UNIVERSITÀ DEGLI STUDI FIRENZE

DIEF Dipartimento di Ingegneria Industriale

CHALLENGES IN THE TRANSITION FROM FOSSIL TO HYDROGEN-BASED FUELS IN THE AVIATION SECTOR

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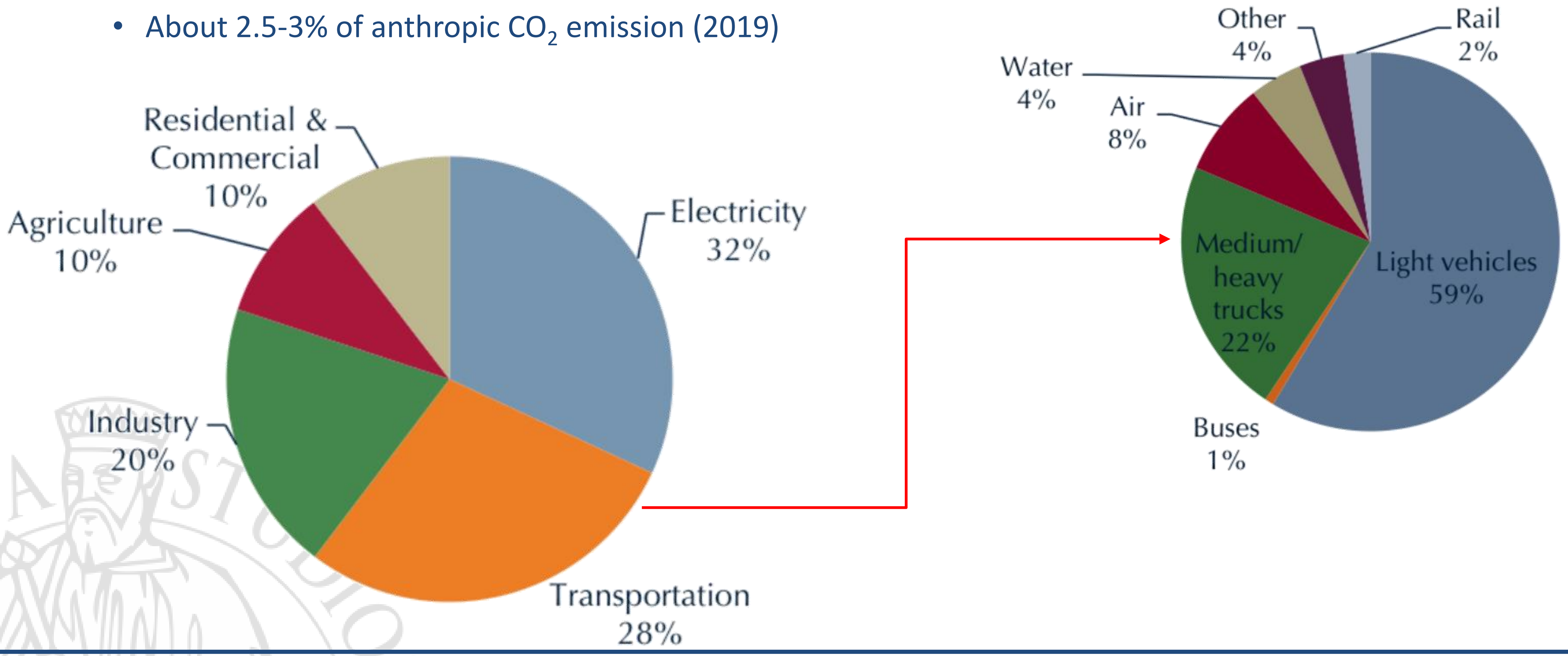
Giornata di Studio

IDROGENO E TECNOLOGIE PER LA GENERAZIONE ENERGETICA E LA PROPULSIONE NEI TRASPORTI GREEN

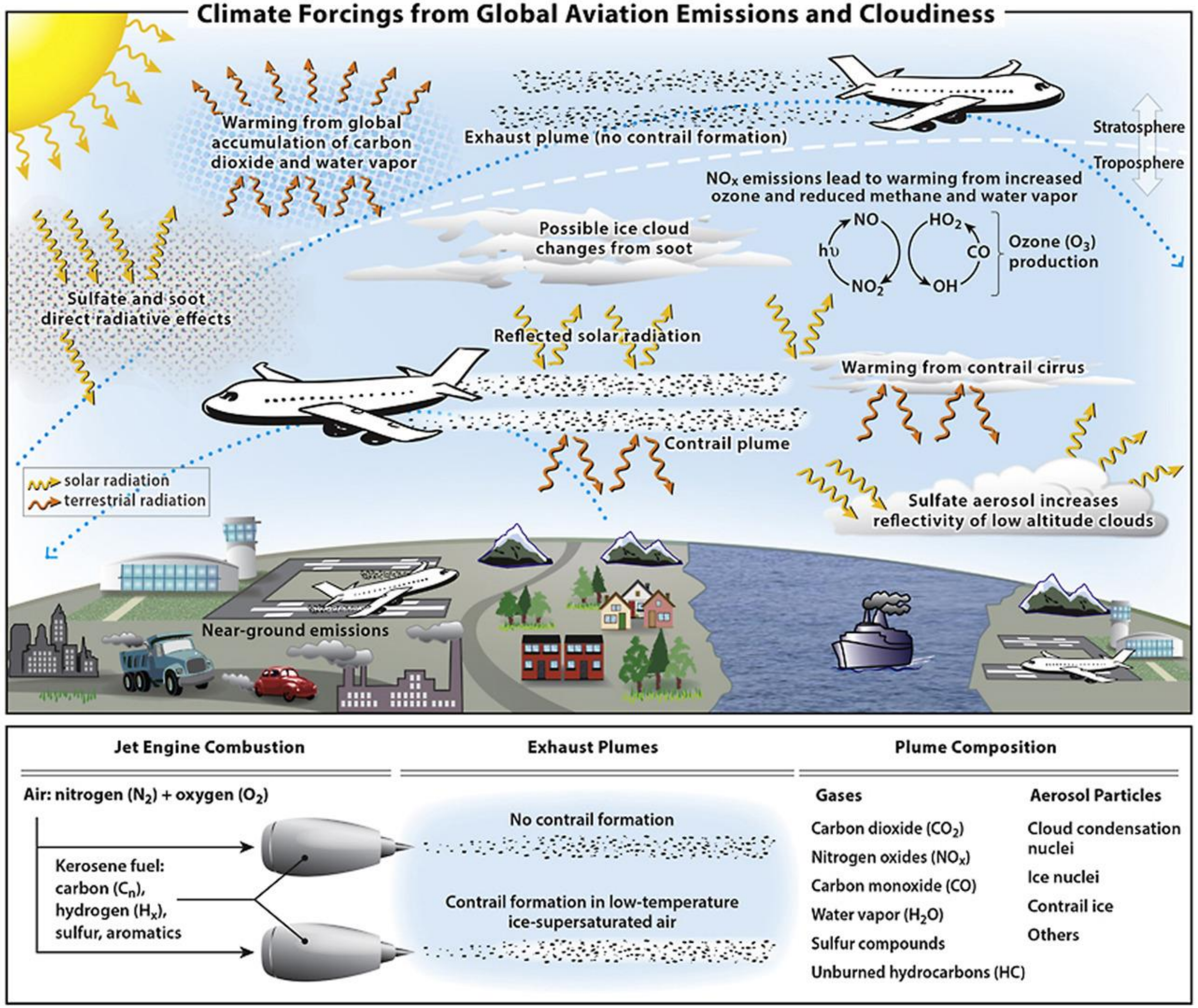
Genova, 25 Gennaio 2024

Carbon footprint of civil aviation

- How much aviation contribute to climate change?
  - Typical aircraft engines emit 3.15 kg of CO_2 for each kg of fuel burnt
  - More than 900 million tons of CO_2 per year
    - About 2.5-3% of anthropic CO_2 emission (2019)



Climate impact is not only due to CO_2 emissions



- Positive RF (warming)
  - CO_2, water vapor, NOx, PM emissions and from contrail cirrus
    - CO_2 stays 50-100 years in the upper atmosphere
- Negative RF (cooling)
  - sulfate aerosol
- →Net RF from NOx
  - warming
    - short-term ozone increase
  - cooling
    - decreases in methane and stratospheric water vapor, and a long-term decrease in ozone

