Conception optimale pour l’ingénieur (Aerospace)

Overview by Prof. J. Morlier

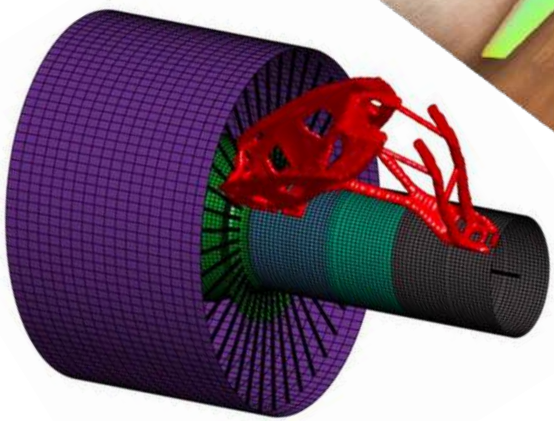
2025

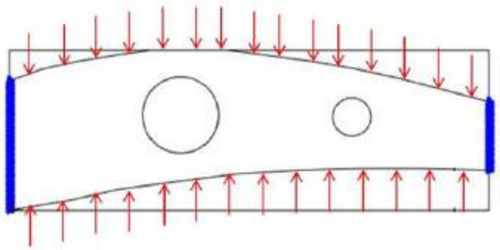
Institut Supérieur de l'Aéronautique et de l'Espace

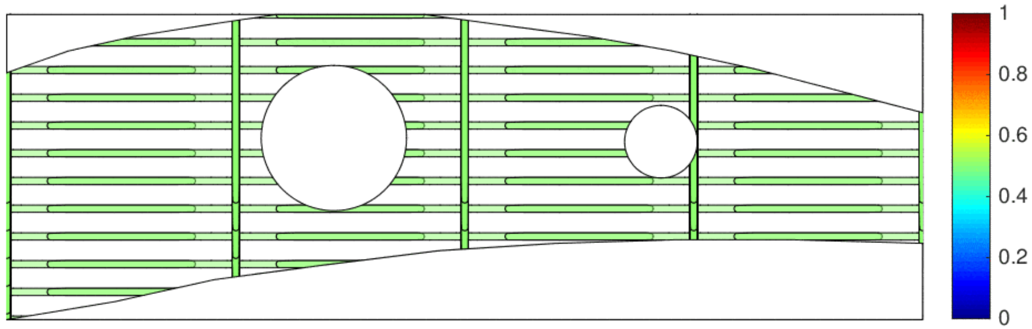
SUPAERO

About Me?

- Prof in Structural and Multidisciplinary Optimization



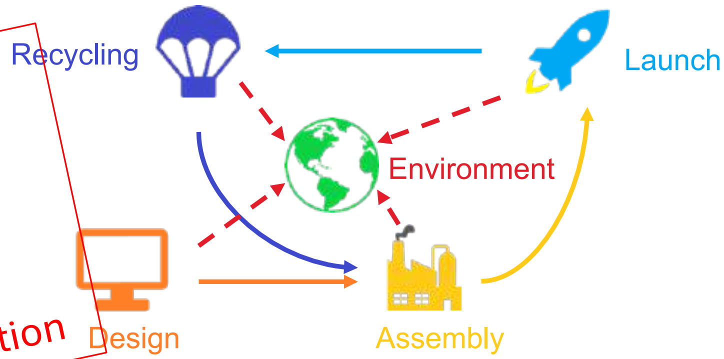




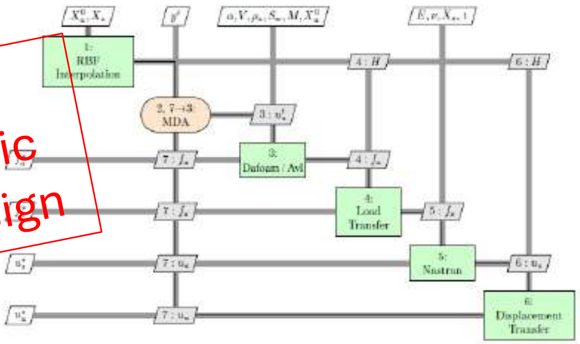
About Me? https://ica.cnrs.fr/en/author/jmorlier/

- 6 PhDs, 3 MsCs

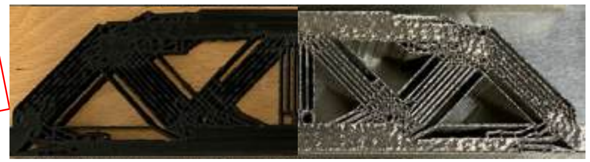
MDO for Aerospace systems Including LCA := EcoOptimization



MDO for Aeroelastic Wing design

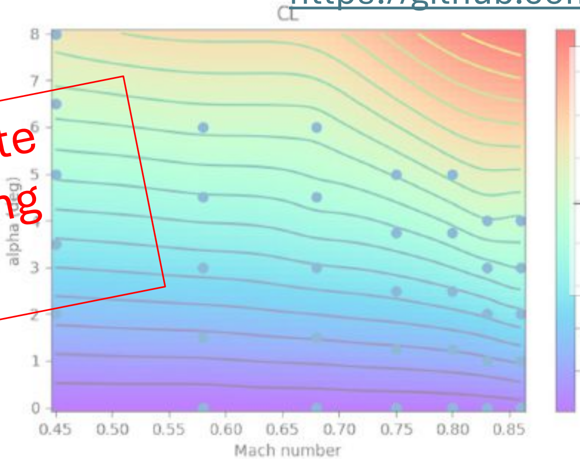


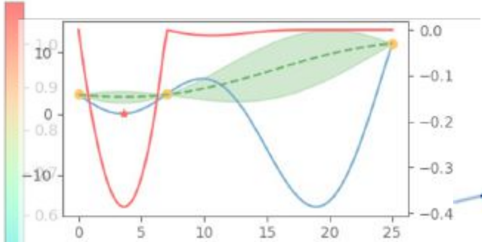
Digital fabrication



https://github.com/SMTorg/SMT

Surrogate modeling AI4E

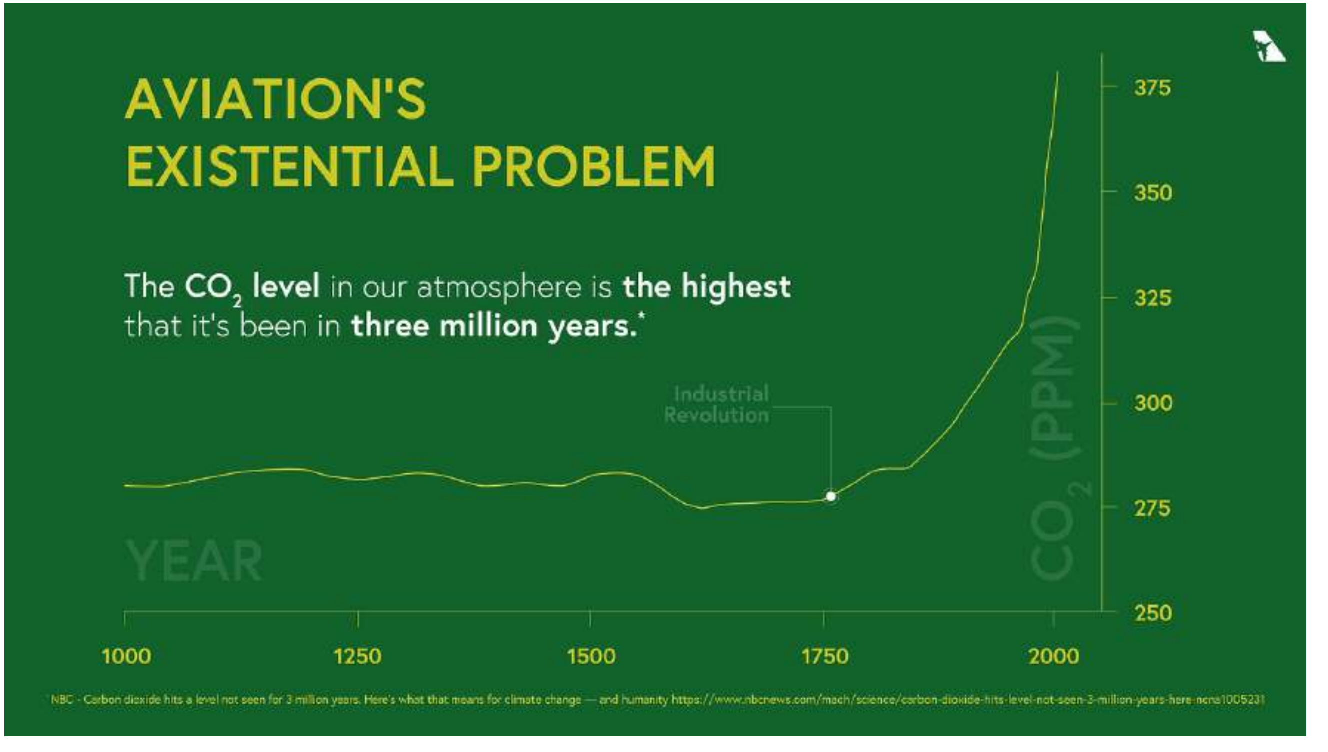




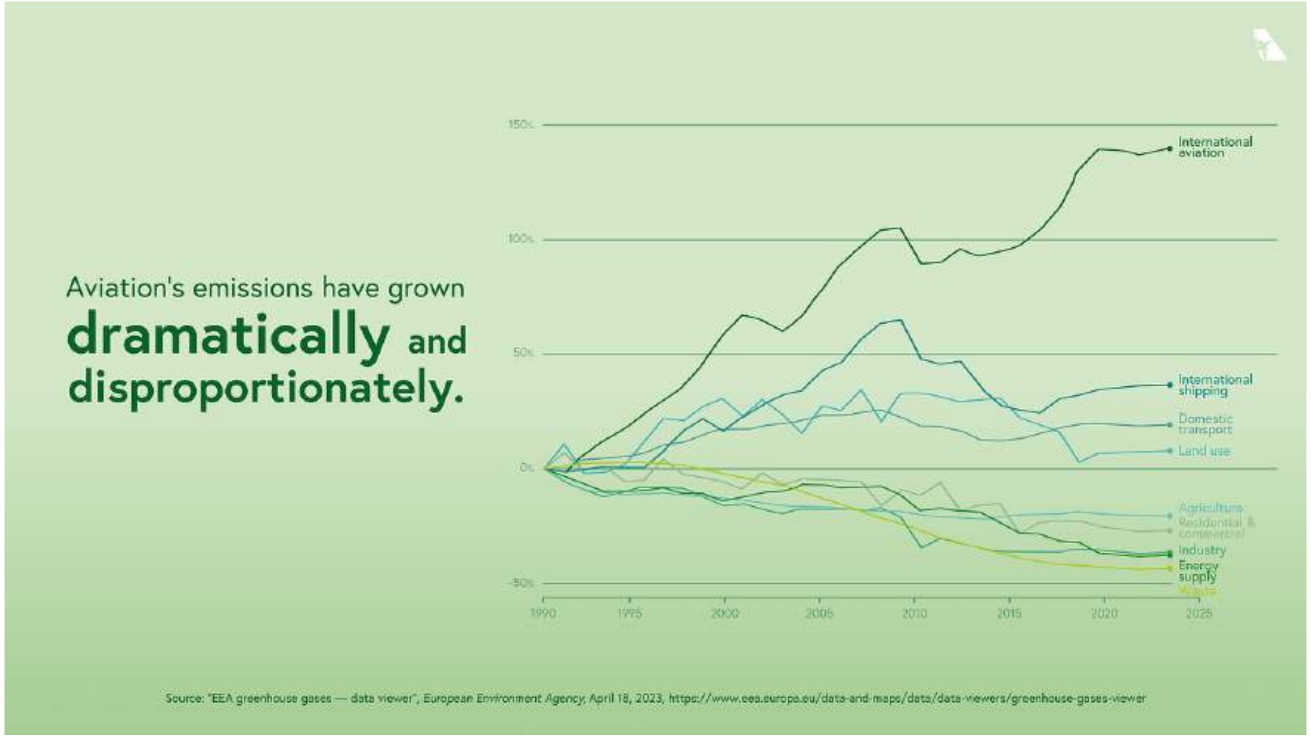
EMSM207

Sustainable aviation?

