Local and global energy considerations

What future for aviation ?

19/11/2024

Foreword

Many content is inspired by the work conducted by

Yri-Amandine KAMBIRI,

Phd student ENAC-SUPAERO

Outline

1) Energy transition : from World to Aviation

2) Aviation Energy Pathways

3) Carcassonne airport : an example

4) Toward Air Transport System (ATS) analysis

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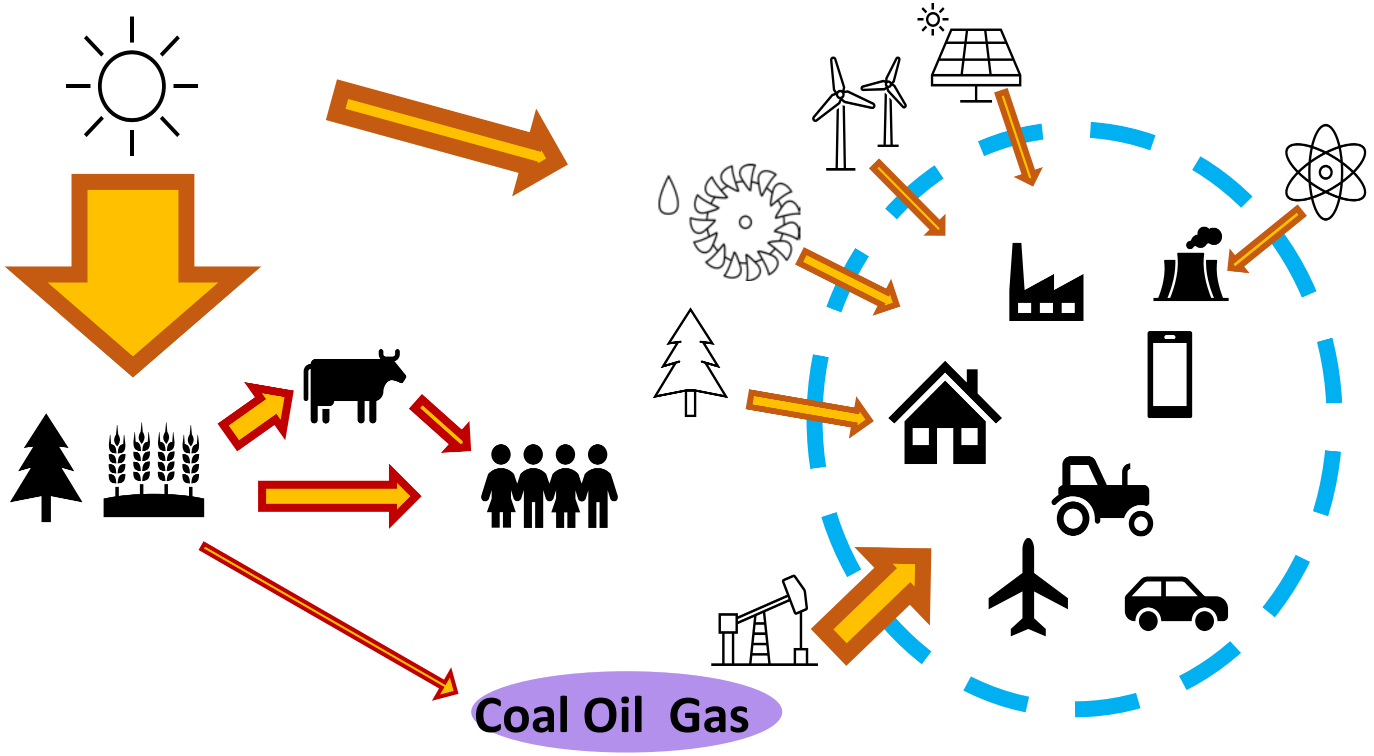
Human society and energy



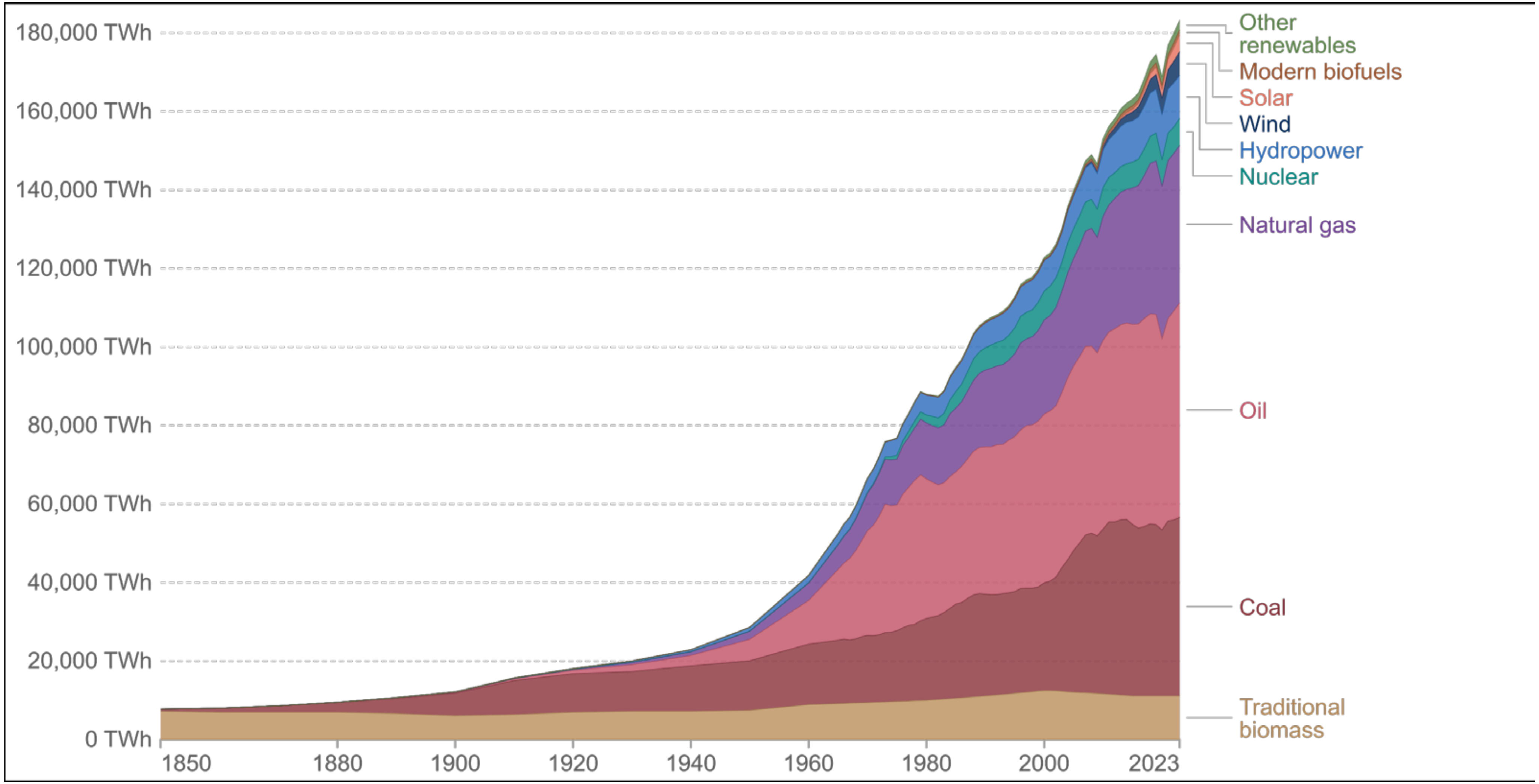
Primary energy includes all energy products not transformed, directly exploited or imported.

It mainly includes

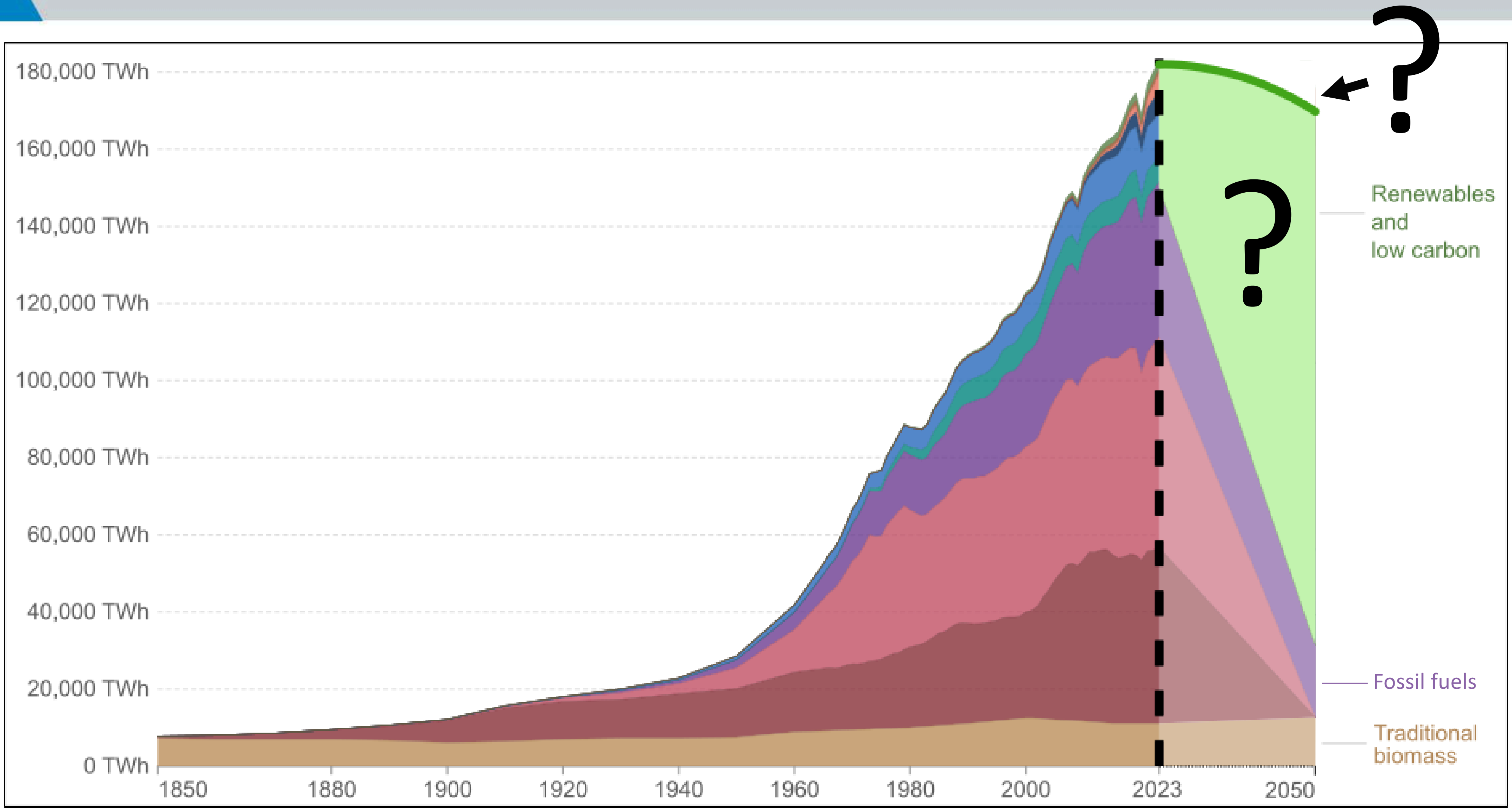
- *crude oil, oil shale, natural gas, solid mineral fuels*
- *biomass*
- *solar radiation, hydraulic energy, wind energy, geothermic energy*
- *and the energy taken from uranium fission.*