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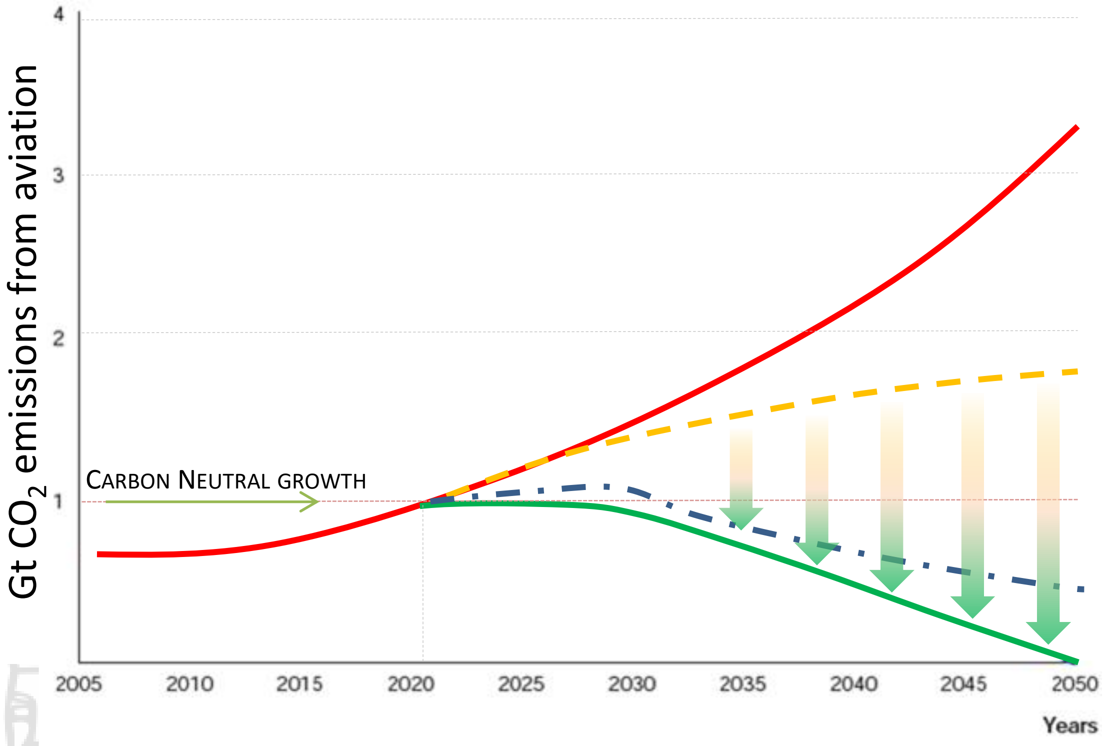
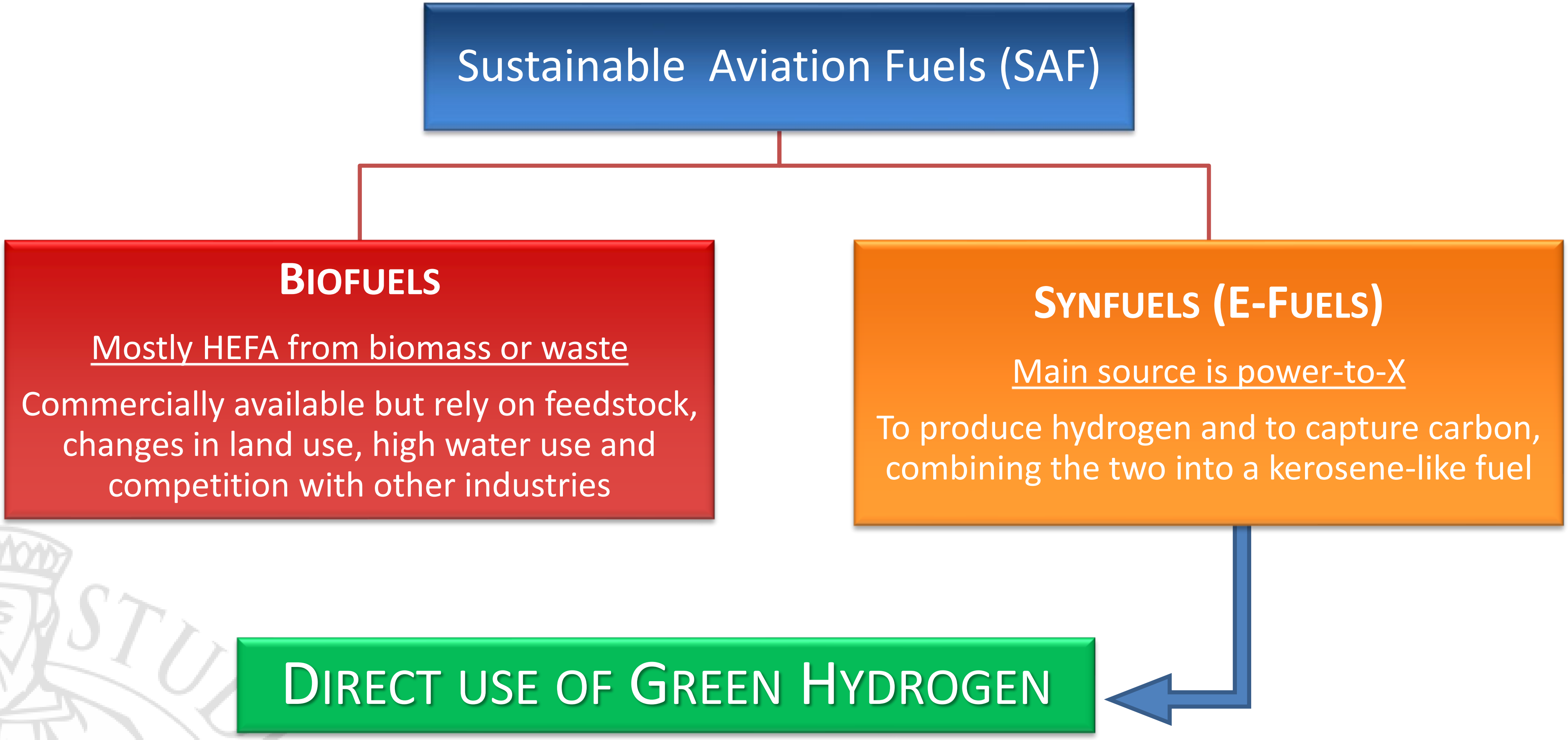
- Fuel efficiency per revenue passenger km has roughly increased by 50% in the last 30 years