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



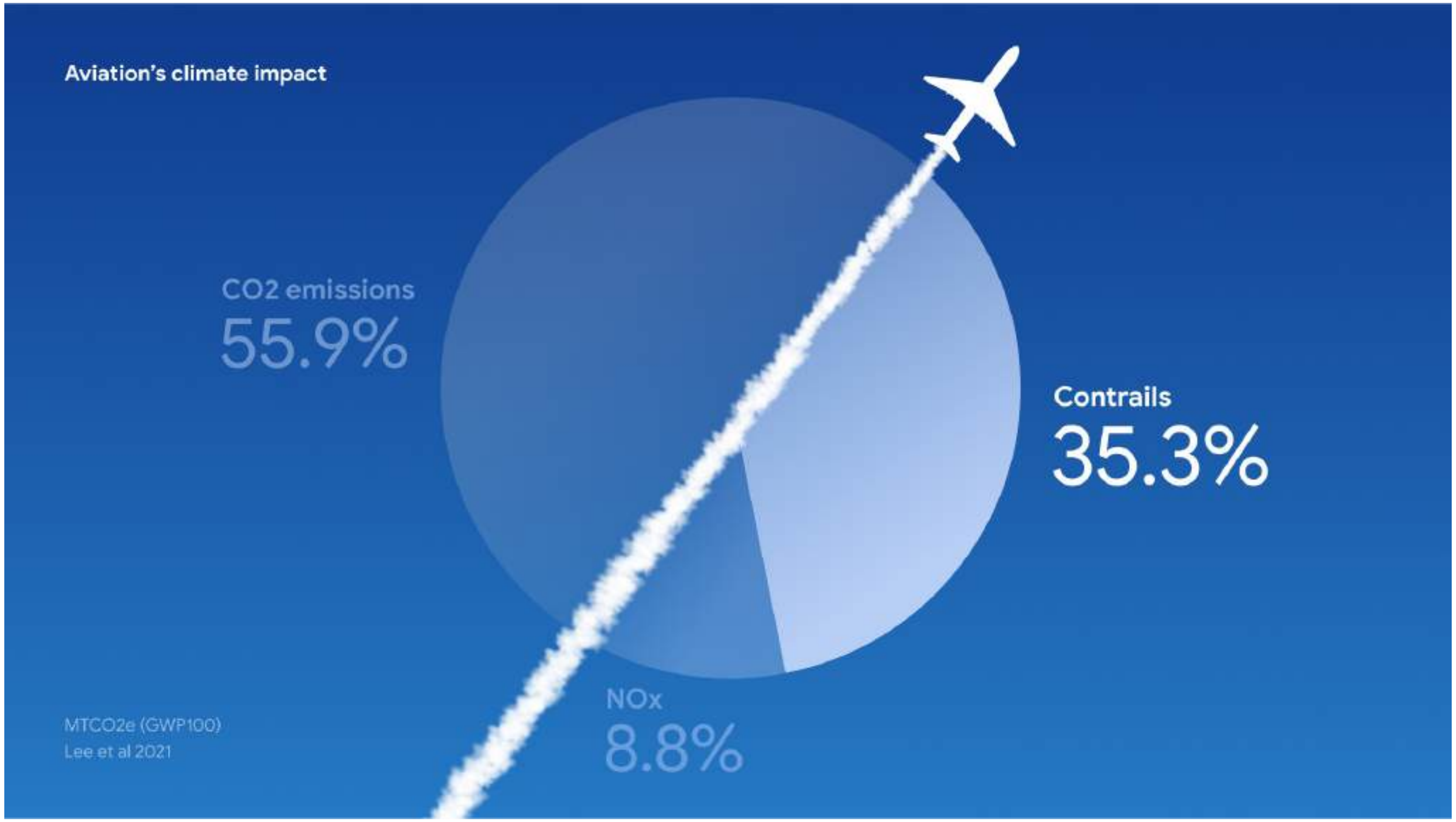
Sustainable aviation?



Sustainable aviation?

Sustainable aviation?

Sustainable aviation?



Our goal: Give you the basis in 20+hours only !

Evaluated by :

- An Airbus Project
- Personnal work
- Lot of notebooks to start

How to start an
ENGINEERING (aerospace)
DESIGN OPTIMIZATION
problem that includes ecodesign approach?

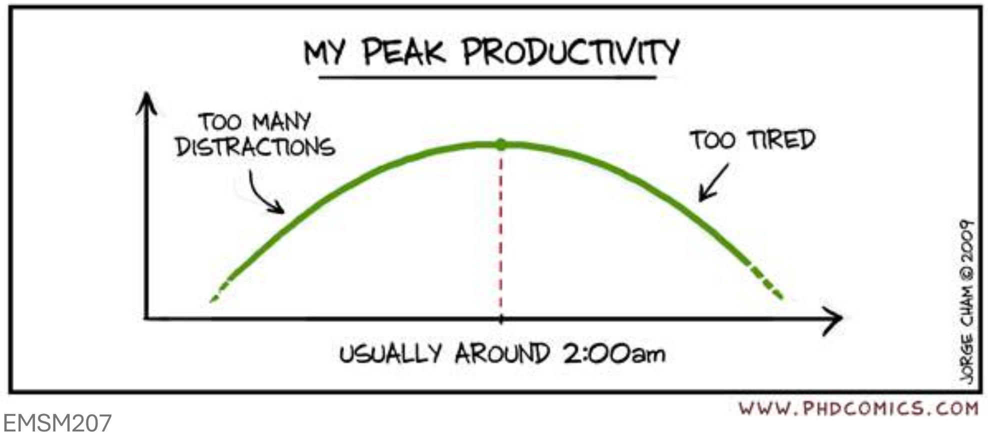
UPSKILLING

This lightening session has been prepared especially for ISAE's group mobility week, it should:

- Refresh your Design Optimization {DO} basis with updated contents from MIT, UoM, etc…
- Open your mind to recent researches (including mine)
- Give lots of Tips and Tricks
- Challenge your existing skills in Design Optimization with simple exercises

Morning: Lessons and simple exercices

Afternoon: Team Projects



AU PROGRAMME

Python based

lundi 31 mars 2025			
		09h15 - 12h45	MORLIER Joseph
		14h00 - 16h15	MORLIER Joseph
mardi 01 avril 2025			
		09h15 - 12h45	MORLIER Joseph
		14h00 - 16h15	MORLIER Joseph
mercredi 02 avril 2025			
		09h15 - 12h45	MORLIER Joseph MURADÁS ODRIOZOLA Daniel
		14h00 - 16h15	MAS COLOMER JOAN MURADÁS ODRIOZOLA Daniel
jeudi 03 avril 2025			
		09h15 - 12h45	MAS COLOMER JOAN MURADÁS ODRIOZOLA Daniel

Intro: Sustainable Aviation (Materials) With Both Eyes Open
Design optimization 1: constrained optimization, MOO, Sensibility with examples
Project DO 1 2 3

Topology Optimization with examples
Material ecoselection, Ashby Diagram and more

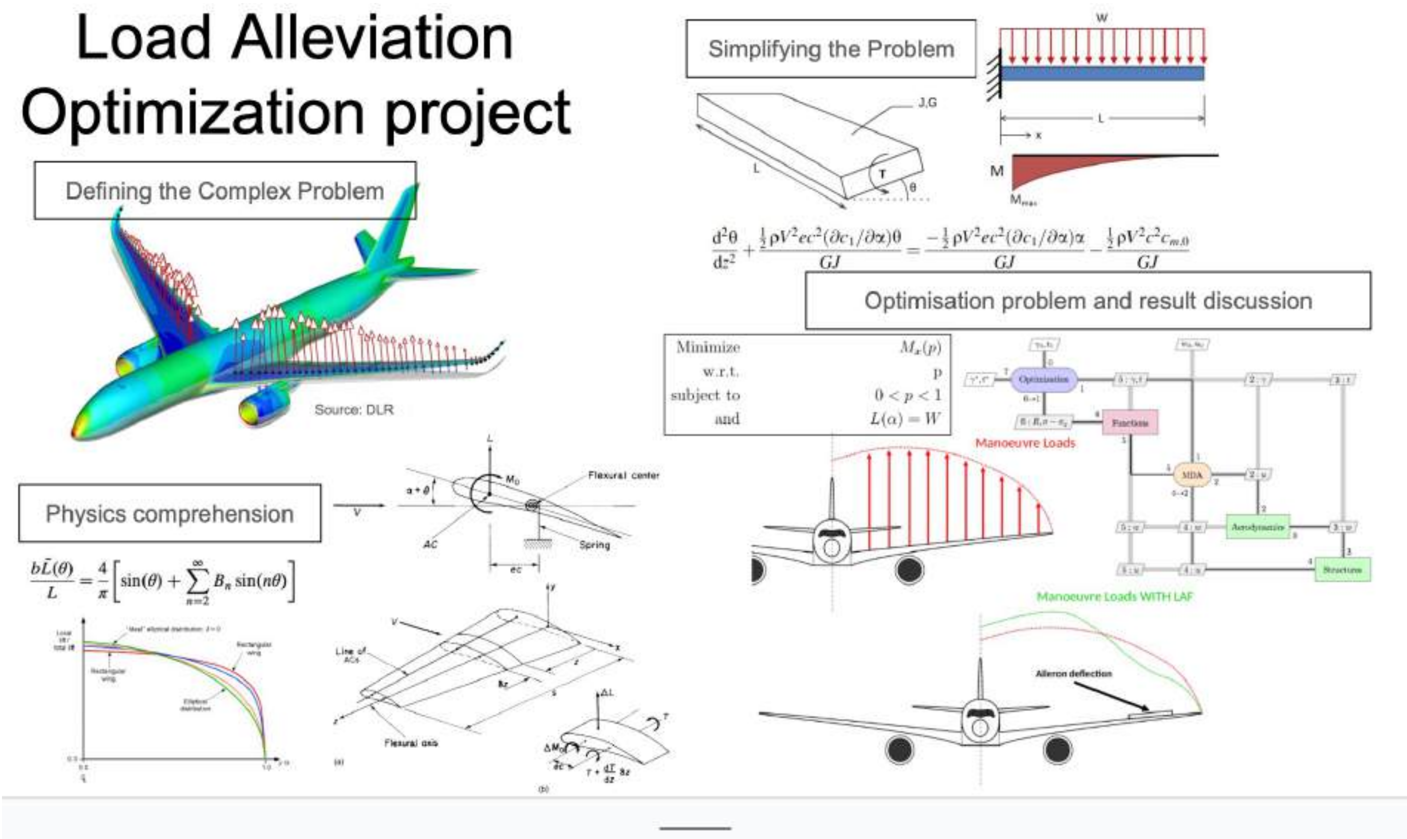
Projet DO 1 2 3
Wrap up and demo from students

Intro to MDAO **Static Aeroelastic problem is a MDAO problem**
Airbus PROJECT by TEAM of 3 (marked*)

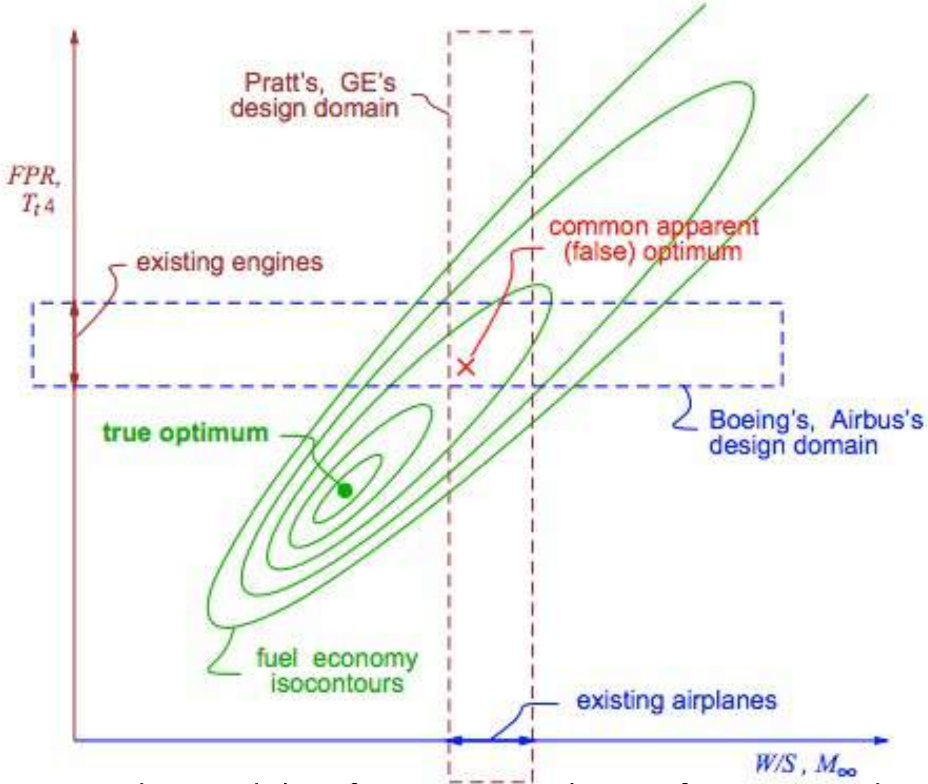
vendredi 04 avril 2025		**ORAL MARKED***	
		09h15 - 11h30	MORLIER Joseph MURADÁS ODRIOZOLA Daniel