World primary energy

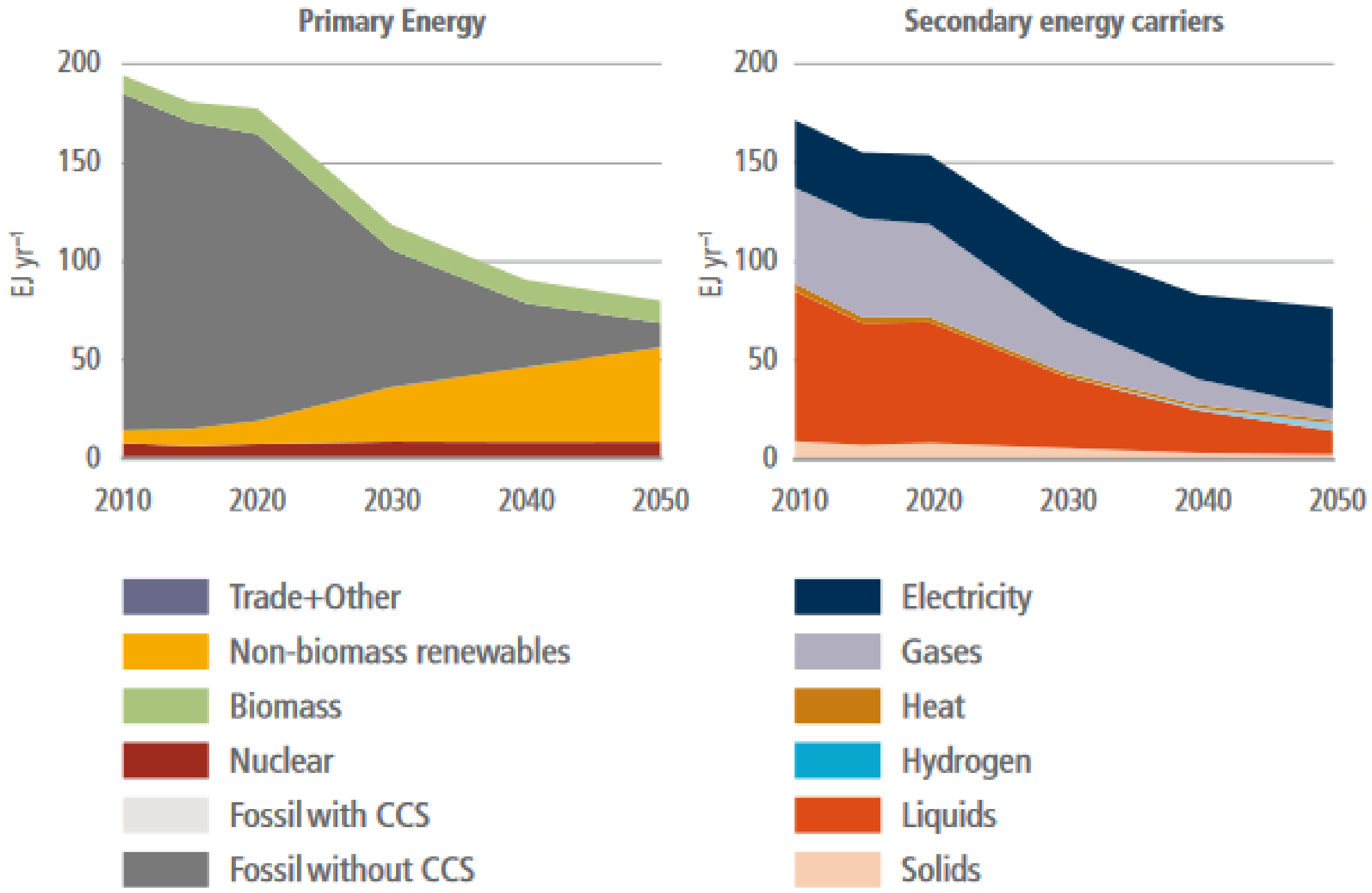
Data source : Energy Institute, (Smil 2017), substitution method
OurWorldinData.org/energy | CC BY



Energy transition



Energy transition in developped countries



IPCC 2022 : Mitigation of Climate Change,
Working Group III Contribution to AR6, Box 6.11, p690

- Strong decrease of fossil fuels
- Increase of non-biomass renewables (Wind, solar PV)
- Increase of electricity production

How to achieve this ?

- Electrification of Industry and transport (when possible)
- Build new electricity production units

-> Electricity production will not balance fossil fuel primary energy : efficiency gain.

Primary energy : 3 conventions

Three definitions of primary energy from non combustible sources :

- **Physical energy content** :
  heat for nuclear, geothermal / electricity for hydro-power, wind, solar PV
  Ex : *heat for nuclear, geothermal and electricity for hydro. Wind or tide/wave/ocean or solar PV*

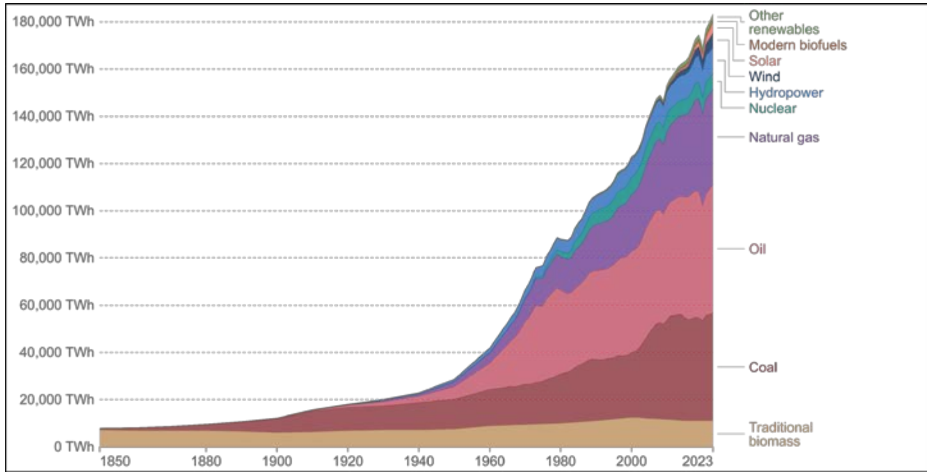
- **Direct equivalent** :
  1 kWh of secondary energy from non combustible = 1 kWh of primary
  Ex *: electricity for nuclear*

- **Substitution :**
  account non-combustible energy as if substitued for combustible energy
  Ex : *1 kWh of electricity (wind, solar, hydro, nuclear) is accounted as 2.63 kWh*
  (as if generated by a fossil fuel plant with an efficiency of 38%)*

IPCC, 2014 : Annex II: Metrics & Methodology',
in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to AR5, p 1294*

