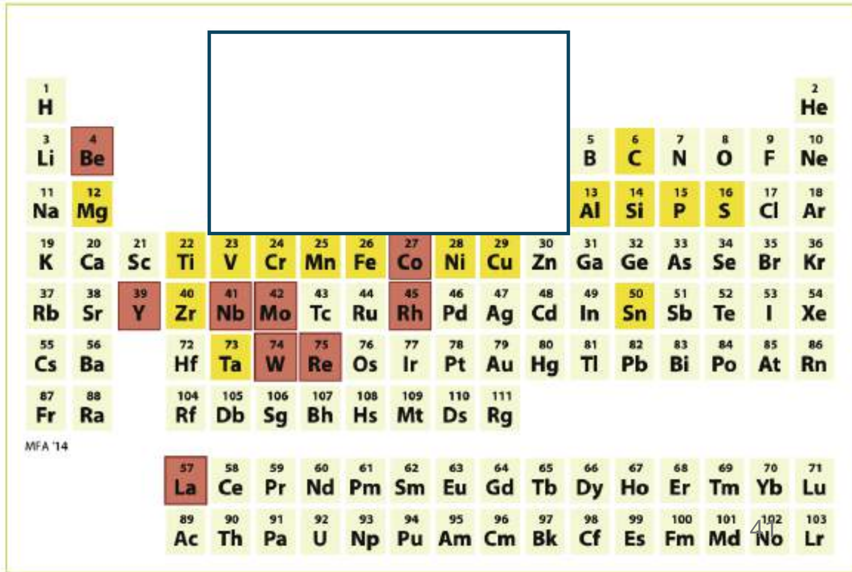




Quiz

- One system is older than the other !
- The elements in an early aircraft engine and a gas turbine of today mapped onto the periodic table.

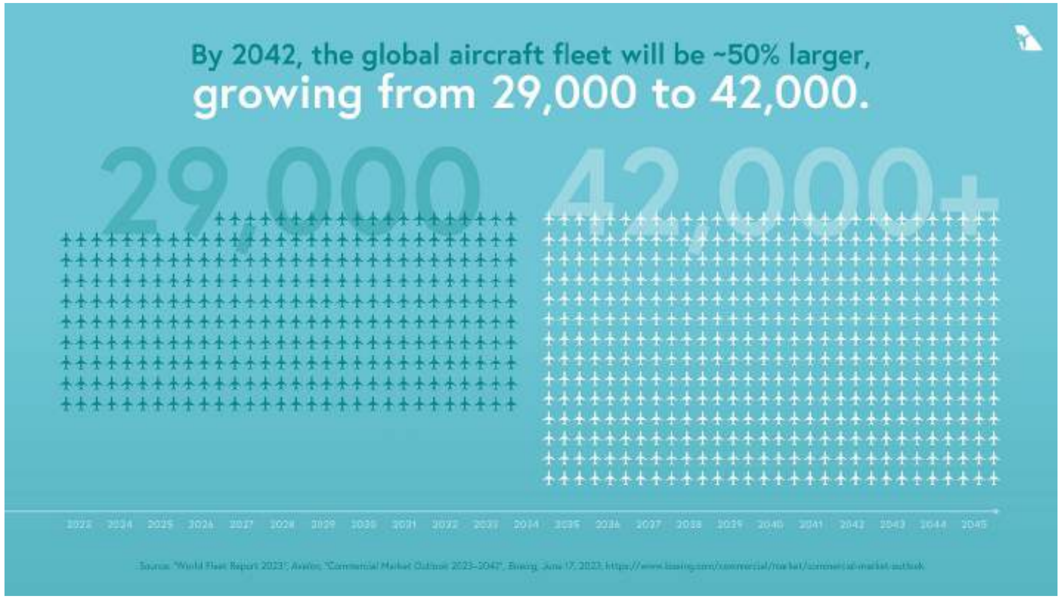


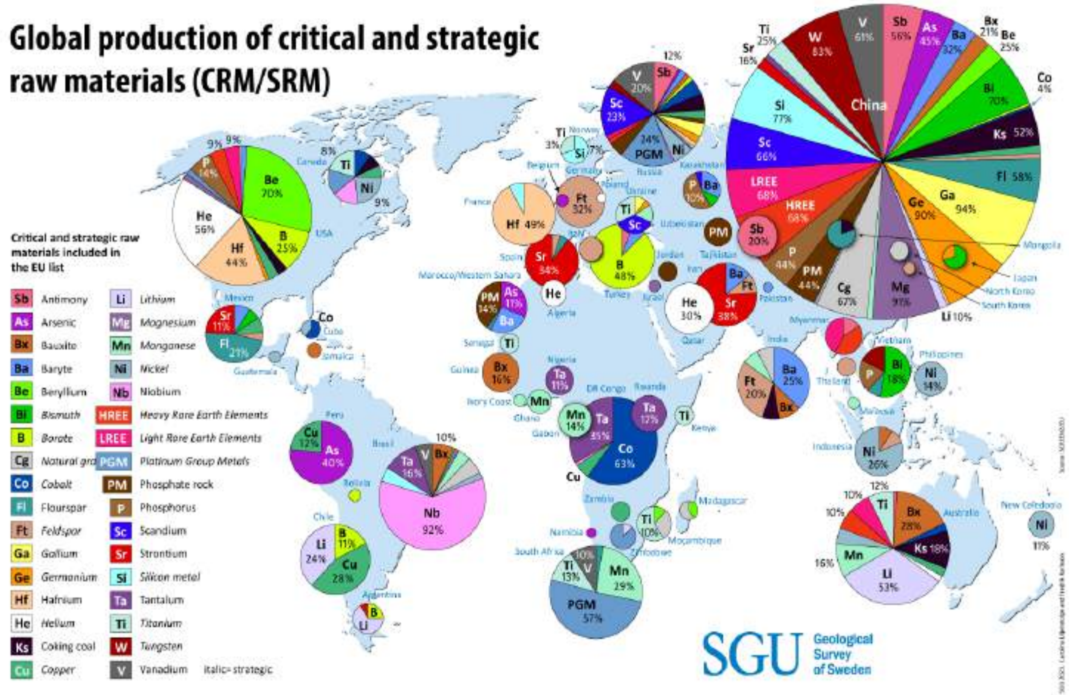


Critical materials are colored red,
other materials used in the product are in darker yellow.

Sustainable aviation?

Critical materials + geostrategic problem→ cost of materials will increase… delay …





Quiz

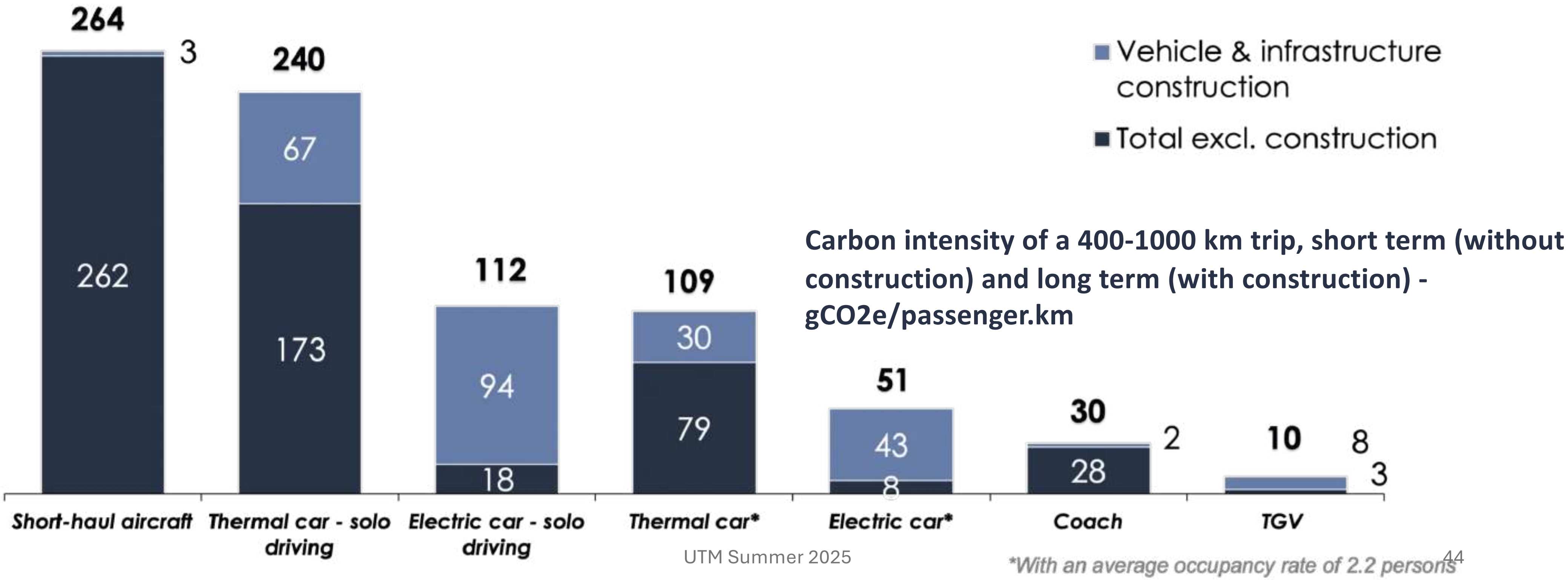
Sustainable Development Goals (SDGs)

- What are these coloured boxes ?