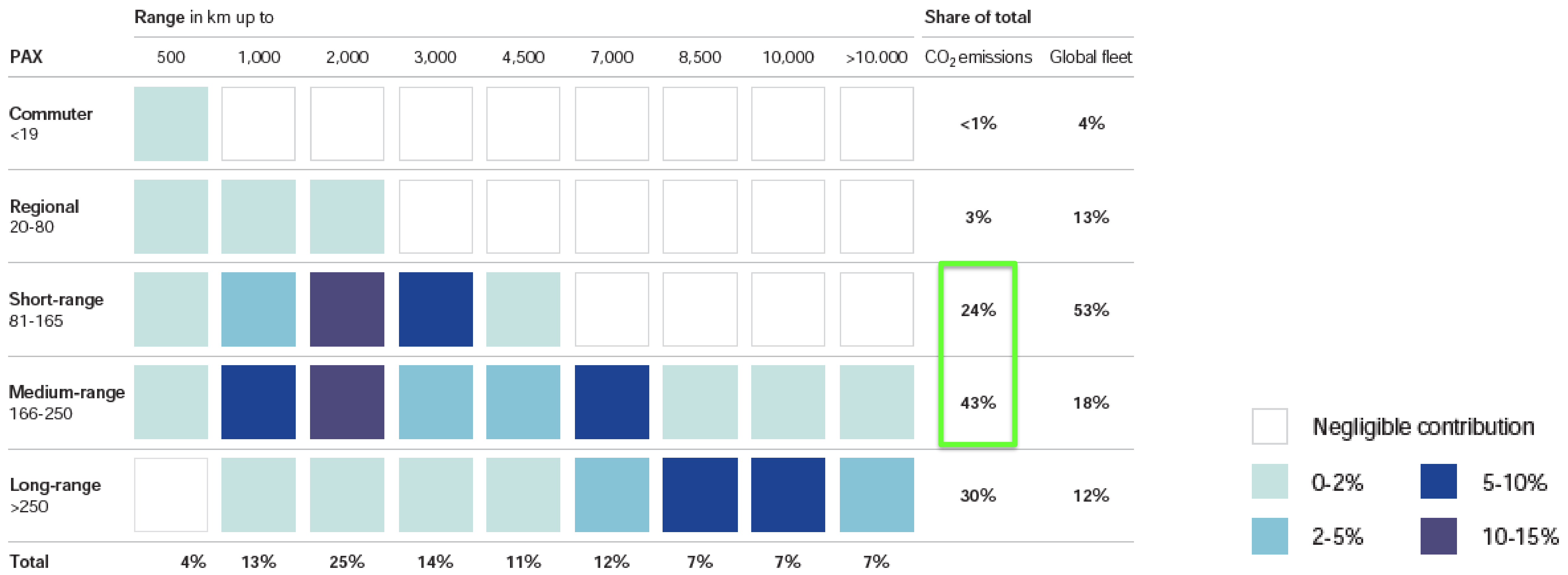


1. Assumption based on growth projections from ATAG, IATA, ICCT, WWF, UN
2. ICAO ambition incl. efficiency improvements in aircraft technology, operations and infrastructure

To fully decarbonize aviation new fuels and disruptive propulsion technologies are required


Sustainable Aviation Fuels (SAF)
BIOFUELS
Mostly HEFA from biomass or waste
Commercially available but rely on feedstock, changes in land use, high water use and competition with other industries
SYNFUELS (E-FUELS)
Main source is power-to-X
To produce hydrogen and to capture carbon, combining the two into a kerosene-like fuel
DIRECT USE OF GREEN HYDROGEN

CO_2 emissions per segment and range



- Short and medium range flights cause 2/3 of current aircraft emissions (count for 70% of fleets)
  - Regional and commuter contribute for 5%

SAF and new technologies

Comparison vs. kerosene	Biofuels	Synfuels	Battery-electric	Hydrogen
Commuter <19 PAX	No limitation of range	No limitation of range	Maximum ranges up to 500-1,000 km due to lower battery density	No limitation of range
Regional 20-80 PAX				
Short-range 81-165 PAX				
Medium-range 166-250 PAX			Not applicable	Revolutionary aircraft designs as efficient option for ranges above 10,000 km
Long-range >250 PAX				
Main advantage ✓	Drop-in fuel – no change to aircraft or infrastructure	Drop-in fuel – no change to aircraft or infrastructure	No climate impact in flight	High reduction potential of climate impact
Main disadvantage ✕	Limited reduction of non-CO_2 effects	Limited reduction of non-CO_2 effects	Change to infrastructure due to fast charging or battery exchange systems	Change to infrastructure

- Batteries still suffer from low gravimetric energy densities of 0.2 to 0.5 kW/kg and limited life-time cycles

Reduction potentials

Ongoing scientific debate about **full climate** impact, in particular:

- Contrail/cirrus formation
- Aggregate measure

Total climate impact could be 2 to 4 times compared to CO_2 emissions alone

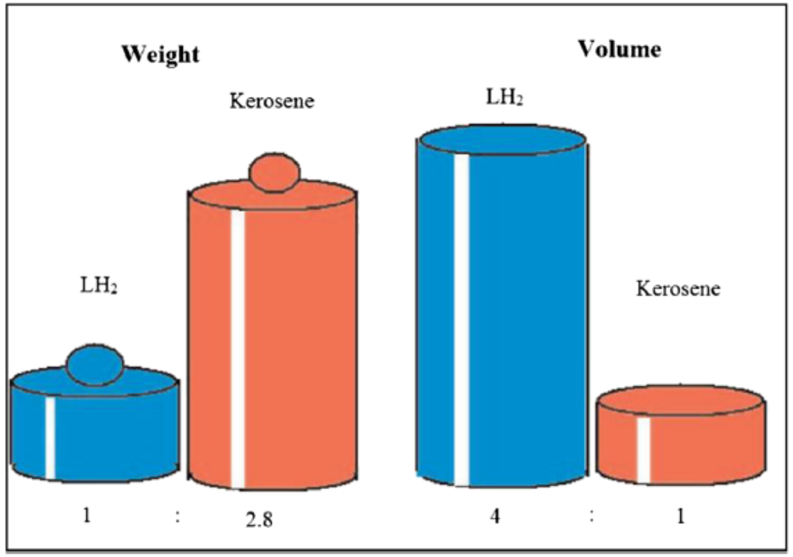
Change of in-flight emissions and emission related effects[1]

	Direct CO_2	NO_x	Water vapor[2]	Contrails, cirrus	Climate impact reduction potential[4]
Synfuel turbine	-0% / -100% (Net) [3]	-0%	-0%	-10-40%	-30-60%[3]
Hydrogen turbine	-100%	-50-80%	+150%	-30-50%	-50-75%
Hydrogen fuel cell	-100%	-100%	+150%	-60-80%	-75-90%

- Hydrogen propulsion is projected to be two to three times more effective than other synthetic fuels in reducing aviation's climate impact

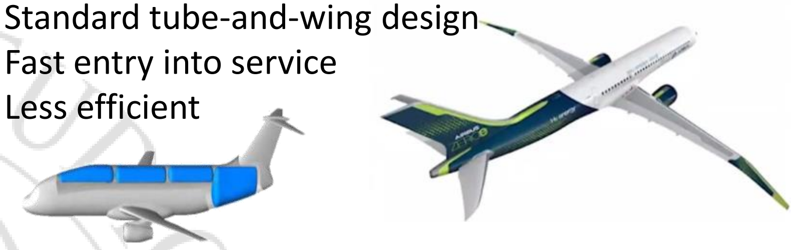
Feasibility and cost of H_2 propulsion

- H_2 can be stored as pressurized gas or liquid
  - Gaseous storage
    - suitable for shorter flights, commercially available
    - Not favorable energy density, weight of tanks
  - Liquid Hydrogen (LH2)
    - LH2 storage tanks require roughly half as much volume and weight than gaseous hydrogen.
      - Fundamental for short- to long-range segments
      - Tanks are still about four times as big compared to jet-A
      - Needs cryogenic cooling down to 20 K with dedicated HW



Evolutionary aircraft

- Standard tube-and-wing design
- Fast entry into service
- Less efficient



Revolutionary aircraft

- Optimized design for LH2 tank integration
- Long, unpredictable
- commercialization process

Medium-range (250 PAX, 7,000-kilometer range)

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Evolutionary aircraft powered by Turbofan engine