Example

Substitution method



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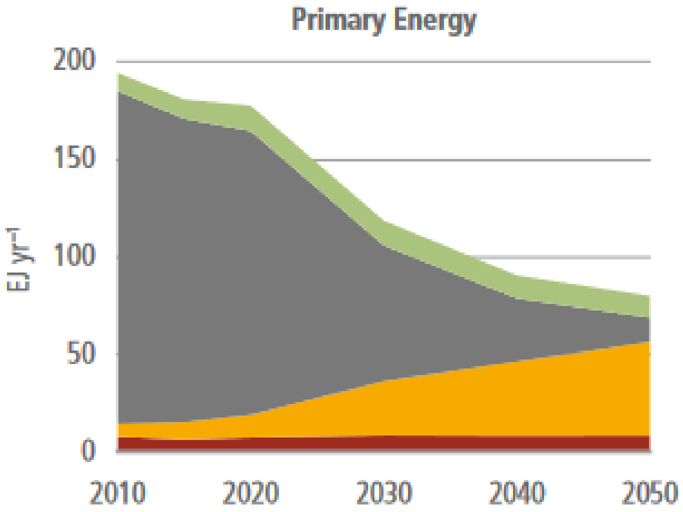
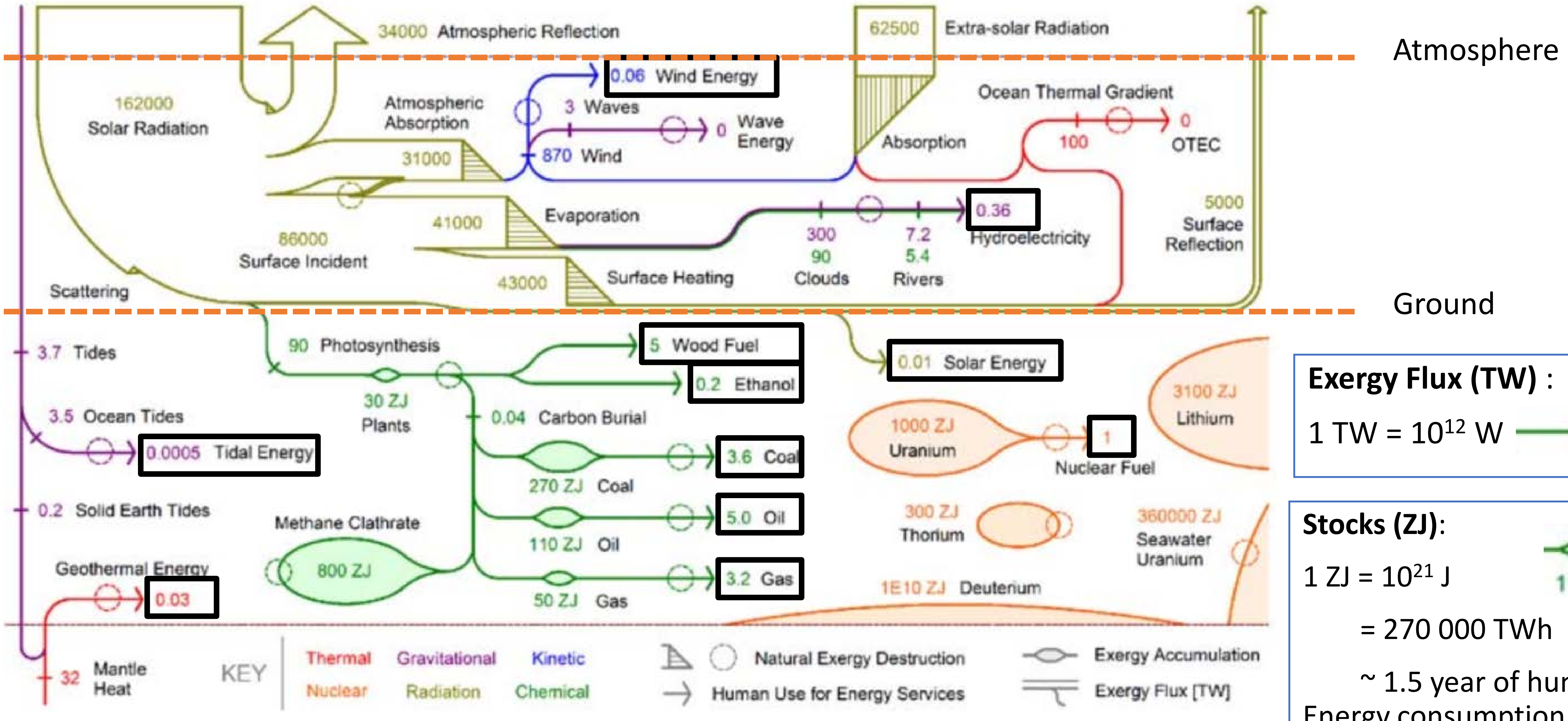
Direct equivalent method



En(x)ergy at Earth level

Hermann, Quantifying global exergy resources, Energy 31, 2006



Exergy Flux (TW) :

1 TW = 10^{12} W — 5.0 Oil

Stocks (ZJ):

1 ZJ = 10^{21} J — 110 ZJ Oil

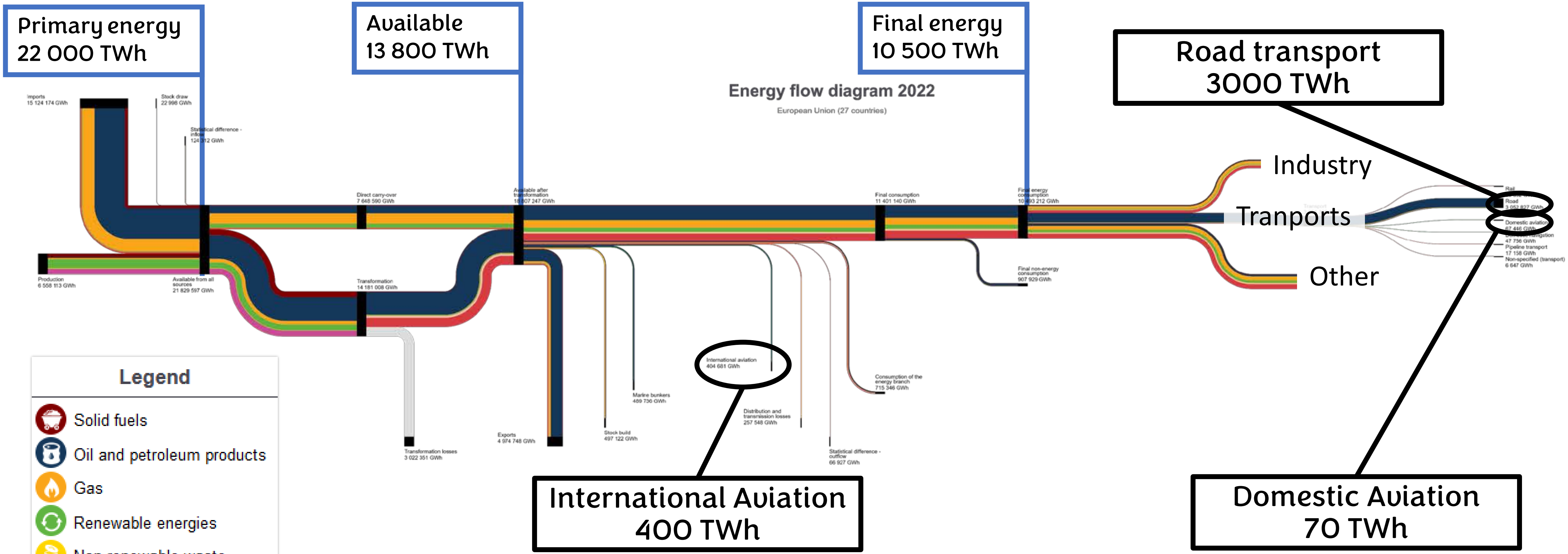
= 270 000 TWh

~ 1.5 year of human Primary Energy consumption (2023 level)

Global reservoirs, flux, and anthropogenic destruction of exergy (Hermann, 2006).

Energy at European level, 2022

Source: Eurostat, 2022



Commercial flights in Europe « consume » 3.4 % of today available energy after transformation (without exports)

Example of road transports

	Travelled Distance 2050* (10^9 Veh.km)	Energy consumption Combustion engine (liquid fuel TWh)	Energy consumption Electric cars (electricity TWh)
Light vehicles	4500	3100	950
Trucks, vans	580	1100	?
Total	5080	4200	?

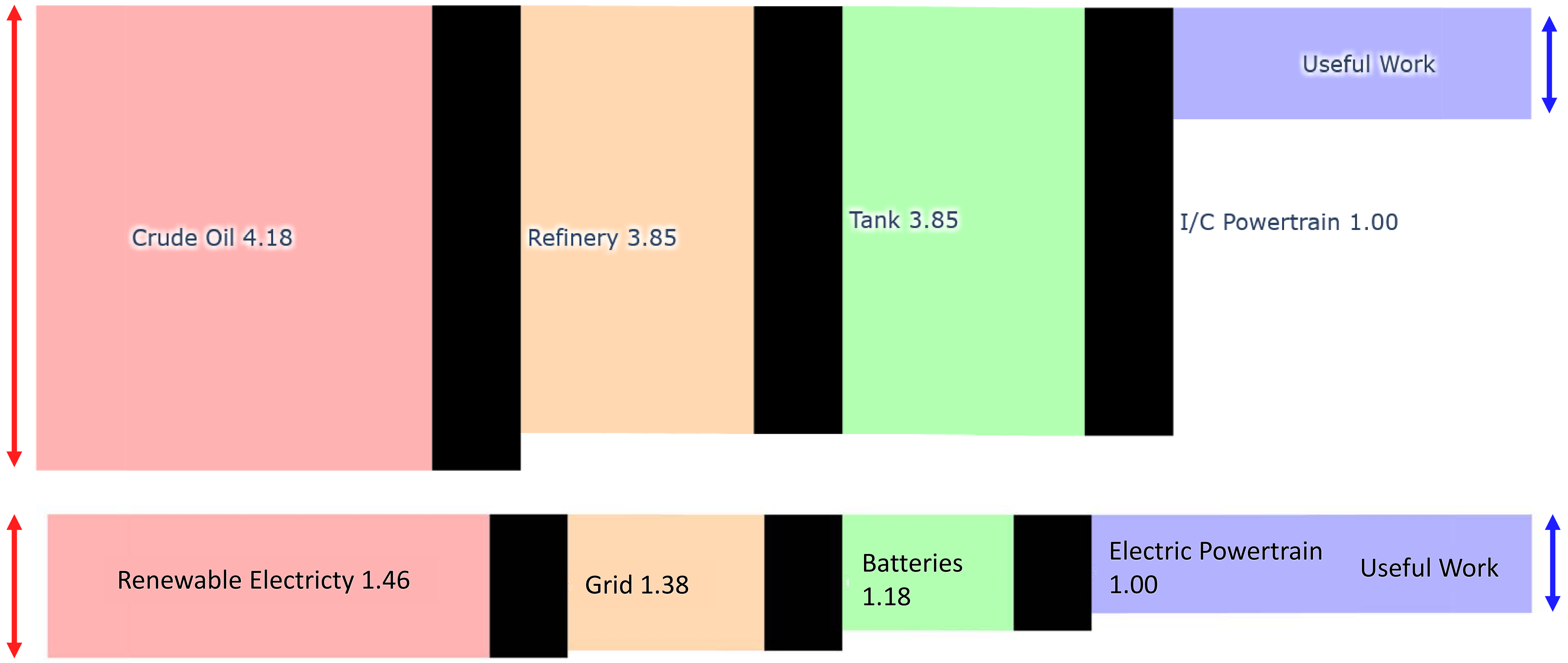
- **Combustion engine cars**
  - efficiency : $\eta = 0.26$ (C_d = 7 l/100 km = 70 kWh/100km)
- **Electric cars**
  - efficiency : $\eta = 0.85$ (C_d = 21 kWh/100 km)

$$\frac{Distance\ (m)}{Energy\ (J)}$$

$$\eta = \frac{Drag * Distance}{Energy_{input}}$$

*Krause, J. *et al.* (2020) 'EU road vehicle energy consumption [...]', *Energy Policy*

Energy Pathways : Combustion cars and Electric cars



Road transport and aviation

ROAD transport

- Better powertrain efficiency
- « Onboard energy » storage in batteries
- Nearly the same useful work

➔Rely on Renewable Electricity

(more than ~950 TWh)

Air transport

- Which powertrain efficiency ?
- Onboard Energy storage must be as « light » as possible
- Not the same useful work depending on airplane energy vector (mass)

➔Rely on Renewable electricty …

But how much ?