ReNew the way we travel from A to B

https://www.carbone4.com/en/analysis-faq-aviation-climate

Is it better to travel by plane or by car, even alone?



ReNew the way we travel from A to B

Is air transport for the elite only?

Here are some figures to illustrate:

- less than 1% of the world's population is responsible for more than 50% of commercial aviation emissions.
- 80% of the world's population has never flown

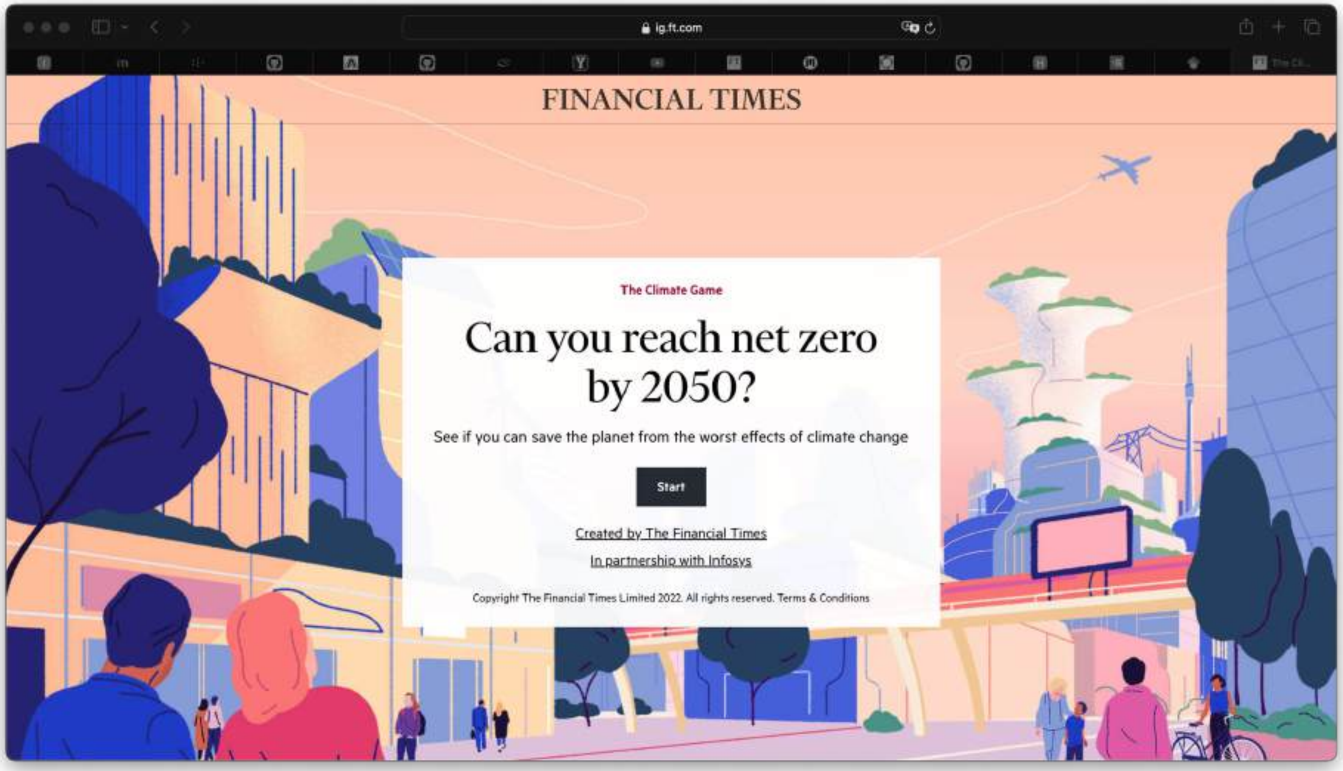
Low cost air company (easyjet, ryanair) ?

They do not permit to decarbonize the industry as they are cheaper than train

ReNew the way we travel from A to B

UAM R&D
https://www.aurora.aero/2022/08/08/aurora-supports-university-of-california-san-diego-on-vehicle-design-for-urban-air-mobility/

https://ig.ft.com/climate-game/



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Take Away informations

https://www.carbone4.com/en/analysis-faq-aviation-climate

Aviation greanER (not green)

It raises the question of the future of some hubs, such as Dubaï, fourth global airport in frequentation in 2019…

- Should aviation fear the physical effects of climate change?

Other climate hazards can also disrupt air traffic from running smoothly. The heat wave that **stuck 50 planes** to the ground in Phoenix (Arizona, USA) in 2017 was an illustration of the vulnerability of aviation to heat. No taking off on too short runways or with some types of regional aircrafts (hot air is less dense, reducing lift), and accelerated wearing of the tarmac with time.

Aviation greanER (not green)

Airbus recently announced its plan to develop a H2-powered single-aisle aircraft …
in 2035 range of1,500 km, i.e. a regional range,
… **6% of aviation emissions today.**

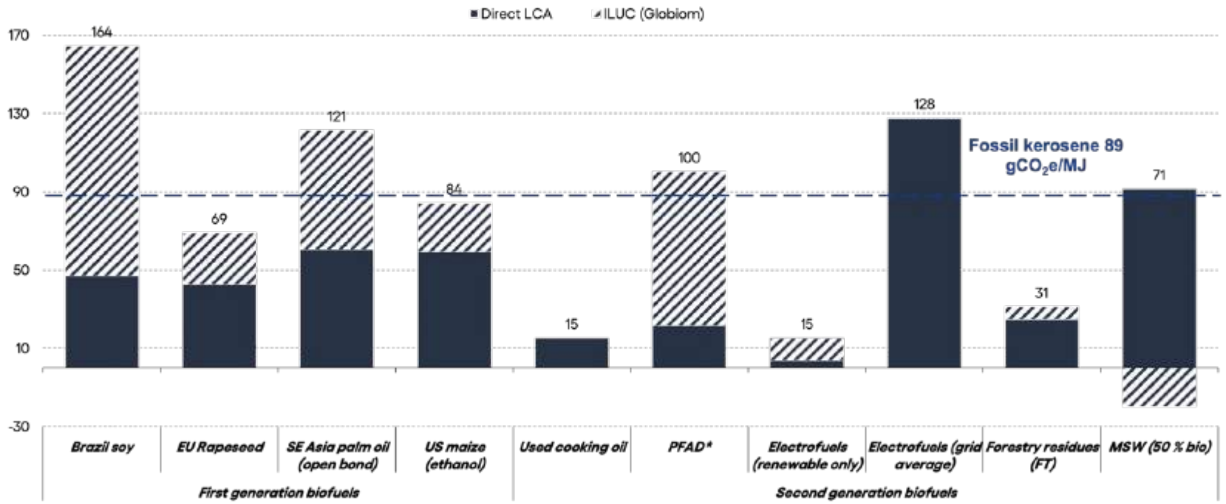
- Will hydrogen or electric aircrafts decarbonize aviation by 2050?

In the case of hydrogen, this could **reduce the carbon footprint by up to -65% (non-CO2 effects included).** Hydrogen has a better energy density per unit of mass, but not at all per unit of volume: even in its liquid form (**which requires cooling to -253°C!)**, it takes three times more space than kerosene, and also has greater safety constraints than the latter. Hydrogen therefore suffers from some of its physical characteristics, which also requires modifying the entire airport ecosystem and infrastructure (hydrogen production, storage, aircraft refueling, etc.).

Aviation greanER (not green)

- Sustainable Aviation Fuels (known as "SAF") ?

