# 2MAE006 – Aviation and Environment

## C1-C2: Climate, Energy and fuels

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# Mainly one question for this lecture

**CAN WE REDUCE (OR EVEN CANCEL) THE IMPACT OF AVIATION ON RADIATIVE FORCING, WITHOUT INCREASING THE QUANTITY OF ENERGY NEEDED AND COST?**

# Mainly two sources for this lecture

**Source: Référentiel Aviation – Climat, ISAE-SUPAERO report, 2021**

**Source: Impact of climate on aviation (ICCA), French research project, involving the following partners**

CERFACS – CENTRE EUROPÉEN DE RECHERCHE ET DE FORMATION AVANCÉE EN CALCUL SCIENTIFIQUE

METEO FRANCE

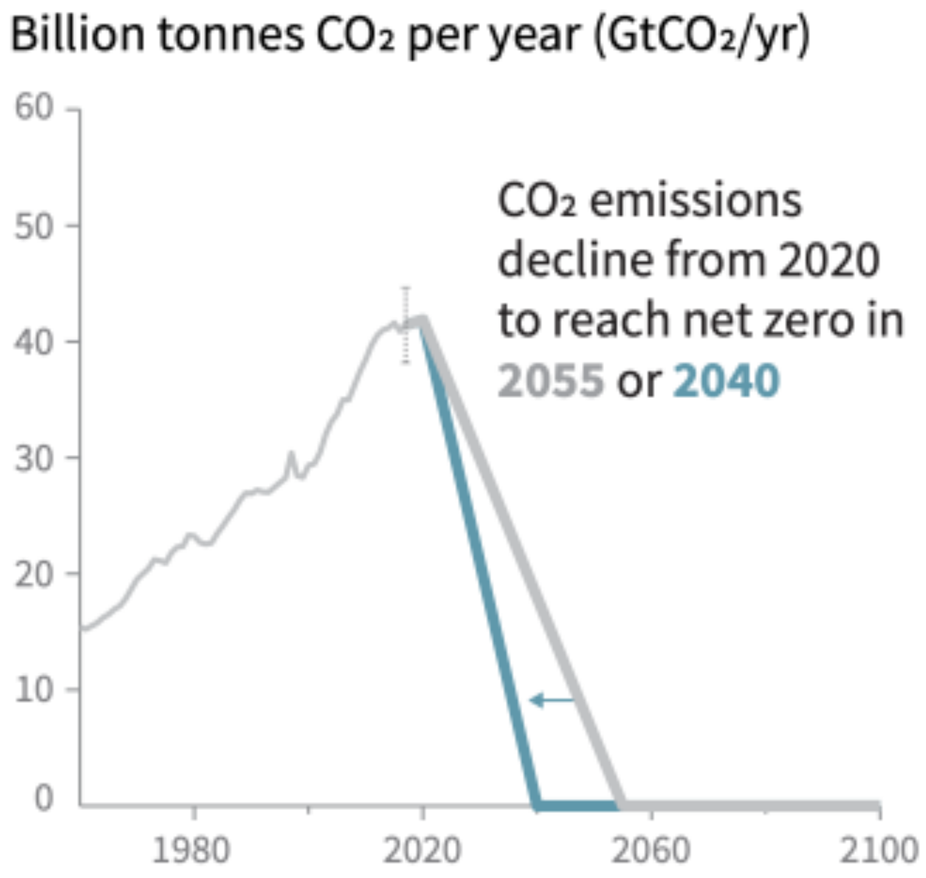
isae – Institut Supérieur de l'Aéronautique et de l'Espace – SUPAERO

ENAC

ONERA – THE FRENCH AEROSPACE LAB

AIRBUS

# Aviation: Climate & Energy




**Scheme of potential CO2 emissions trajectories to limit global warming to +1.5°C**

Note: blue curve has a better chance of success


Chap. 1 Relationship climate & aviation

1.1 Impact of aviation on climate change

1.2 Impact of climate change on aviation

Chap. 2 Energy: fossil fuels

2.1 General considerations

2.2 The particular case of aviation

2.3 Energies for the future of aviation

# Chap. 1 Climate and aviation

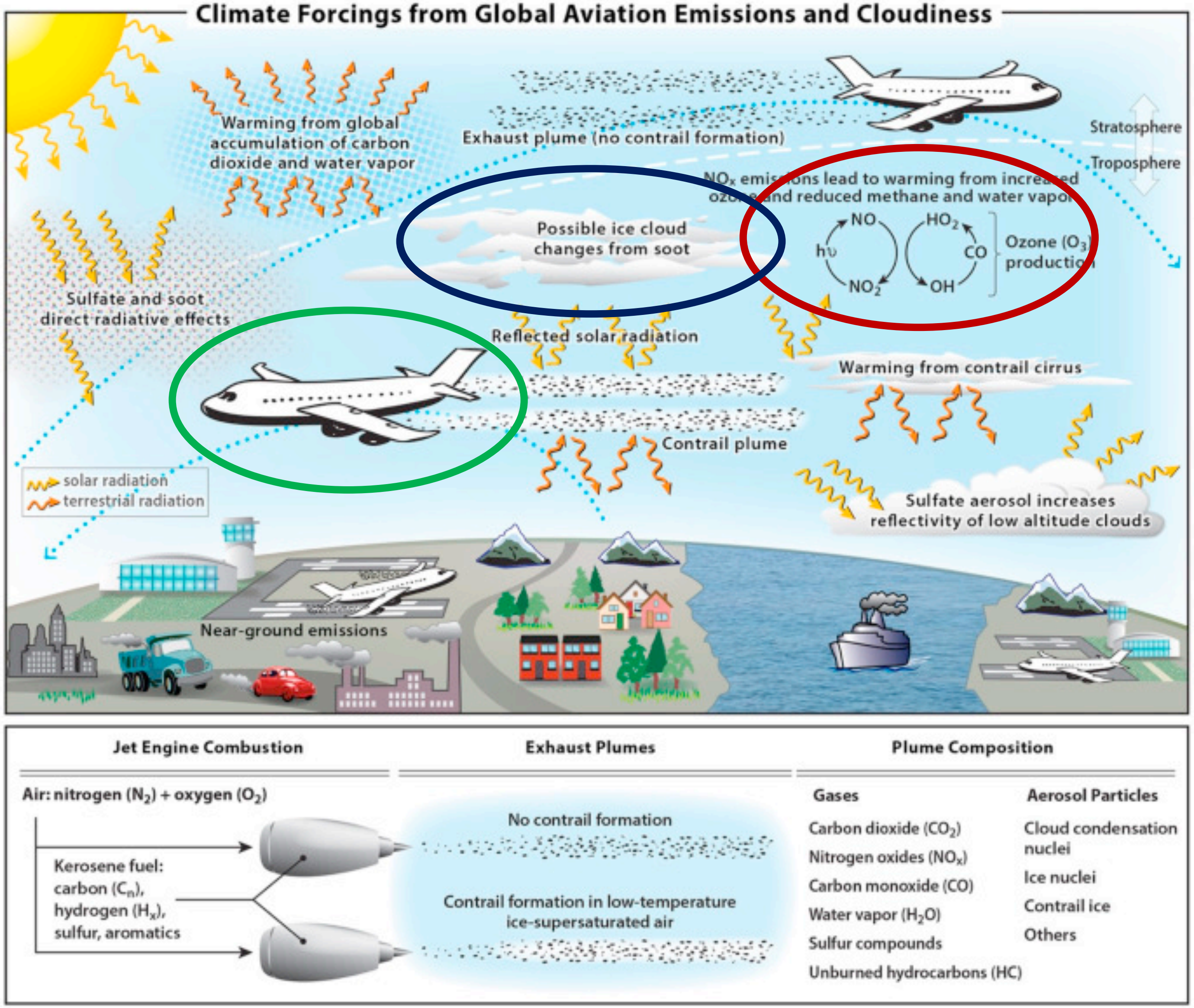

**Road, Sea and Air Transportation represents about 27% of greenhouse gas (GHG) emissions in Europe**

# Chap. 1 Climate and aviation

**What is the part of CO2 emissions due to aviation?**

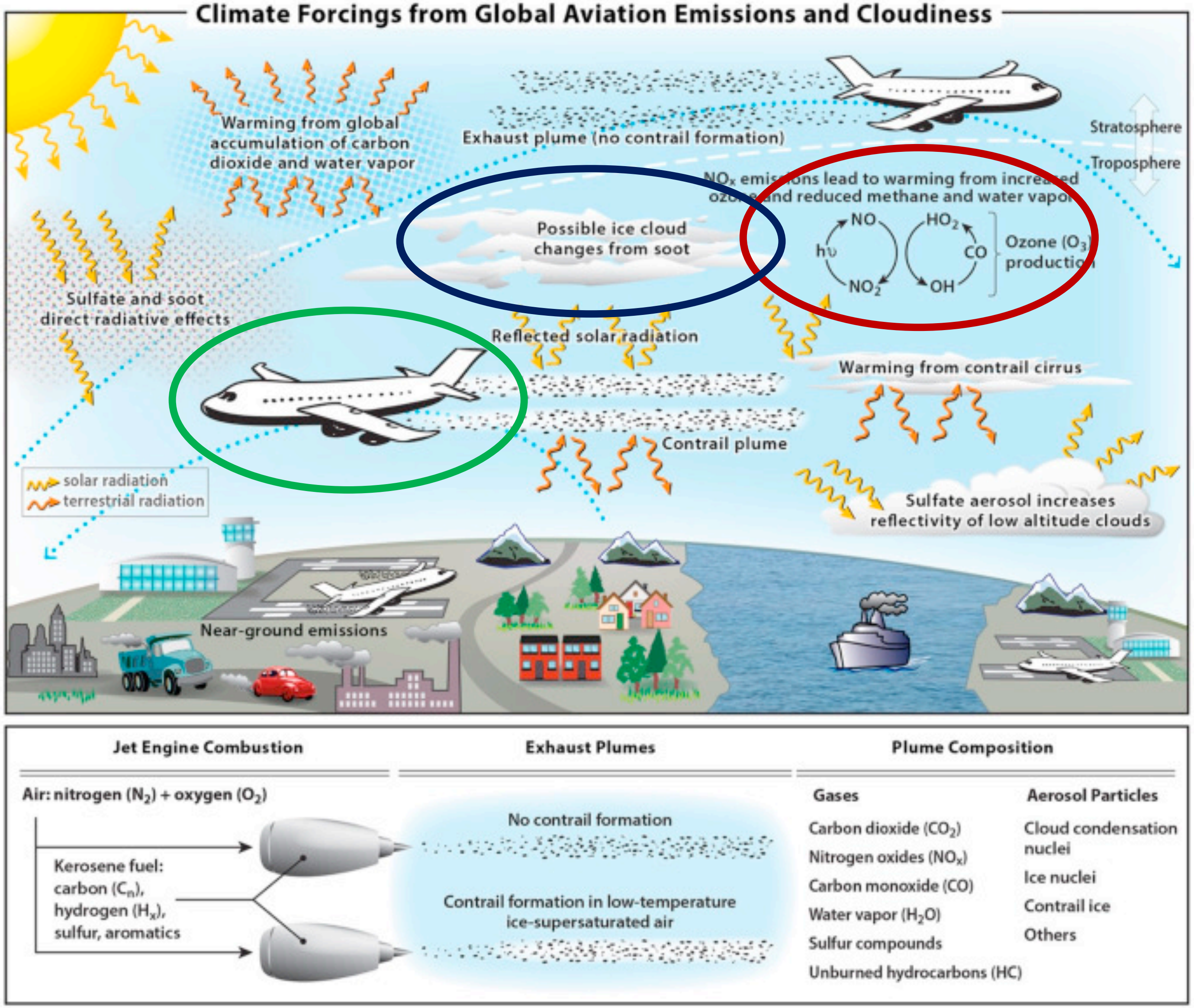
- **0.5%**
- **2.5%**
- **5.0%**
- **10.%**


## Origin of radiative forcing due to aviation?




**Source: Lee et al., 2020**

## Origin of radiative forcing due to aviation?




Source: Lee et al., 2020

**Radiative forcing =**

**CO2**

**+**

**NOx**

**+**

**Cirrus Contrails**

**+**

**Soots**

| Effect | $GWP_{20}$ | $GWP_{50}$ | $GWP_{100}$ |
|---|---|---|---|
| $CO_2$ (ref) | 1034 | 1034 | 1034 |
| Contrails ($eqCO_2$) | 2395 | 1127 | 651 |
| $NO_x$ ($eqCO_2$) | 887 | 293 | 163 |
| Total ($eqCO_2$) | 4128 | 2366 | 1797 |
| Ratio ($eqCO_2$ / $CO_2$) | **4.0** | **2.3** | **1.7** |

Note : global warming potential (GWP) in millions of tons of CO2. Marginal effects (aerosols and water vapour) have been removed for clarity

***Source : Lee et al., 2020, Atmospheric Environment***

**GWP*: average annual rate of CO2-warming-equivalent emissions**

**50% to 66% of aviation impact on climate change comes from non-CO2 effects (contrails++)**

| Effect | $GWP_{20}$ | $GWP_{50}$ | $GWP_{100}$ |
|---|---|---|---|
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Note : global warming potential (GWP) in millions of tons of CO2. Marginal effects (aerosols and water vapour) have been removed for clarity

***Source : Lee et al., 2020, Atmospheric Environment***

**Which part of the Global Warming Potential is related to aviation?**

| Effect | $GWP_{20}$ | $GWP_{50}$ | $GWP_{100}$ |
| --- | --- | --- | --- |
| $CO_2$ (ref) | 1034 | 1034 | 1034 |
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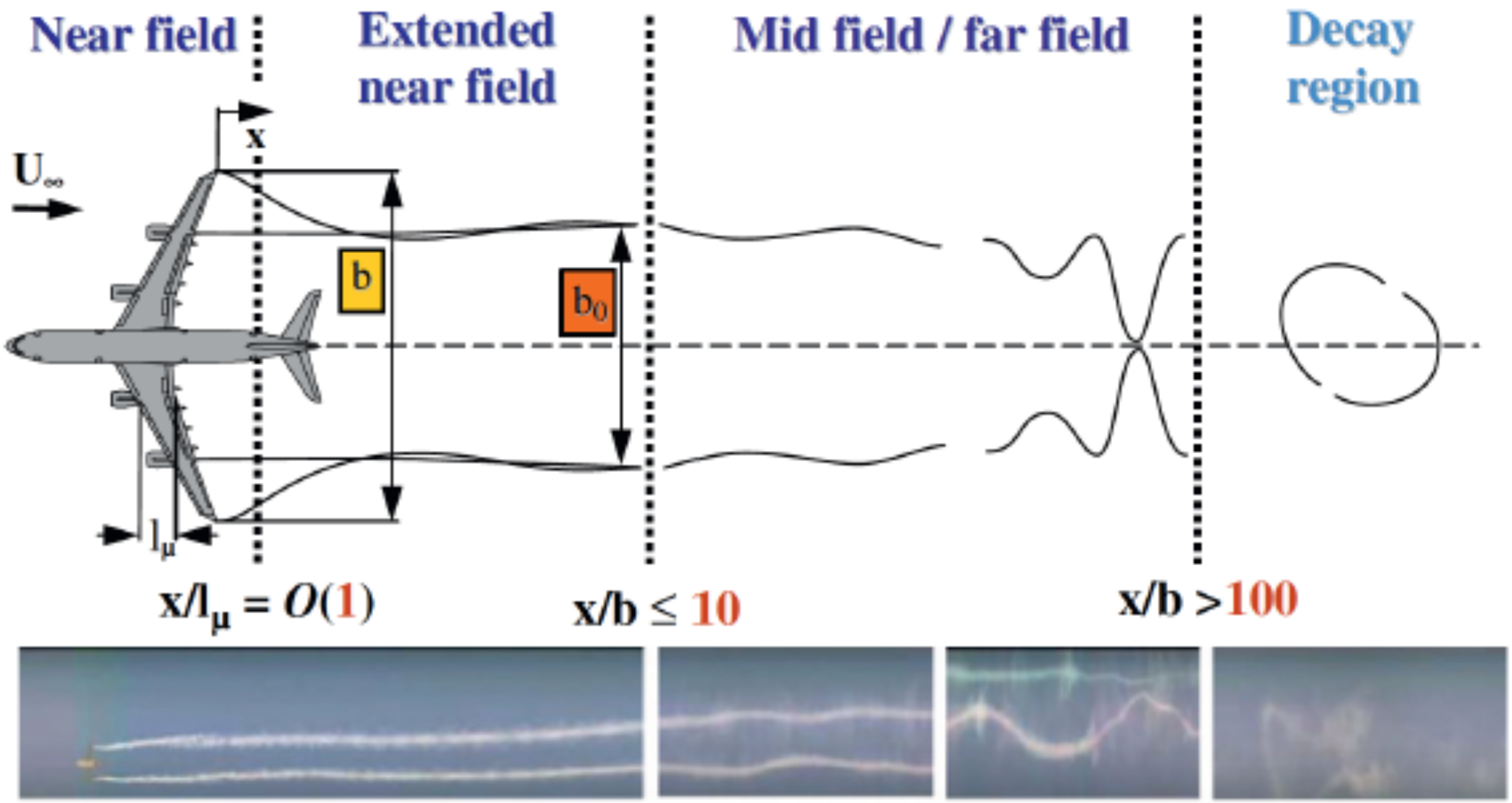
***Source : Lee et al., 2020, Atmospheric Environment***