EMSM207

Evaluation? Miniprojet Airbus



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

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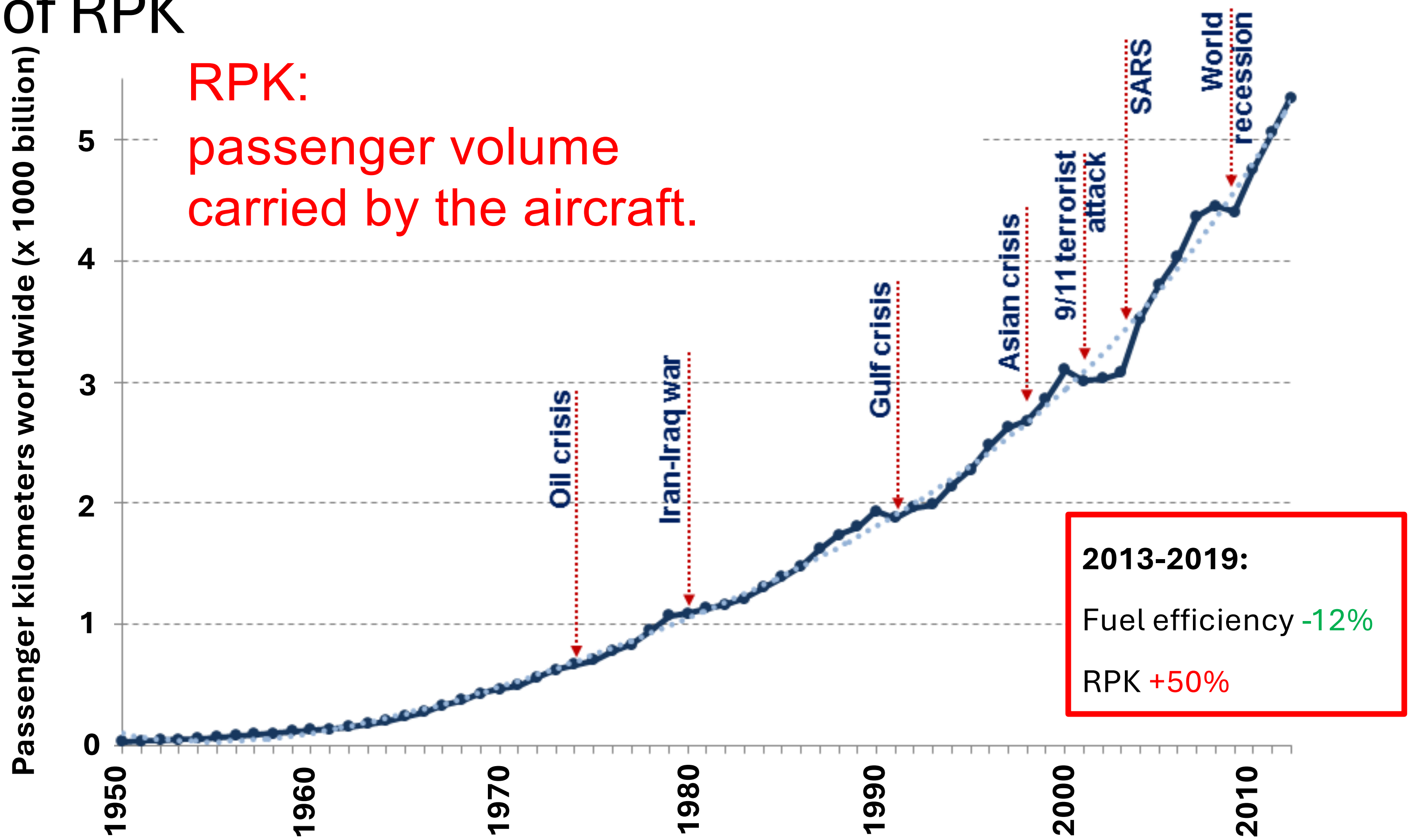
Efficiency improvements vastly surpassed by exponential growth of RPK

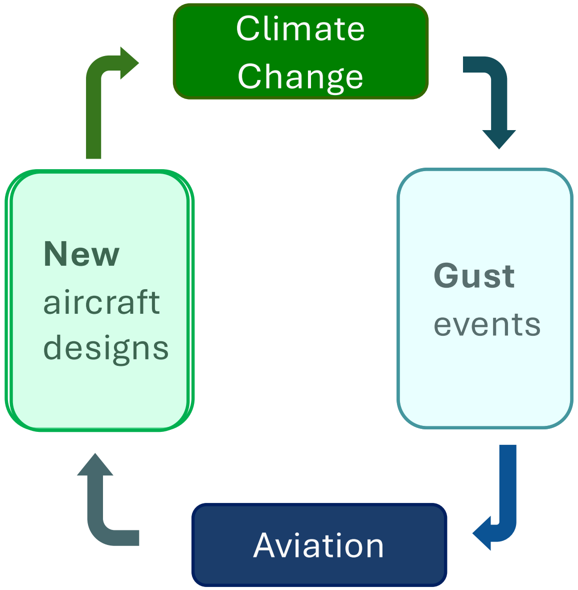


Current situation

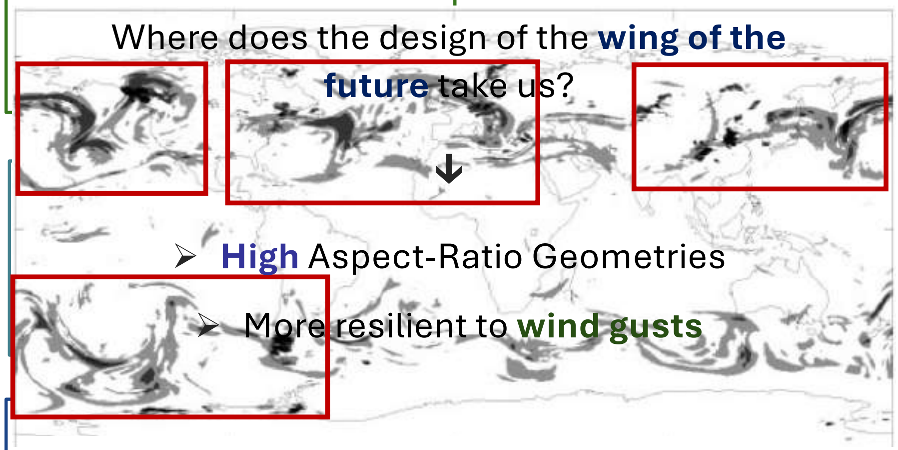
- Fuel consumption per passenger per km is comparable to that of a modern car
- The **large distances** and **massive number of passengers** cause significant climate impact
- Aviation currently accounts for **2.5%** of the global CO_2 emission
- This percentage will rise if we do not act
- Furthermore, **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



Where does the design of the **wing of the future** take us?



- **High** Aspect-Ratio Geometries
- More resilient to **wind gusts**

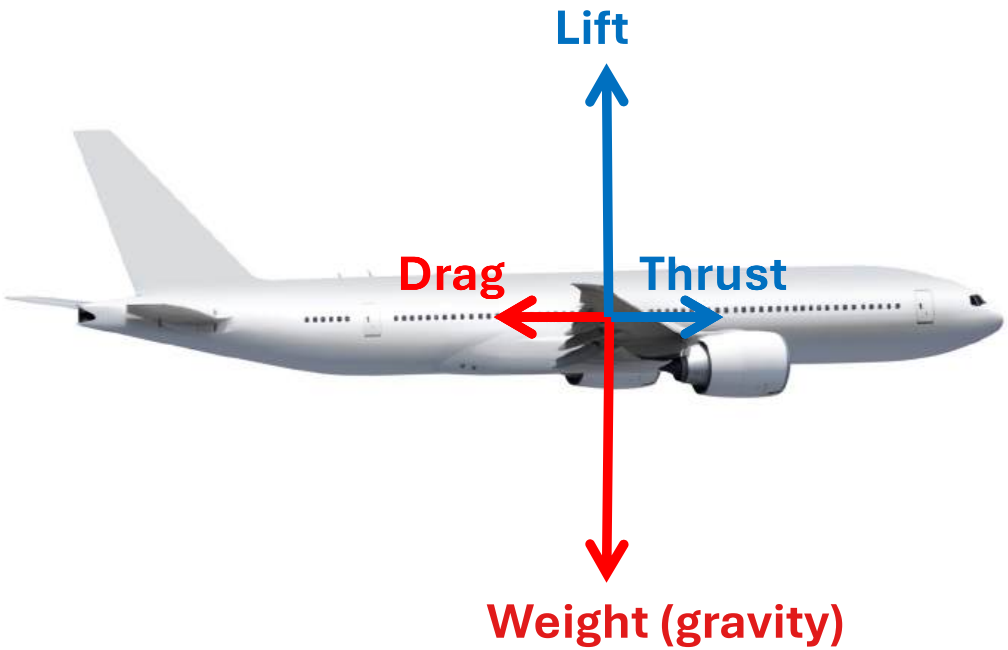
Source:
Gill, Meteorology Applications, 2014.

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

Source: Airbus ©

Energy-efficient planes are the key

And weight is a determining factor...



Why?

$$\begin{array}{c}\text{"The rate of} \\ \text{aircraft weight reduction"}\end{array} = \begin{array}{c}\text{"The rate of} \\ \text{fuel weight burned"}\end{array}$$

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

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

The Breguet Range Equation (BRE)

It *makes sense*!

(BRE) is named after a French aircraft designer, but was actually derived in the 1920's by J G Coffin

The incremental distance dS (Range) covered during cruise
https://www.aircraftflightmechanics.com/AircraftPerformance/RangeandEndurance.html

Fly light

$$dS = -\frac{1}{c_t\ g}\sqrt{\frac{2\ W}{\rho\ S}}\ \frac{C_L^{1/2}}{C_D}\ \frac{1}{W}\mathrm{d}W$$

Fly with low c_t

Fly high

Fly with max $\frac{C_L^{1/2}}{C_D}$

Ct for:
turbojet - mass of fuel burned per unit of thrust per second
turboprop - mass of fuel burned per unit of power per second

The equation above says:

- Range is inversely proportional to fuel burn ct, which makes sense
- Range is inversely proportonal to weight W, which makes sense (combine the two into W^-1/2)
- Range is inversly proportional to density so proportional to altitude (aircraft cruise at altitude)

- We see that the best range is given at the aerodynamic condition (that is, the velocity) corresponding to the maximum value of CL^1/2/ CD
- For equilibrium, lift must equal weight, so for the *best CL* , this occurs at a single airspeed
- Fuel is burned, so the aircraft gets *lighter*, so looking at the definition of the lift coefficient:C_L=\frac{2\,W}{\rho\,S\,V^2}
- To maintain the best , *either* the velocity has to reduce or the density has to reduce.

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:

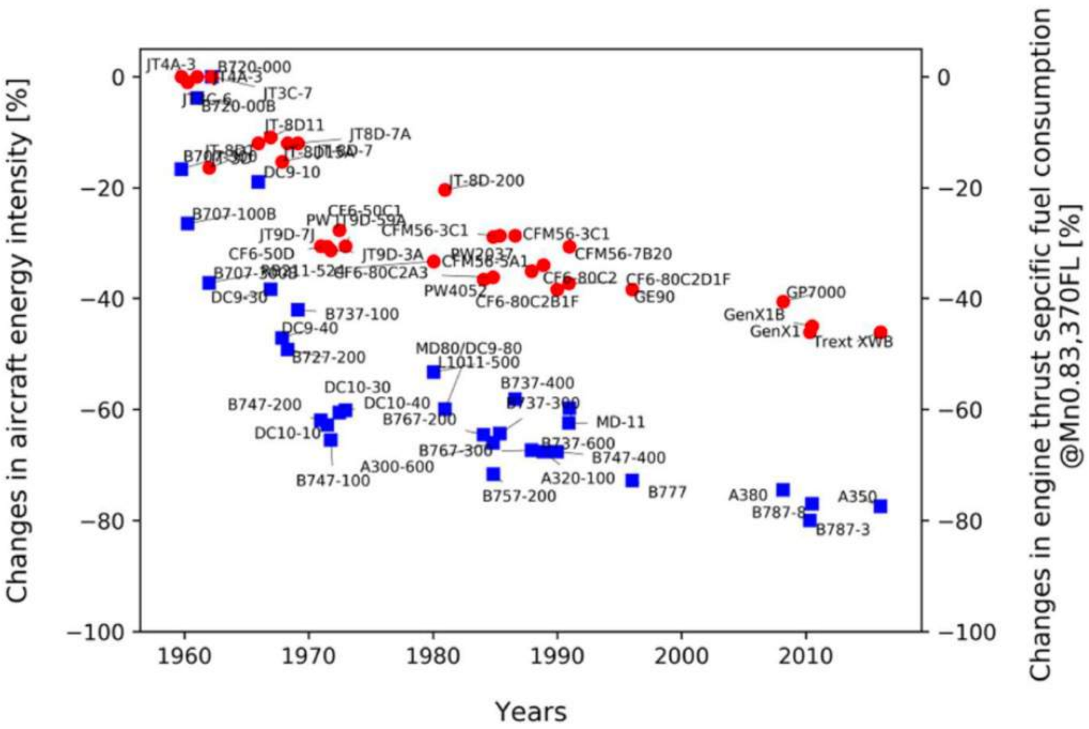
Type	MTOW [kg]	MLW [tonnes]
Airbus A380-800	575,000	394
Boeing 747-8F	447,700	346.091

One can argue that

- Aviation is an energy problem

All is energy

- Linked to this evolution is the concerning growth of both pollutant and noise emissions with prejudicial consequences for the well-being of both humans and ecosystems, even though technological improvements have allowed for reductions of these emissions.
- These technological improvements, mainly in the propulsive system, have allowed for reductions up to 80% and 75% in terms of fuel burn and noise emissions, respectively, when compared to the early commercial aviation days.