Regarding GHGs, new fuels can reduce CO2 emissions, combustion is counted at 0 thanks to CO2 storage upstream (plant growth, use of captured CO2), and adding transport emissions, **a reduction of up to -70/80% is obtained for bio-kerosene**.
→do not have an impact on NOX or water, because it is the same type of combustion
→contrails, are reduced.
Thus, the reduction in **non-CO2 effects would only be about 12%,** which translates into an overall reduction of up to 50% in climate impact.
Biofuels are currently 2 to 5 times more expensive than fossil kerosene



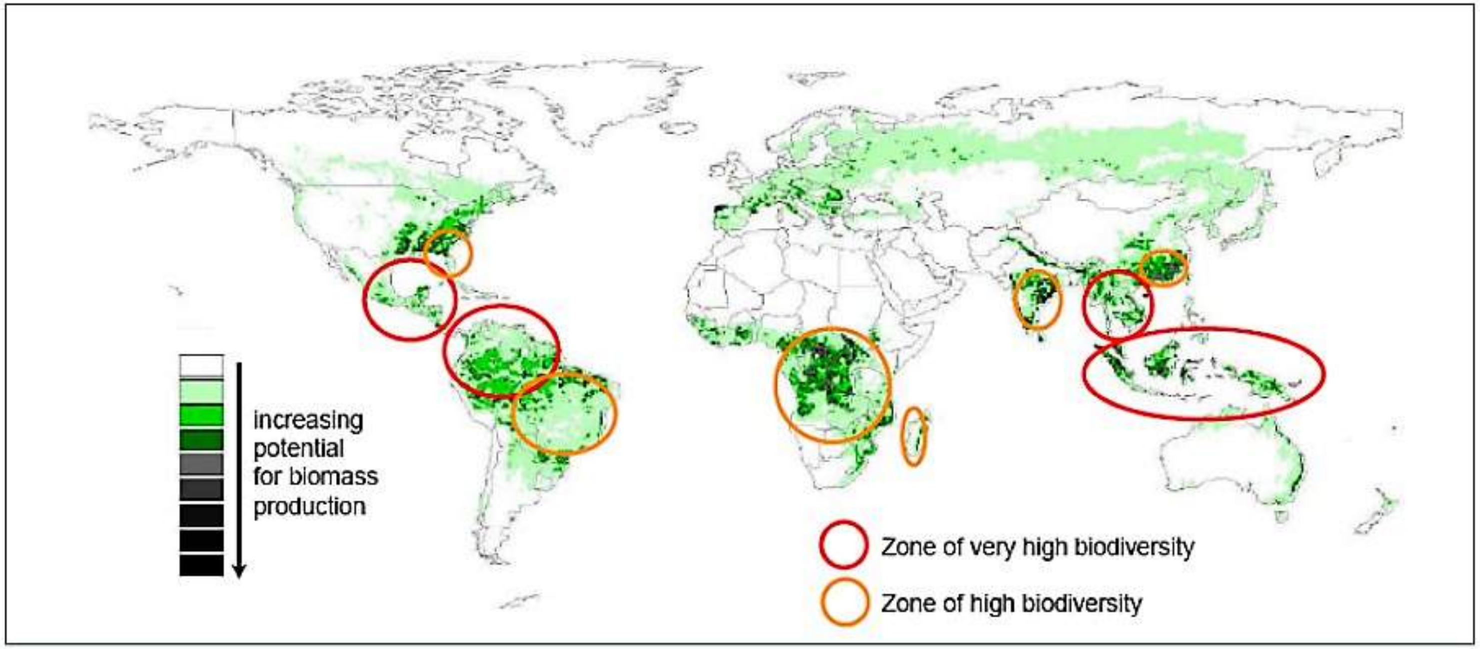
*Palm fatty acid distillate

Example of improvement

https://mluyat.github.io/MorlierOpenSky/

The massive production of intensively cultivated biofuels has environmental consequences (weaken the soil, threaten biodiversity, alter the water cycle etc...) and social risks.

You can buy SAF with your ticket... SAF are storable: a liter of SAF produced in May in Spain can be used in September in France



Source: IIASA, Kraxner 2007, Rokiyanskiy et al. 2006
Data from UNEP IMAPS

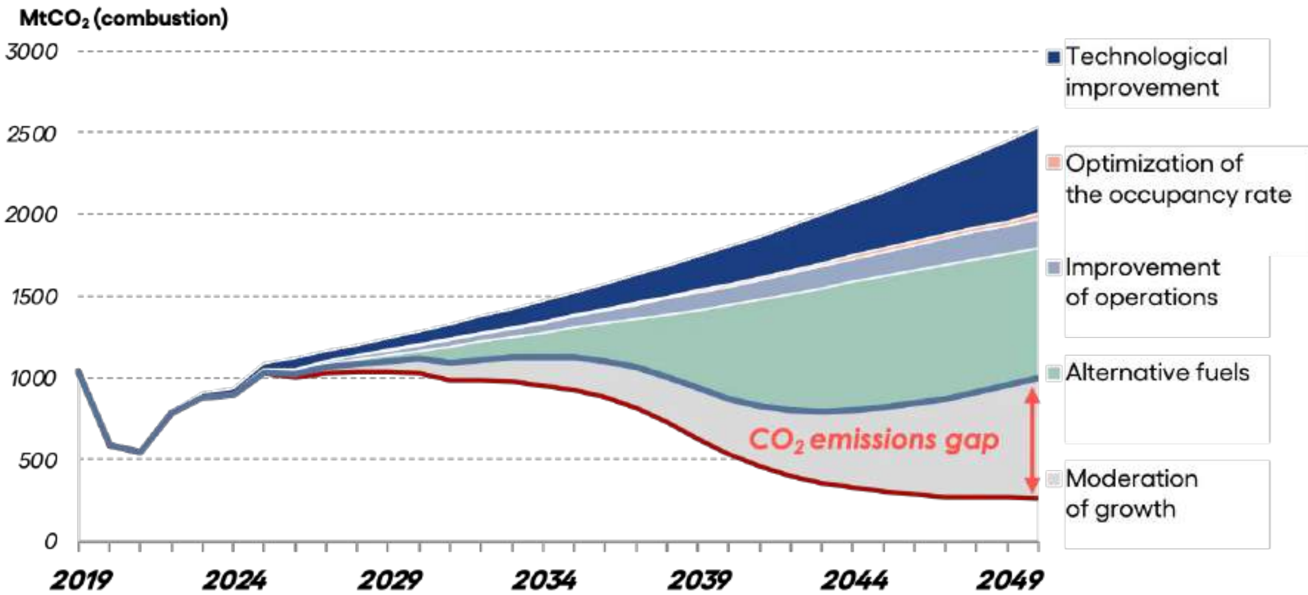
Aviation greanER (not green)

What if we limit traffic, instead the 3% increase per year?

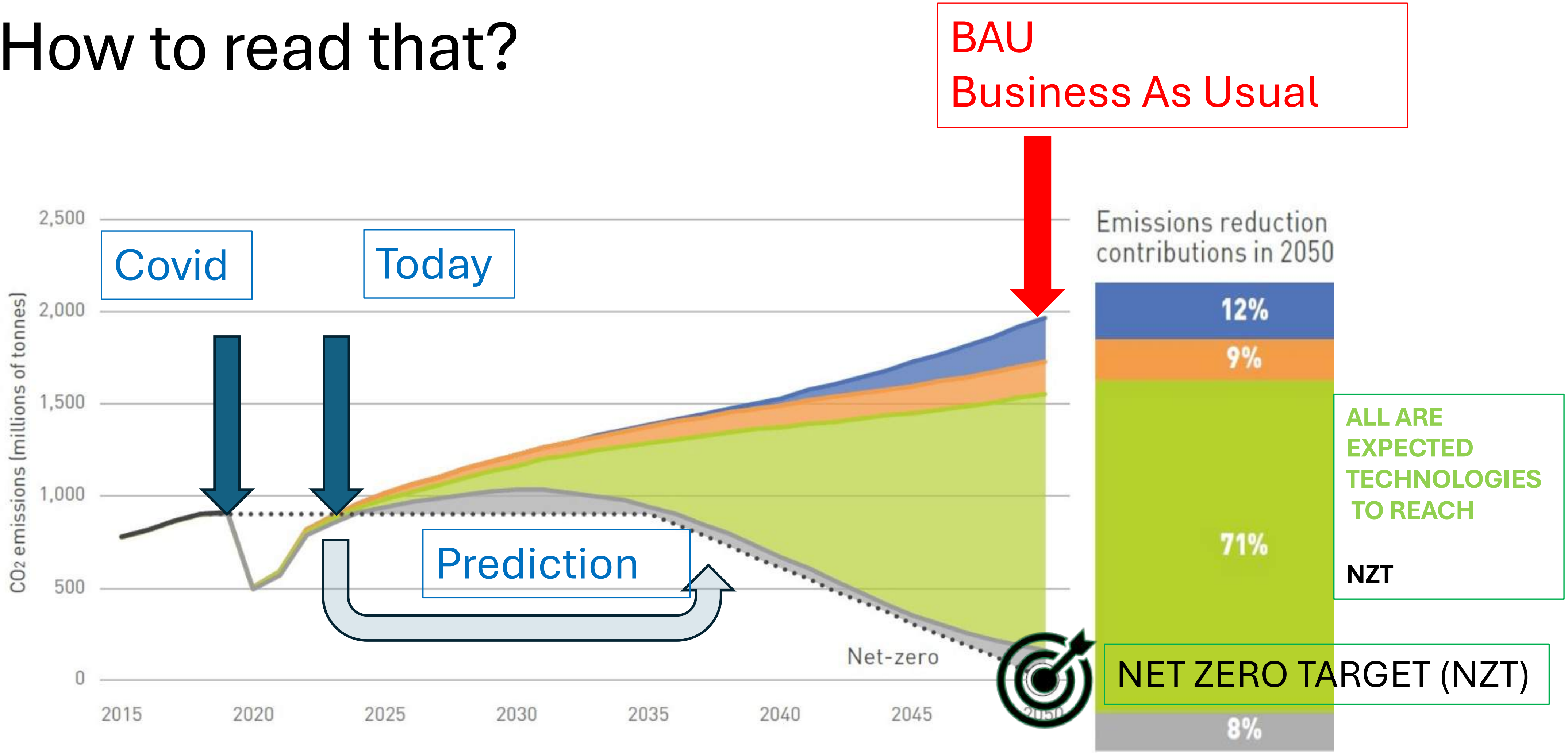
- Can aviation meet its climate targets without reducing growth?