**Two ways to count (both are ok):**

- **Period [1750 - 2011]: 3.5% of the total GWP is due to aviation**
- **Period [2005 - 2011]: 5.9% of the total GWP is due to aviation**

## What is the origin of contrails?

## What is the origin of contrails?



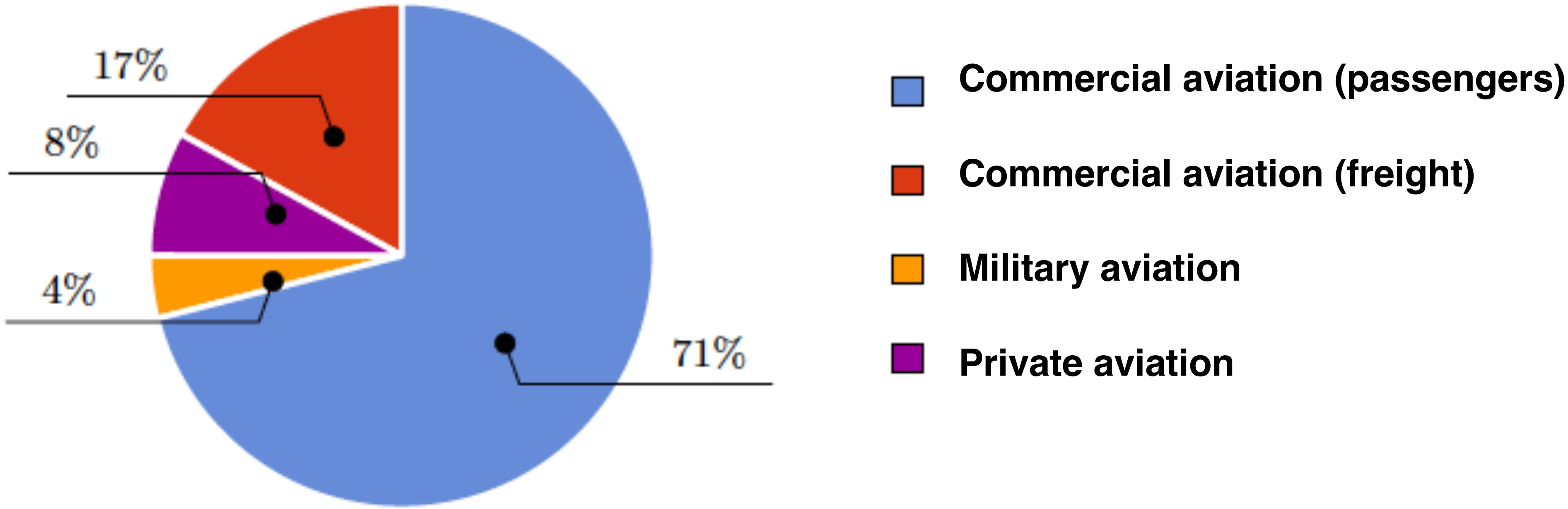

**Scheme of the different steps towards the formation of contrails from the wake vortices (Breitsamter, 2011)**

Note: Mean aerodynamic chord is noted $l_\mu$ and span is $b$

**Key number: Annual CO2 emissions = about 1Gt CO2eq.**

**(2.5% of the total)**

**Share of CO2 emissions for global aviation in 2018 (Gössling et Humpe, 2020)**



## Which are the impacts of climate change on aviation?

| Climate risk | Impact | Actors | Key: |
|---|---|---|---|
| **Precipitation change** | • disruption to operations e.g. airfield flooding, ground subsidence<br>• reduction in airport throughput<br>• drainage system capacity<br>• inundation of underground infrastructure (e.g. electrical)<br>• inundation of ground transport access (passengers and staff)<br>• loss of local utilities provision (e.g. power). | ✈ AO ANSP<br>✈ AO ANSP<br>AO<br>AO<br>✈ AO ANSP ☎<br>✈AO ANSP ☎ | Aircraft operators: ✈<br>Airport operators: AO<br>ANSP: ANSP<br>External: ☎ |
| **Temperature change** | • Changes in aircraft performance<br>• Changes in noise impact due to changes in performance<br>• heat damage to airport surface (runway, taxiway)<br>• increased heating and cooling requirements<br>• Increased pressure on local utilities e.g. water and power (for cooling). | ✈ ANSP<br>✈ AO ANSP<br>AO<br>AO<br>☎ | |
| **Sea-level rise** | • loss of airport capacity<br>• impacts on en-route capacity due to lack of ground capacity<br>• loss of airport infrastructure<br>• loss of ground transport access | ✈ AO ANSP<br>✈ ANSP<br>AO<br>✈ AO ANSP ☎ | |
| **Wind changes** | • convective weather: disruption to operations<br>• convective weather: route extensions<br>• jet stream: increase in en-route turbulence<br>• local wind patterns: disruption to operations and changes to distribution of noise impact | ✈ AO ANSP<br>✈ ANSP<br>✈ AO<br>✈ AO | |
| **Extreme events*** | • disruption to operations, route extensions<br>• disruption to ground transport access<br>• disruption to utilities supply | ✈ AO ANSP<br>✈ AO ☎<br>AO ☎ | |

**Source: Burbidge, 2018**

**Heat waves will drastically increase the temperature at the ground level (dozens of flights cancelled in 2017 at Phoenix, again in 2021 at Dallas)**

**B737 Phoenix airport during the heat wave in 2017 (source : T. Tingle)**

## Impact on aircraft performance

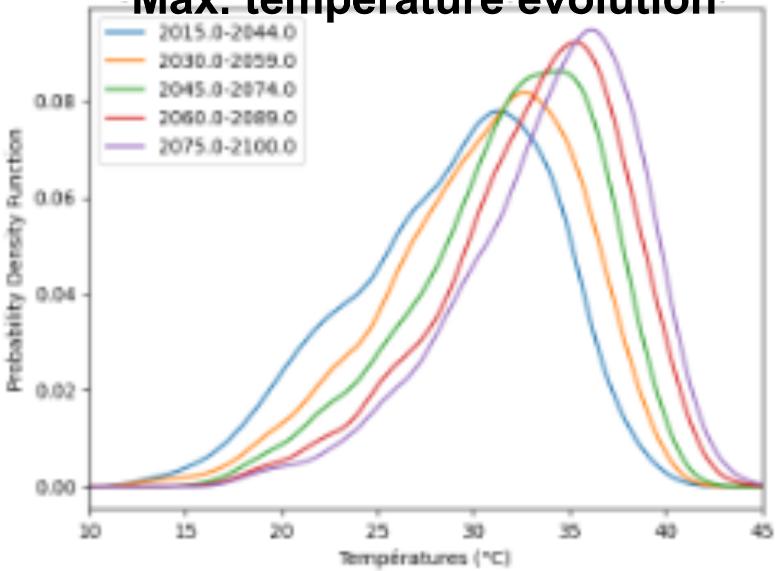
**Effect of humidity (+) and air temperature (++) at the ground level on take-off distance**

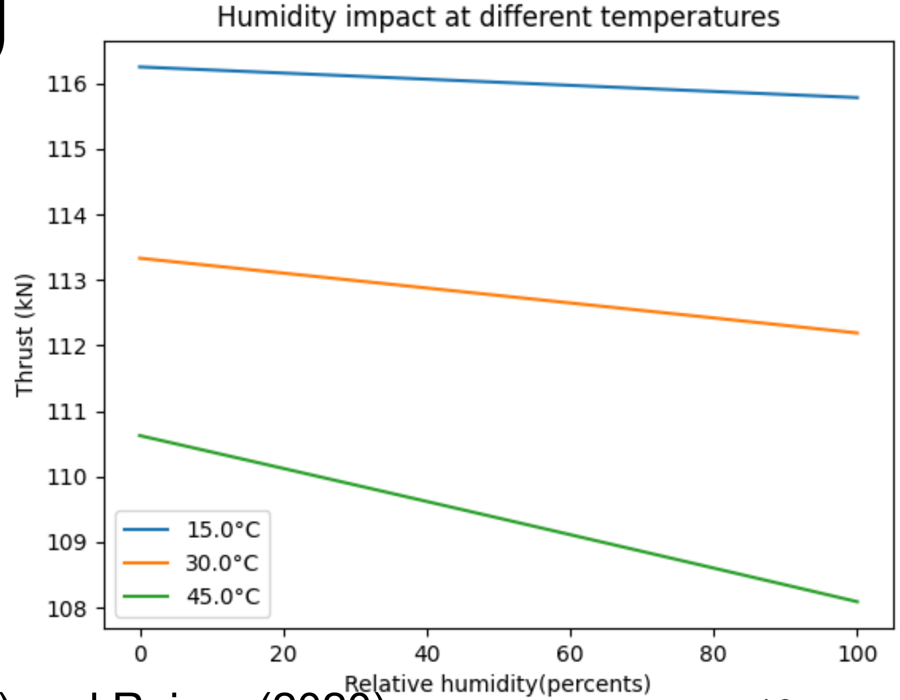
$$L = 15.5MG + 100 \text{ où : } MG = \frac{TOW^2}{CZmaxFnS\rho}$$ with

- ***L***: take-off distance
- ***TOW***: take off weight
- ***$C_{z,max}$***: max lift coeff.
- ***Fn***: engine thrust
- ***S***: lifting surface

$$\boxed{MTOW = \sqrt{\frac{\rho C z_{max} F_n S (L-100)}{15.5}}}$$

**Max. temperature evolution**



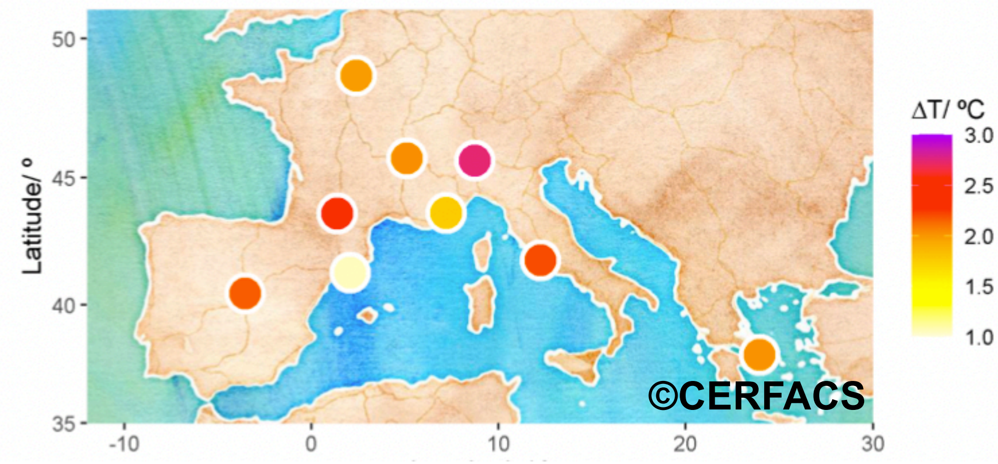



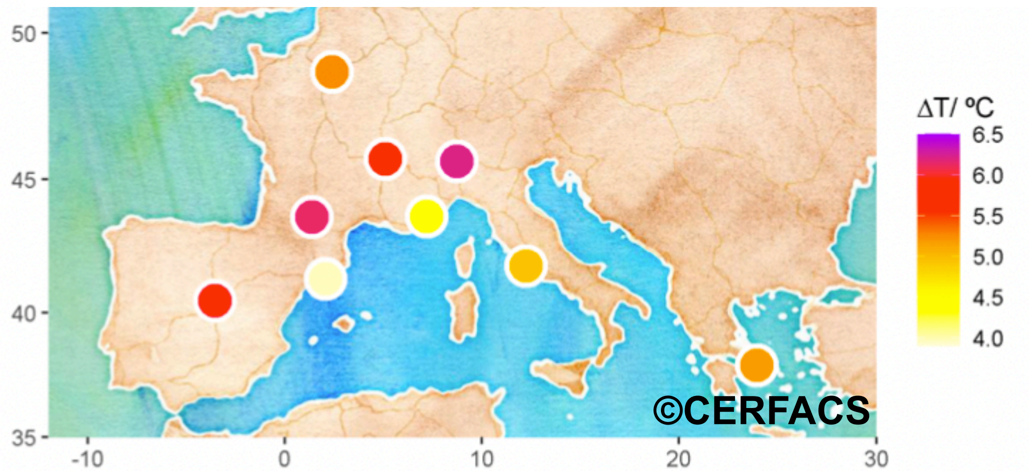

From Prado (2019) and Roiron (2020)

## Impact on aircraft performance

**Effect of humidity (+) and air temperature (++) at the ground level on take-off distance**

**PhD of V. Gallardo**



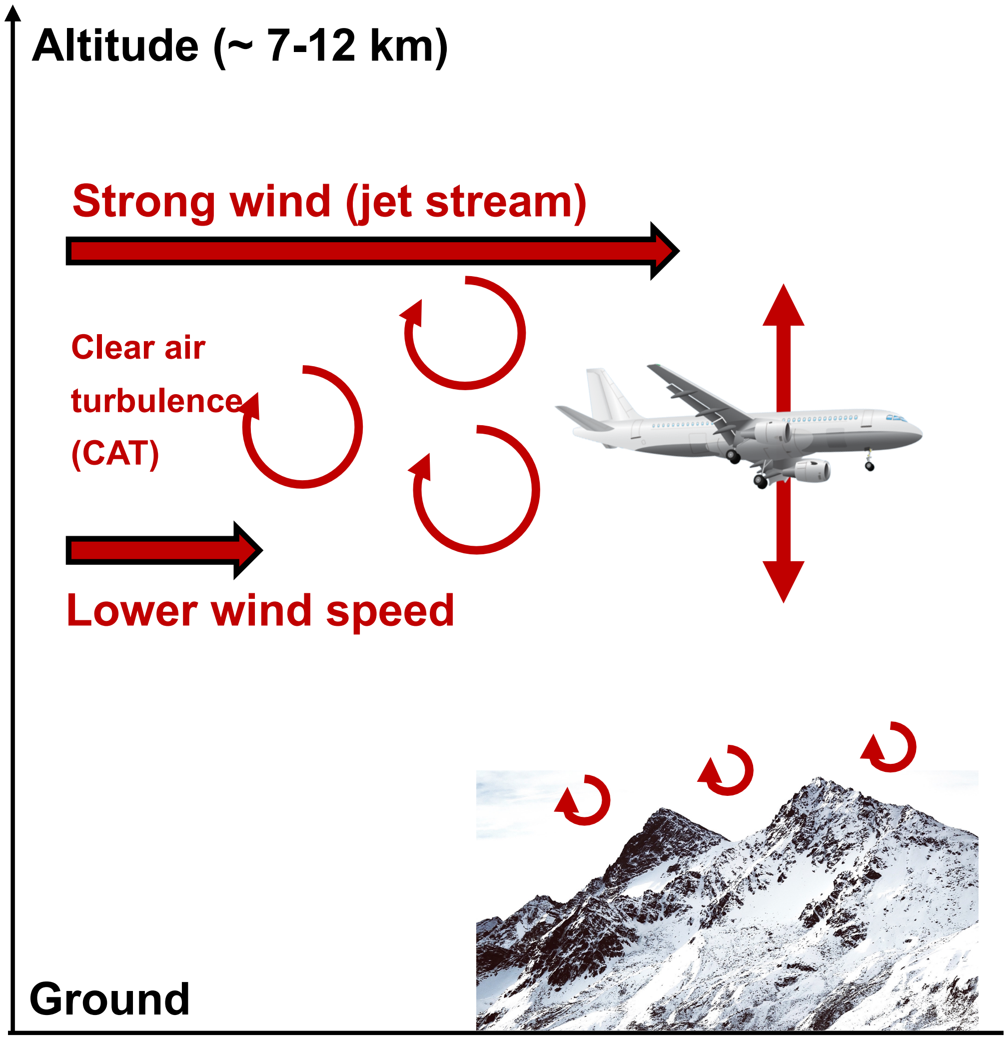




**Weight restrictions: +10–30% of aircraft commercial capacity (>2050)**

**Take-off distance: +[1.0–6.5]% (2021-2050) ; up to 11% (2071–2100)**

## Impact on meteorological conditions

**Effect of increased Jet Stream strength on Clear Air Turbulence (CAT)**

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**About 75% of accidents due to meteorological conditions are due to CAT**