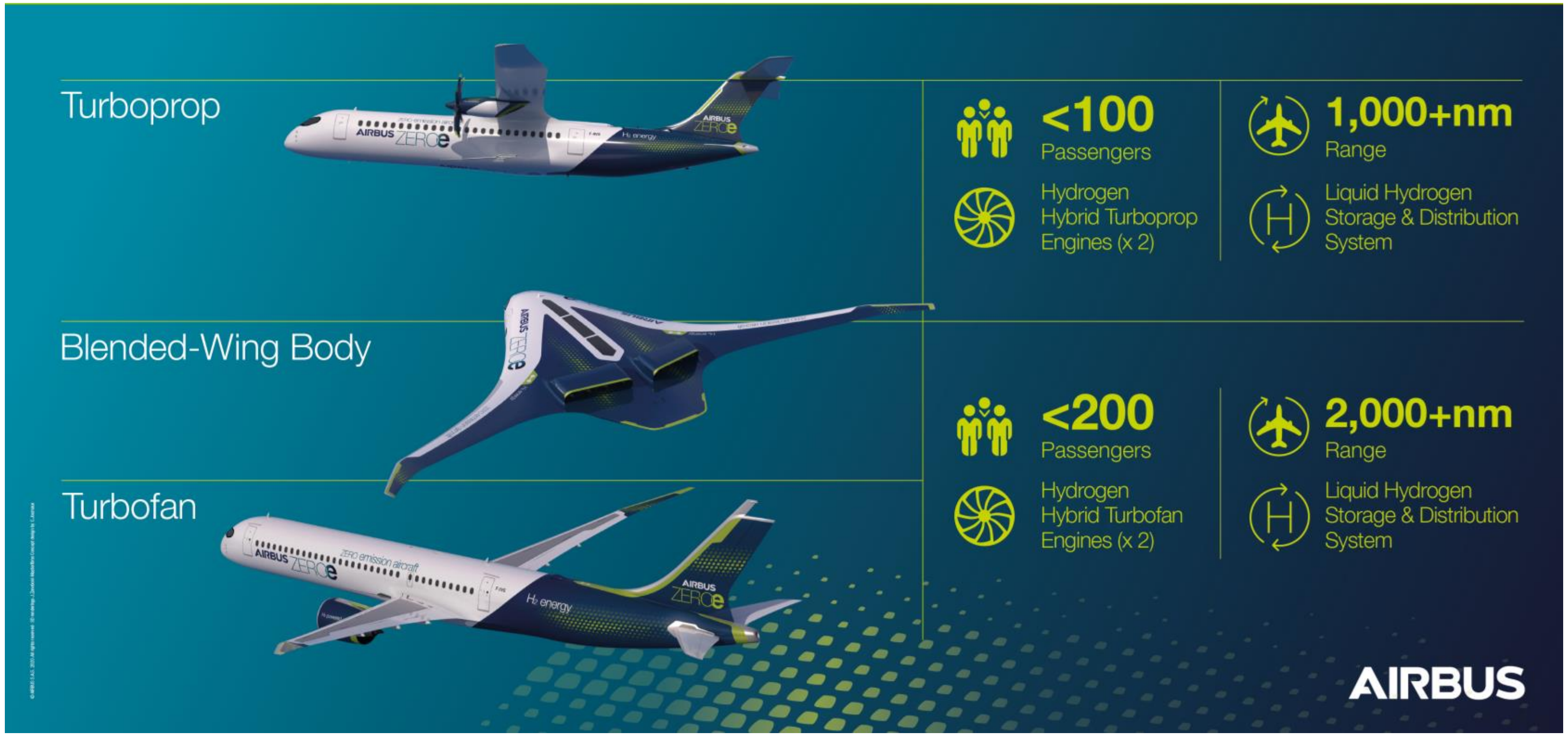
Design mission: 250 PAX, 7,000 km range, cruise speed Mach 0.82

- 2 LH_2 **tanks** in front and back of PAX cabin - added weight: 29 tons
- H_2 **turbines** generating propulsion power

Energy demand[1]	+22%
CO_2 reduction	100%
Climate impact reduction	50-60%
Additional cost	30-40% CASK[2]
Entry into service	20 years
Propulsion power	H_2 turbine
MTOW[3]	+12%

1. Major assumptions: 37% gravimetric index of LH_2 tank, 92% useable LH_2 fuel, 47% H_2 turbine cruise efficiency, 80% fan efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

AIRBUS ZEROe Programme



- Turbofan and turboprop Fuel Cells - Gas Turbine hybrid engines fueled by LH2
  - First flight demonstrator by 2027
  - Entry into service by 2035

Hydrogen as a fuel → issues

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	Hydrogen	Natural gas
Density:	0.09 kg/m³	0.68 kg/m³
Energy density: (gravimetric)	120 MJ/kg	54 MJ/kg
Energy density: (volumetric)	0.01 MJ/L	0.036 MJ/L

Laminar flame speed ($\phi = 0.8$)

1.7 m/s

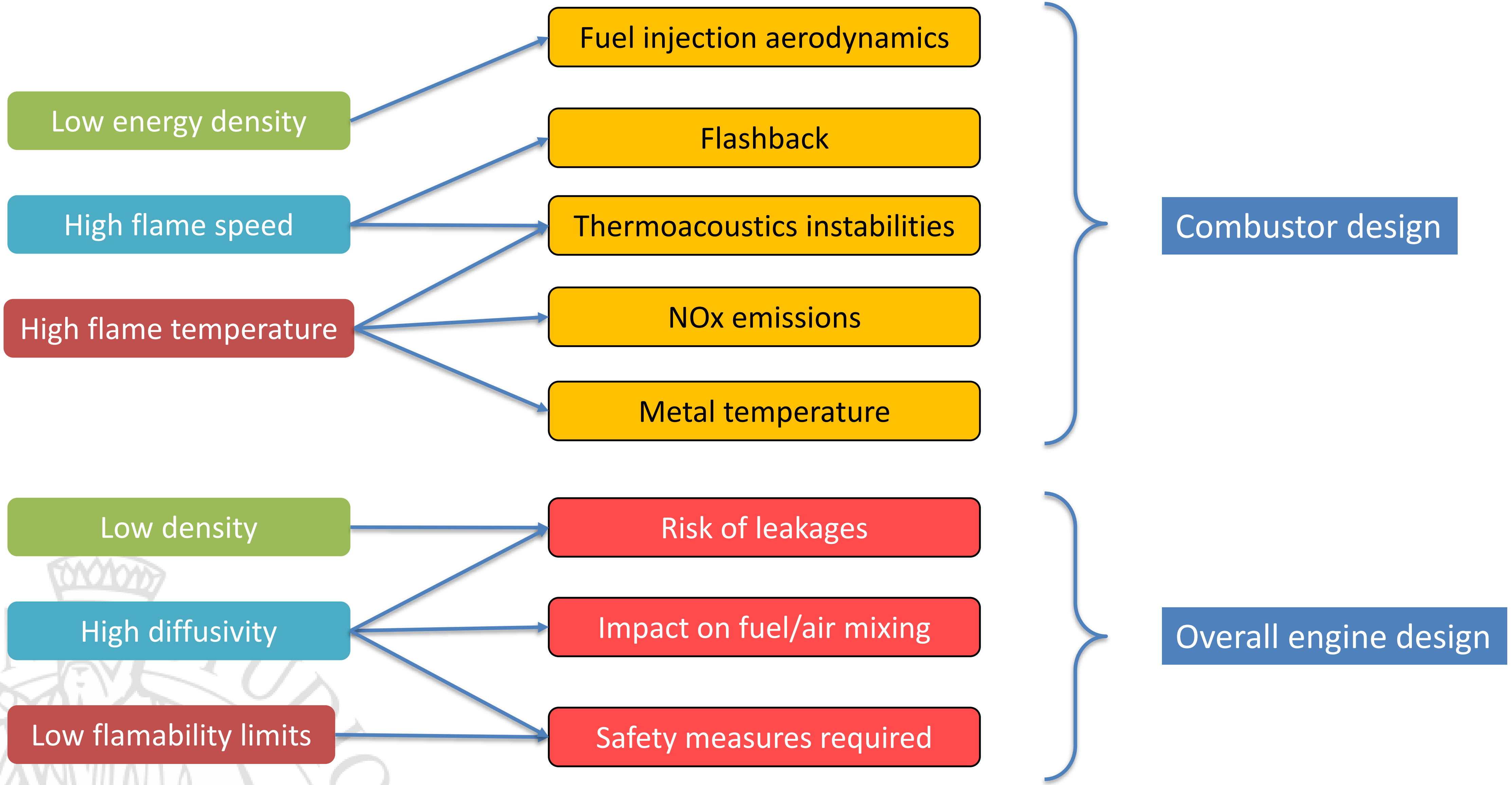
0.25 m/s

Adiabatic flame temperature ($\phi = 0.7$)

2000 K

1800 K

General challenges



On going EU funded research actions

- Low TRL – Horizon RIA projects

HESTIA

HydrogEn combuSTion In Aero engines

From: 1 September 2022 to: 31 August 2026

FFLECS

novel Fuel-Flexible ultra-Low Emissions Combustion systems for Sustainable aviation

From: 1 January 2024 to: 31 December 2026

H2OPE

Hydrogen Optimized multi-fuel Propulsion system for clean and silEnt aircraft

1 January 2023 to: 31 December 2026

OVERLEAF

nOVel low-prEssure cRyogenic Liquid hydrogEn storAge For aviation.

1 May 2022 to: 30 April 2025

MYTHOS

Medium-range hybrid low-pollution flexi-fuel/hydrogen sustainable engine

1 January 2023 to: 31 December 2026

BeCoM

Better Contrails Mitigation

From: 1 June 2022 to: 31 May 2026

MINIMAL

Minimum environmental impact ultra-efficient cores for aircraft propulsion.