EU 27 electricity production (2022) : 2500 TWh

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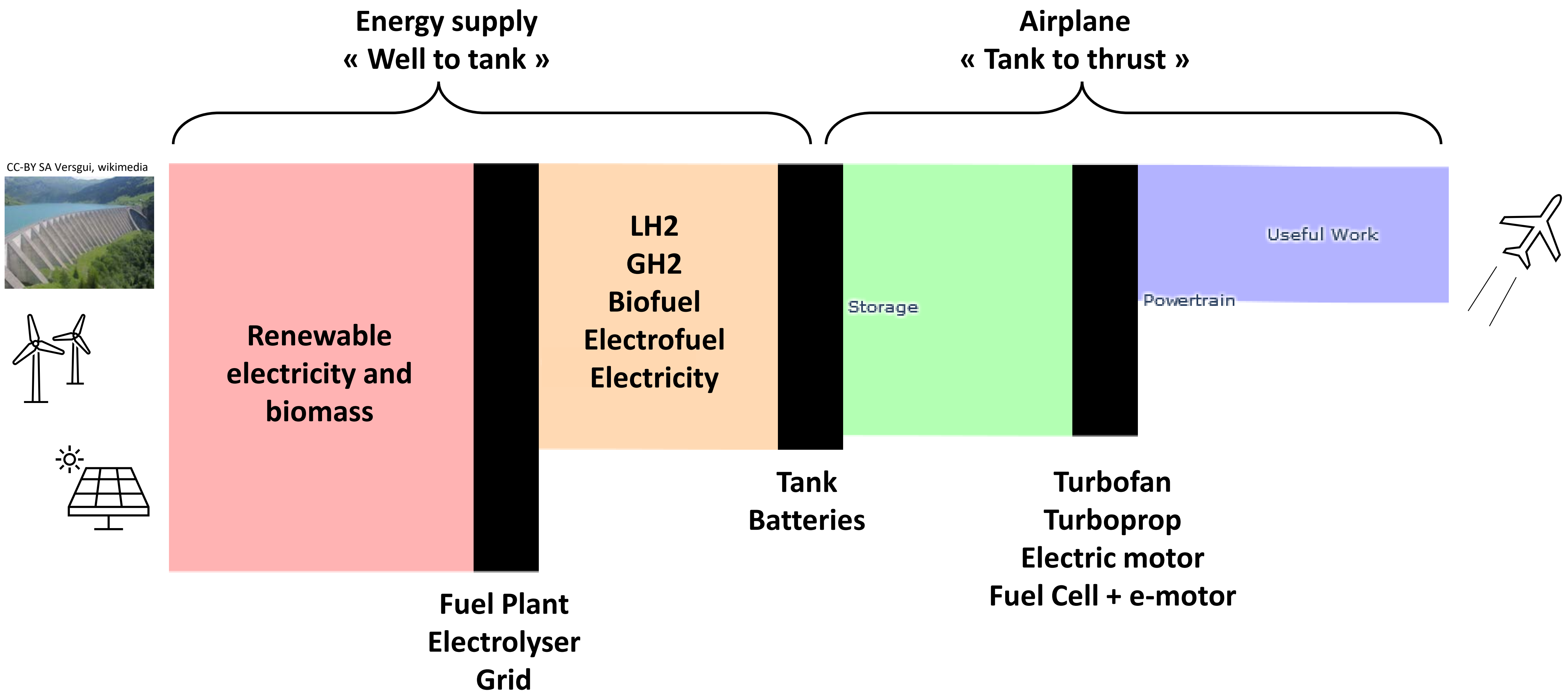
Aviation energy pathways



Aviation energy pathways

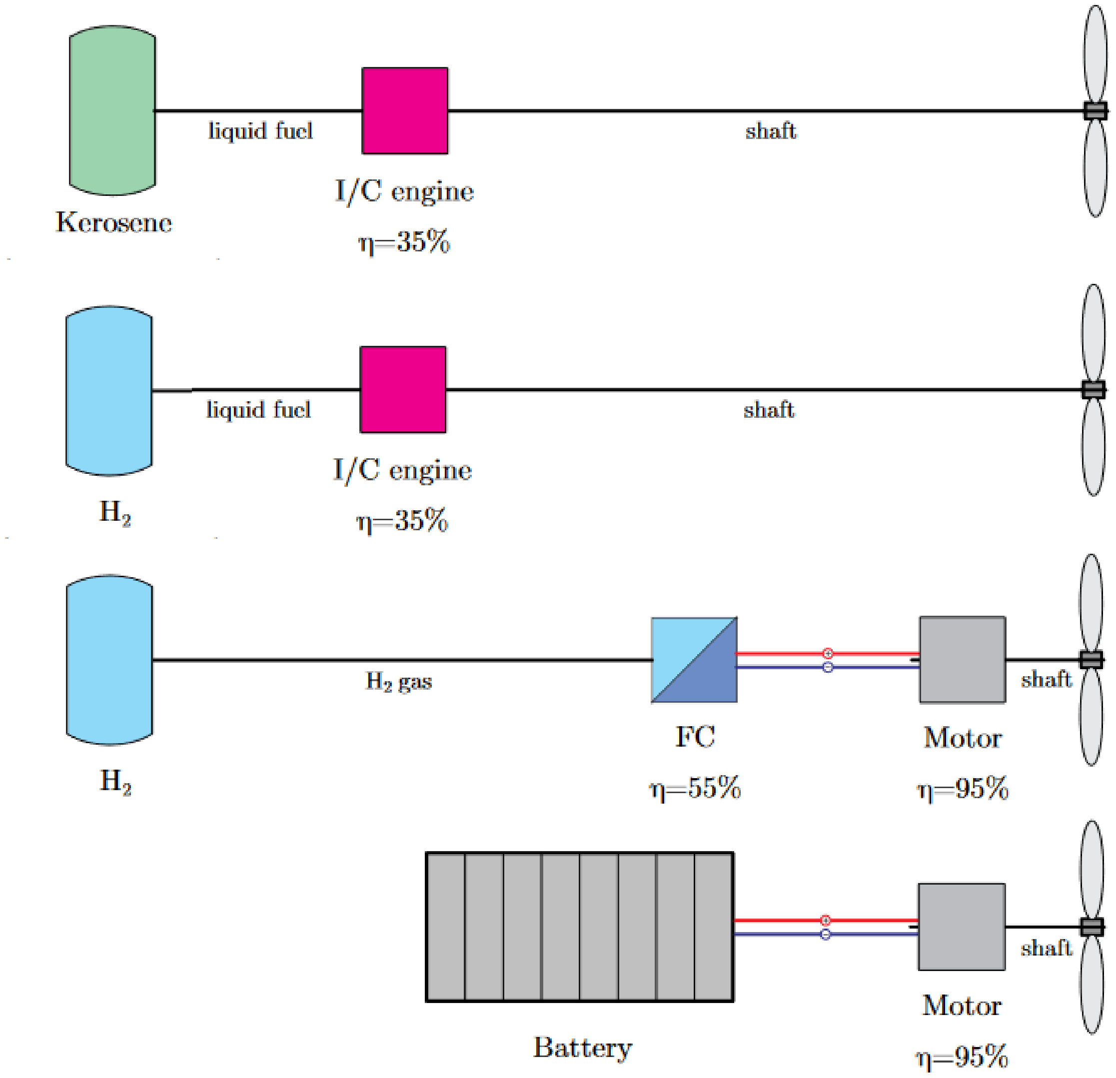
Ground side

- Renewable electricity production
- (electric grid)
- Electrolyzer (H2)
- Tanks and refueling
- Biofuels “refinery”
  - Land use (farming)
  - Use of organic wastes
- Electrofuels plants
  - Direct air capture (DAC)
  - Concentrated source
  - Fisher-Tropsch/methanol

Airplane side

- Conventional airplane
- Conventional airplane* (SAF)
  - biofuels
  - Electrofuels
- Hydrogen airplane
  - Combustion/fuel cell+electric motor
  - Liquid/gaseous storage
- Electric airplane (batteries)
- Methane airplane ?

Airplane future powertrains



Kerosene I/C engine	$\eta \simeq 0.35$	Kerosene combustion
Hydrogen I/C engine	$\eta \simeq 0.35$	Hydrogen combustion
Hydrogen Fuel Cell	$\eta \simeq 0.5$	Hydrogen + Fuel Cell + Electric powertrain
Battery	$\eta \simeq 0.9$	Batteries + Electric powertrain

Hepperle, M. (2012) *Electric Flight – Potential and Limitations*

Airplane design matters !