F. Yin and A.G. Rao, "A review of gas turbine with inter-stage turbine", *Progress in Aerospace Sciences*, Vol. 121, 100695, 2020, https://doi.org/10.1016/j.paerosci.2020.100695

Energy is all

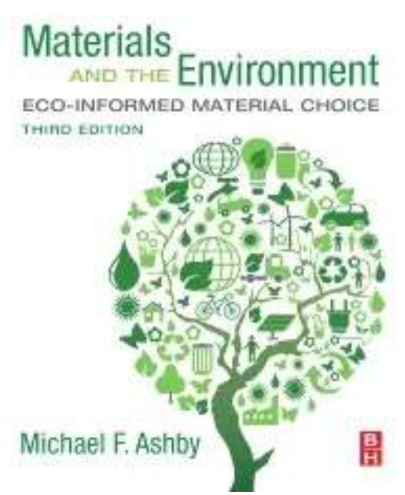
- According to Lee et al. (2021), aviation industry is responsible for only 3.5% of the anthropogenic climate changes with non-CO2 related emissions, namely contrails, presenting a similar impact to the CO2 related ones. Despite this value being smaller than other means of transportation, the energy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

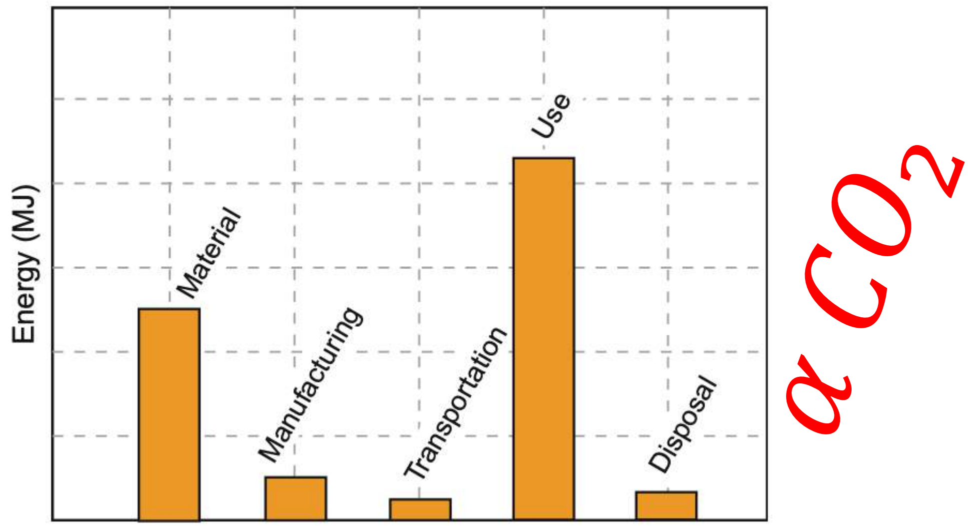
Transportation Vehicles	MJ/(PAX.km)
Buses	0.15 - 0.49
Electric and Hybrid Cars	0.31 - 0.45
High Speed Trains	0.35 - 0.64
Diesel Cars	0.65 - 1.05
Petrol Cars	0.79 - 1.6
Aircraft	1.11 - 1.62

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

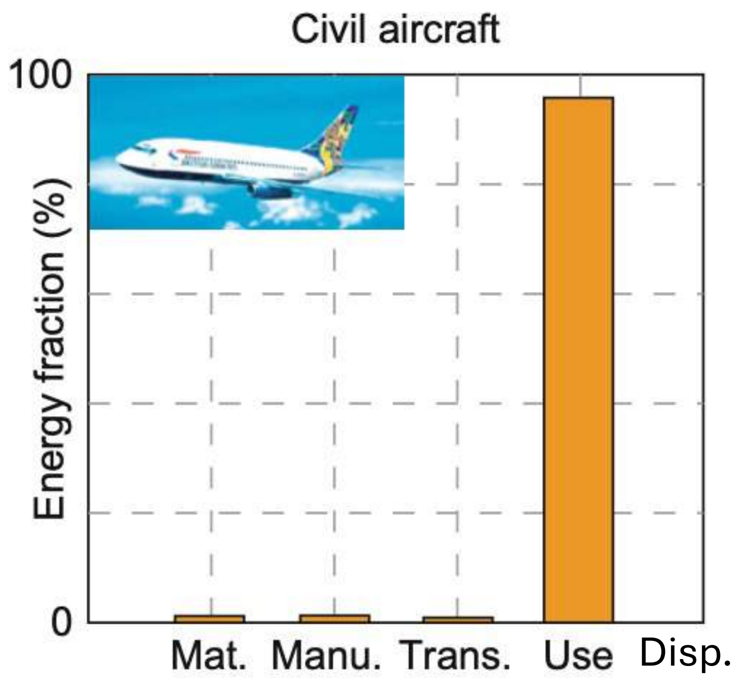
Environnemental Footprint





Breakdown of energy into that associated with each life phase

Green aviation



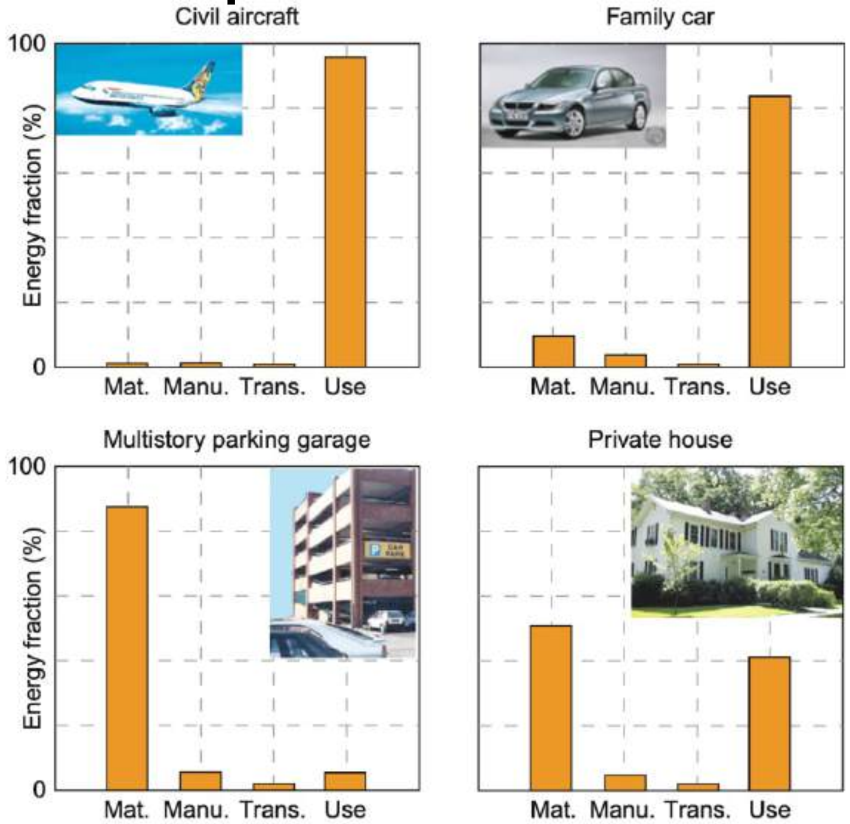
Embodied energy

$$E_e = \frac{\sum \text{Estimated energy required for primary production}}{\text{Mass of primary material production}}$$

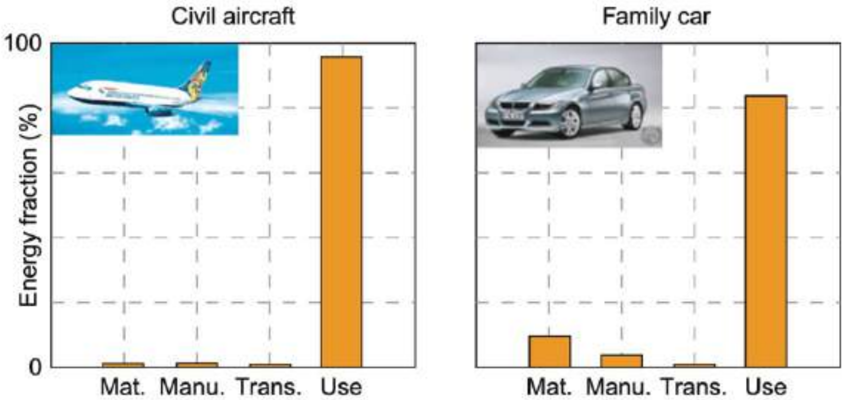
CO2 emission

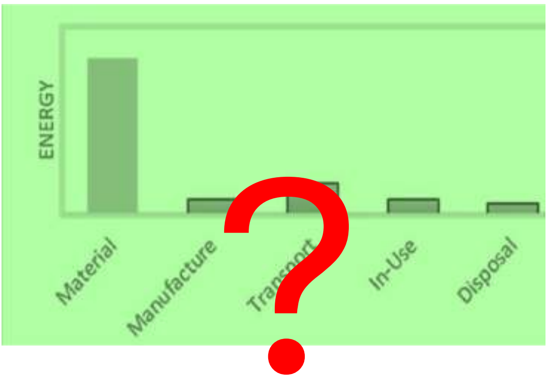
$$E_c = \frac{\sum \text{Mass of CO2 arising from production}}{\text{Mass of material produced}}$$

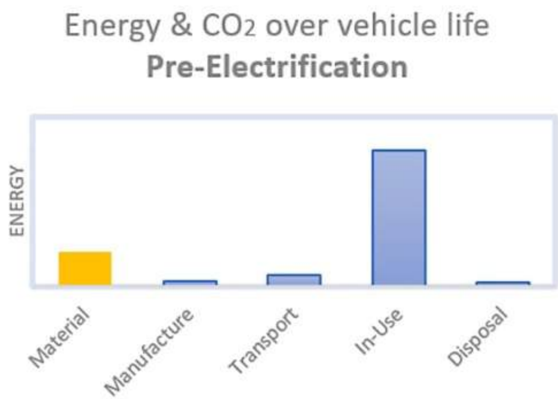
Different products … different impacts

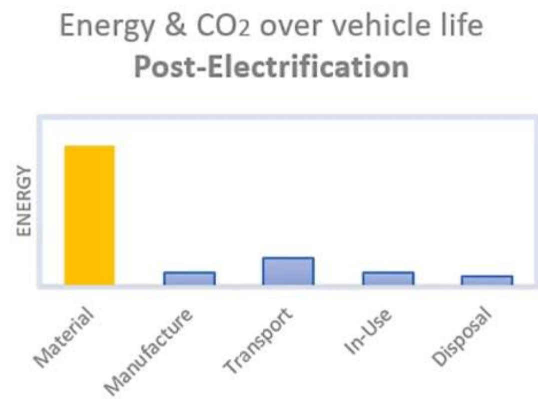


Electrification example (from automotive)