**Hard to detect with embedded systems**

**About 200 millions dollars each year due to**

- **Delays**
- **Passengers injuries**
- **Aircraft damages**

## Impact on meteorological conditions

**Effect of increased Jet Stream strength on Clear Air Turbulence (CAT)**

### Low

**Rise/drop: 1 meter**

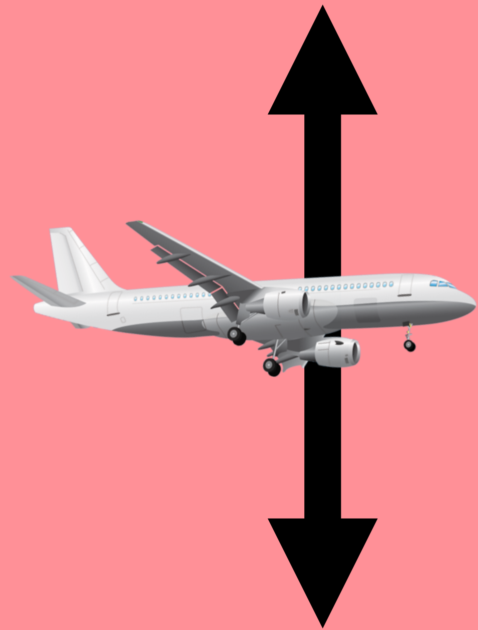
**Not significant for passengers**

### Moderate

**Rise/drop: 3-6 meters**

**Beverages spilled on the floor**

### Severe



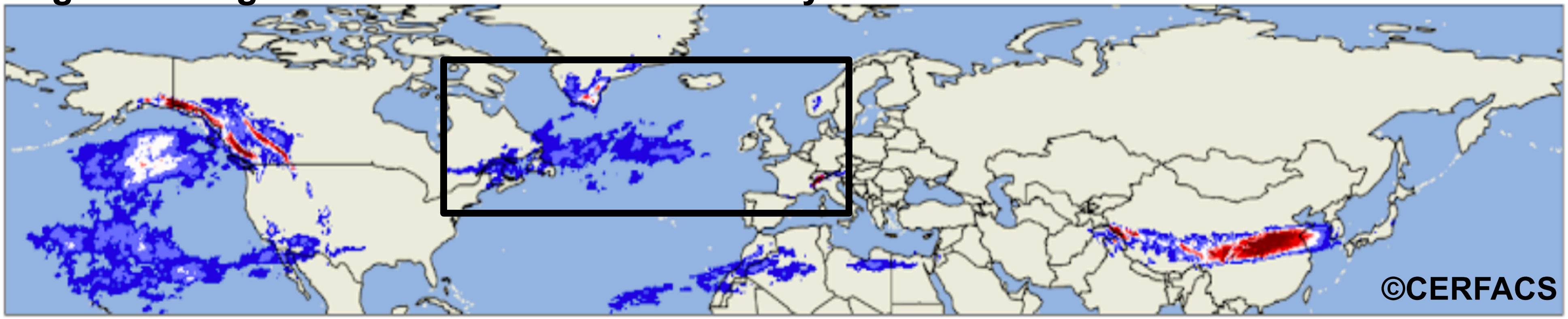
**Rise/drop: 30 meters**

**Passengers are thrown if belts are not fasten**

## Impact on meteorological conditions

**Effect of increased Jet Stream strength on Clear Air Turbulence (CAT)**

**Regions of high Clear air turbulence sensitivity**



## Impact on meteorological conditions

### Effect of increased Jet Stream strength on Clear Air Turbulence (CAT)

**Increase of CAT due to climate change between 1950 and [2050 - 2080]**

| | Cas 1 | | Cas 2 | | Cas 3 | | Cas 4 | |
|---|---|---|---|---|---|---|---|---|
| CAT intensity | 10 km | 12 km | 10 km | 12 km | 10 km | 12 km | 10 km | 12 km |
| Moderate | +30.8 | +19.6 | +46.5 | +30.0 | +143.3 | +74.4 | +34.3 | +26.0 |
| Severe | +34.7 | +20.5 | +51.6 | +34.2 | +181.4 | +88.0 | +51.1 | +40.2 |

Source: Storer et al. 2017

**Case 1 : World average for period December to February**

**Case 2 : World average for period March to May**

**Case 3 : Annual average for North Atlantic**

**Case 4 : Annual average for Africa**

**CAT +50% in average**

**Until +150% in North Atlantic**

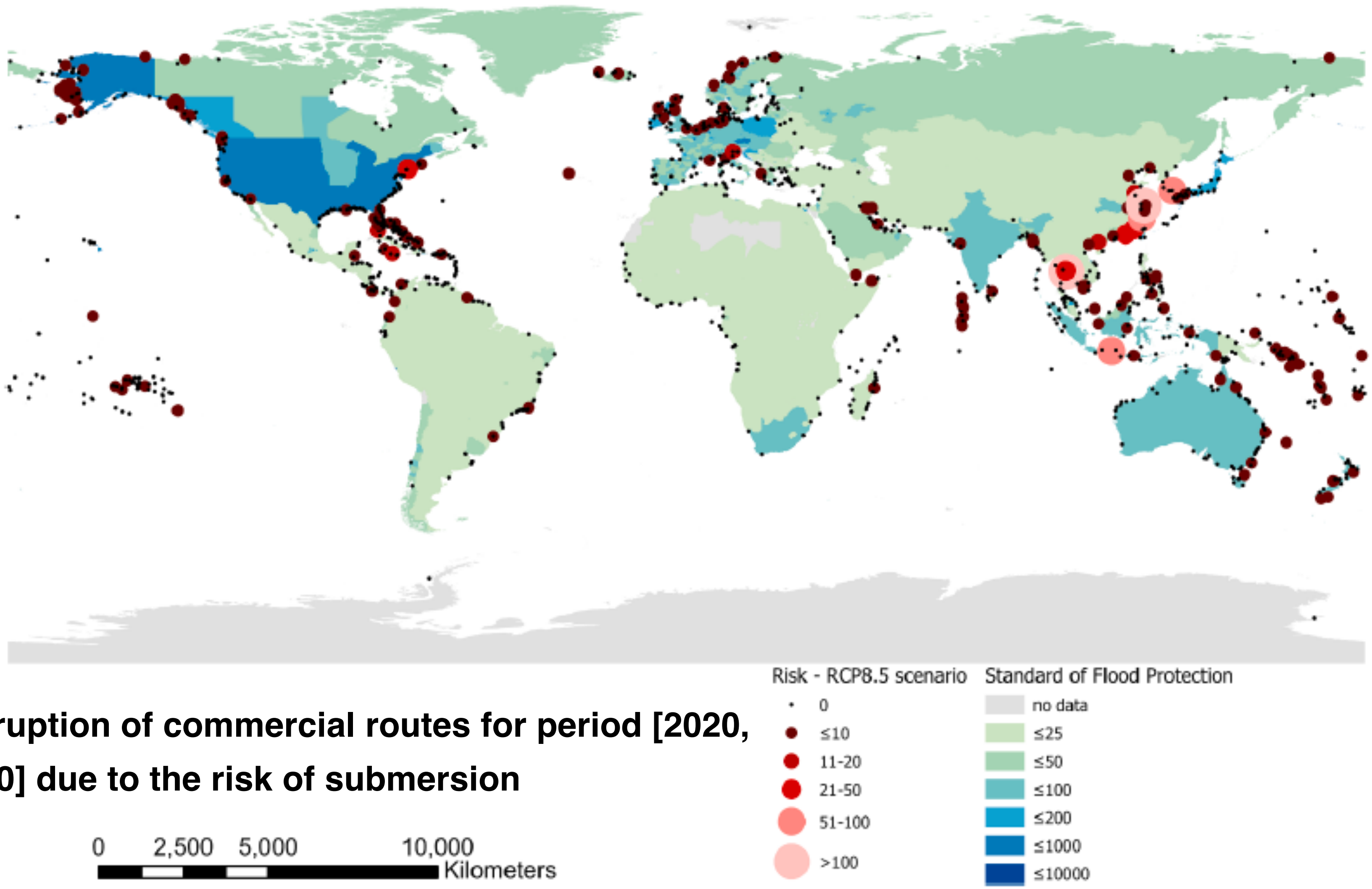
## Impact on meteorological conditions

**Effect of extreme events (storm) and submersion (sea level rise)**

**International airport of Kansai (Japan) in 2018 after storm Jebi (source : M. Shimbun)**

## Impact on meteorological conditions

**Effect of extreme events (storm) and submersion (sea level rise)**

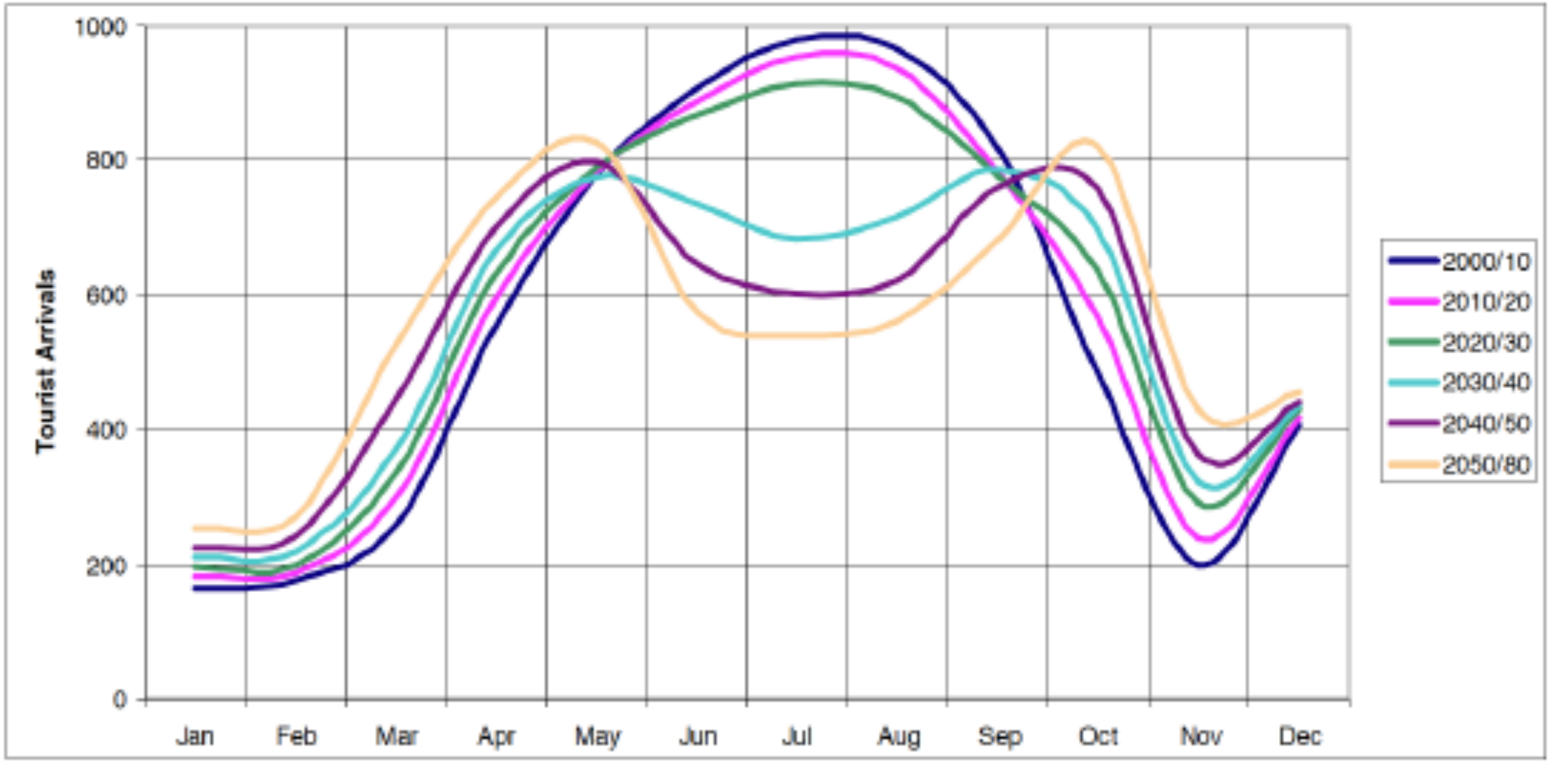



**Disruption of commercial routes for period [2020, 2100] due to the risk of submersion**

**Source: Yesudian et Dawson, 2021**

## Impact on tourism

**Modification of touristic demand in Greece, for different time horizons**




Thomas et Drew, 2010

**First modifications no later than during decade [2020, 2029]**

**Important reduction of the number of tourists (-40%) during summer (> 2040)**

## Conclusion

### Aviation and contribution to climate change

- Aviation contributes to 2.5% of the annual CO2 emissions
- This contribution to the effective radiative forcing is at last double of that

### Climate change will impact aviation

- Direct impacts (modification of aircraft performance, CAT, submersion, etc.)
- Indirect impacts (socio-economic aspects like modification of touristic demand)