Mass of stored energy

Range equation

$E_{mission}/LHV$

(fuels) $$Range = \frac{L/_D\, \eta\, LHV}{g} \ln\left(1 + \frac{m_{fuel}}{m_{end\,of\,cruise}}\right)$$

$E_{mission}/E^*$

(batteries) $$Range = \frac{L/_D\, \eta\, E^*}{g} \frac{m_{bat}}{m_{airplane}}$$

Energy carrier	LHV or E* (MJ/kg)
Kerosene	43
Hydrogen	120*
Methane	50*
Battery (Li-ion 350 Wh/kg))	1.3

* Tank mass not included gravimetric index

$$GI = \frac{m_{H_2}}{m_{H_2} + m_{tank}}$$

Conceptual airplane design tool

« CADO airplane database »

230 civil transport airplane database

Avalaible at recherche.data.gouv:

https://doi.org/10.57745/LLRJO0


CADO airplane database

Version 1.3

MONROLIN, Nicolas; DRUOT, Thierry; PETEILH, Nicolas; ROCHES, Pascal; KAMBIRI, Yri-Amandine, 2024, "CADO airplane database", https://doi.org/10.57745/LLRJO0, Recherche Data Gouv, V1, UNF:6:PrOS8wpPSswguppl7TJlRg== [fileUNF]

Citer le jeu de données ▾

Pour en apprendre davantage sur le sujet, consulter le document Data Citation Standards [en].

« Generic Airplane Model »

Python library

Available on Gitlab

https://gitlab.com/m6029/genericairplanemodel.git

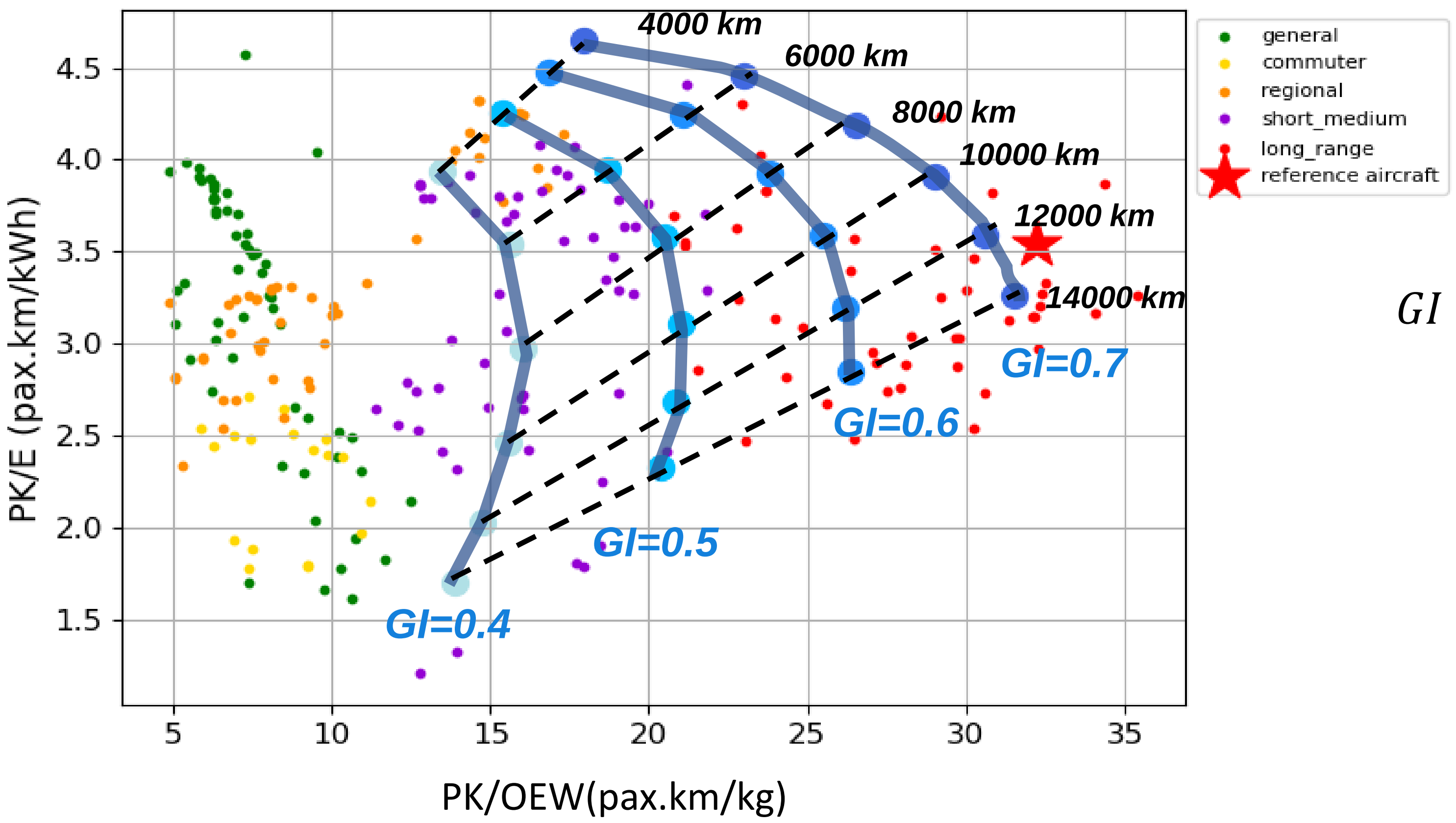
Airplane « Tank to thrust »

- Design range : 5500 km
- Mach 0.78
- Cruise altitude 35 000 ft

Energy carrier	Cd (kWh/pax/100 km)	MTOM (t)	MZFM (t)	Payload max (t)
Kerosene	19.3 (2 L/pax/100 km)	73.6	60.2	19.8
LH2 (combustion)	30.0	88.8	82.5	19.8
LH2 (fuel cell)	35.5	130	122	19.8
CH4	21.9	80.9	68	19.8

DO NOT TAKE THIS RESULTS FOR GRANTED !

Influence of the gravimetric index



$$GI = \frac{m_{H_2}}{m_{H_2} + m_{tank}}$$

PK = design pax capacity

×

design range

Kambiri *et al.* (2024) 'Energy consumption of Aircraft with new propulsion […]', *AIAA SCITECH 2024*

Well to tank

- Biomass -> kerosene : **biofuel**
  Biomass -> methane : biogas

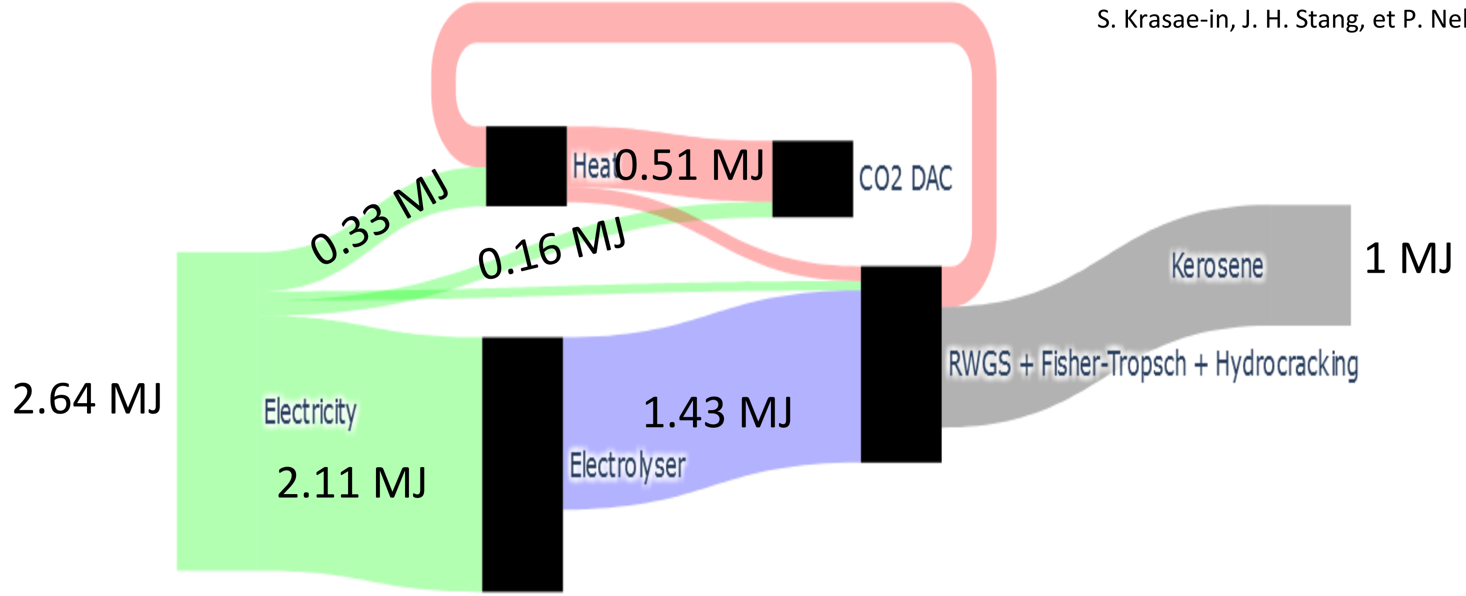
- Electricity + CO2 -> kerosene : **electrofuel**