From: 1 September 2022 to: 31 August 2026

Coordination: **SAFRAN** – 5M€ budget – 48 Months – 18 Universities – 6 EU engine manufacturers

Task 1.1

Why H_2 ignition is challenging?

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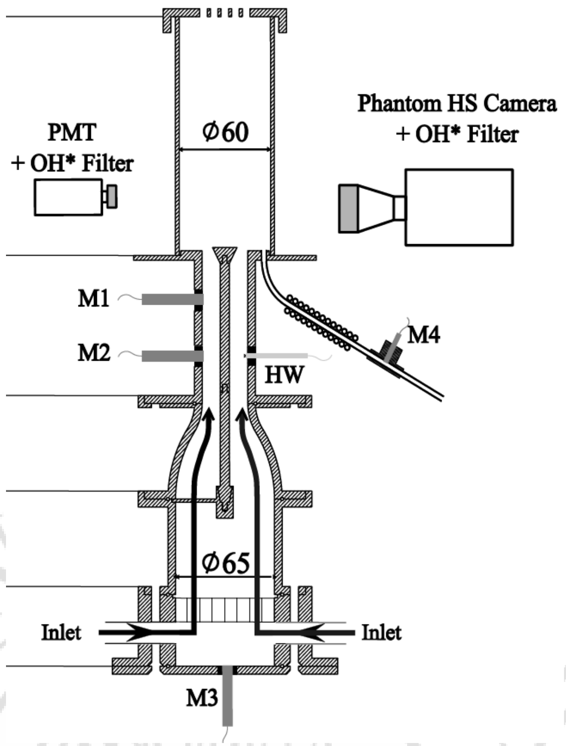
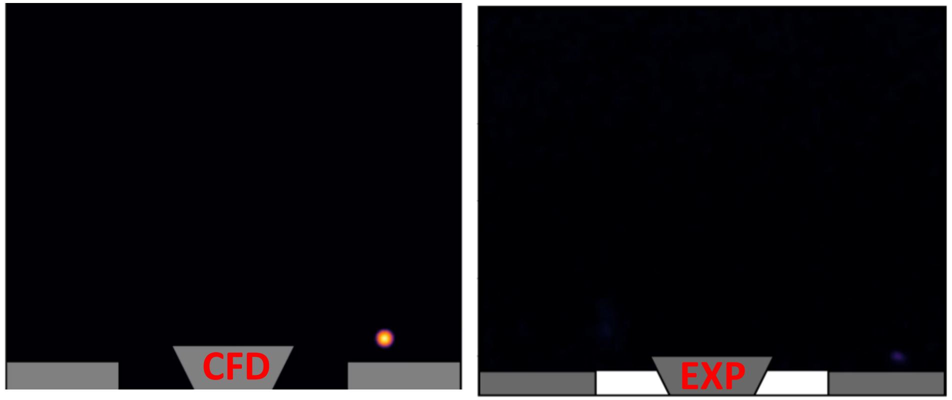
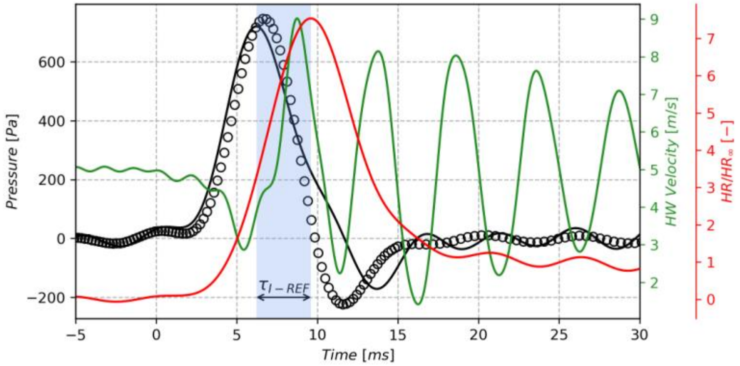
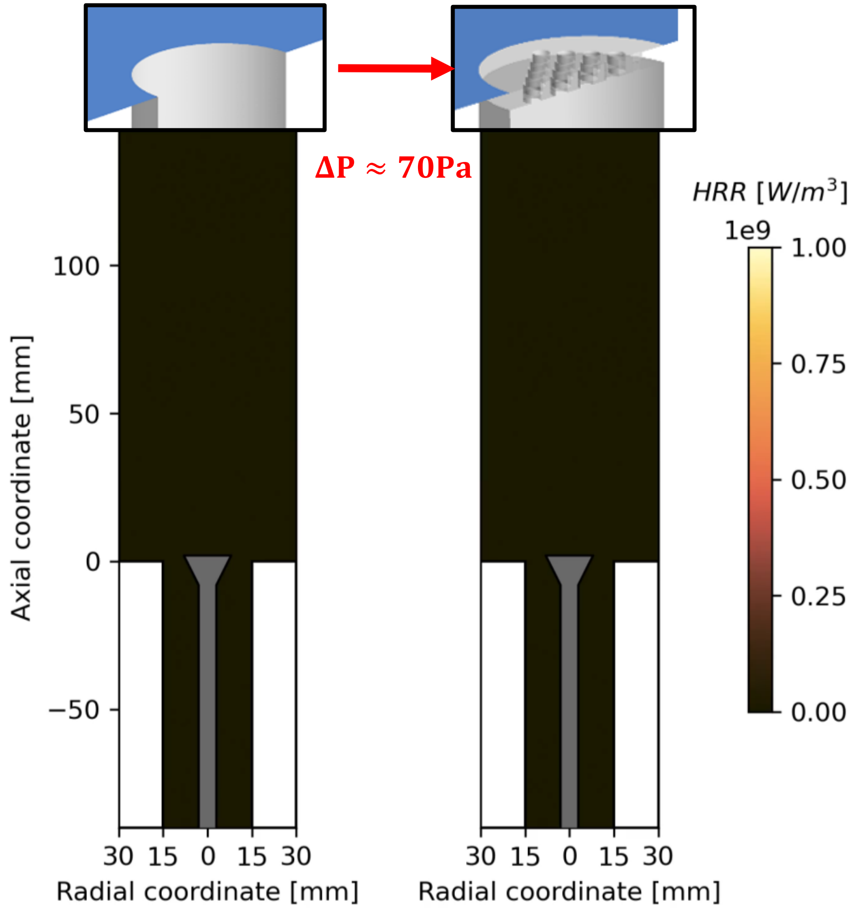
Partner, ≈ 400k€ budget
LES and Exp

…strong pressure fluctuations – risk of flashback…





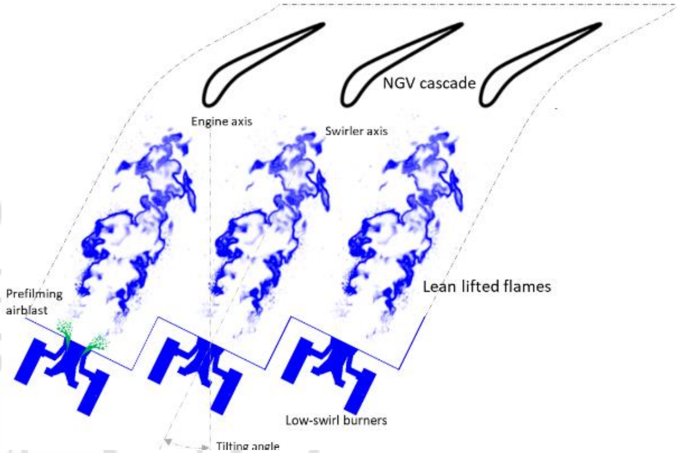




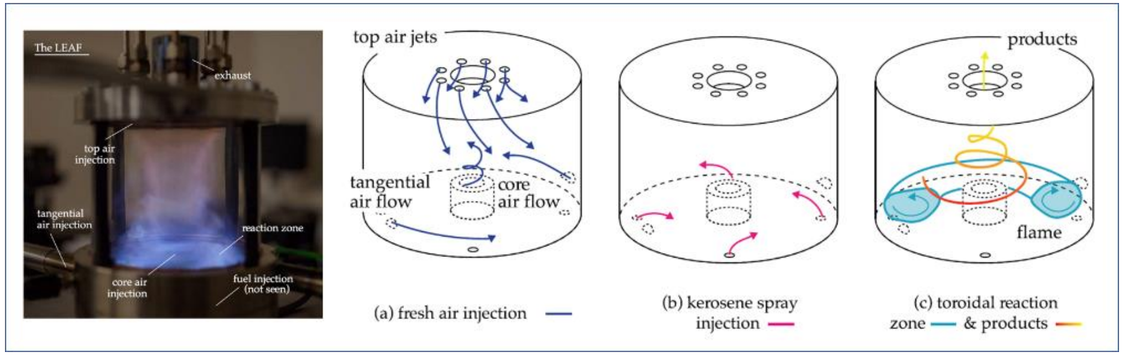
Coordination: **UNIFI** – 3M€ budget – 36 Months – 8 Universities – EEAB engine manufacturers