## Perspective

**Chap. 2 energy!**


Chap. 1 Relationship climate & aviation

1.1 Impact of aviation on climate change

1.2 Impact of climate change on aviation


## Chap. 2 Energy: fossil fuels

**2.1 General considerations**

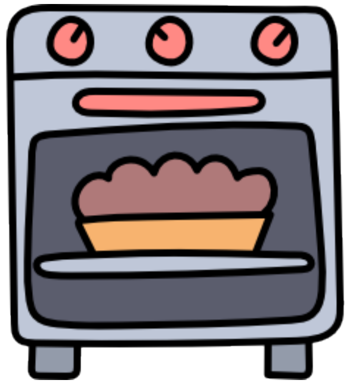
**2.2 The particular case of aviation**

**2.3 Energies for the future of aviation**


**Energy is everywhere!**


1:37 / 3:14

**Production of 1 kW during 1 h** =



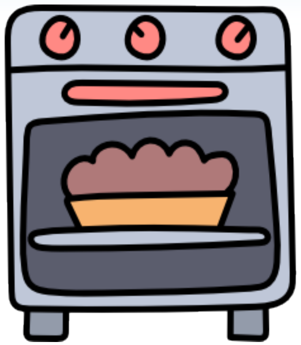
**Cook a cake with an electric oven**

**How many cyclist pedalling at 20km/h during 1h are needed to produce 1 kWh to cook the cake?**

- **A : 2**
- **B : 5**
- **C : 10**
- **D : Lance Armstrong alone**

**Production of 1 kW during 1 h**

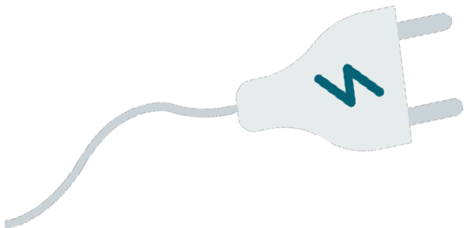
=



**10 cyclists**

=

**100 €**



**Electric plug**

=

**0,10 €**

## How to produce 1kWh?

**Variable production (storage?)**


With a wind turbine of 5 m of diameter during 1h*

**Through a dam of 50m height**

8 000 L of water

* Considering average climatic conditions in France

## How to produce 1kWh?

### Variable production (storage?)


With a wind turbine of 5 m of diameter during 1h*

### Through a dam of 50m height

8 000 L of water

### In a thermal facility

Wood

1 log

Fossil energies

| Gas | Coal | Oil |
|---|---|---|
| 1.5L** | A heap of coal | 33cl |

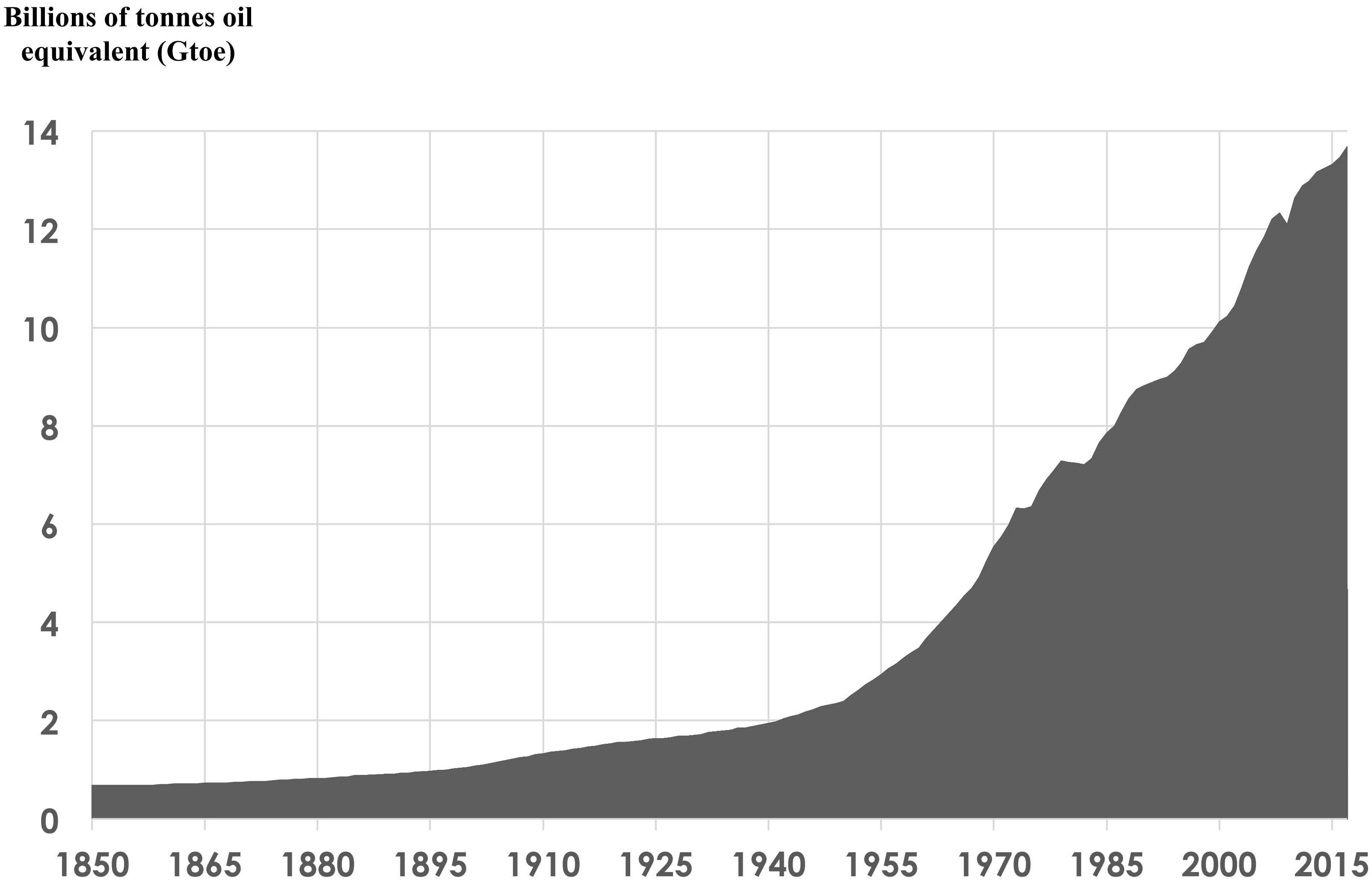
Uranium

A pinch

* Considering average climatic conditions in France / ** stored at 200 bar

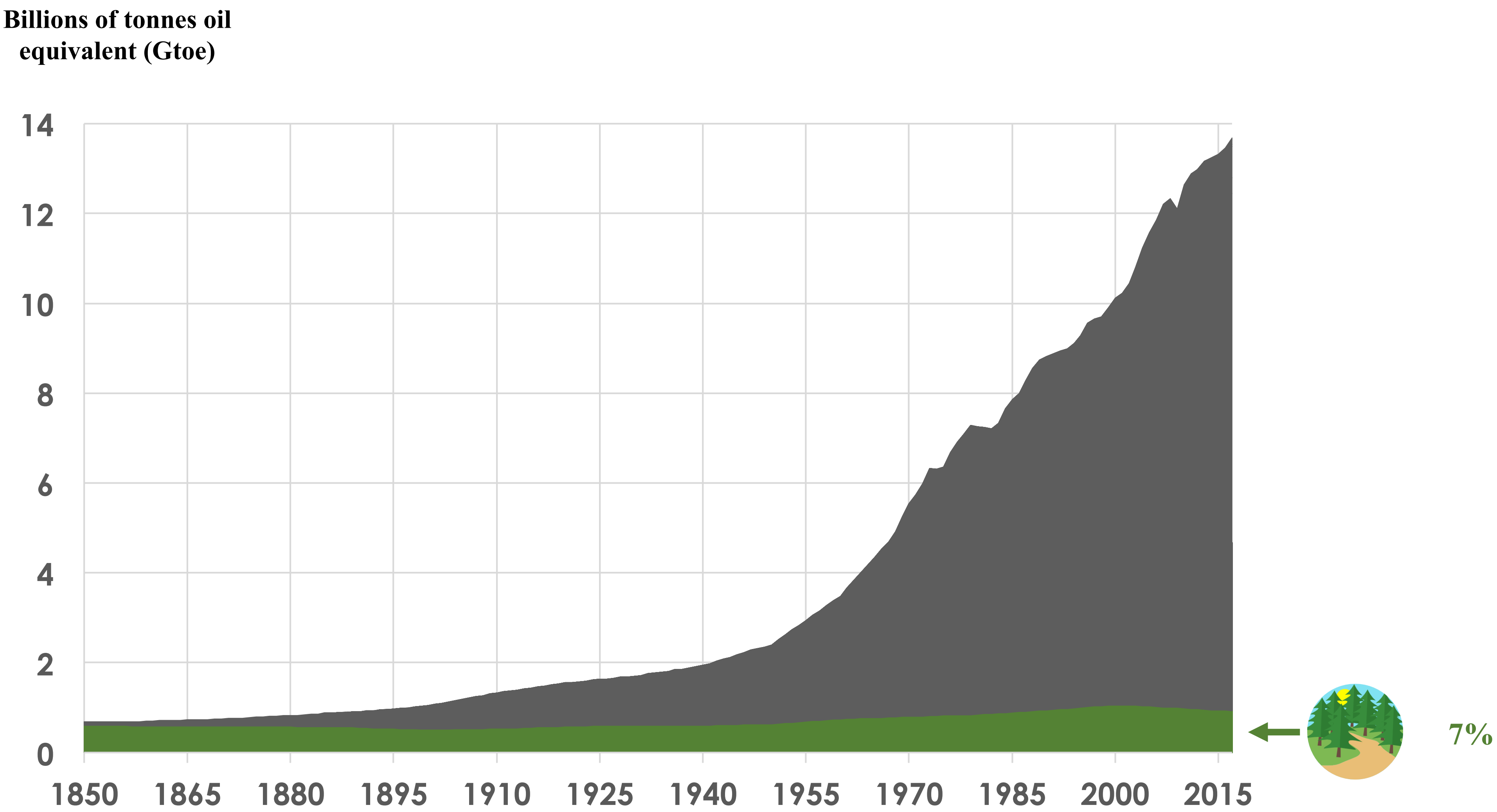


AVENIR CLIMATIQUE
PARLONS CLIMAT AVEC ÉNERGIE !




**Evolution of the consumption of primary energy in the World (Gtoe) – tonne oil equivalent**

Vaclav Smil (2017). Energy Transitions: Global and National Perspectives. & BP Statistical Review of World Energy (2017)

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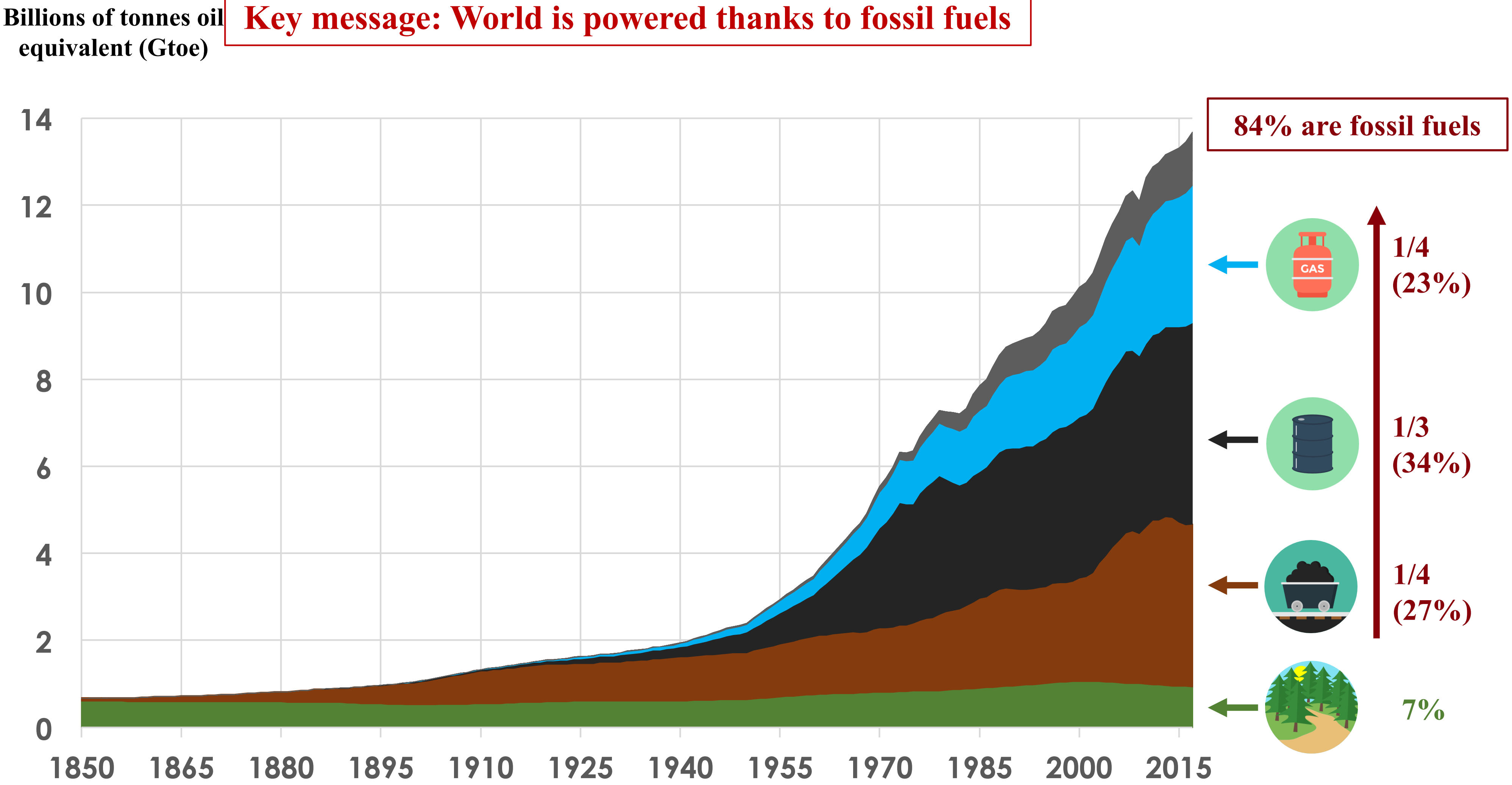
Key message: World is powered thanks to fossil fuels

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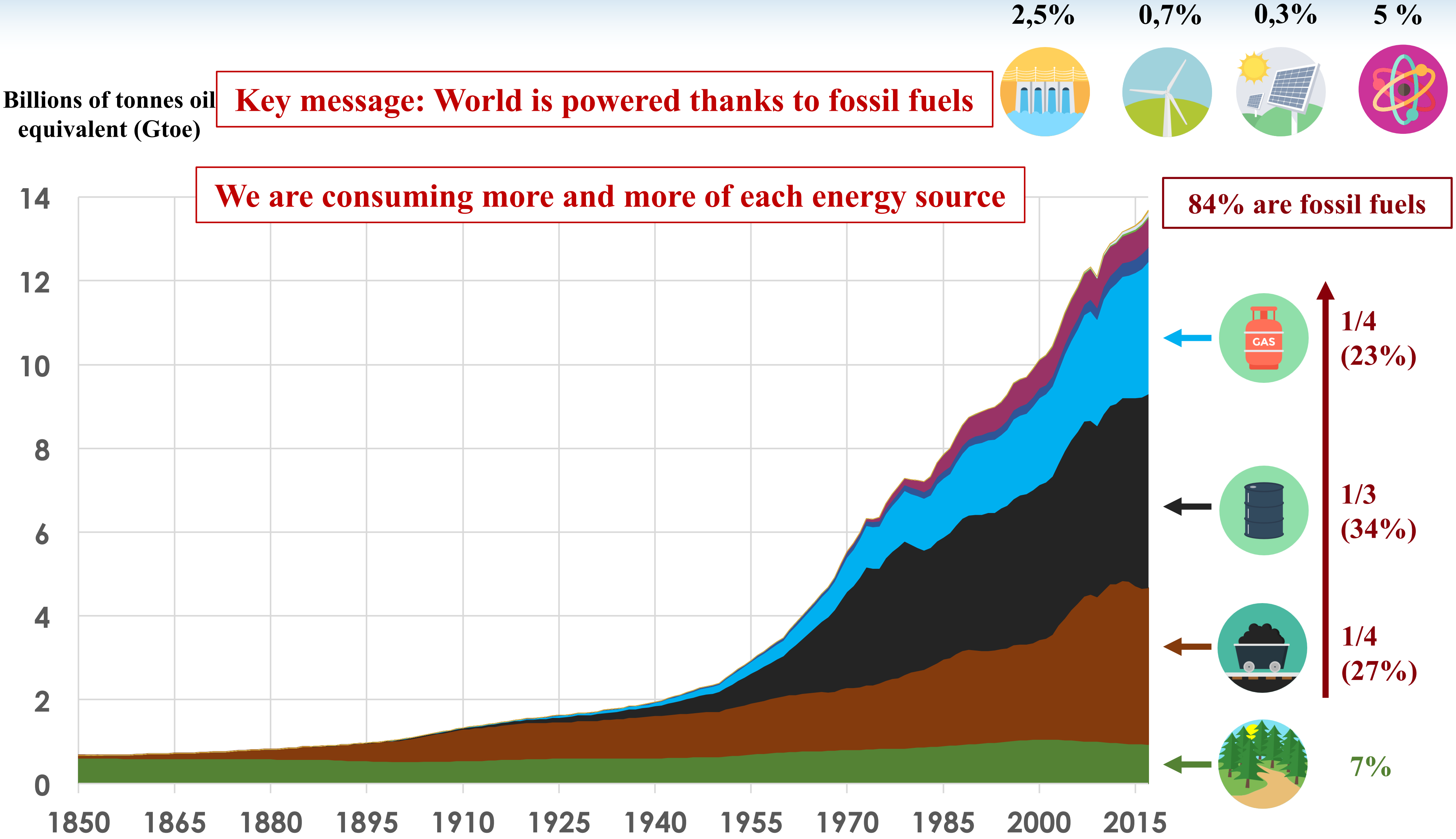


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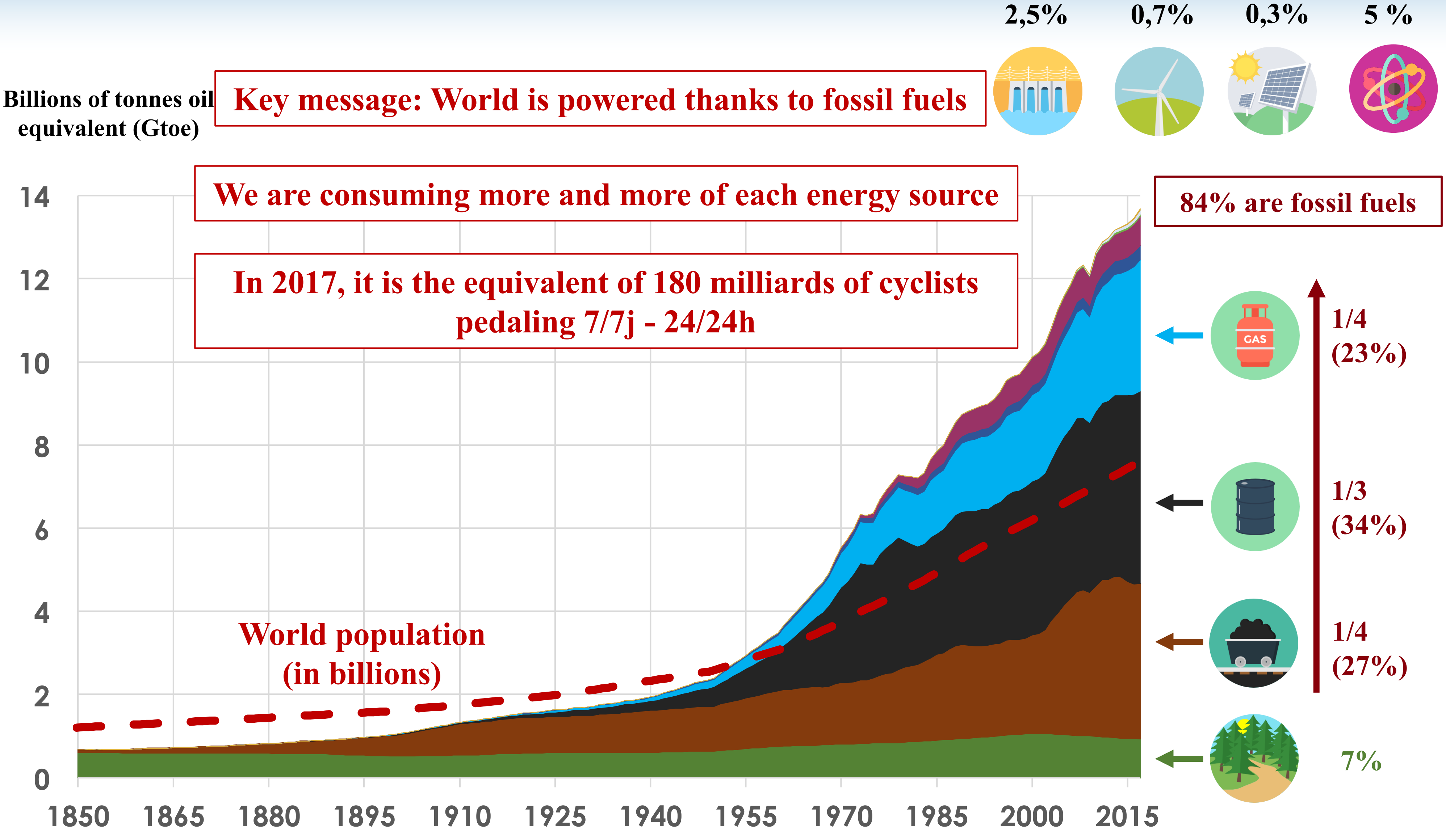