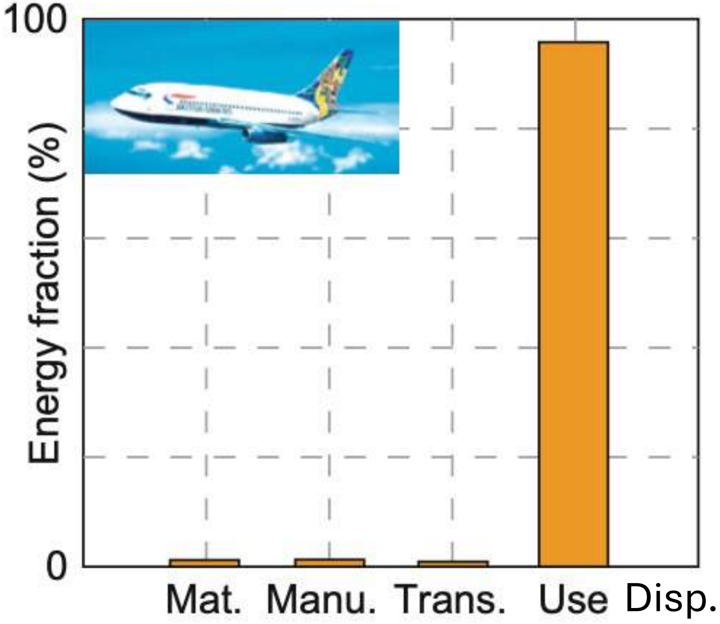




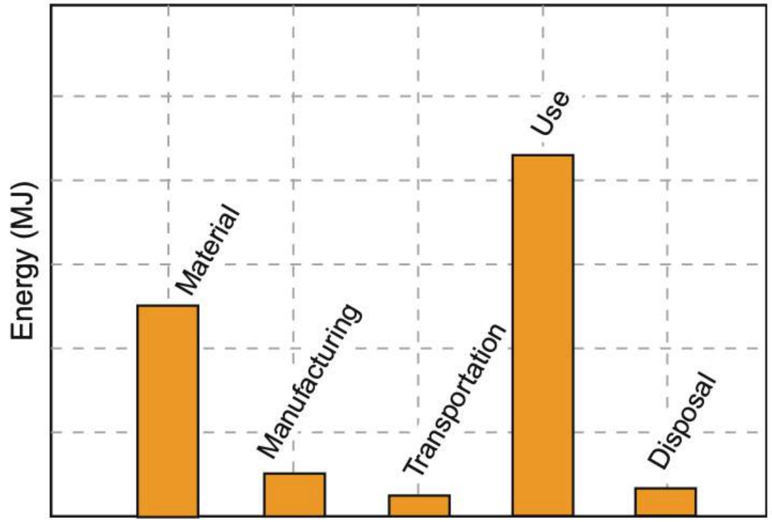
Energy $\propto$ CO_2 footprint

Fuel burn
+ non CO_2
such as contrails

Civil aircraft



Future Sustainable Air vehicule

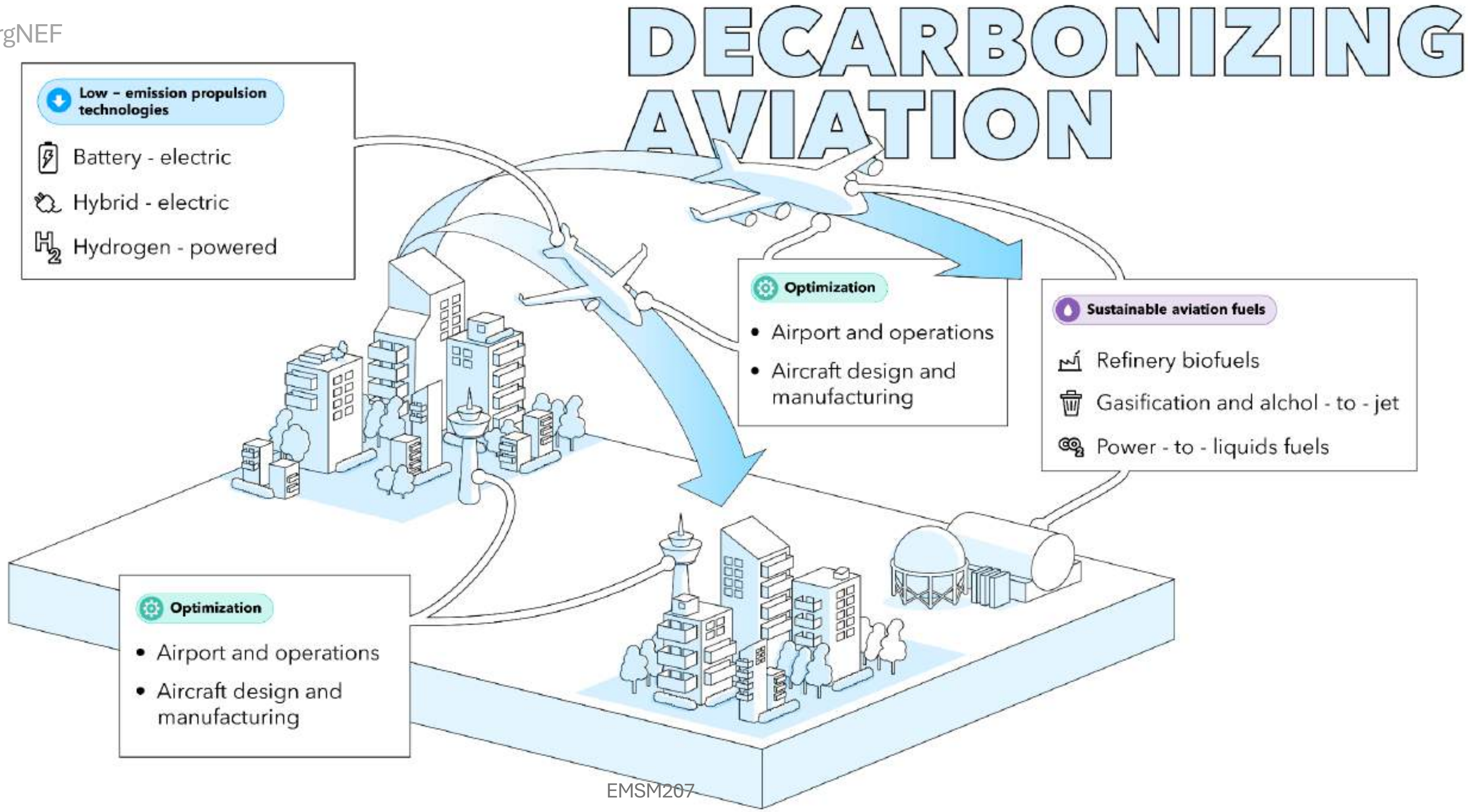


Breakdown of energy into that associated with each life phase

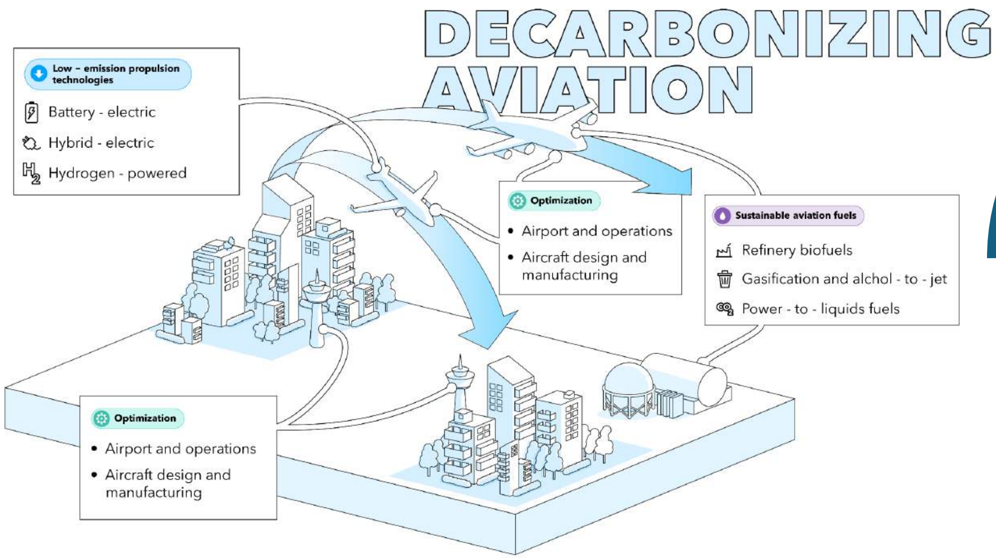
Hydrogène, SAF, Electric/Hybrid Propulsion…

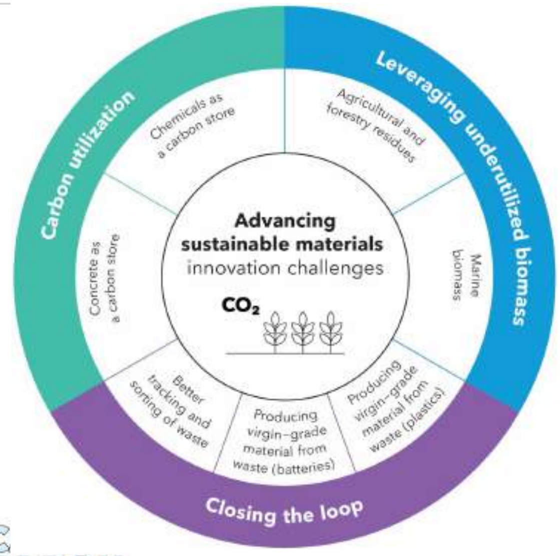
Overview

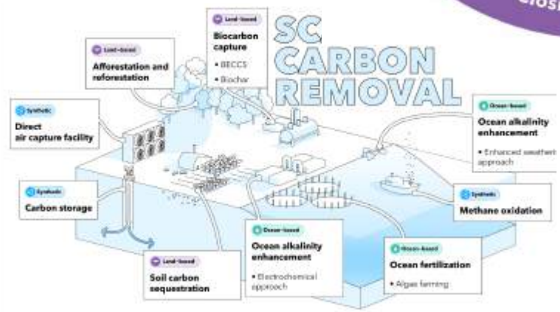
from BloombergNEF



New Techs interdependency



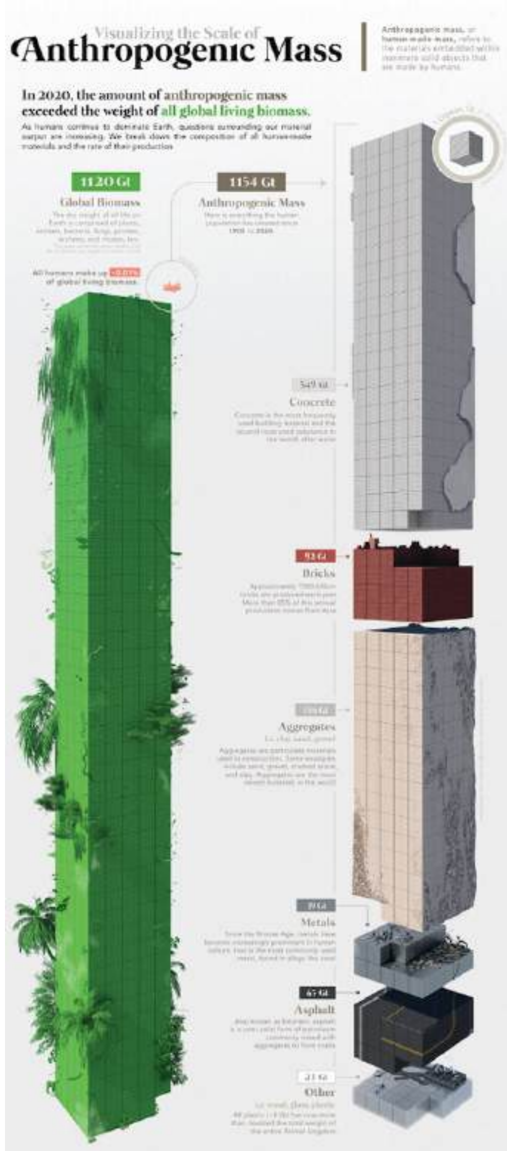




An important figure

Massive Demand in Energy and Materials

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]