CHAIRlift concept (UNIFI – KIT)

- "low swirl" **lean lifted spray flames** with **helical** arrangement
  - high degree of premixing → strong NOx emissions reduction
  - strongly reduced risk of flashback and a reduced susceptibility to thermo-acoustics instabilities
  - Helical arrangement → interaction of adjacent flames in circumferential direction → improve stability
  - Compact combustor – low-solidity NGV cascade → reduce weight and cooling air
  - Nano–pulsated plasma discharges further enhance stability with ultra lean mixtures



LEAFinnox concept (Cambridge – IC)



- combustor concept based on **MILD** combustion principles
  - Moderate or Intense Low oxygen Dilution
    - strong mixing with hot combustion products
    - detached flames
    - widened reaction zones ← intense strain rates
    - amalgams of normal thin flames and wide regions of autoigniting fluid

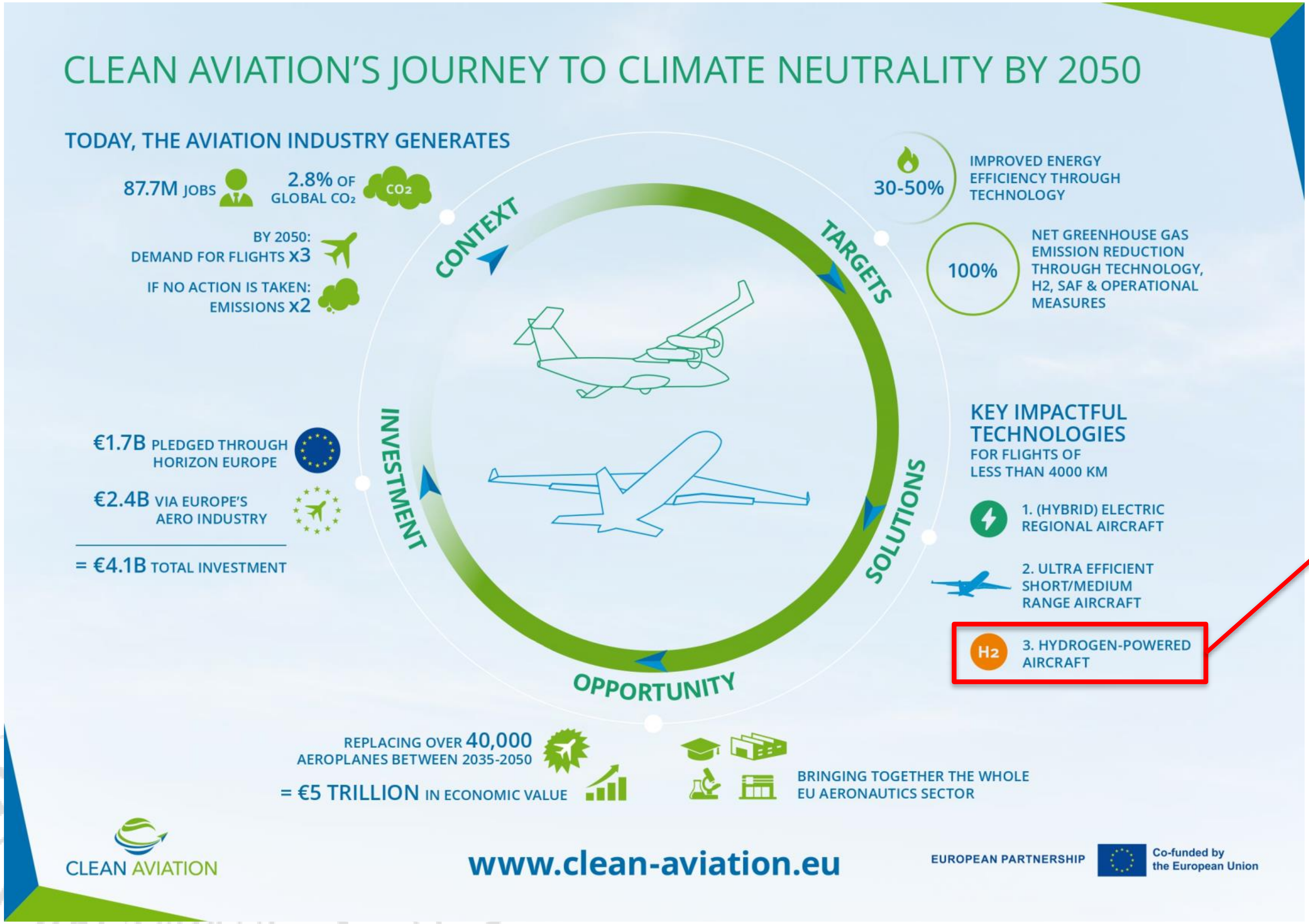
→ ultra-low NOx

→ quiet operations (i.e. very low propensity for thermoacoustics)

→ virtually no soot even from heavy liquid fuels (jetA, SAFs)

- Significant fuel-flexibility already proved by tests (H2)

Clean Aviation Joint Undertaking



CAVENDISH
Hydrogen and dual fuel combustion technologies
ROLL ROYCE (*)

HYDEA
Hydrogen engine integration in flying platform
AVIO AERO (*)

NEWBORN
NExt generation high poWer fuel cells for airBORNe applications
HONEYWELL (*)

H2ELIOS
HydrogEn Lightweight & Innovative tank for zerO-emisSion aircraft
ACITURRI (*)

FLHYing Tank
Liquid hydrogen load bearing tank for commuter
PIPISTREL (*)

HyPoTraDe
Hydrogen Fuel Cell Electric Power Train Demonstration
PIPISTREL (*)

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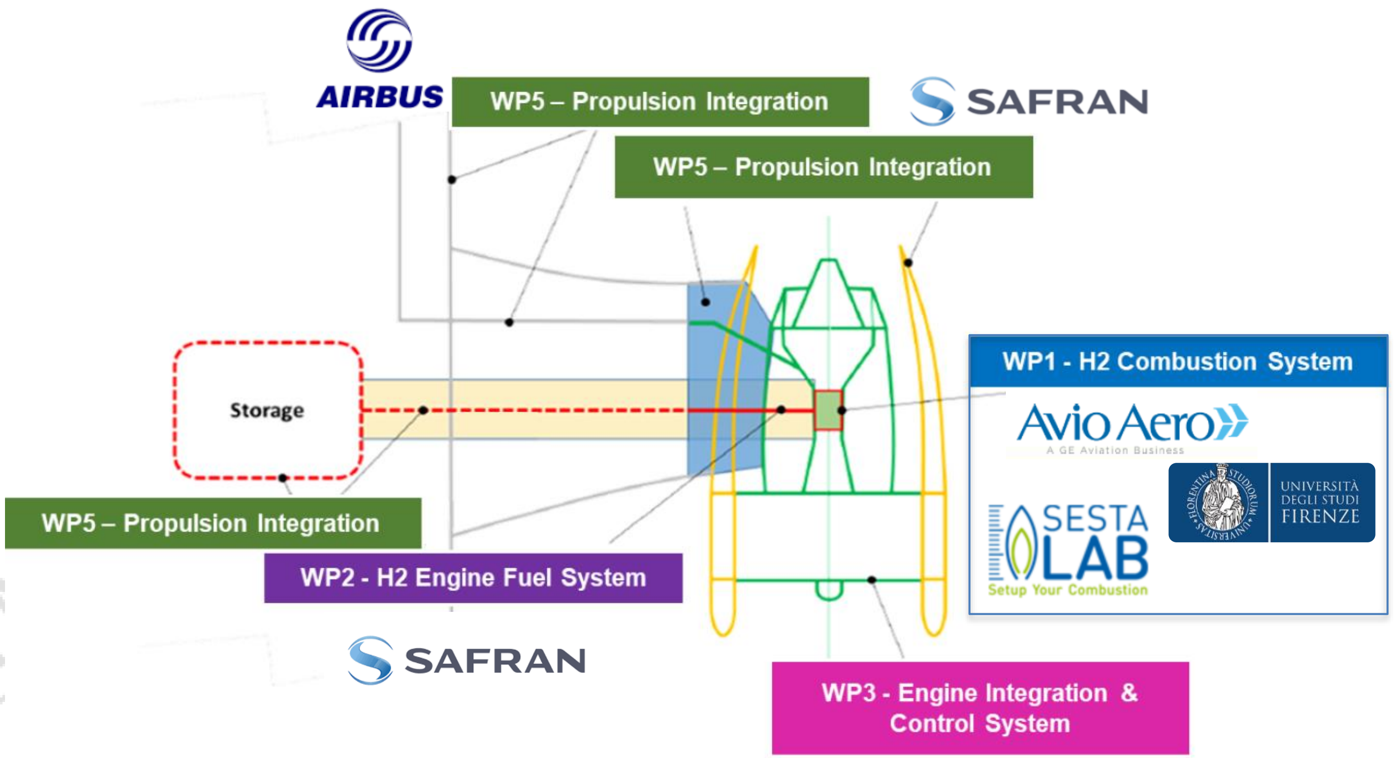
HYdrogen DEmonstrator for Aviation