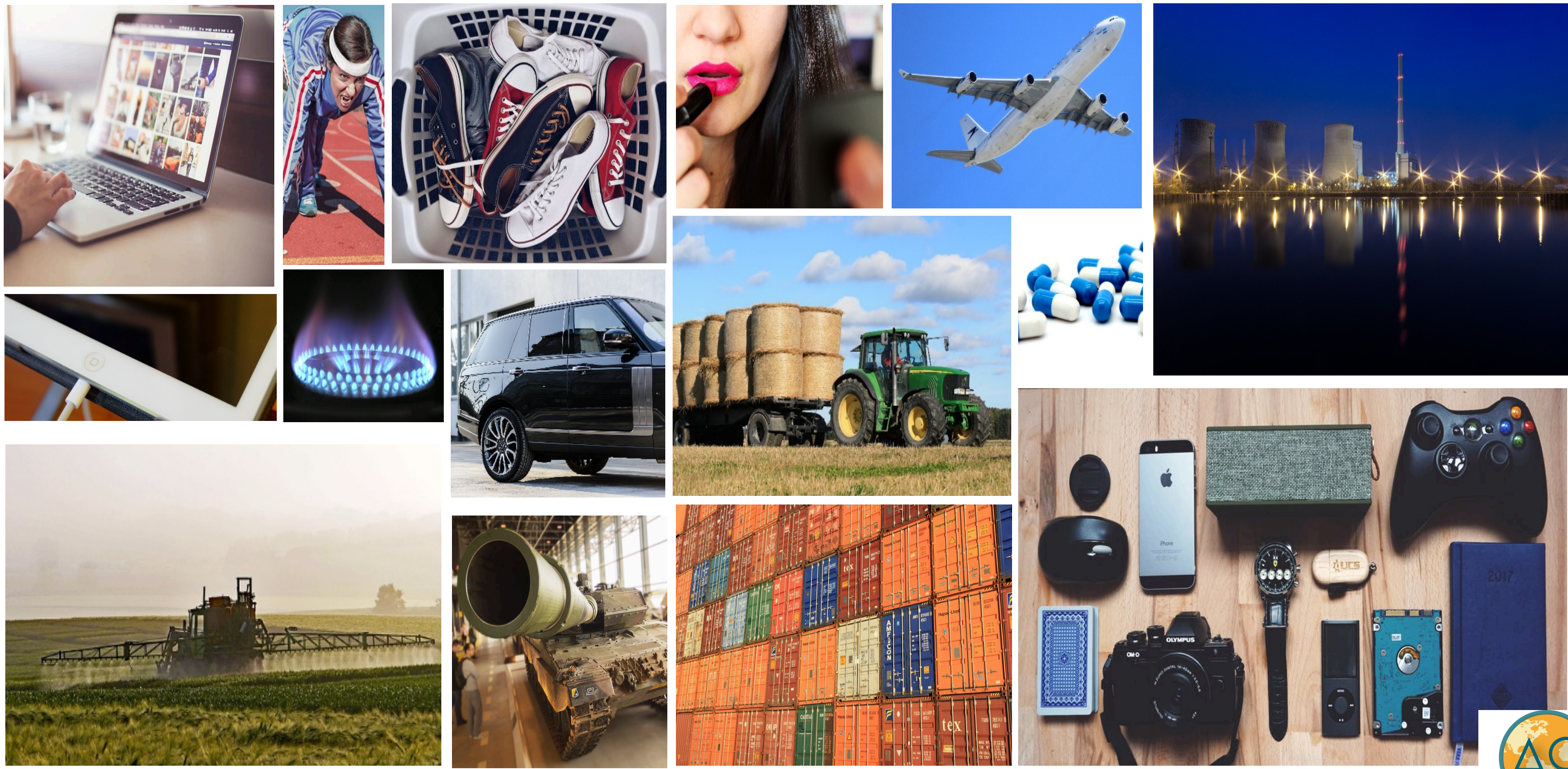

**Evolution of the consumption of primary energy in the World (Gtoe) – tonne oil equivalent**

Vaclav Smil (2017). Energy Transitions: Global and National Perspectives. & BP Statistical Review of World Energy (2017)

**For all these, we are burning 100 millions of oil barrels each:**

- Day?
- Month?
- Year?

**Note: 1 barrel ≈ 159L**





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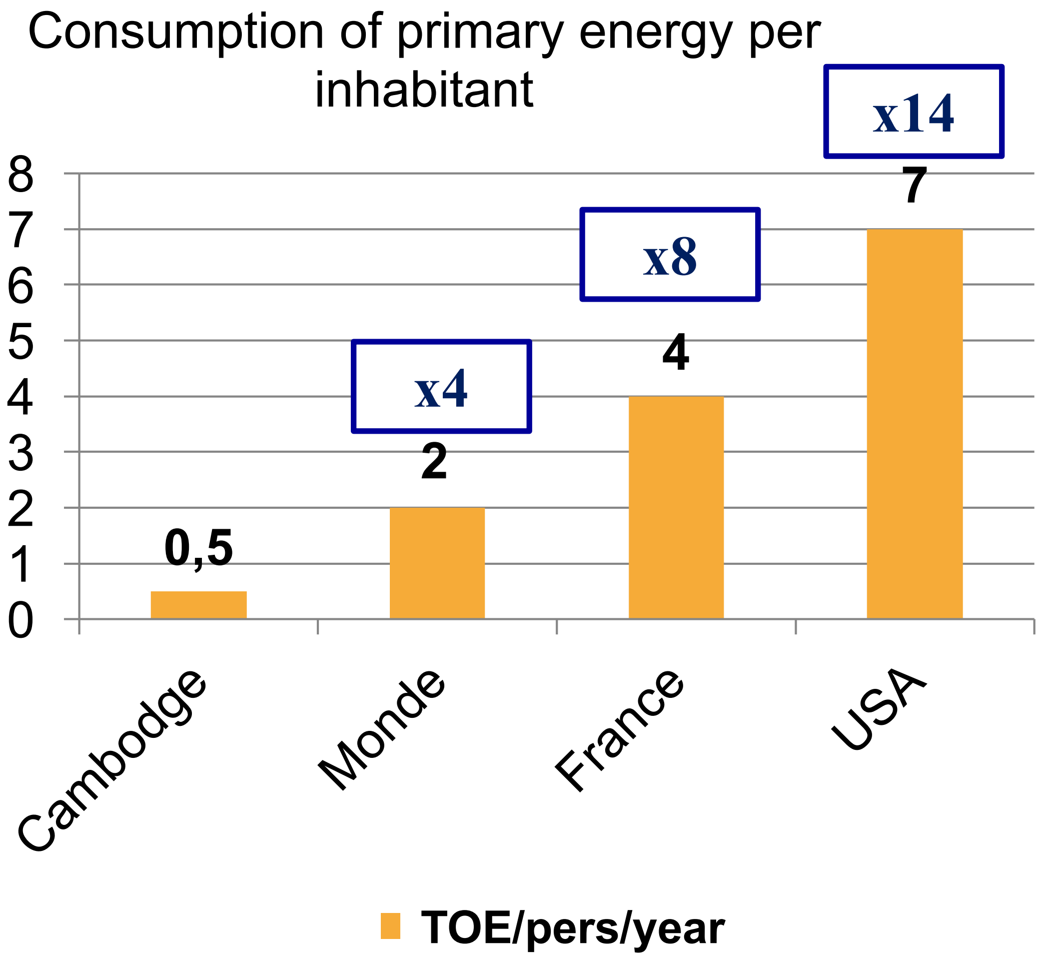
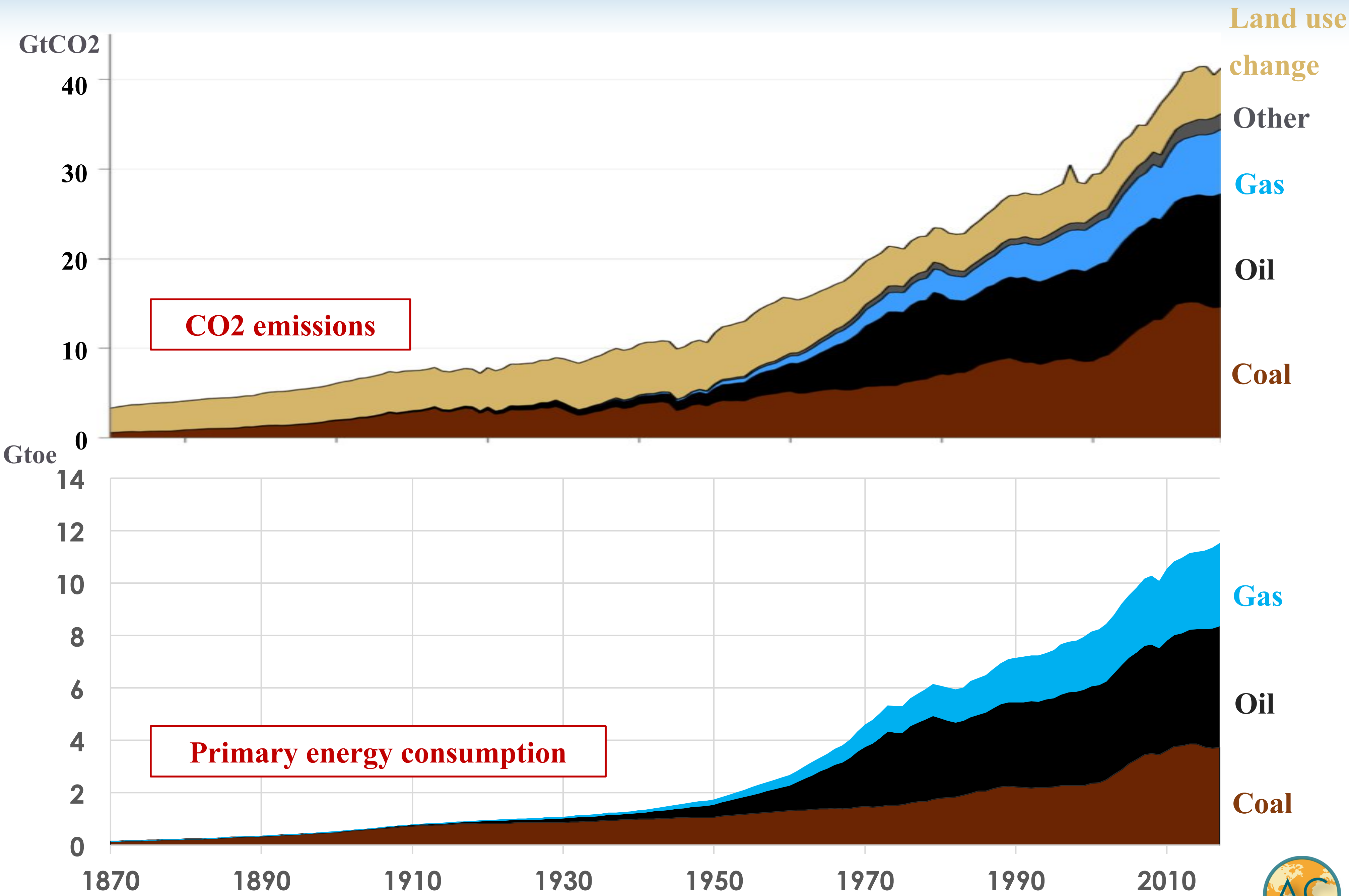
PARLONS CLIMAT AVEC ÉNERGIE !




Source : IEA 2017


A lot of people in different countries would like to consume more energy

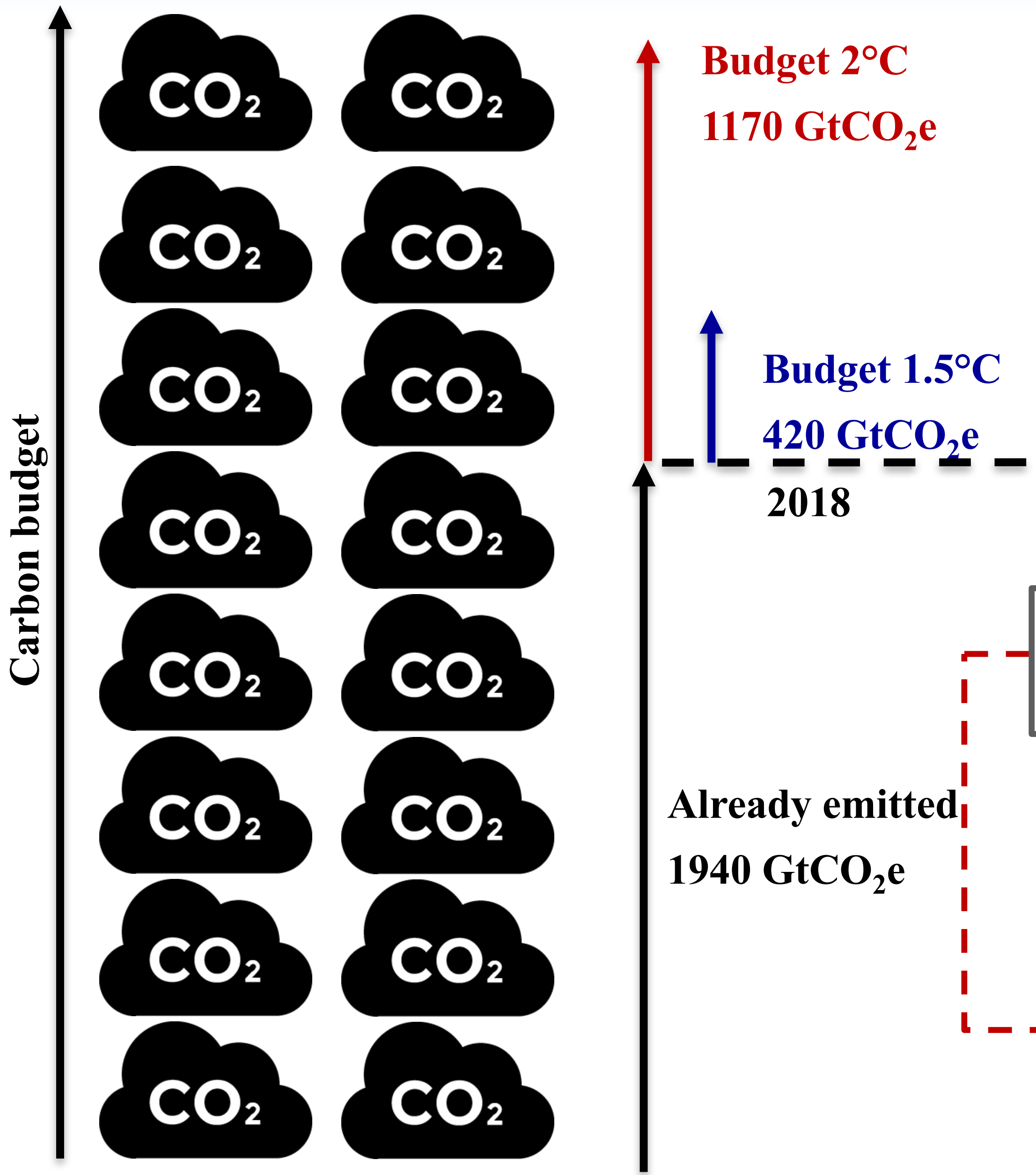
- **Energy is a measure of the world transformation: strongly linked to human development (and well-being?)**
- **All energy sources are not equivalent (some can be stored or more easily transformed). By far, oil is the most versatile source of energy at the moment**
- **80% of the energy consumed in the World is coming from fossil fuels (oil, coal and gas)**
- **The access to energy is not the same for all of us: some are wasting it, while some need more to ensure necessary needs (food, housing, etc.)**




Source : Global Carbone project – Data CDIAC/GCP/UNFCCC/BP/USGS



AVENIR CLIMATIQUE
PARLONS CLIMAT AVEC ÉNERGIE !