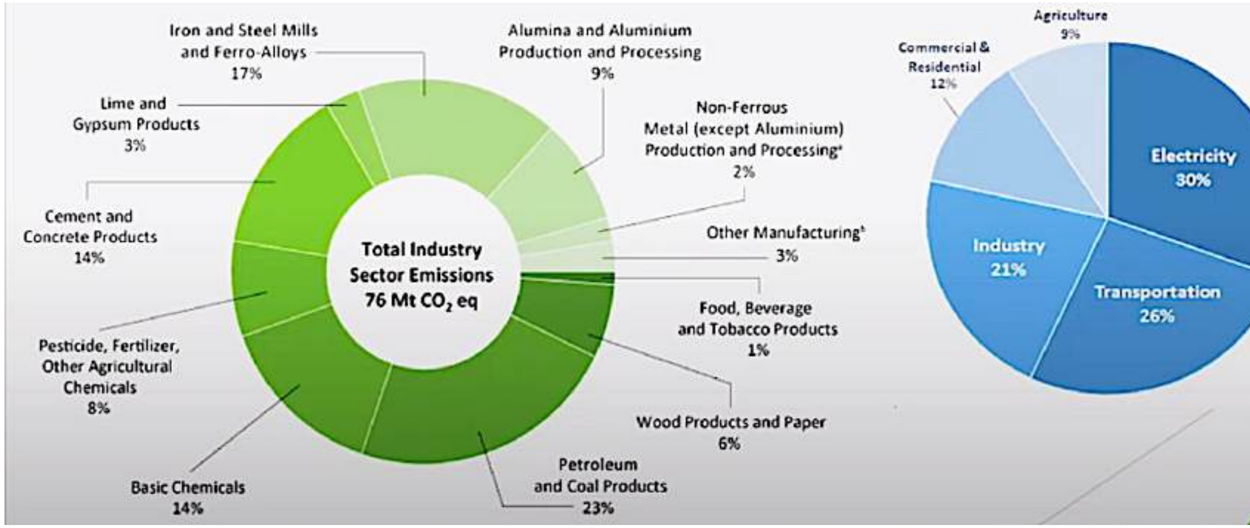


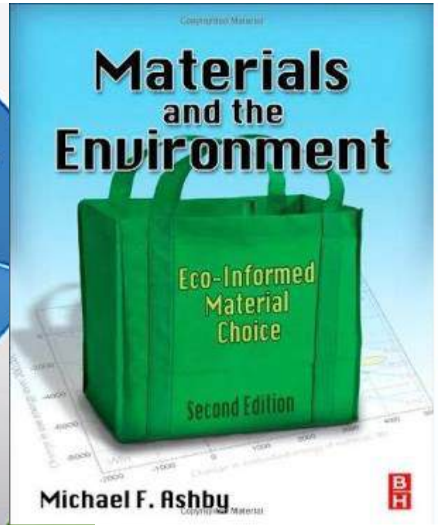
Materials and Energy ressources are linked and limited…

#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.

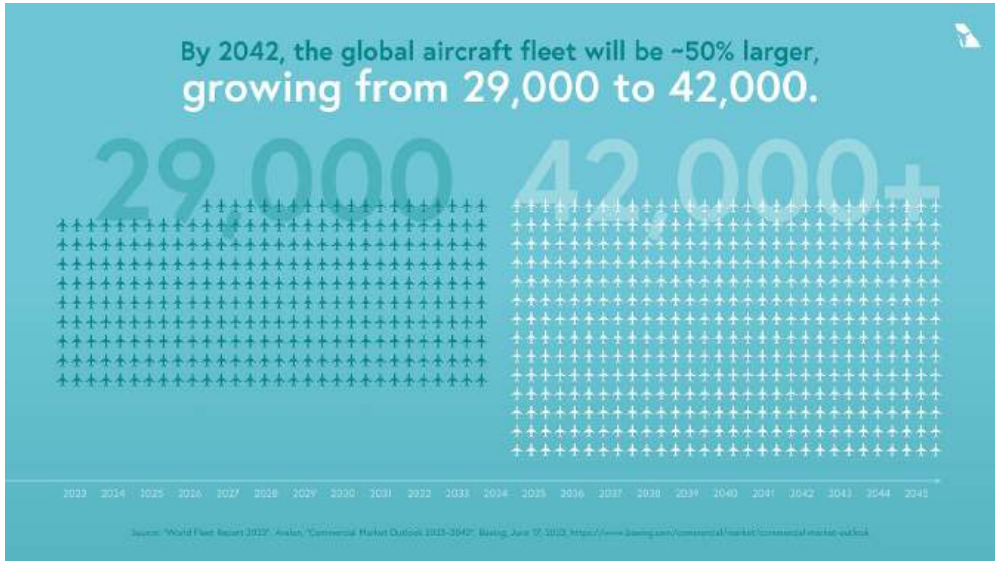
#In anticipation of 2050, the total tonnage of concrete, steel, aluminum etc… necessary for the development of these energies will be 2 to 8 times the world production of 2010. !!!

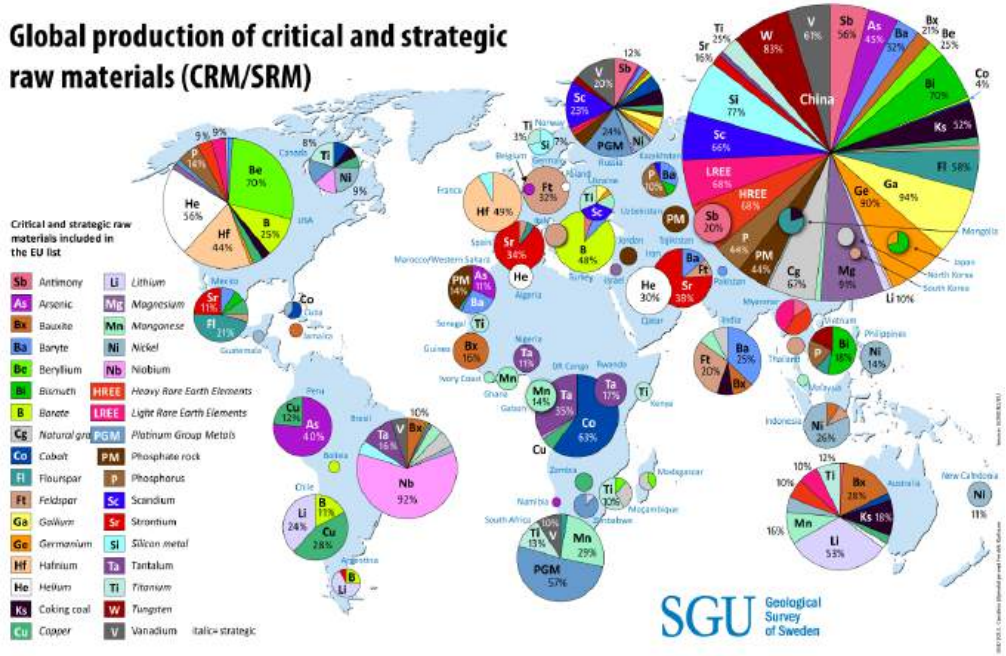




Sustainable aviation?

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





Quiz

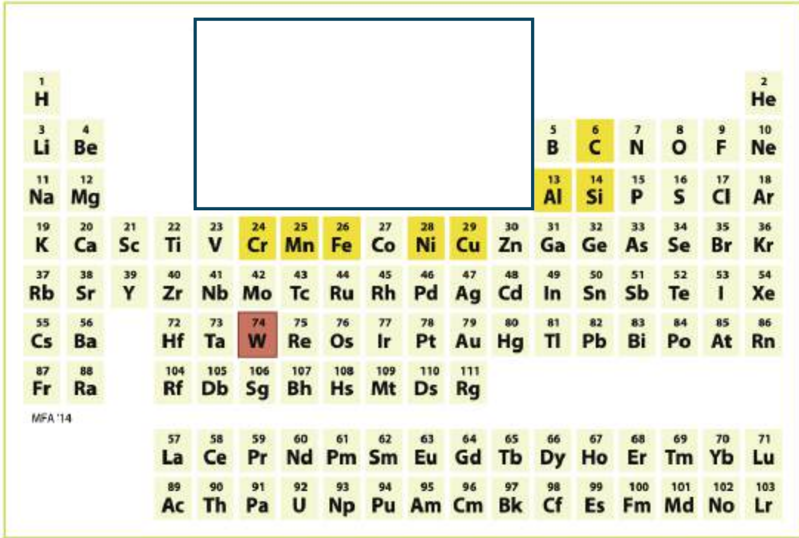
sustainable development goals (SDGs)

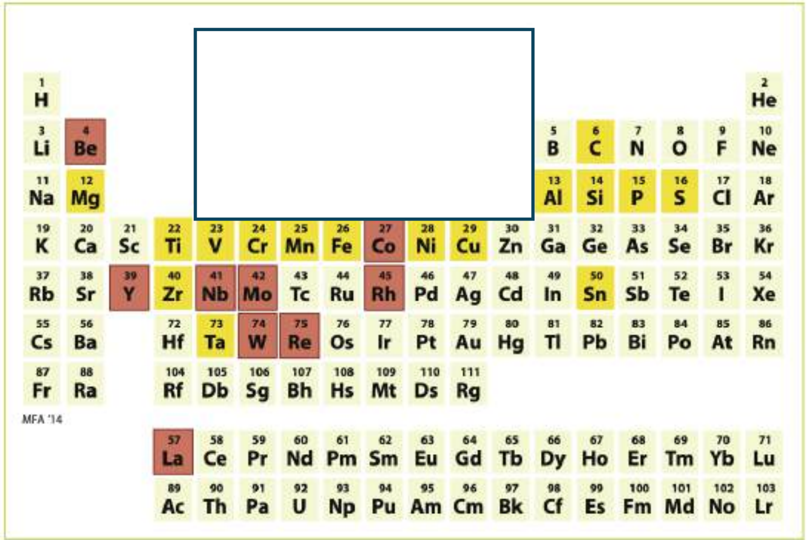
- What are these coloured boxes ?

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.



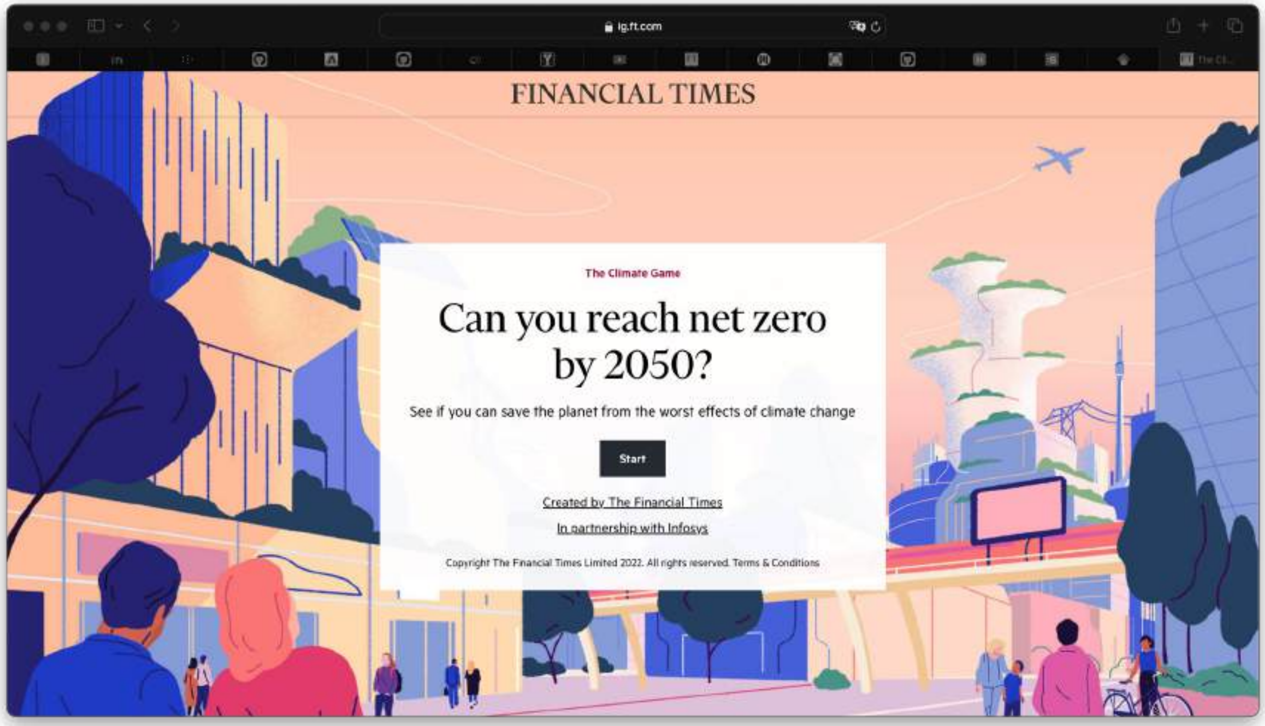


Petit Quiz 3/3

- Metals and energy transition

Energie éolienne	
Panneaux solaires	
Mobilité électrique	
Outils de communication (PC, téléphones, etc.)	