- Development of a LH2 turbofan engine
  - Ground test demo

Avio Aero
A GE Aviation Business



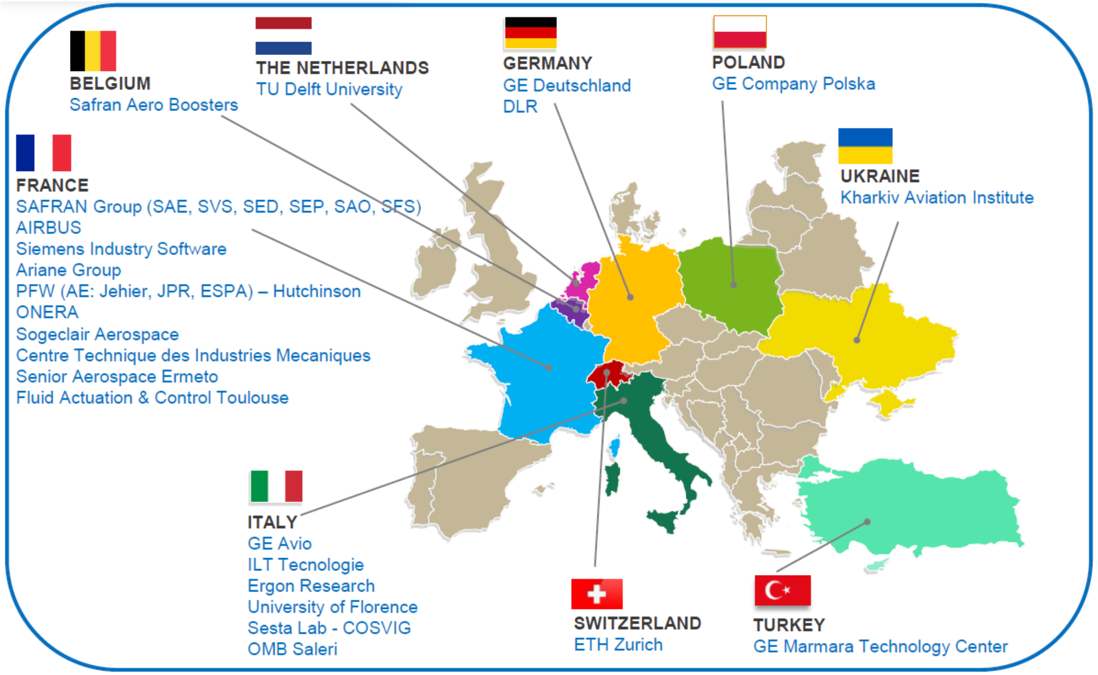
CLEAN AVIATION

Co-funded by the European Union

29 Partners from 9 countries
28 Beneficiaries (+3 A.E.)
1 Associated Partner
17 IND, 4 RTO, 4 SME, 4 UNI

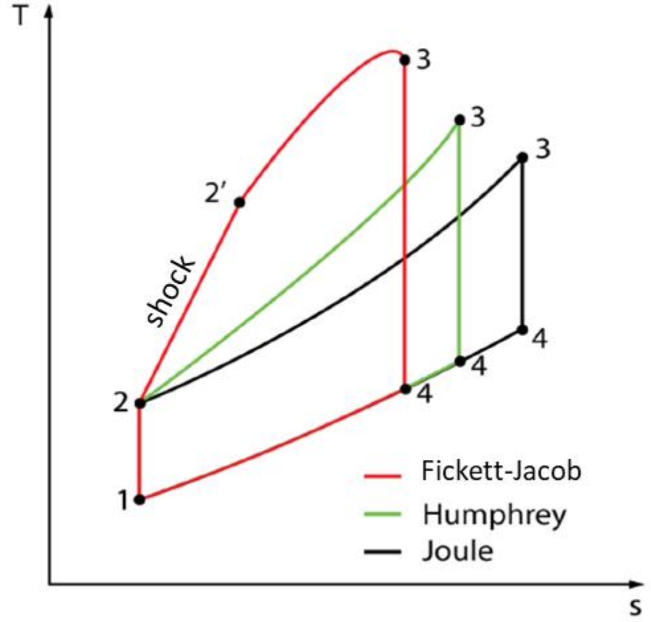
Jan 2023 – Dec 2026

Total Project cost: 116.7 M€
EU Contribution: 80.5 M€
In-kind Contribution: 148.9 M€



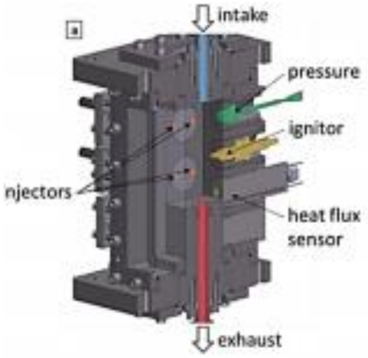
Long term solutions – revolutionary concepts

- PGC - Pressure Gain Combustion



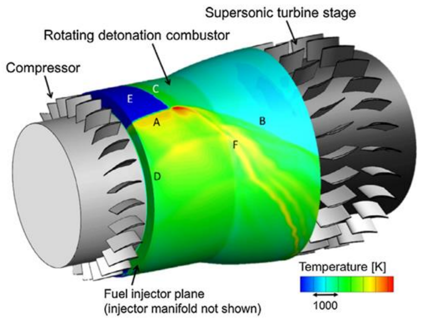
CVC – Constant Volume Combustion

- Piston-less combustion chamber controlled by valves
- Deflagrative regime
- Low cycle frequency – poor turbine integration



RDC – Rotating Detonation Combustion

- Detonation wave propagating around the annular combustion chamber
- No moving parts required
- High frequency process – more efficient turbine integration
- High temperature - cooling issues – complex control

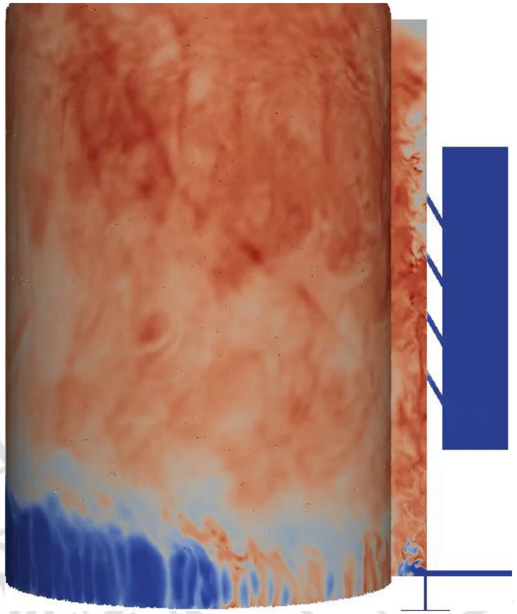


- PGC solutions are expected to be key technologies for the efficient use of carbon neutral fuels such as hydrogen.
- USA research centers and industry far ahead Europe on this technology