GHG emissions per year

≈ **50** $GtCO_2e$/an

**Remaining time at constant emissions**

**2°C : 23 years**

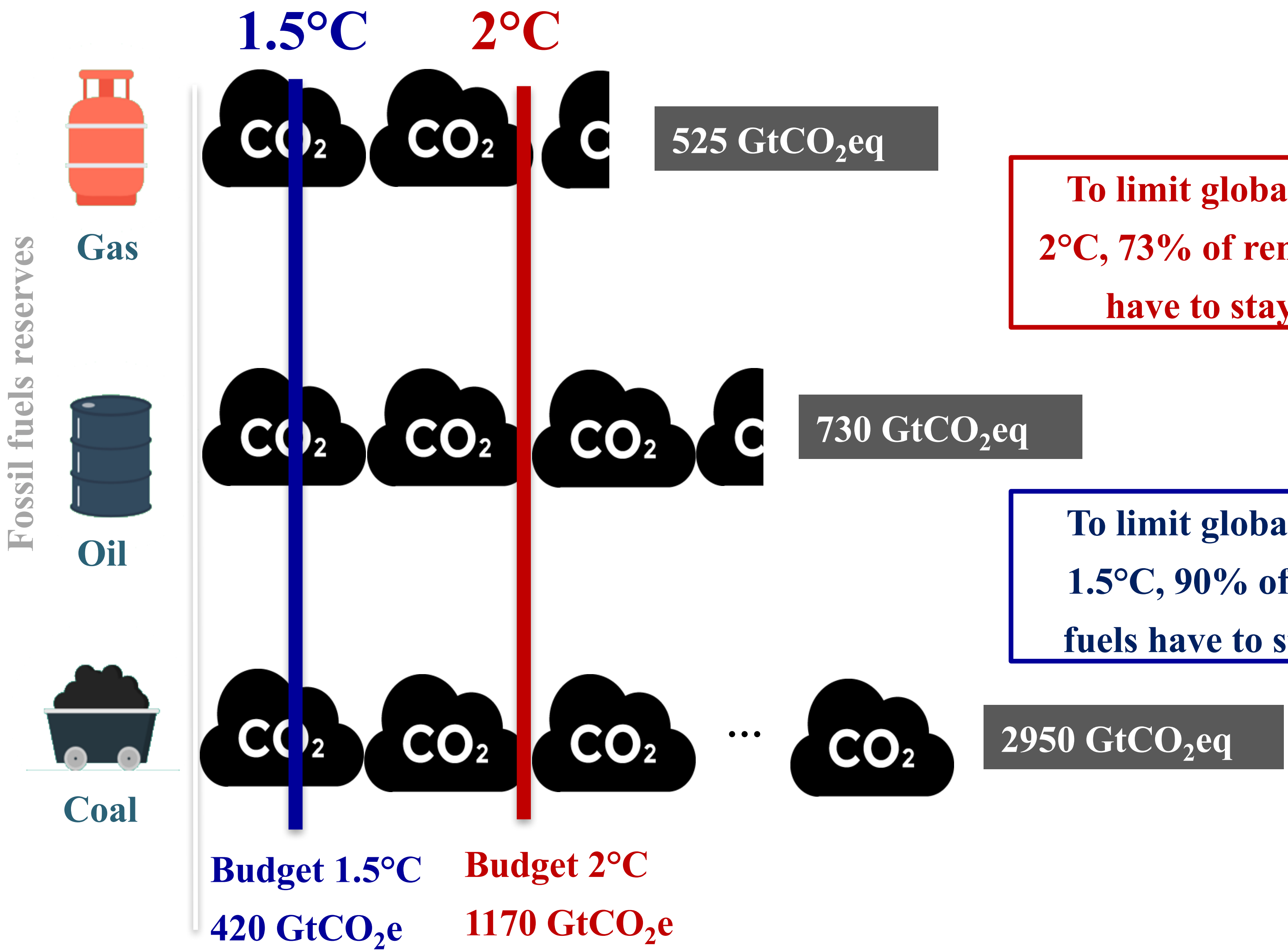
**1.5°C : 8 years**

*GHG equivalent (200 $GtCO_2eq$)*

Source : IPCC SR15, 2018



AVENIR CLIMATIQUE
PARLONS CLIMAT AVEC ÉNERGIE !




**To limit global warming below 2°C, 73% of remaining fossil fuels have to stay underground**

**To limit global warming below 1.5°C, 90% of remaining fossil fuels have to stay underground**

Source : IPCC SR15, 2018

*GHG equivalent (200 $GtCO_2eq$)*

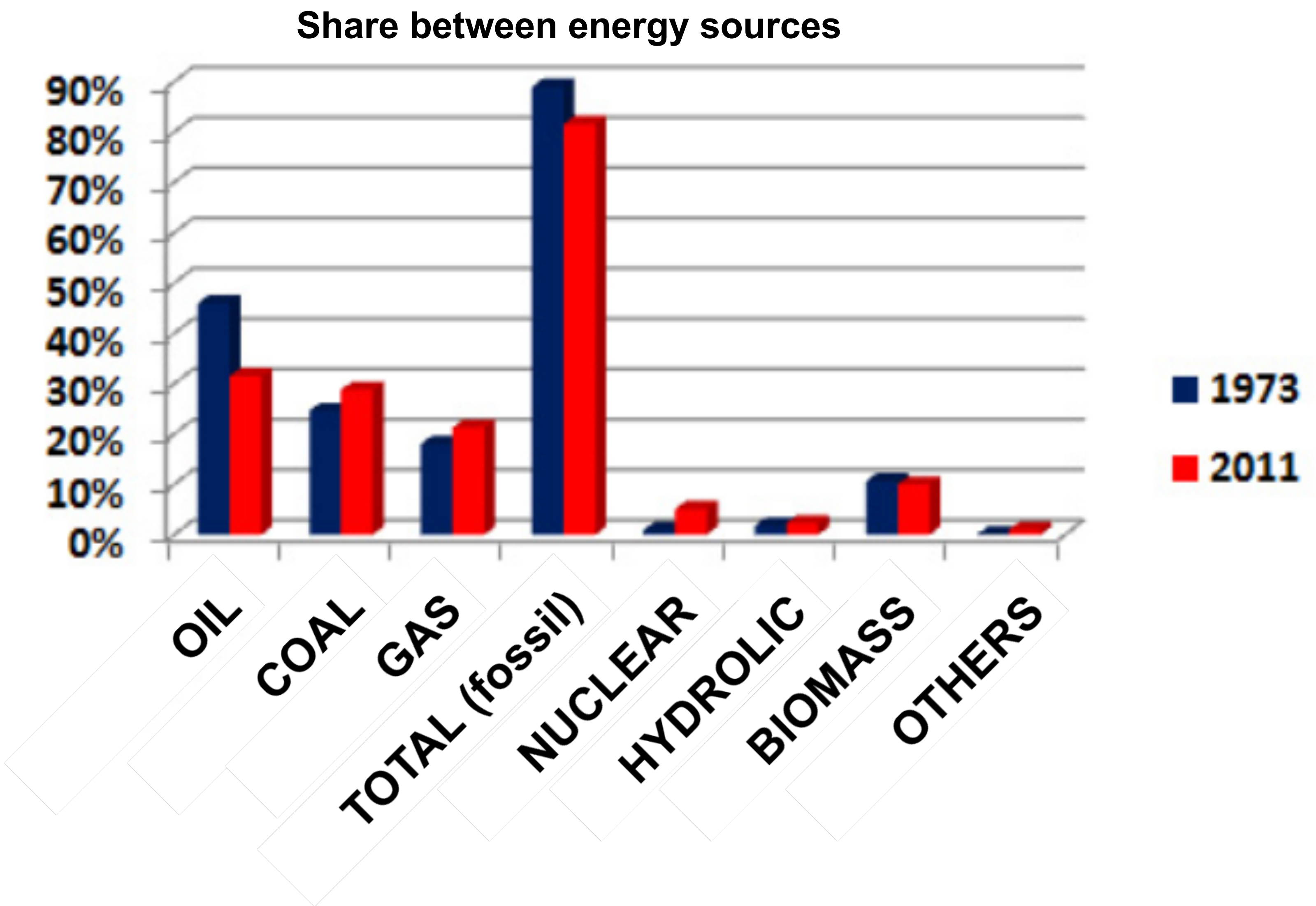
## Low level of CO2 emissions

- Wind: 9−10 $gCO_2eq/kWh$
- Hydraulic: 10−13 $gCO_2eq/kWh$
- Biogas: 11 $gCO_2eq/kWh$
- Solar (thermal): 13 $gCO_2eq/kWh$
- Biomass: 14−41 $gCO_2eq/kWh$
- Solar (electric): 32 $gCO_2eq/kWh$
- Geothermal : 38 $gCO_2eq/kWh$
- Nuclear : 12 $gCO_2eq/kWh$

## High level of CO2 emissions

- Gas : 443 $gCO_2eq/kWh$
- Fuel cell (hydrogen) : 664 $gCO_2eq/kWh$
- Oil: 778 $gCO_2eq/kWh$
- Coal: 960−1050 $gCO_2eq/kWh$

## What about the energy decarbonizing?



## What about the energy decarbonizing?

500 kg

1948


More efficient engines

+

−

More security, more equipment, more everything

2018

1500 kg

OBJECTIF 2050 : neutralité carbone

Objective of the European Union is a reduction by -40% of $CO_2$ per km from 2007 to 2022 (only 50% of the objective is achieved)

Source : France Strategie

## What about the energy decarbonizing?

500 kg

1948


4 to 5 L for 100 km

More efficient engines

More security, more equipment, more everything

1500 kg

2018

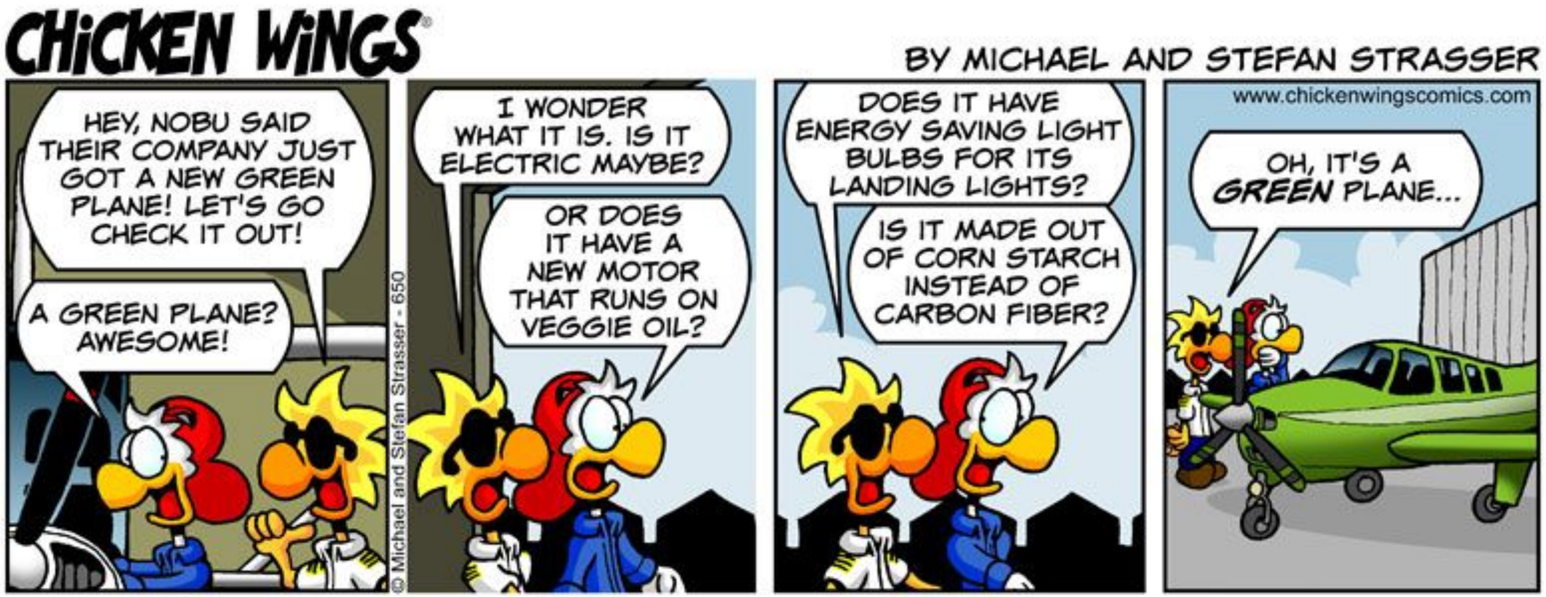
4 to 5 L for 100 km

OBJECTIF 2050 : neutralité carbone

Objective of the European Union is a reduction by -40% of $CO_2$ per km from 2007 to 2022 (only 50% of the objective is achieved)

Source : France Strategie

**The Jevons paradox: the rebound effect**



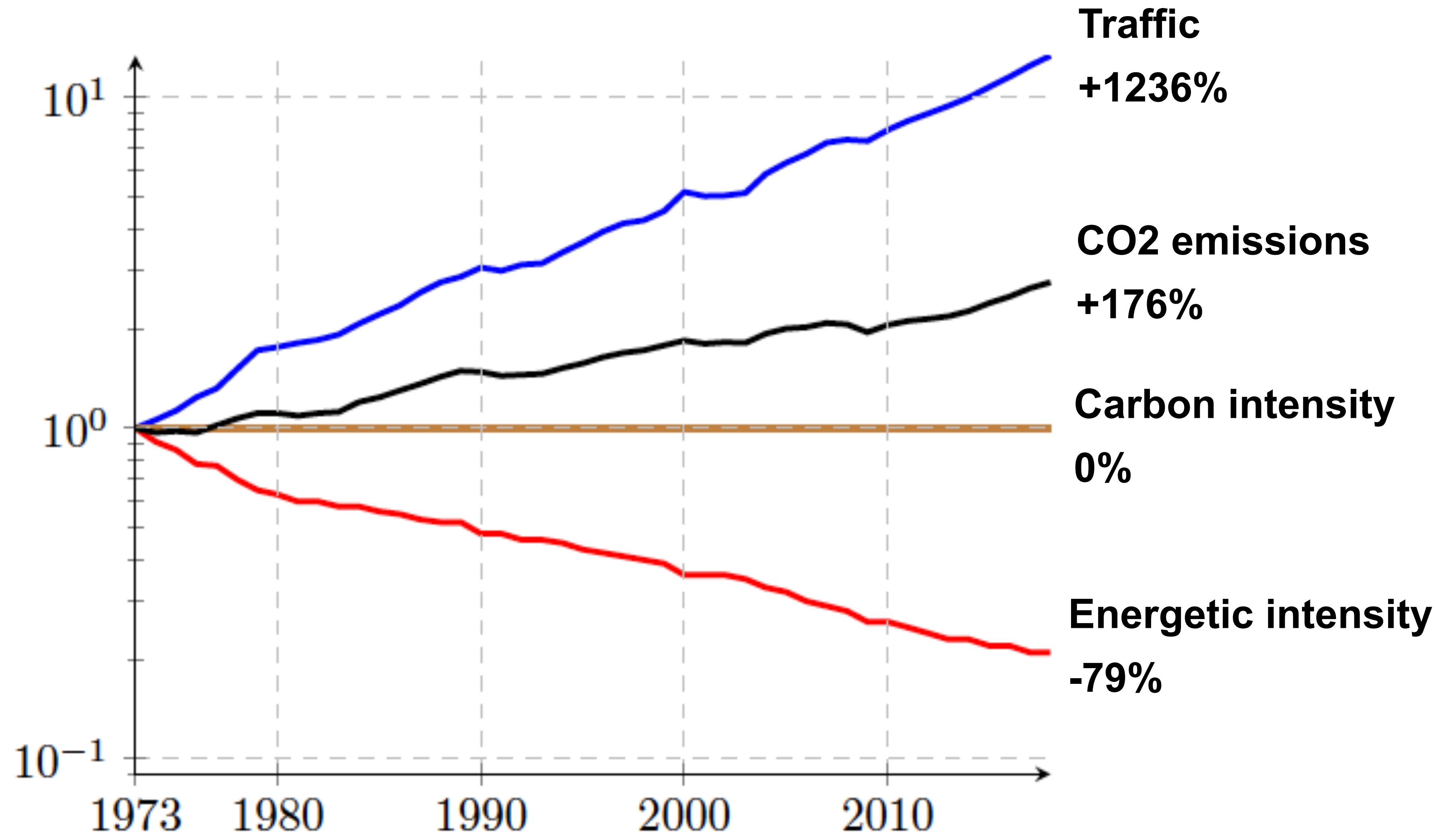

**8% of oil in the World is burned into an aircraft engine (similar to shipping)**

**Here is a classical decomposition used to show the dependency of energy and climate (the so-called Kaya decomposition, here applied to aviation)**