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



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10 Take away informations

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

The wheel of metals

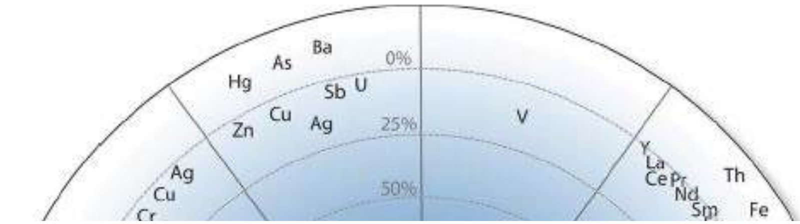
The energy transition will require a lot of metals, whether in quantity (tons) or in number of different metals. The balance between supply and demand will be delicate because demand is expected to increase rapidly in the coming years.

An interesting and often under-popularized point is that most metals are co-products or by-products: they are not mined for themselves.

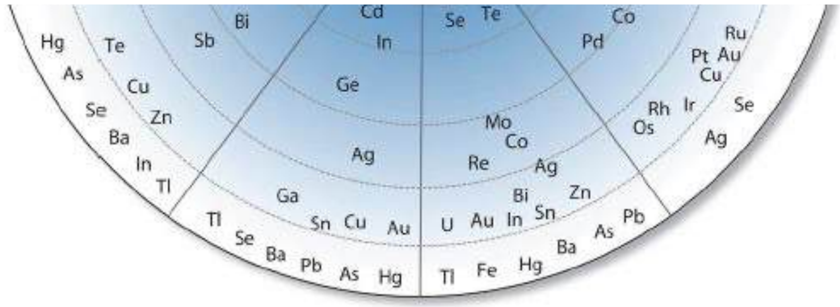
For example, 98% of cobalt is a by-product of copper and nickel mining (https://lnkd.in/d-8ZFh_m). Gallium is a by-product of aluminum or zinc mining.

A recent report from the International Institute for Sustainable Development discusses this point in detail and what it implies for the production of critical metals for the transition. It 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

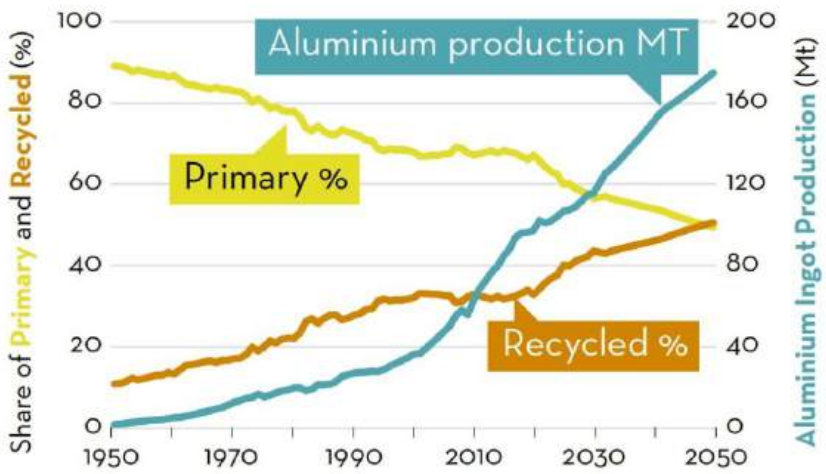
Aluminium

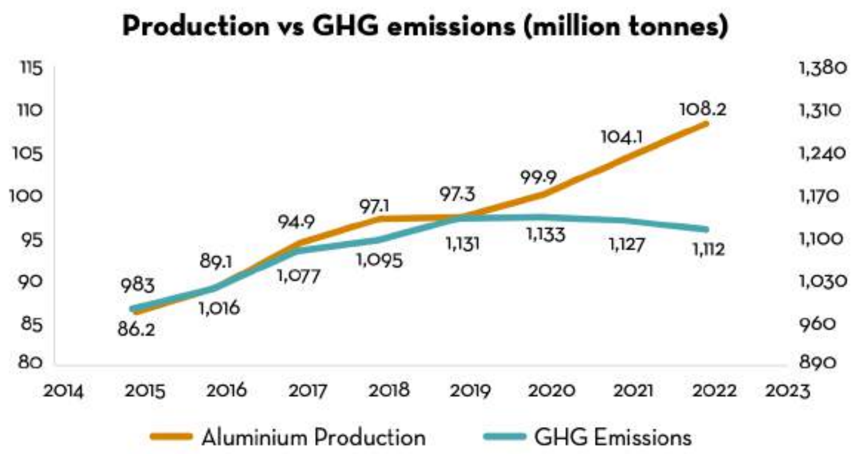
Titane

CFRP

Steel

Can you comment that ?





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

Aluminium?

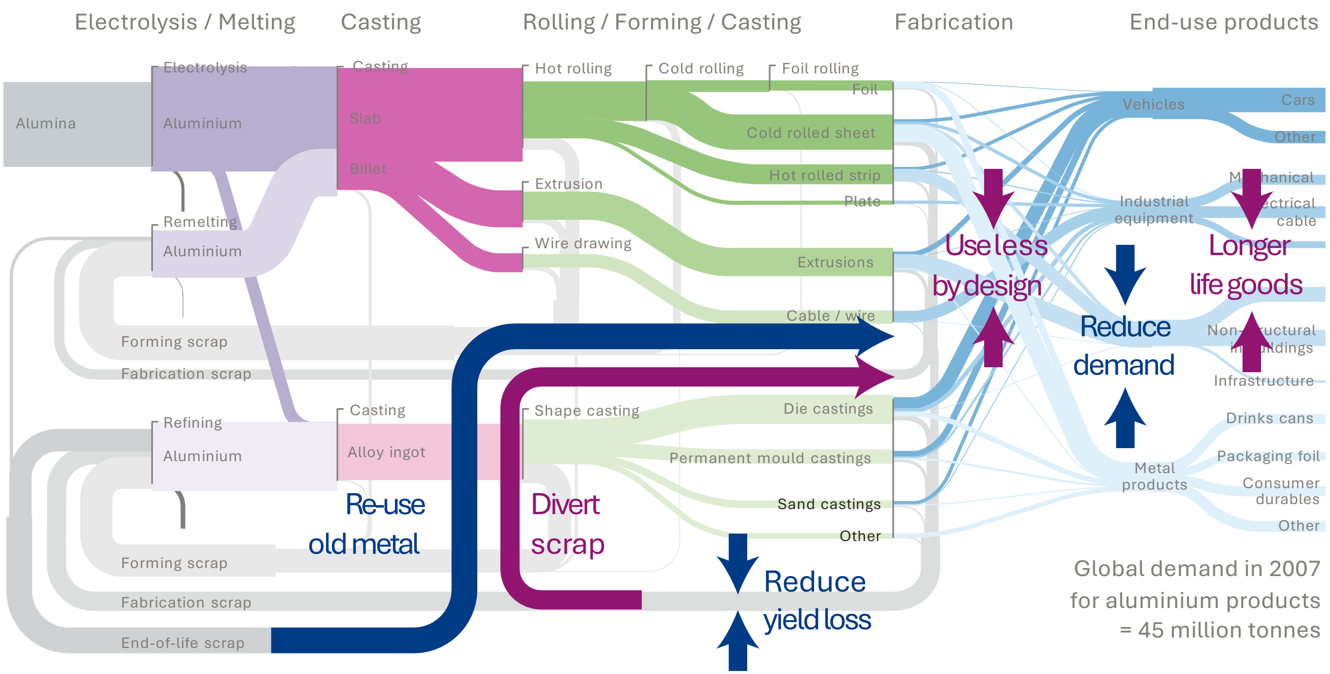
- https://www.visualcapitalist.com/aluminum-the-metal-extraordinaire/
- https://elements.visualcapitalist.com/how-is-aluminum-made/
- https://alucycle.world-aluminium.org/public-access/#global
- https://www.youtube.com/watch?v=6cUz7xCRk_E
- https://www.youtube.com/watch?v=BXHPNgww5Q8

With both eyes open in Aircraft Manufacturing

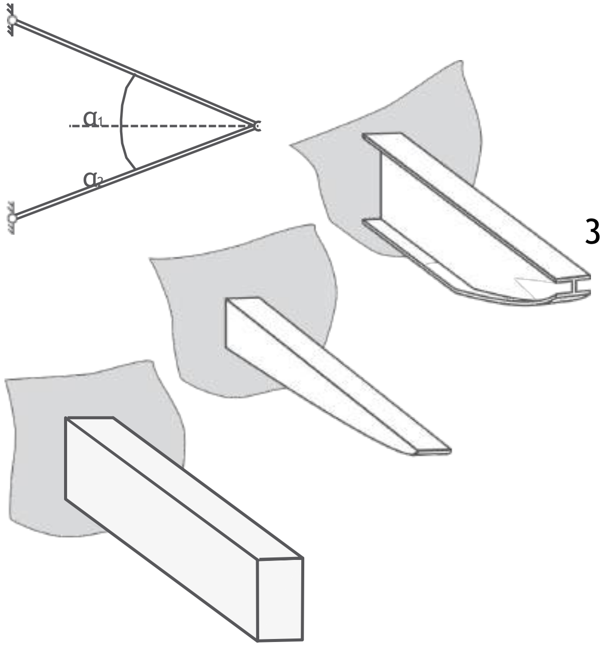
HTTPS://TINYURL.COM/CO2AEROSPACE

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??



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

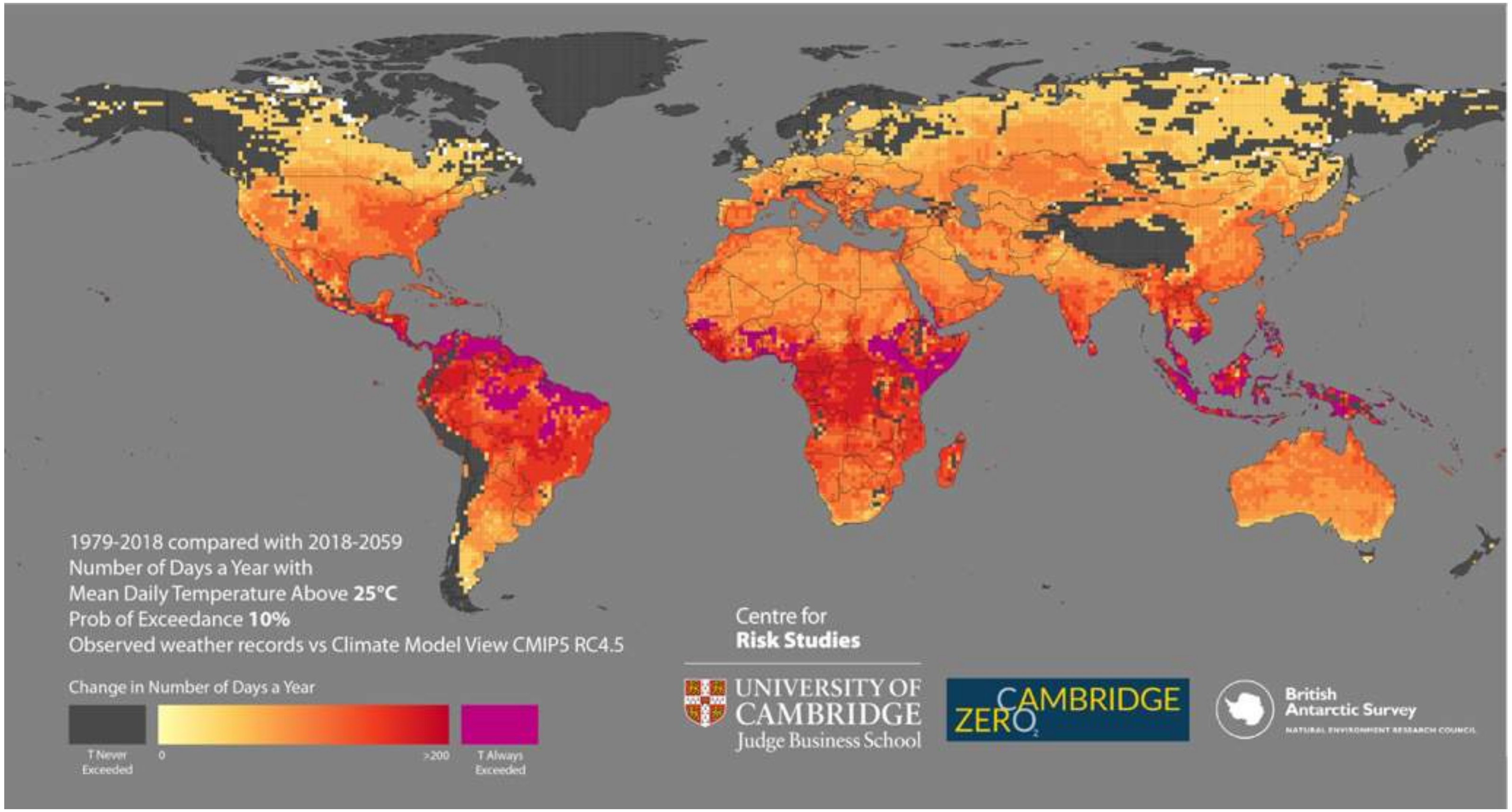
With both eyes open in Product design — what else can we do??