- Electricity + water -> Hydrogen

- Electricty to batteries

Energy pathways models

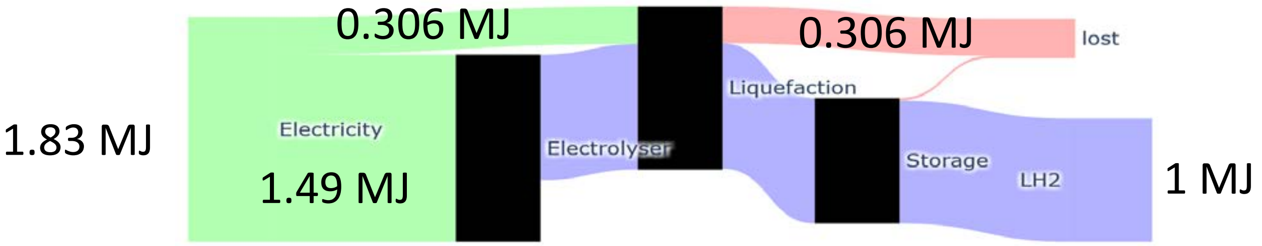
Soler et Schmidt, « E-Fuels: A Techno-Economic Assessment of EU Domestic Production and Imports towards 2050 », 2024
S. Zs. Al Ghafri *et al.*, *Energy Environ. Sci.*, 2022
S. Krasae-in, J. H. Stang, et P. Neksa, *International Journal of Hydrogen Energy*, 2010



Electrofuel (FT + DAC)

- Electricity
- Hydrogen
- Efuel
- Heat or losses

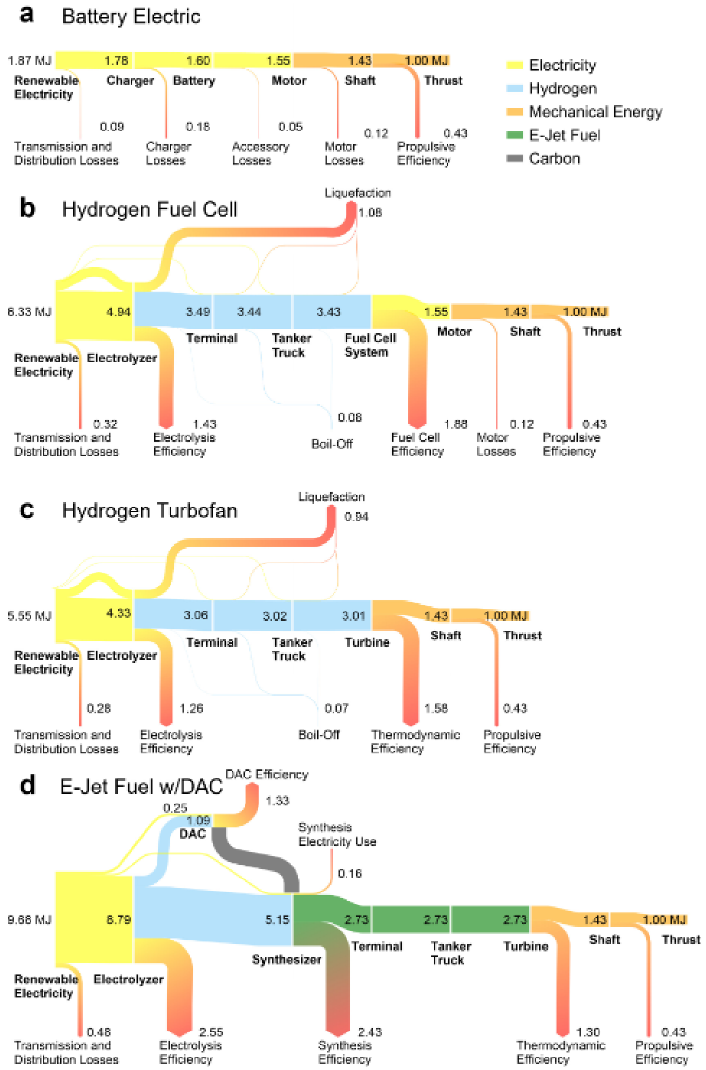
DAC : Direct Air Capture
FT : Fischer Tropsch
RWGS : Reverse Water Gas Shift



Liquid Hydrogen

Sankey diagrams

Wallington, T.J. *et al.* (2024)
'Green hydrogen pathways, energy efficiencies, and intensities for ground, air, and marine transportation', *Joule*, 8(8), pp. 2190–2207.



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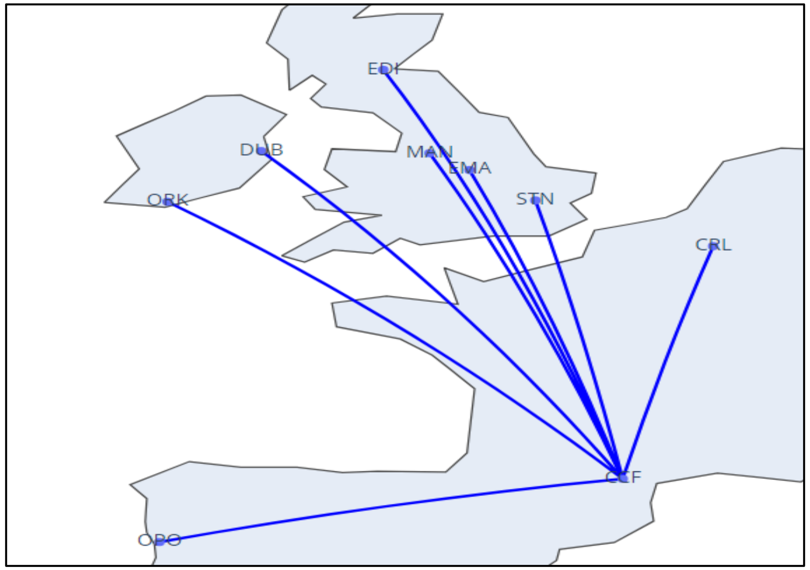
Case study : Carcassonne airport

Carcassonne network in 2022.



Airplanes operated in 2022

Aircraft	737-800 winglets
Design range (km)	5400
Offered seats	160
Energy type	kerosene

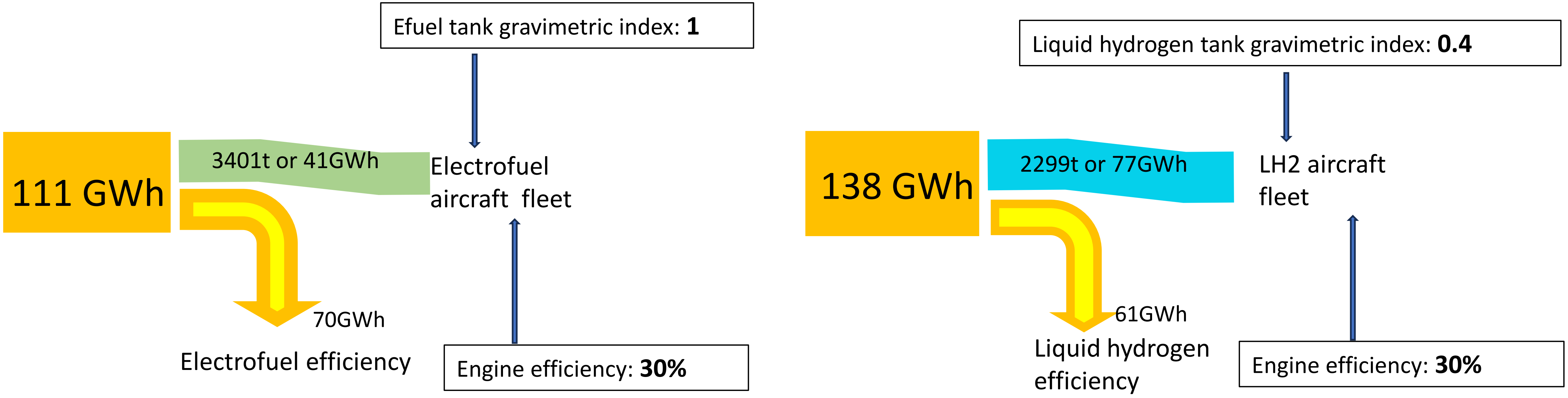
Two scenarios :

- **Full Electrofuel aircraft fleet**
- **Full Liquid hydrogen aircraft fleet**

Source : OAG database (Official Airline Guide)

Carcasonne airport: Result

Electricity and energy needed to refuel the Carcassonne fleet



DO NOT TAKE THIS RESULTS FOR GRANTED !

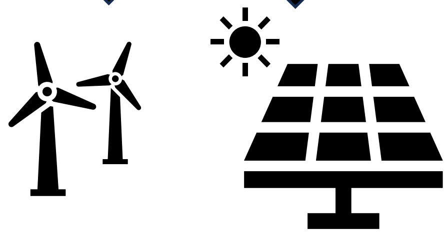
Annual efuel consumption
Annual electricity need
Annual LH2 consumption