In order to keep global warming below +2°C, the aviation sector has set a target of zero net emissions (with ~135 $MtCO_2$ of residual emissions, i.e. a reduction of 85%, according to ATAG). This challenge will be all the more ambitious given that it anticipates a growth in passenger traffic ranging from 3.1% to 3.6% per year, i.e. a **multiplication by at least 2.5 by 2050**.

Evolution of CO_2 emissions (combustion and upstream) of global air transport (excluding regional traffic), respecting a 2°C budget defined by ISAE Supaéro

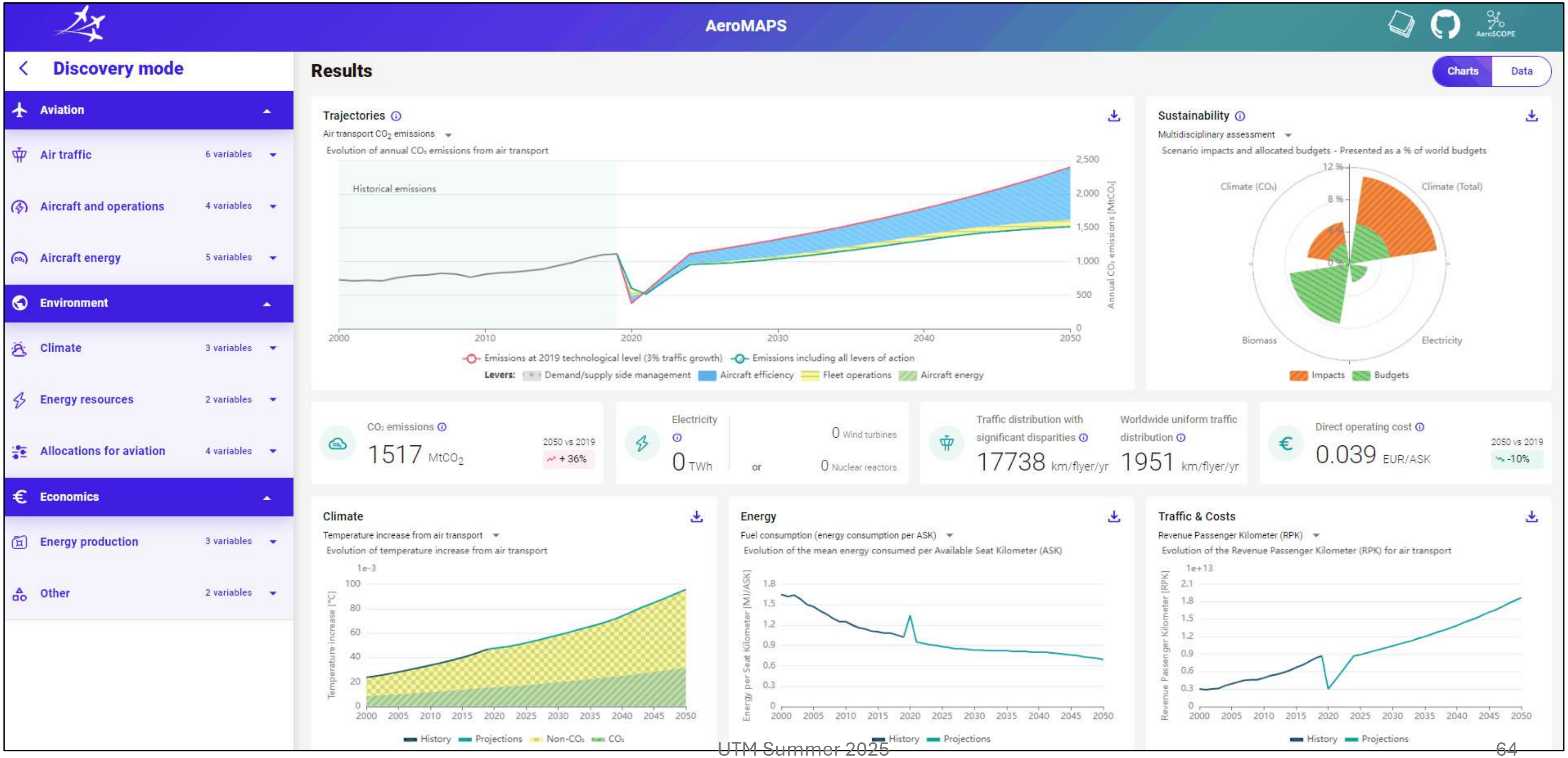


How to read that?



AeroMAPS: an opensource framework for air transport prospective scenarios

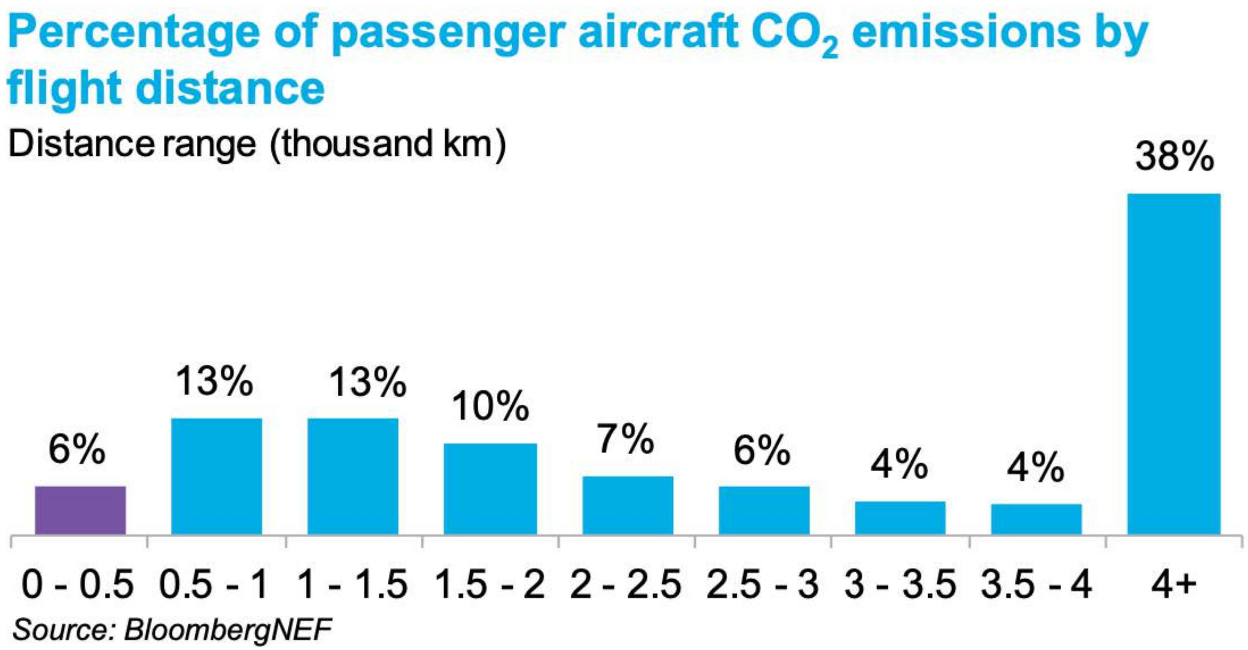
https://github.com/AeroMAPS/AeroMAPS



Simple ideas to start !

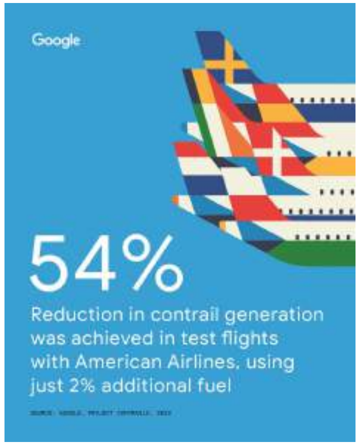
What should we tackle first with new Energy tech?