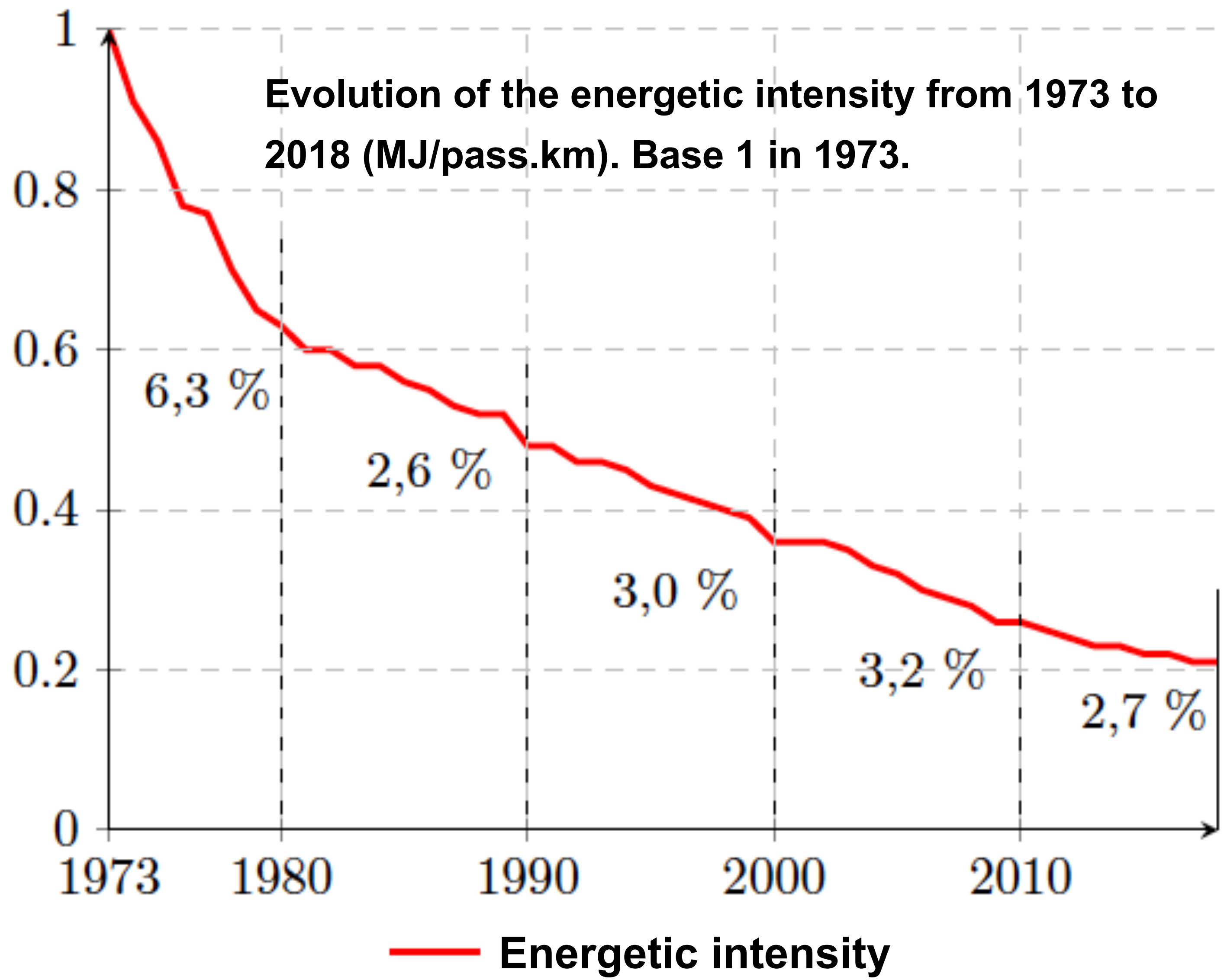
$$CO_2 = \frac{CO_2}{E} \times \frac{E}{RPK} \times RPK$$

| GHG Emissions | Carbon intensity | Energetic intensity | Traffic |
|---|---|---|---|
| MtCO2 | MtCO2/EJ | EJ/pass.km | pass.km |

**Note: RPK (Revenue Passenger x km)**

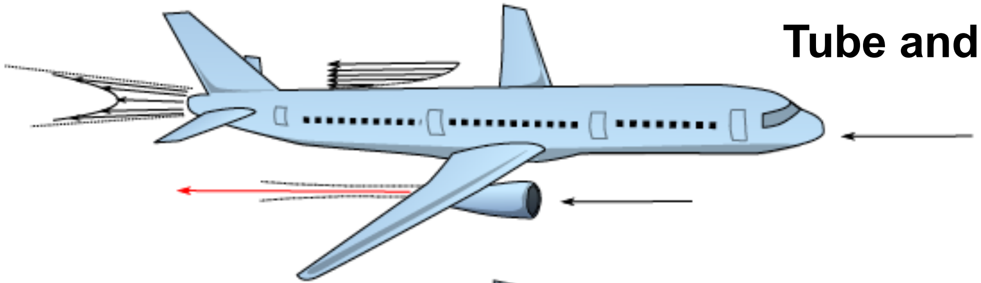



**Energetic intensity is reduced thanks to the increase of the aircraft energetic efficiency (aerodynamic, mass reduction, etc.), the filing rate and the number of seats available (size)**

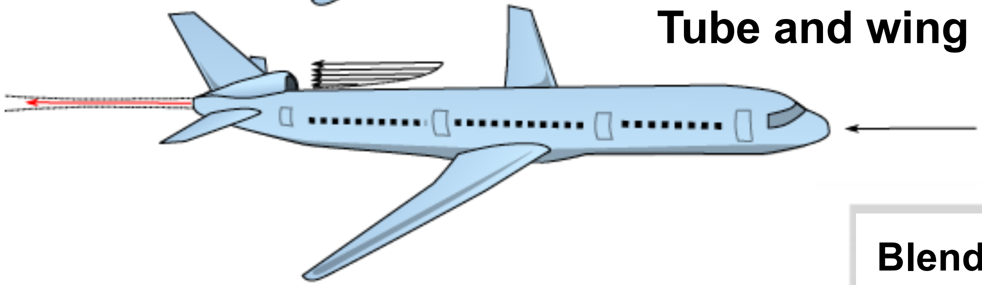



**The % corresponds to the compound rate for each decade; e.g. from 1980 to 1990, the energetic efficiency has been increased by 2.6%/year. From IEA and OACI data.**

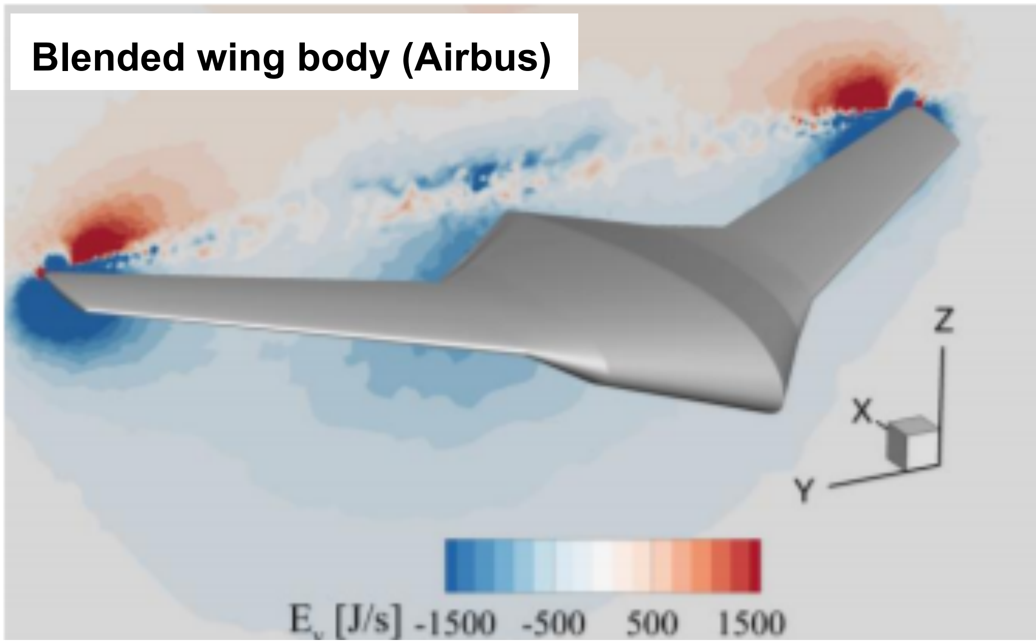
## Energetic intensity: where the improvements come from?



Tube and wing (conventional)

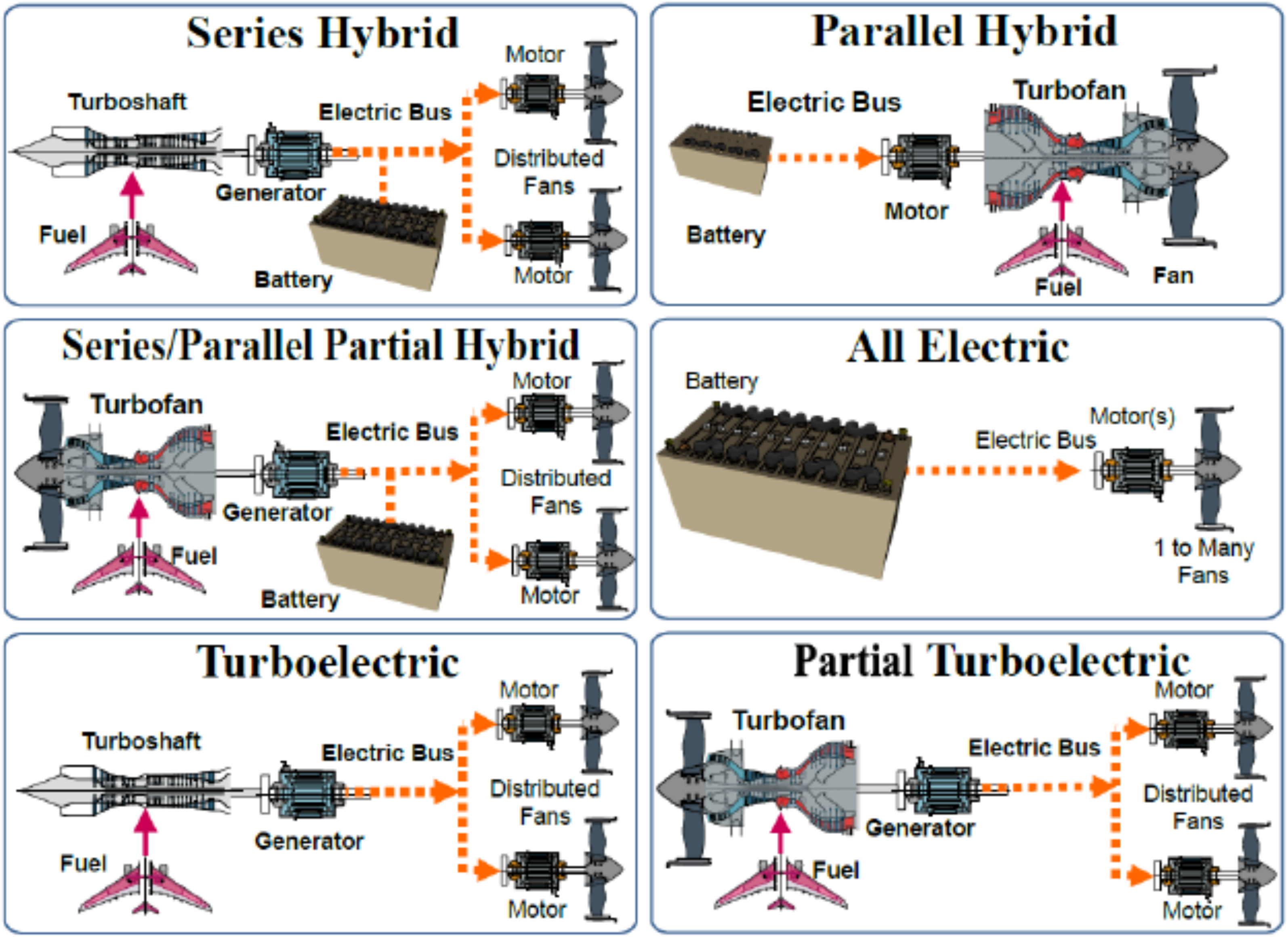


Tube and wing (boundary layer ingestion)




PhD Coyle, 2021

## Energetic intensity: where the improvements come from?




Thauvin, 2018

## Energetic intensity: where the improvements come from?

| Current & future improvements | Potential gains on fuel consumption (per pass.km) |
|---|---|
| New engine architectures (Ultrafan, openrotor, UHBR) | ~ 20 to 25% |
| New thermodynamic cycles (active control, new composite gen.) | ~ 10 to 20% |
| Aerodynamic improvement (laminar, wing tip, etc.) | ~ 10 to 15% |
| Improved systems (green taxiing, more electric aircraft) | ~ 1 to 5% |

Data: IATA

## Carbon intensity: how to replace kerosene with a lower environmental impact?

**Electricity?**

**Hydrogen?**

**Biofuels?**

**Electrofuels?**

## Carbon intensity: how to replace kerosene with a lower environmental impact?

### <u>Electricity</u>

**Advantage:**

- no emissions during flight, contrails are also greatly reduced

**Drawback:**

- Can not be produced onboard (for a small regional aircraft ~ 14 000m2 of solar panels)
- Not a primary source of energy: still massively produced with fossil fuels (130 g CO2eq/MJ to be compared to 80 g CO2eq/MJ for kerosene)
- Low storage capacity (battery ~ 1MJ/kg to be compared to 43 MJ/kg for kerosene)

**Limited to regional aircraft (typically max. 20 pax on less than 1000 km)**

## Carbon intensity: how to replace kerosene with a lower environmental impact?

### Hydrogen (H2)

**Advantage:**

- no emissions during flight, contrails are also moderately reduced
- Previous successful experiences (e.g. flight of the Tupolev 155 in 1988)
- High mass density (3.3 x better than kerosene)
- Can be burned on-board or store to run a fuel cell

**Drawback:**

- Low volume density (stored at -253°C, tanks still ~ 3 times bigger than for kerosene)
- Not a primary source of energy: still massively produced with fossil fuels and high energy intensity (12 kg of $CO_2$eq for 1 kg of $H_2$)

**Carbon intensity: how to replace kerosene with a lower environmental impact?**

## Hydrogen (H2)

**Energetic efficiency of H2-based architecture**

**(e.g H2-based long haul needs +42% of energy per km.pax)**

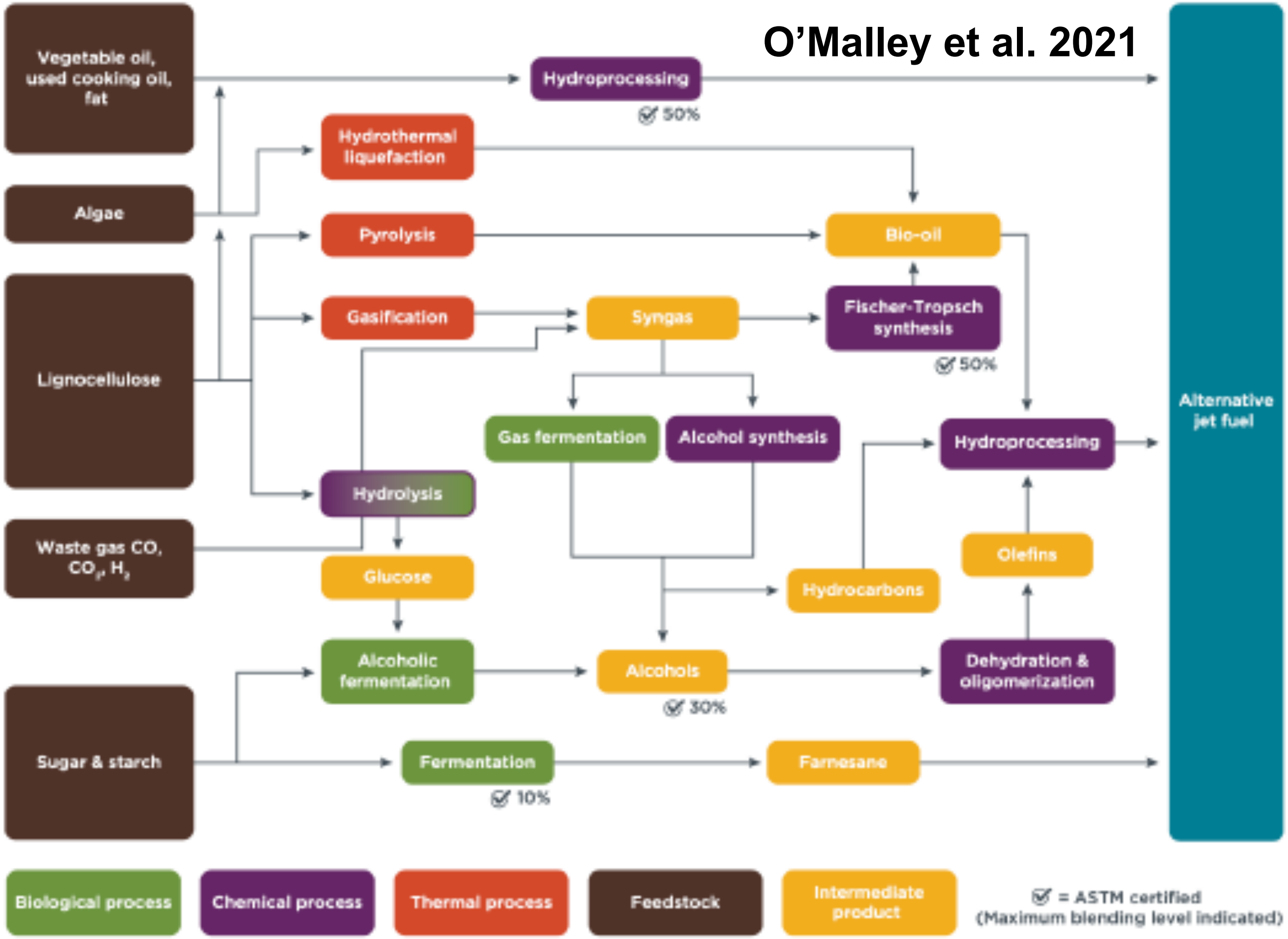
| Source | Type | Short haul | Medium haul | Long haul |
|---|---|---|---|---|
| Clean Sky[McK20] | P/T/H | -4 % | +22 % | +42 % |
| Verstraete[92] | T | +18 % | +5 % | -12 % |
| Renewables in transport 2050[SZWR16] | P | -10 % | -10 % | -10 % |
| CRYOPLANE[Gmb03] | T | +14 à +18 % | +10 % | +9 à +14 % |