Carcasonne airport: Result

Energy-self-sufficiency scenario 1: Using airport resources

Electrofuel aircraft fleet

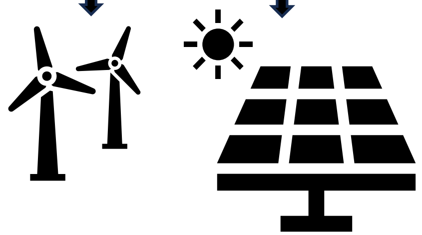
111 GWh



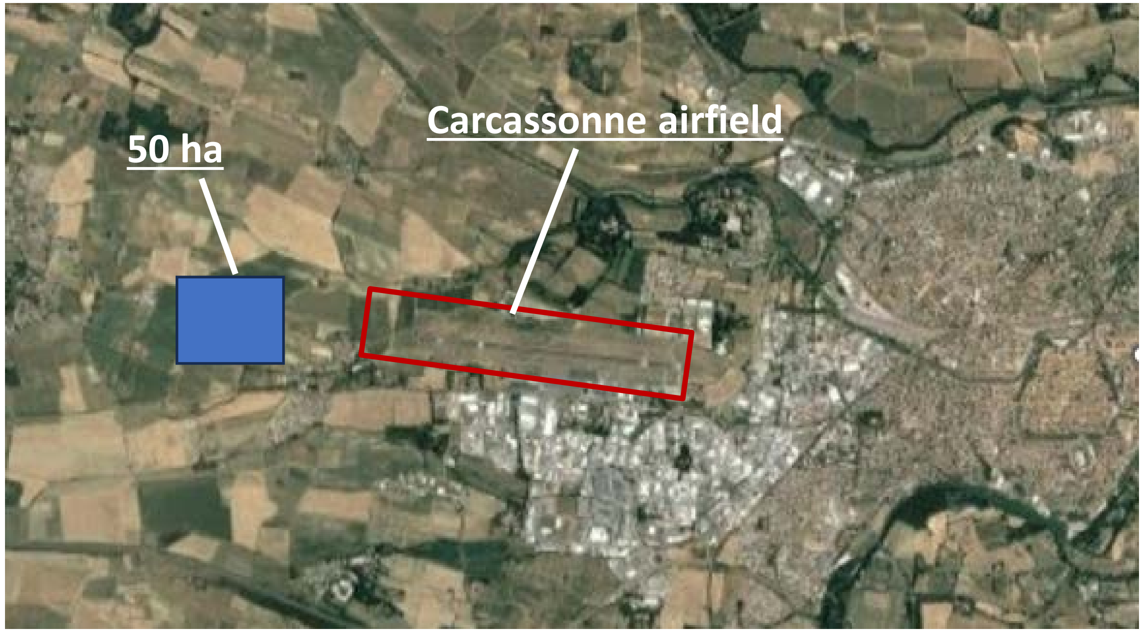
21 or 49 ha

LH2 aircraft fleet

138 GWh



25 or 61 ha

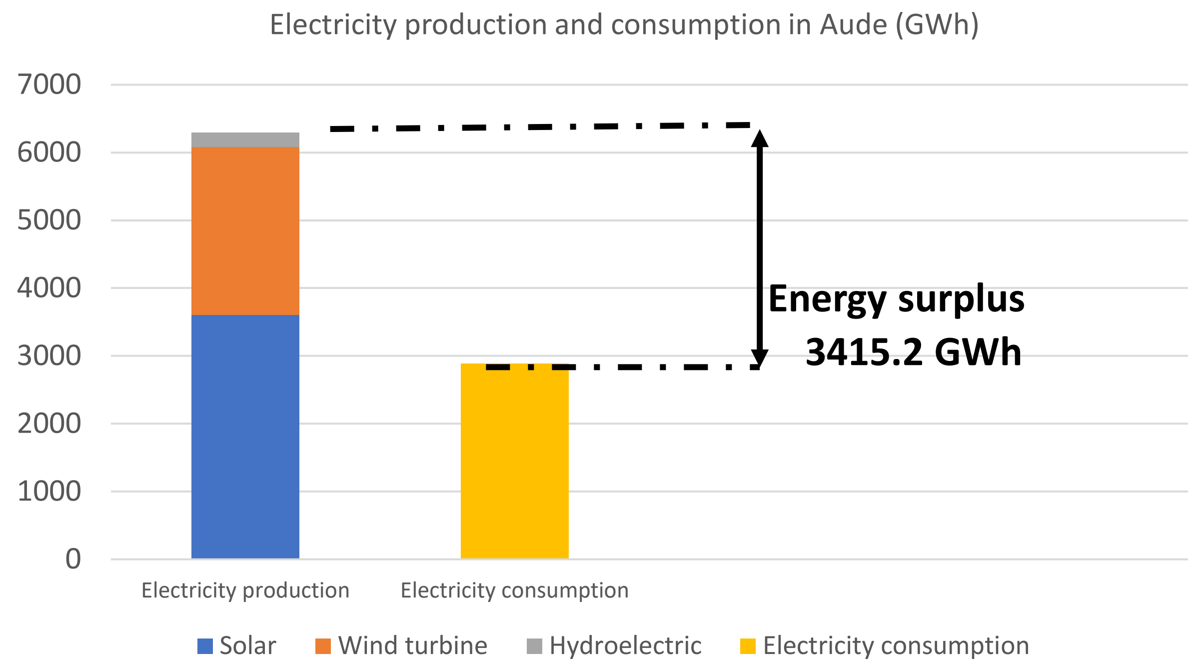


➢ **General assumptions:**

- Solar panel efficiency: 0.15
- Nominal power of an onshore wind turbine: 3MW

Carcasonne airport: Result

Energy-self-sufficiency scenario 2: Using Aude department resources

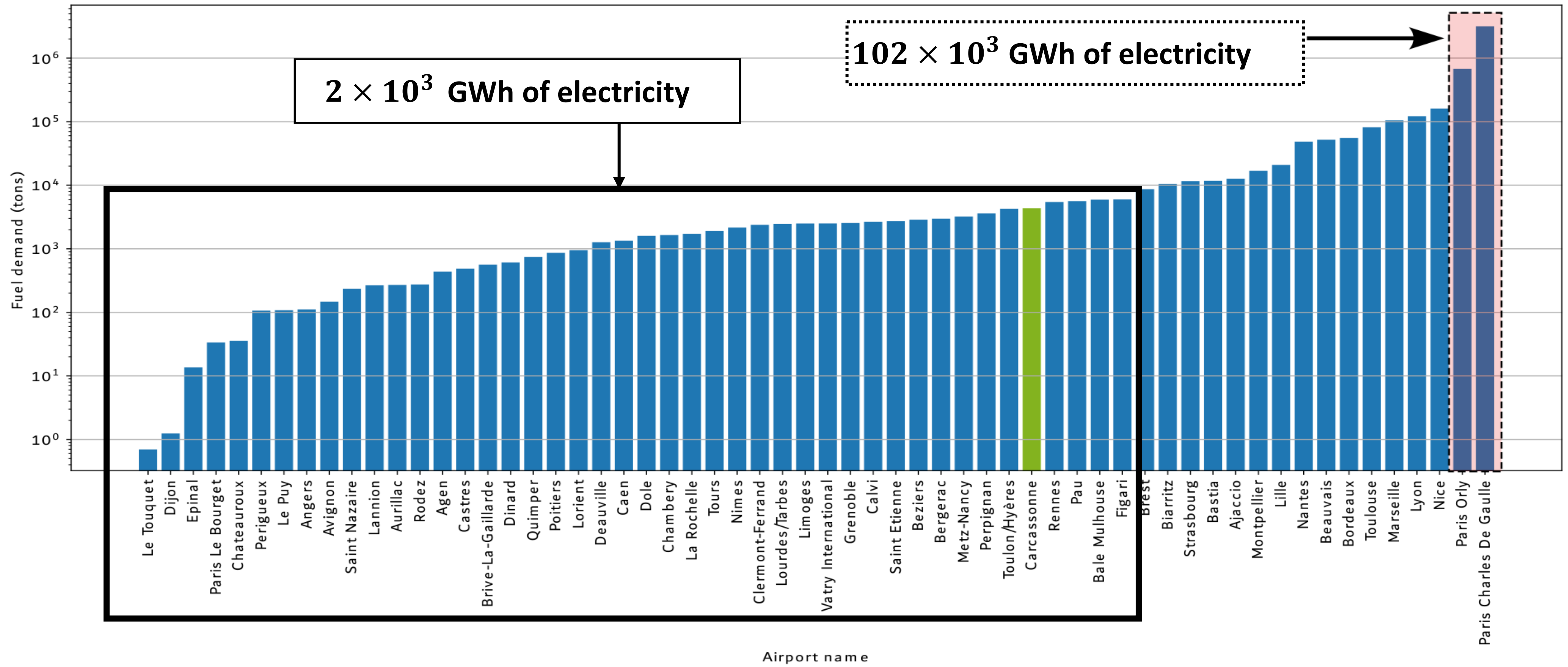


Trend scenario in 2030
Source : Aude Department Projet

Between 3% and 4% of Aude's surplus energy production (trend scenario)

French airport in 2016

Efuel consumption estimation based on the French air traffic data in 2016



Conclusion: Small regional airports have the potential to achieve energy self-sufficiency, taking into account local weather conditions such as solar irradiation and wind.