The best use cases for these technologies currently are short-haul flights (mostly <500km) due to the low volumetric and gravimetric energy densities of battery – and hydrogen – energy storage.



What should we tackle first for contrails?

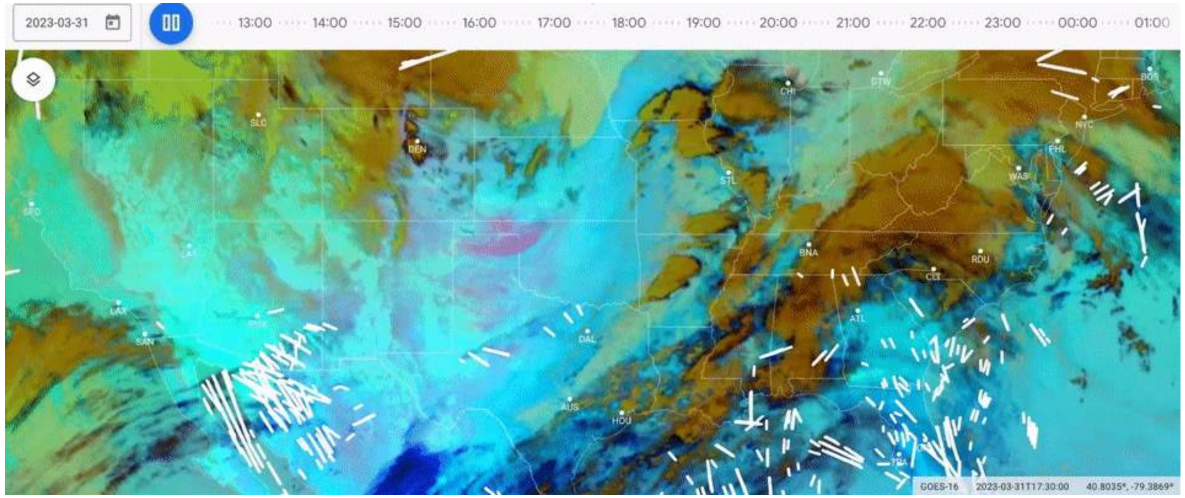
The 2022 IPCC report noted that clouds created by contrails account for roughly 35% of aviation's global warming impact, over half the impact of the world's jet fuel.



AI is helping airlines mitigate the climate impact of contrails/

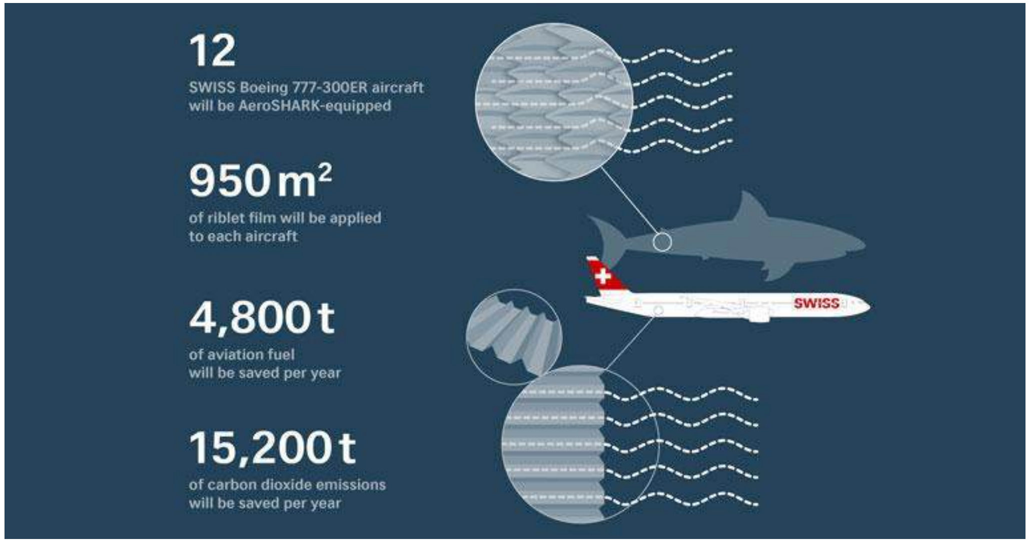
https://blog.google/technology/ai/ai-airlines-contrails-climate-change/

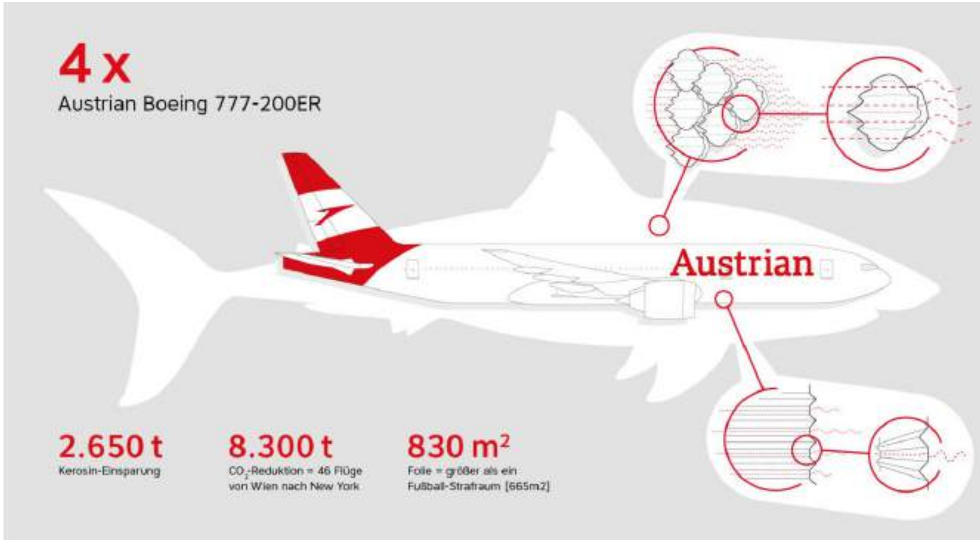
https://py.contrails.org



flights that attempted to avoid creating contrails burned **2% additional fuel**. Recent studies show that a small percentage of flights need to be adjusted to avoid the majority of contrail warming. **Therefore, the total fuel impact could be as low as 0.3% across an airline's flights.**

What should we tackle first for reducing CO2?



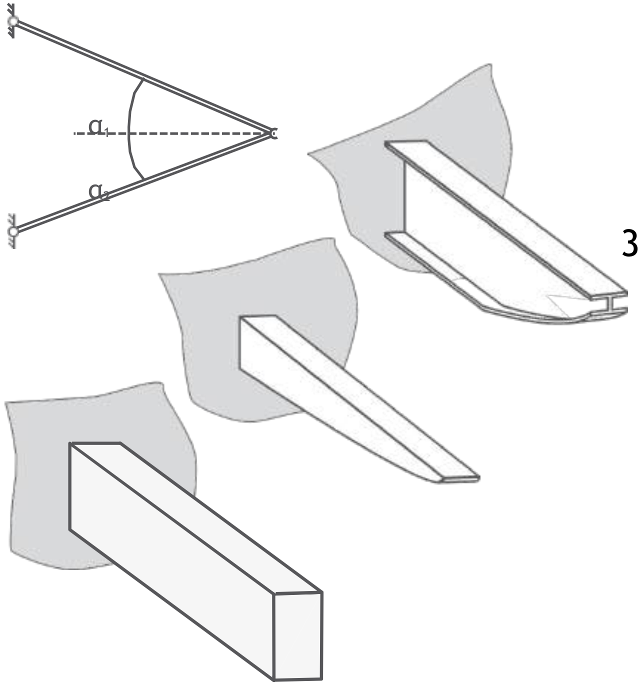


The new AeroSHARK skin technology, developed by Lufthansa Technik and BASF, will reduce SWISS' annual fuel consumption by over 4,800 tonnes.

https://www.youtube.com/watch?v=-m0EiUyoQ48

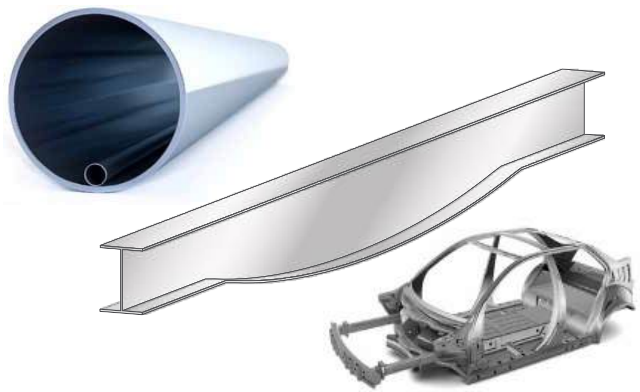
And for internal structures? Materials

With both eyes open in Product design — what else can we do??