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??



WFG Act - Well-being of Future Generations

Finland, Iceland, Scotland, Wales and New Zealand are all members of the Wellbeing Economy Governments partnership.

The coalition, which is expected to expand in the coming months, aims to transform economies around the world to deliver shared well-being for people and the planet by 2040.

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

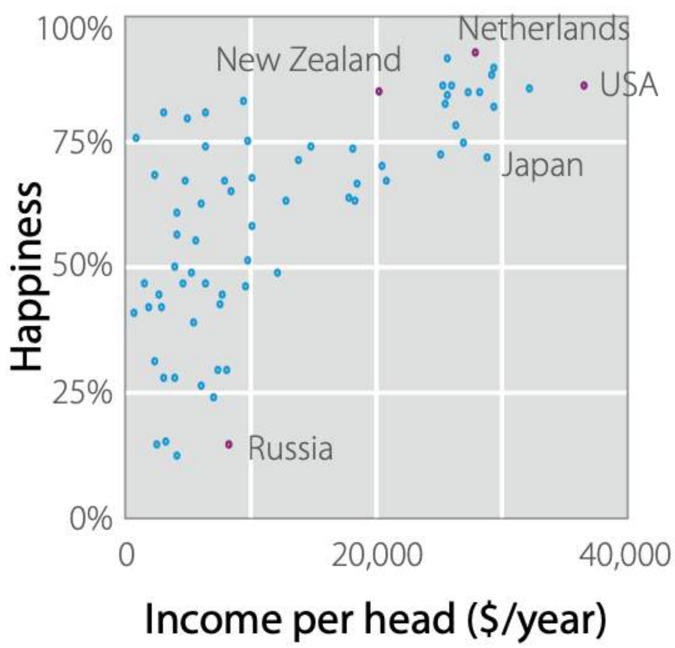


Figure 17.4—**The relationship between GDP and happiness**

If not material efficiency, then demand reduction?
→ Consume Less
→Reuse, Repair, Recycle

https://www.uselessgroup.org

The income method measures GDP by adding together: The Gross Profit of companies and the Self-Employed, plus the wages of employees (Compensation of Employees).plus all Taxes on Products like VAT.

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

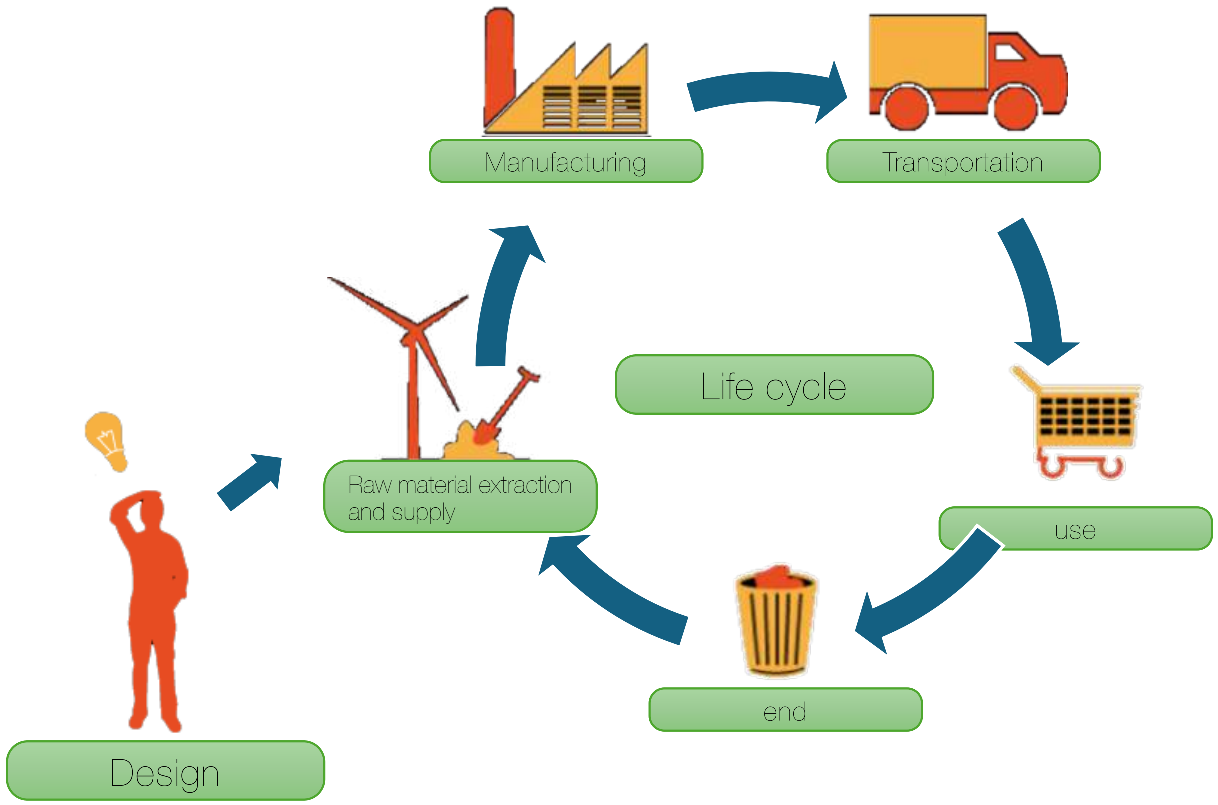
- Ecodesign is both a principle and an approach.
- It consists of integrating environmental protection criteria over a service or a product's lifecycle.
- The main goal of ecodesign is to anticipate and minimize negative environmental impacts (including manufacturing, operations and disposal).
- Simultaneously, 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)

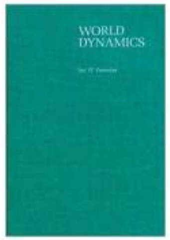
A global Approach



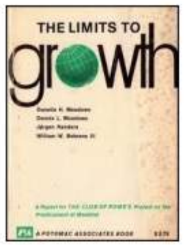
Main metrics (*The limits to Growth)*

- 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

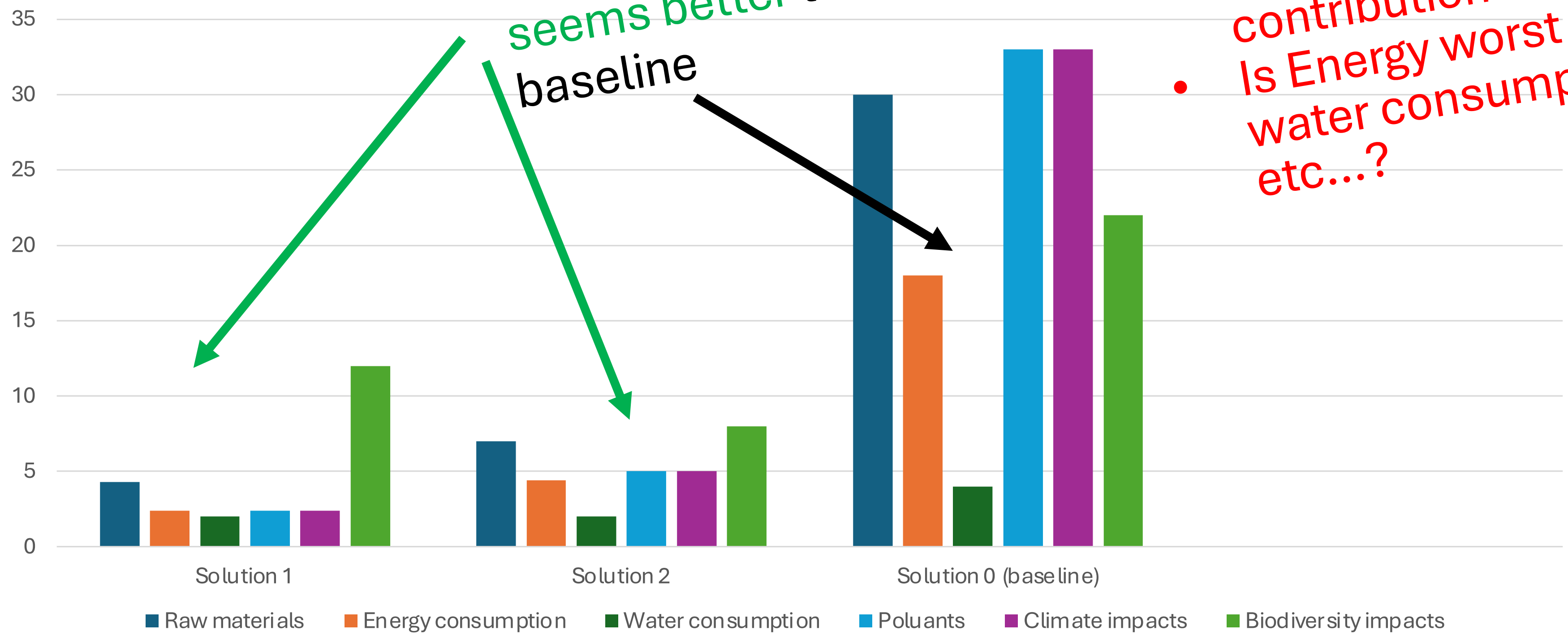
Can you conclude ?

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 CO_2 emission

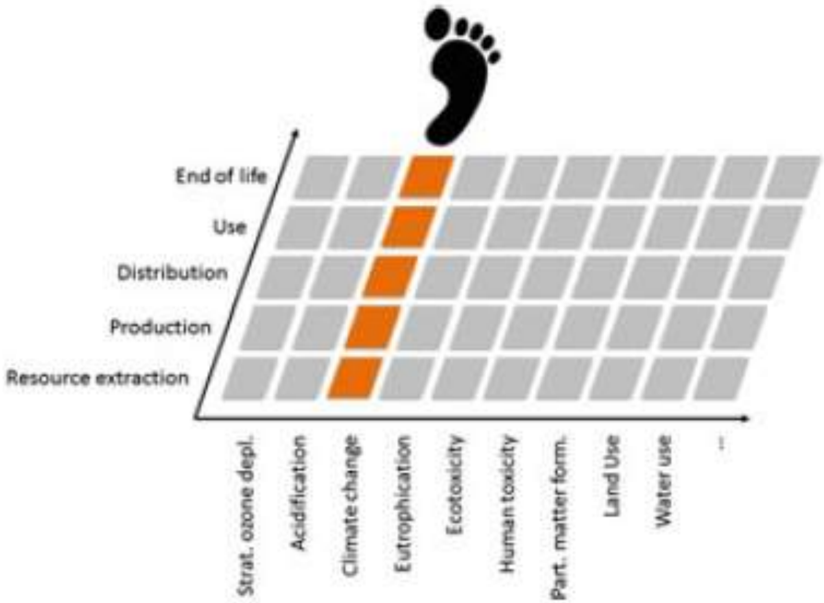
- Example : all GHG emissions are transformed into an equivalent CO_2 emission.

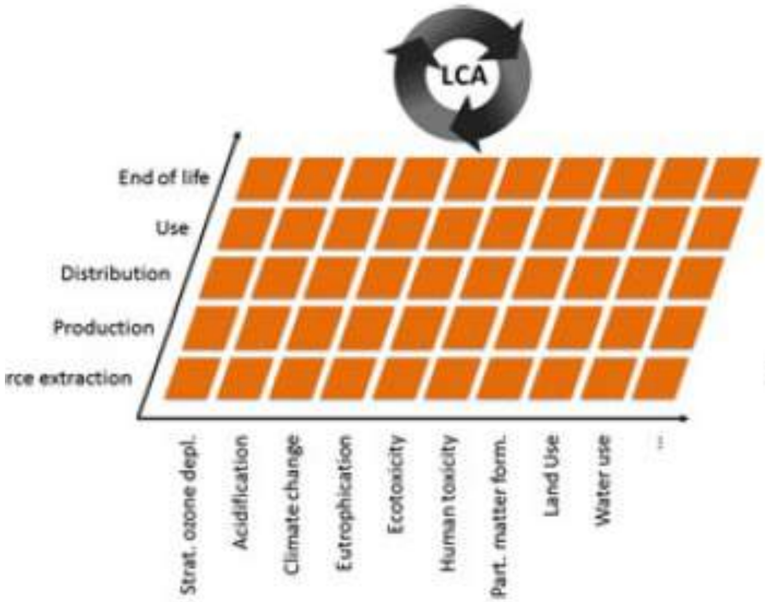
https://en.wikipedia.org/wiki/Carbon_footprint

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