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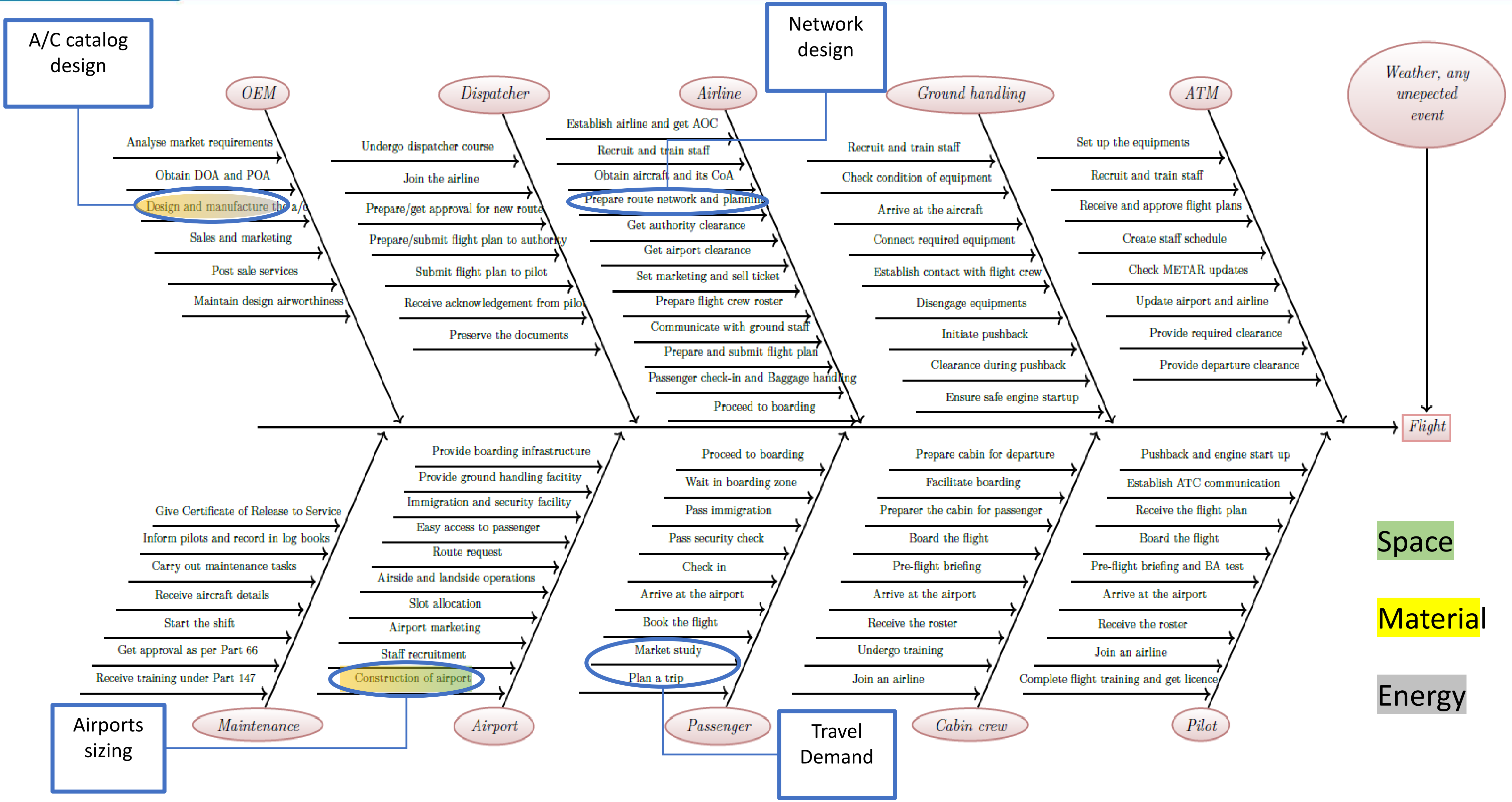
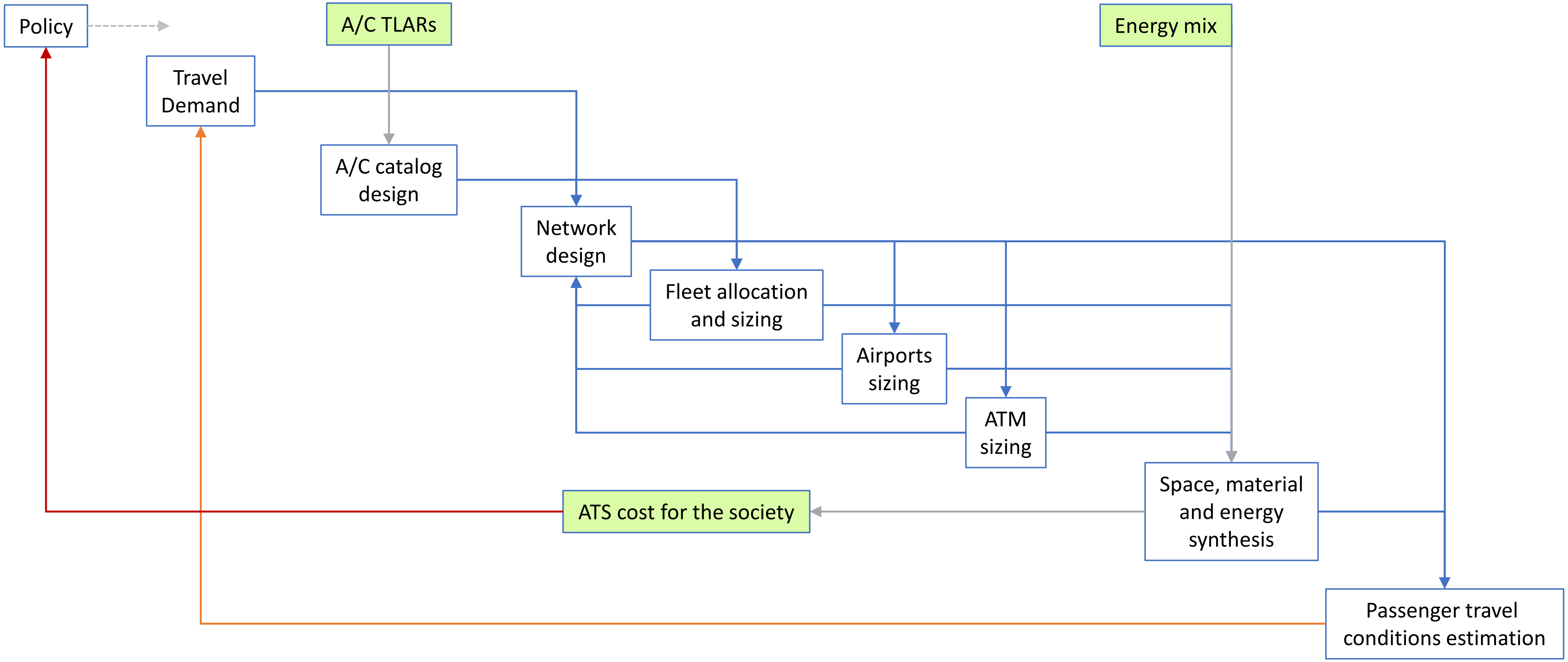
Air transport system



MDA of the air transport system



A set of uncertainty to be quantified

Technology uncertainty:

- Hydrogen tank : GI [0.2 ; 0.6]
- Electrolyzer : efficiency [0.5 ; 0.7] ?
- DAC heat source ?
- Fischer-Tropsch efficiency ?
- Battery energy density in the future ?

Process uncertainty

- Airplane design
- Power plant design ?
- Electrolyzer / FT design ?

Conclusion

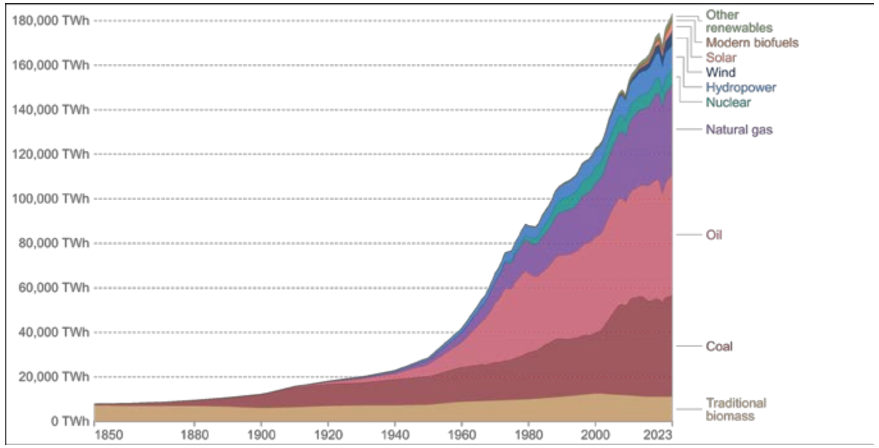
- Energy transition is especially challenging for aviation.
  (energy carrier)

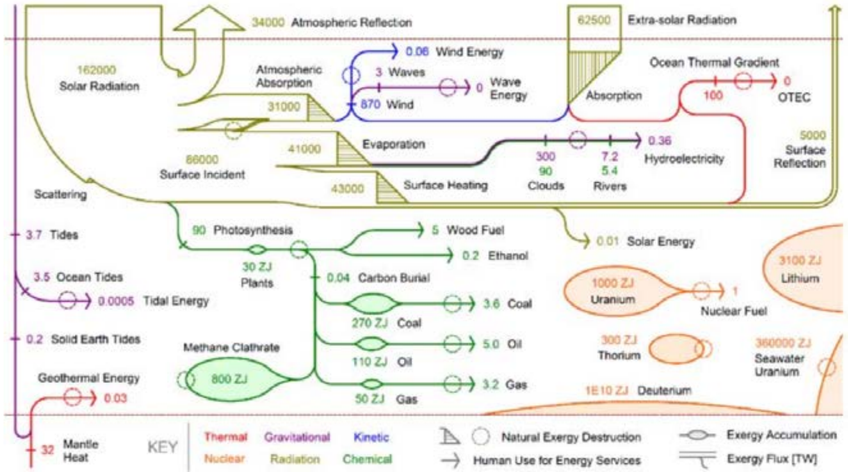
- Which energy pathway for which mission ?

- Comparision of pathways is difficult because of large uncertainties

=> Large green electricity demand

=> LCA to assess sustainability

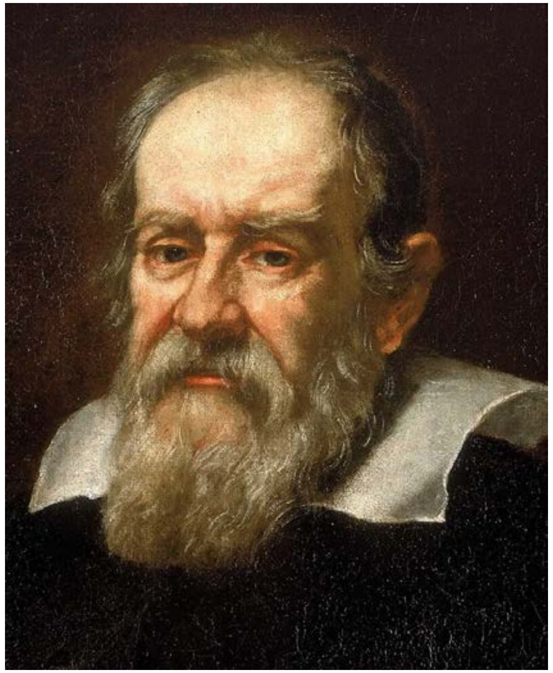




Social inertia

« This grand book [the universe] […] is written in the language of mathematics»

Galileo Galilei, *The Assayer*, 1623



400 years

« I know and respect the opinion of scientists. The problem is that there is real life.»

Patrick Pouyanné, head of TotalEnergies, 2023