5 principles of lightweight design

1. Support multiple loads together
2. Don’t over-specify the loads
3. Align loads with members to avoid bending
4. Optimise the cross-section for bending
5. Choose the best material



Barriers		Opportunities
Loads before use	→	Other supports
Asymmetric risks	→	Rewrite standards
Manufacturing	→	New processes

The wheel of metals

The energy transition will require a large quantity and variety of metals.

Demand for these metals is expected to rise rapidly in the coming years.

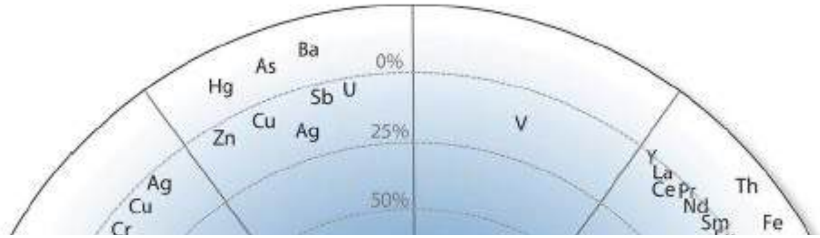
Balancing supply and demand will be challenging due to this surge.

Many essential metals are **co-products or by-products**, not mined directly.

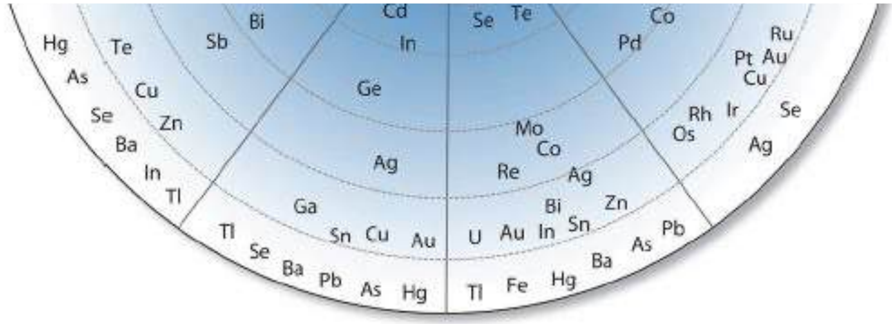
Cobalt: 98% is a by-product of **copper and nickel mining**.
Gallium: Typically a by-product of **aluminum or zinc mining**.

A recent report from the International Institute for Sustainable contains this representation (taken from an article published in 2015) allowing to visualize the production of metals. Source: https://lnkd.in/dGf9Hbdd

FIGURE 3. The metal wheel or metal companionality



Why is it important? Because rapidly increasing the production of co-products mechanically increases the production of the host metal - the demand for which is not necessarily on the same dynamic. Conversely, developing projects for a co- or by-product is theoretically possible, but the question of economic viability arises.

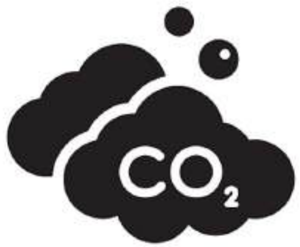


Source: Nassar et al., 2015

Environnemental Metrics

Energy consumption

Carbon footprint



Water consumption

Waste generation

In aeronautics: 4 materials

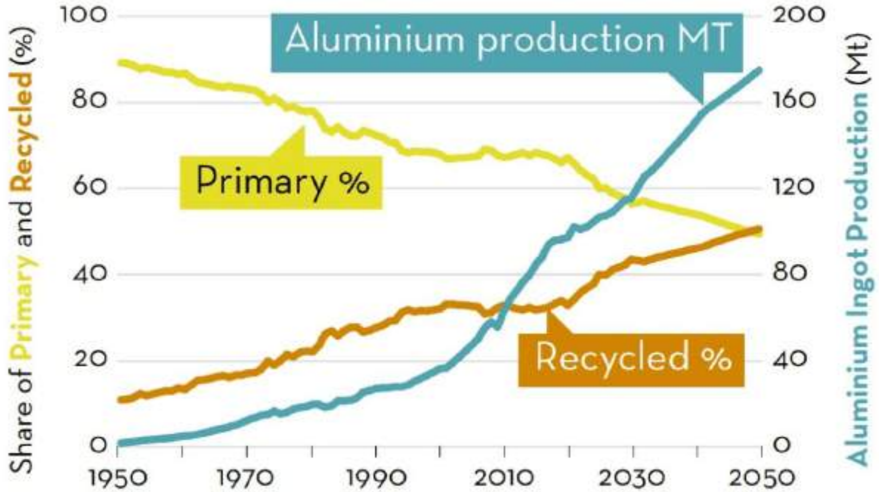
Aluminium

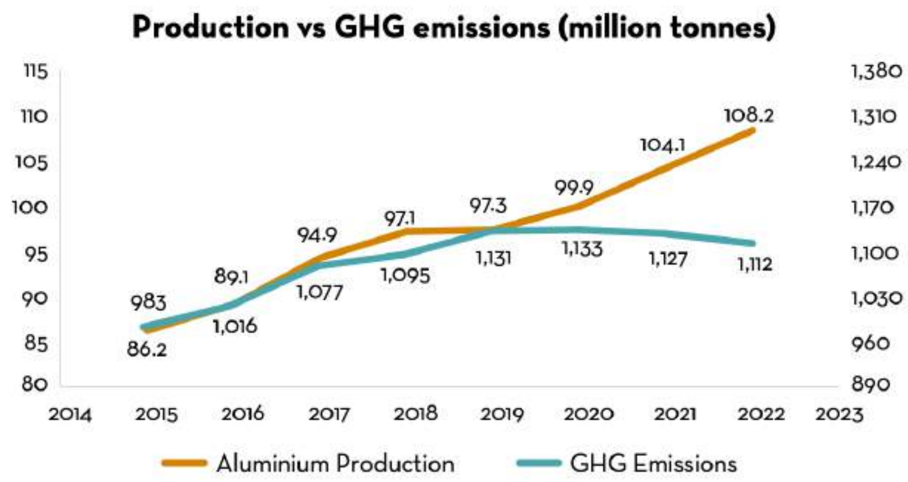
Titane

CFRP

Steel

Can you comment that ?





https://alucycle.world-aluminium.org/public-access/

Aluminium?

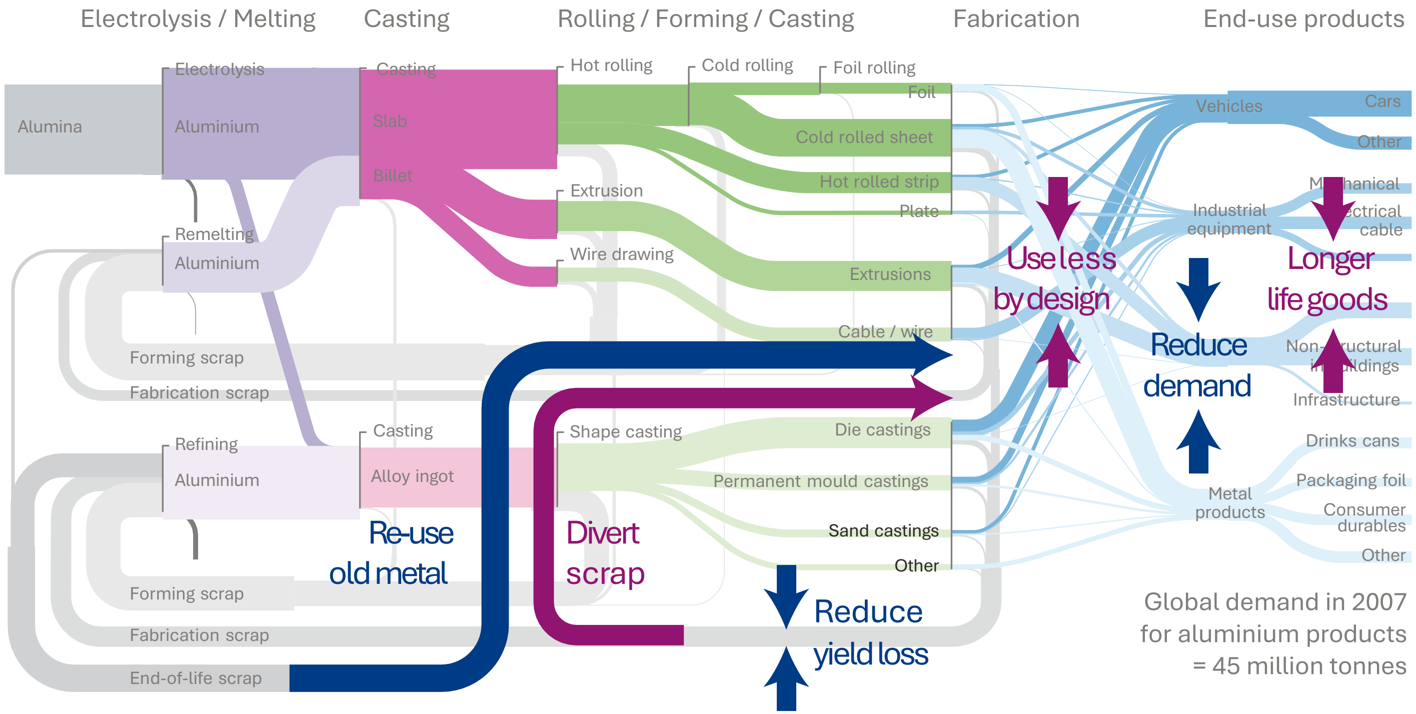
- https://www.visualcapitalist.com/aluminum-the-metal-extraordinaire/
- https://elements.visualcapitalist.com/how-is-aluminum-made/
- https://alucycle.world-aluminium.org/public-access/#global
- https://www.youtube.com/watch?v=6cUz7xCRk_E
- https://www.youtube.com/watch?v=BXHPNgww5Q8