**Note: P (fuel cells); T (gas turbine); H (hybrid)**

**H2 adapted to short/medium haul (typically ATR72 or A320)**

## Carbon intensity: how to replace kerosene with a lower environmental impact?

### Synthetic fuels (Sustainable Aviation Fuels)



## Carbon intensity: how to replace kerosene with a lower environmental impact?

### Synthetic fuels (Sustainable Aviation Fuels)

**Advantage:**

- Large variety of technical means to synthetize fuels

1st generation from vegetal oil, sugar; 2nd generation from lignocellulose; 3rd generation from algae; electro-fuels from $CO_2$ and $H_2$

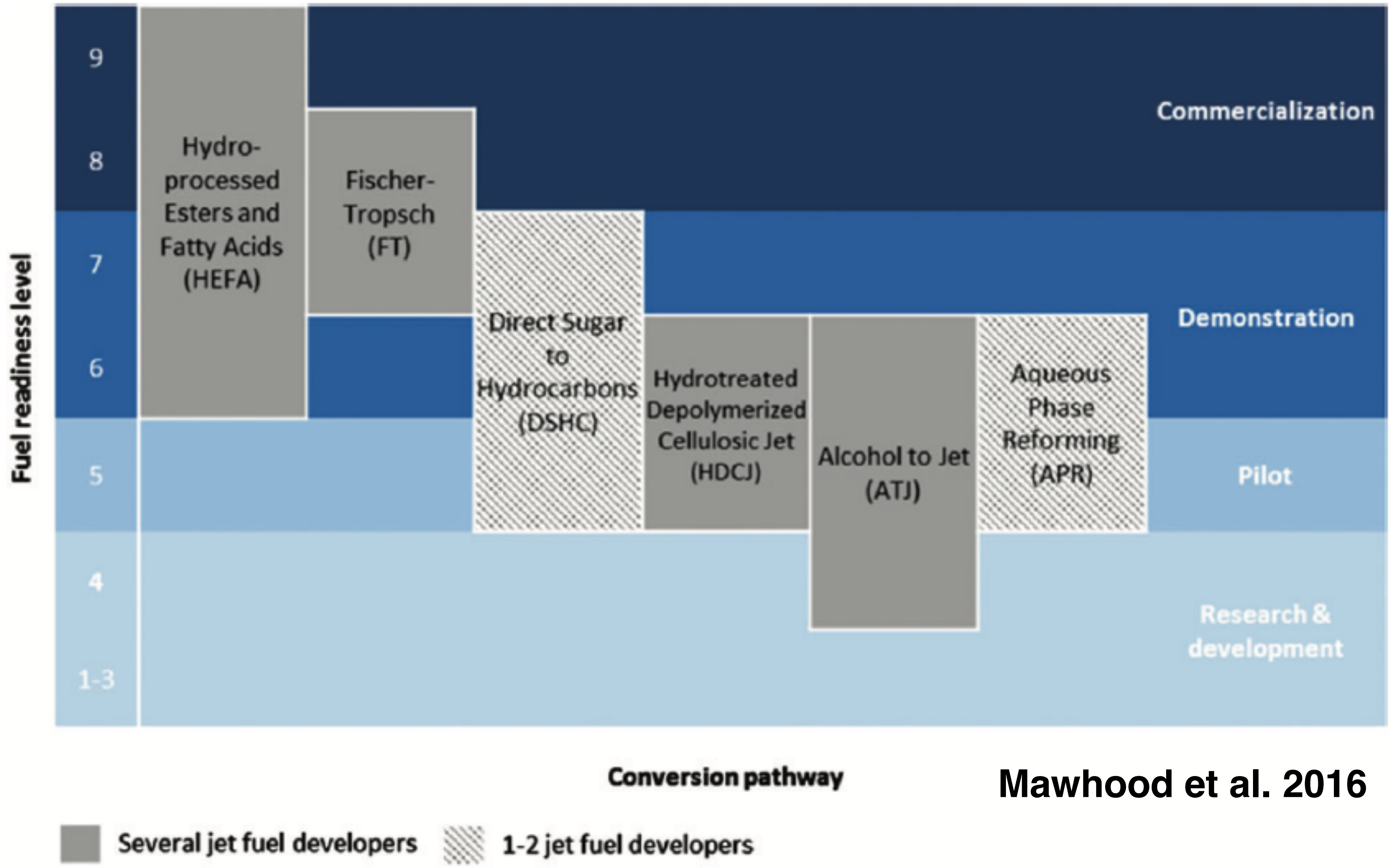
- Can be drop-in (mixed with kerosene)
- Low carbon intensity (< 10g $CO_2$eq./MJ to be compared to 80 g $CO_2$eq./MJ for kerosene)

**Drawback:**

- Low level of maturity for most of them (Fuel Readiness Level < 6)
- Only 1st gen. is mature but with a low availability (represents 0.004% of the World consumption of aviation in 2018)
- Change in land use and competition with food production (1st gen. only)

## Carbon intensity: how to replace kerosene with a lower environmental impact?

### Synthetic fuels (Sustainable Aviation Fuels)

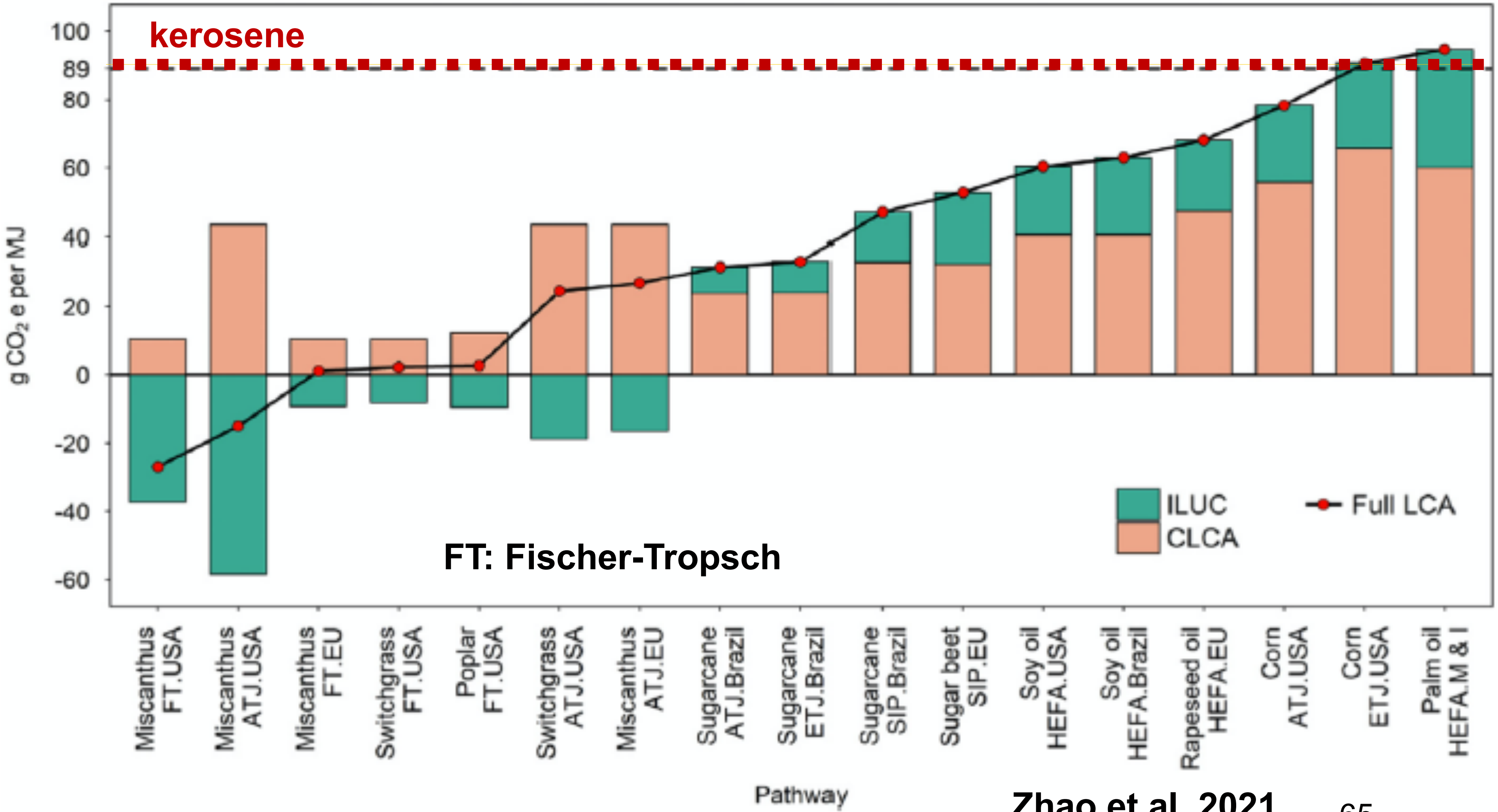



Mawhood et al. 2016

## Carbon intensity: how to replace kerosene with a lower environmental impact?

### Synthetic fuels (Sustainable Aviation Fuels)

Life cycle of biofuels (Including land use change)

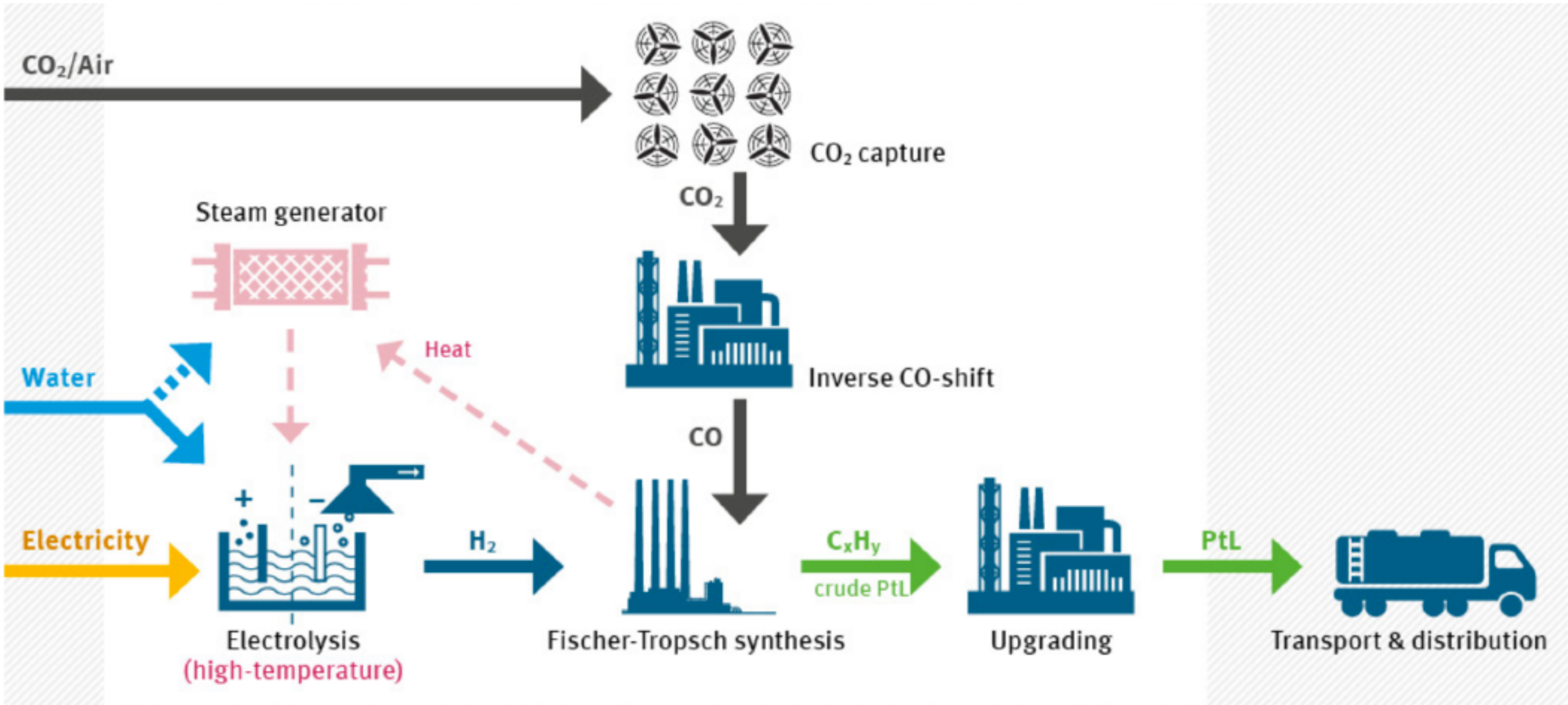



Zhao et al. 2021

**Carbon intensity: how to replace kerosene with a lower environmental impact?**

## Synthetic fuels (Electro Fuels)

**CO2 is coming from Direct Air Capture, but efficiency is still low (40% to 50%)**




**Schmidt et al. 2016**

## Carbon intensity: how to replace kerosene with a lower environmental impact?

### Conclusion (some scenarios)

| Current status (2018): 1.2Gt$CO_2$eq / 14.1EJ | CO2 emissions Variation (%) | Energy consumption And share (%) |
|---|---|---|
| **Scenario 1: full electricity** | | |
| Current world mix | +139% | 22.3 EJ; 23% of avail. elec. |
| Low carbon mix | - 90% | 22.3 EJ; 70% of avail. elec. |
| **Scenario 2: electrofuels** | | |
| Current world mix | +359% | 42.9 EJ; 45% of avail. elec. |
| Low carbon mix | - 81% | 42.9 EJ; 134% of avail. elec. |
| **Scenario 3: Hydrogen** | | |
| Current production | + 76% | - |
| Electrolyse (current mix) | +164% | 24.6 EJ; 26% of avail. elec. |
| Electrolyse (Low carbon mix) | - 89% | 24.6 EJ; 77% of avail. elec. |
| **Scenario 4: biofuels** | | |
| HEFA (Palm oil) | -61% to +18% | 23.7 EJ 43% of avail. biof. |
| Fischer-Tropsch (wood) | -89% to -71% | 50.4 EJ 91% of avail. biof. |


Chap. 1 Relationship climate & aviation

1.1 Impact of aviation on climate change

1.2 Impact of climate change on aviation

Chap. 2 Energy: fossil fuels

2.1 General considerations

2.2 The particular case of aviation

2.3 Energies for the future of aviation

# Conclusion

- **Need to draw an innovative trajectory for aviation (technology, air traffic management, new fuels, new uses, etc.) – will be done with CAST**

- **BIG (MOTIVATING) CHALLENGES, but very difficult to manage decarbonization, reduction of radiative forcing and energy reduction at the same time**

- **What about socio-economic challenges (price, equity, preservation of commons, etc.)?**

# Thanks for your attention!