With both eyes open in Aircraft Manufacturing

HTTPS://TINYURL.COM/CO2AEROSPACE

https://microlearning.groupe-isae.fr/nugget/environmental-impact-of-the-aerospace-manufacturing-sector/view/4530ea46-9f08-4230-8f5f-fd1570ccc69f#nugget_top

With both eyes open in Product design — what else can we do??

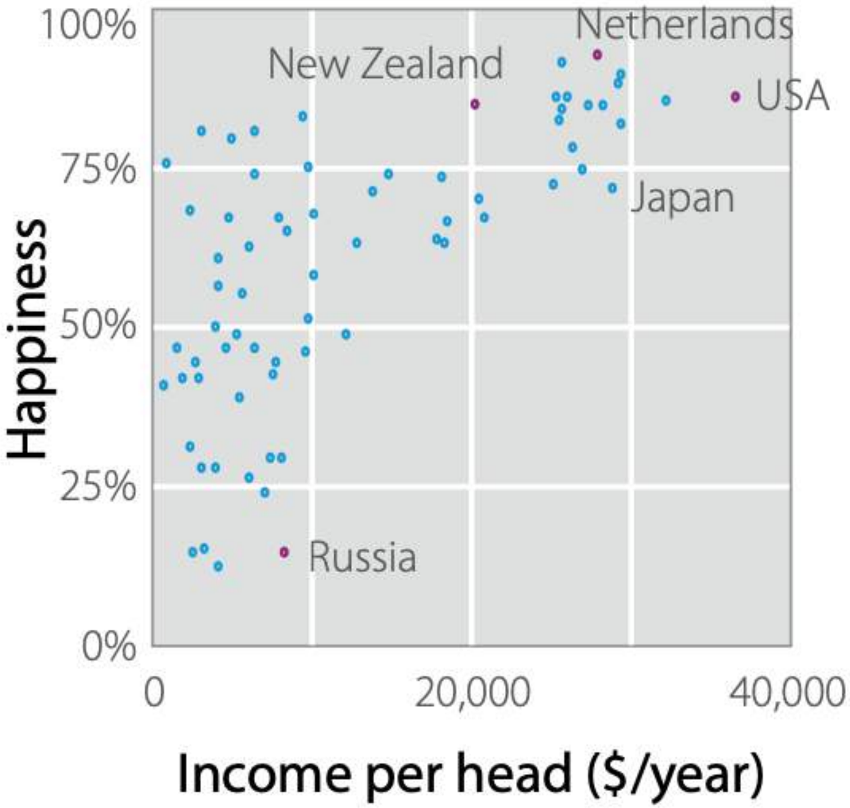


With both eyes open in Product design — what else can we do??

Inspiration from Civil Engineering: developing algorithms to allow designers to reuse material from a structure in new designs : DESIGN FOR ZERO

https://www.istructe.org/journal/volumes/volume-99-(2021)/issue-6/profile-caitlin-mueller/

With both eyes open in Product design — what else can we do??



If not material efficiency, then demand reduction?

→ Consume Less

→ Reuse, Repair, Recycle

https://www.uselessgroup.org

First conclusion: Fly less

Fly less ! And use Ecodesign

Definition of Ecodesign

- **Through an intelligent utilization of the available resources, Ecodesign aims at a product and process design that ensures maximum benefit for all actors involved as well as consumer satisfaction, while causing only minimum environmental impacts.**— United Nations Industrial Development Organization

- An ecodesign approach involves the organization that extracts materials as well as manufacturing. All the people and structures involved along the rest of a product's lifecycle, such as retailers or consumers, are also included. And all the processes along a product's value-chain are covered too.

Ecodesign – A Simple Definition

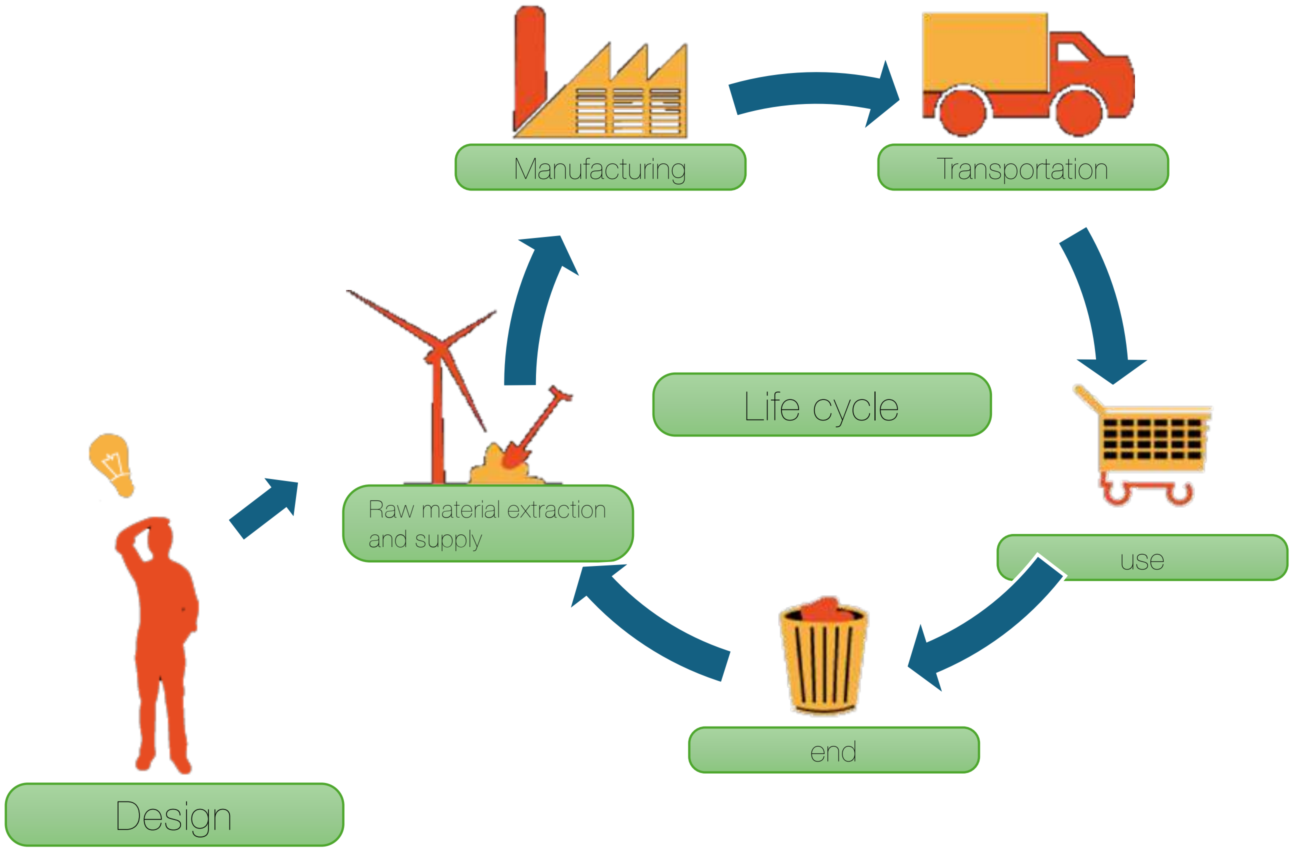
- Ecodesign is both a principle and an approach.
- It consists of integrating environmental protection criteria over a service or a product's lifecycle.
- The main goal of ecodesign is to anticipate and minimize negative environmental impacts (including manufacturing, operations and disposal).
- Simultaneously, eco design also keeps a product's quality level according to its ideal usage.
- The principles of eco design where formally published in 2002 and they can be found in ISO/TR14062.

The Ecodesign Approach

- Ecodesign is part of a global approach called “multi-step” and “multi-criteria”. This approach supports a product’s entire lifecycle in a circular economy perspective by saving and recycling at maximum natural resources. It has to do with considering specific criteria in different **Successive stages:**

1. Raw material extraction and supply
2. Manufacturing
3. Product distribution
4. Consumer use
5. End of life (recovery and recycling)

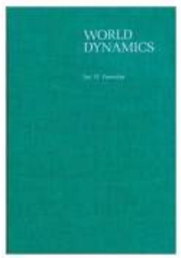
A global Approach



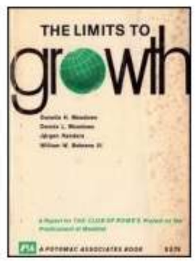
Main metrics (*The limits to Growth)*

- Consumption of raw materials
- Energy consumption
- Releases in the natural environment and other pollutions
- Climatic impacts
- Impacts on biodiversity

World Dynamics
1971, Jay W. Forrester



The Limits to Growth
1972, Donnella H. Meadows, Dennis L. Meadows, Jorgen Rangers, William W. Behrens III



Dynamics of Growth in a Finite World,
1974, Dennis L. Meadows, William W. Behrens III, Donnella H. Meadows, Roger F. Naill, Jorgen Rangers, Erich K. O. Zahn

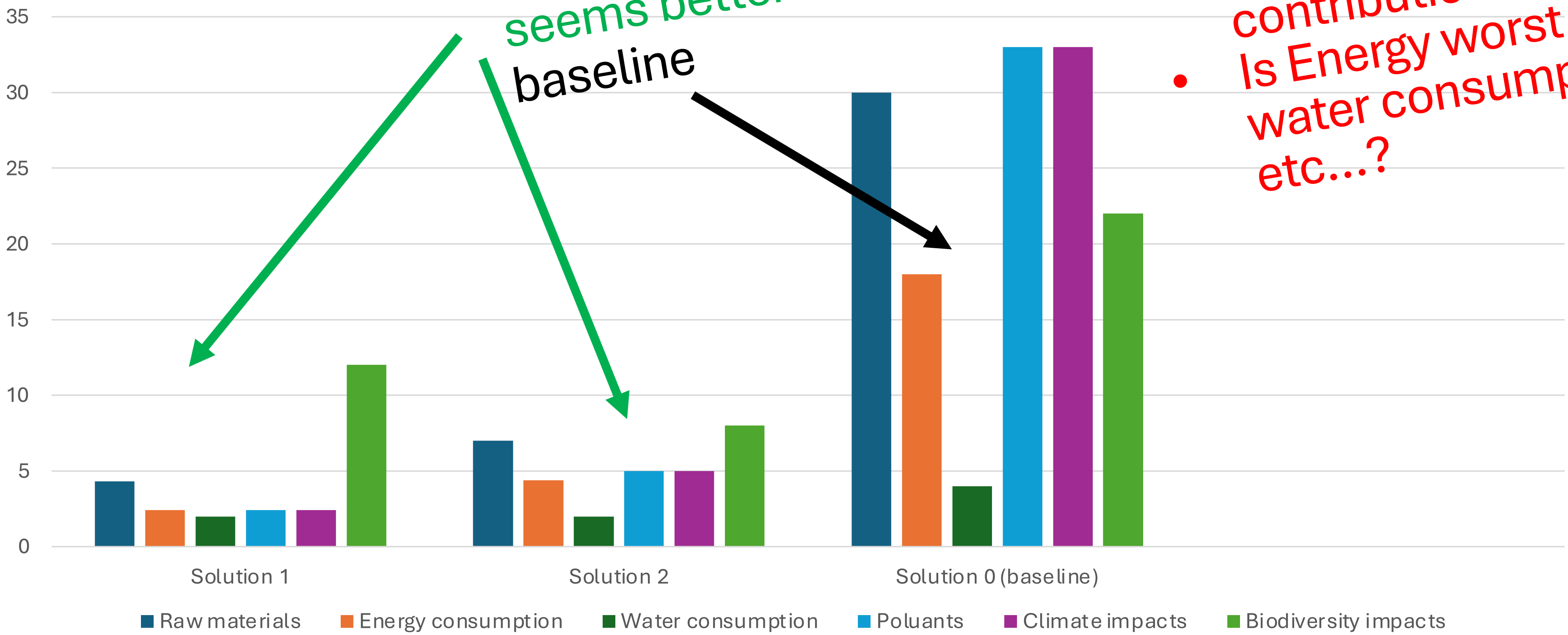
Can you conclude ?

Y axis?

These 2 solutions seems better than the baseline

We need a common metric (*equivalence*)

- Can we sum up contributions?
- Is Energy worst than water consumption etc…?



For climate impacts:= Y axis is CO2 emission

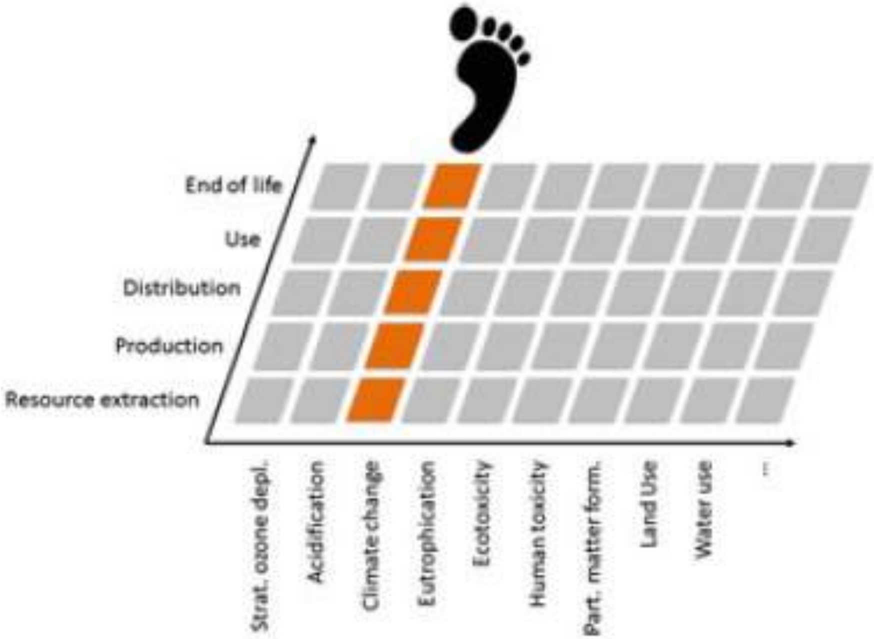
- Example : all GHG emissions are transformed into an equivalent CO_2 emission.

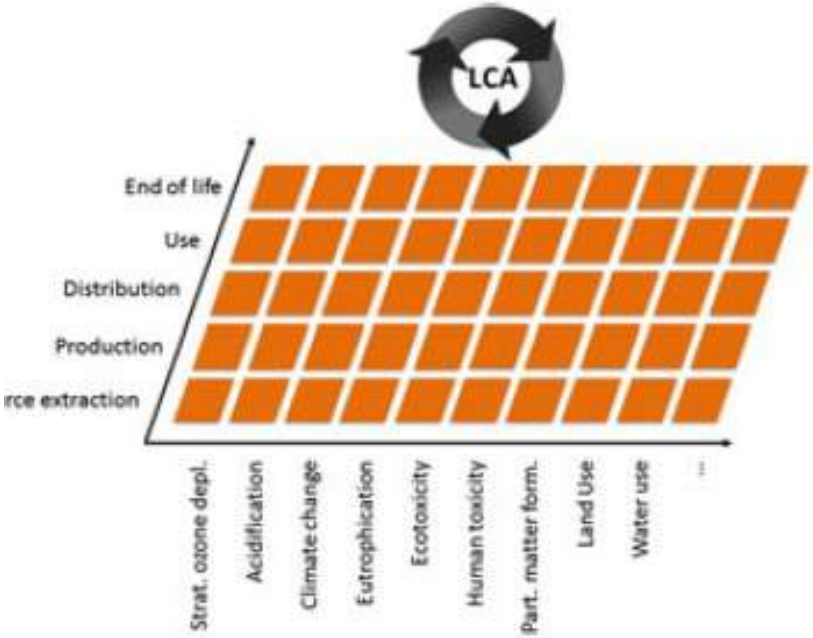
https://en.wikipedia.org/wiki/Carbon_footprint

Possible to compute your own footprint :
https://www.footprintcalculator.org/home/en

CO2 footprint *versus* LCA

- Focusses only on climate change, considered to be most urgent threat
- Enables to have only one indicator := easier for optimization





Some books

- Cambridge