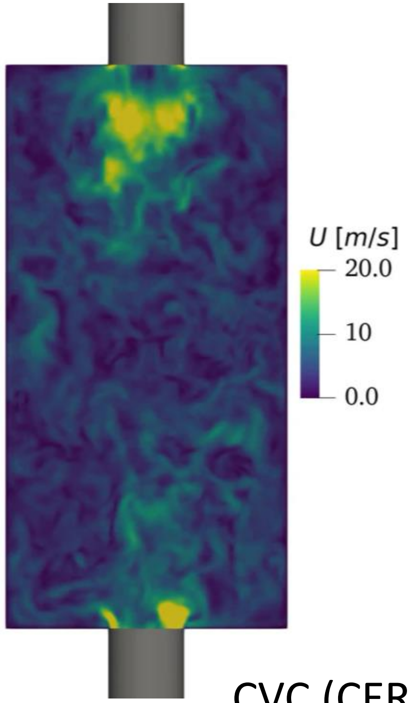
INSPIRE-ETN

INSPIRING PRESSURE GAIN COMBUSTION INTEGRATION RESEARCH, AND EDUCATION

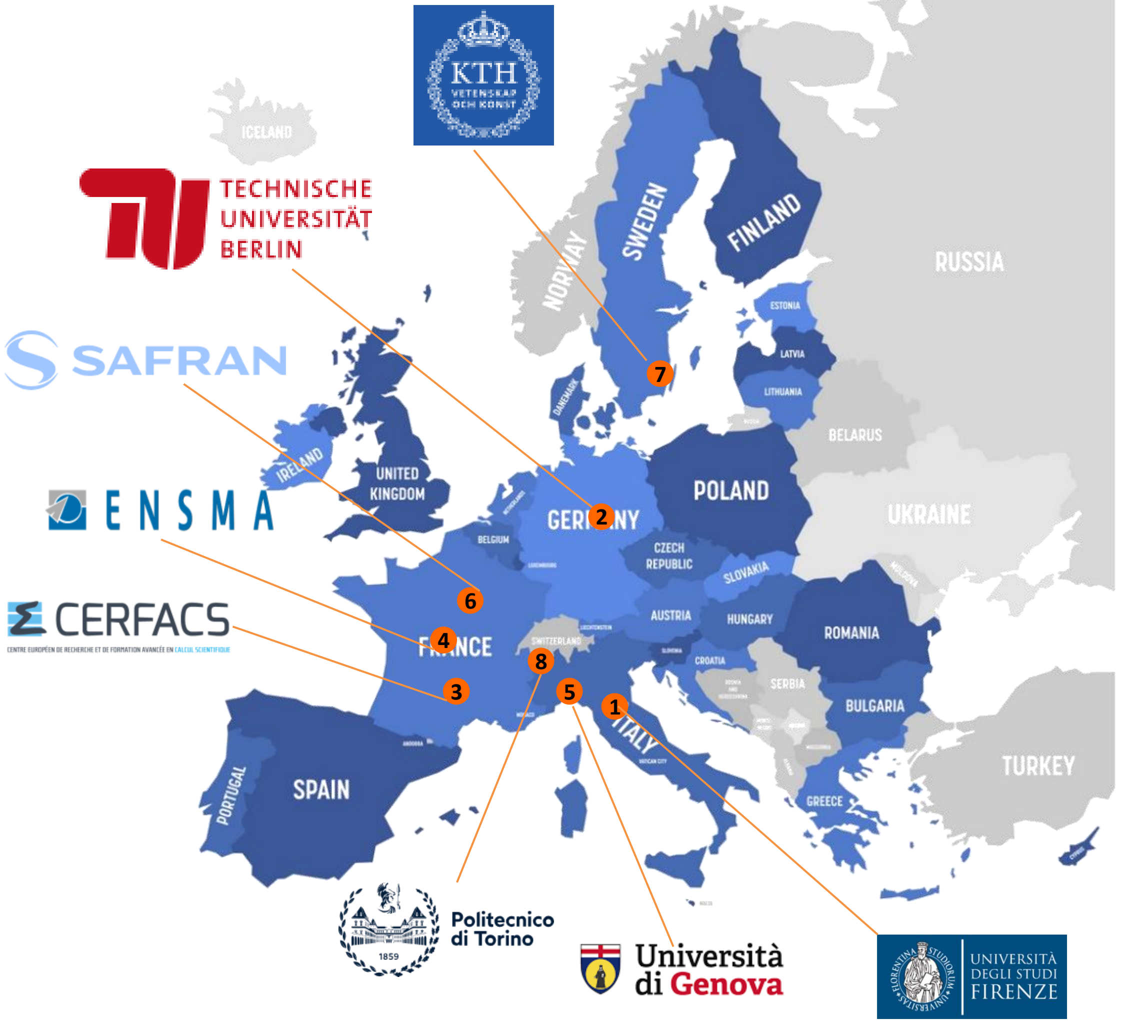
- H2020 MSCA-ETN (2021-2024)
  - Coordination: UNIFI – A. Andreini
  - 15 PhD students working on PGC in a holistic approach



RDC (UNIFI)



CVC (CERFACS)



Final Workshop

October 26 2024 - Florence - Italy

- 2020 – Bruxelles
- 2021 – Virtual
- 2022 - Florence

Questions?

BACKUP SLIDES

Hydrogen properties

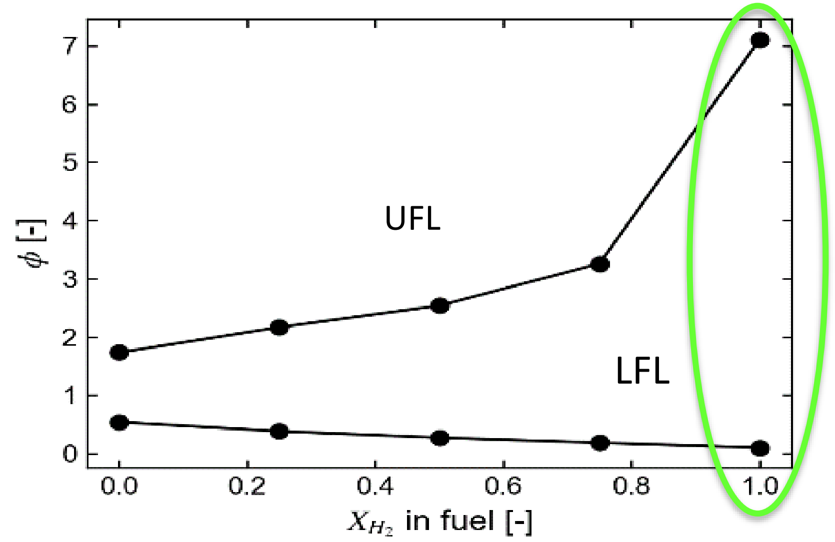
Fuel	H_2	CH_4	C_8H_{18}
LHV [MJ/kg]	120	50	44.3
Energy Density [MJ/m³]	9.6	32.5	30656
Fuel-vol%*	29.5	9.5	1.65
T_{ad} [K]*	2390	2226	2276
Burning velocity[1),3)] [cm/s]*	212**	34	34
Lewis-Number**	**~0.3**	**~1.0**	**~2.0**

*Conditions: $\phi = 1, T_u = 300K, 1\ atm$
** Lewis number = Ratio of thermal to mass diffusivity

$$Le_k = \frac{mass}{energy} = \frac{Sc_k}{\Pr} = \frac{\lambda}{\rho c_p D_k}$$

H_2 is a small molecule: it diffuses faster than heat

Flamability limits H2/CH4 mixture



T = 300K
P=101325 Pa

✓ The Lewis of which species of the mixture has the major impact on flame development?

- From an asymptotic point of view the flame response is controlled by the Le of the limiting species between fuel and oxidiser.
  - ➔ The limiting species can be seen as the "bottle neck" that controls the combustion process

The lean mixtures (H2 defect) have $Le \sim Le_{H_2} < 1$
The rich mixtures (O2 defect) have $Le \sim Le_{O_2} > 1$

Long-range (325 PAX, 10,000-kilometer range)

Evolutionary aircraft powered by Turbofan engine

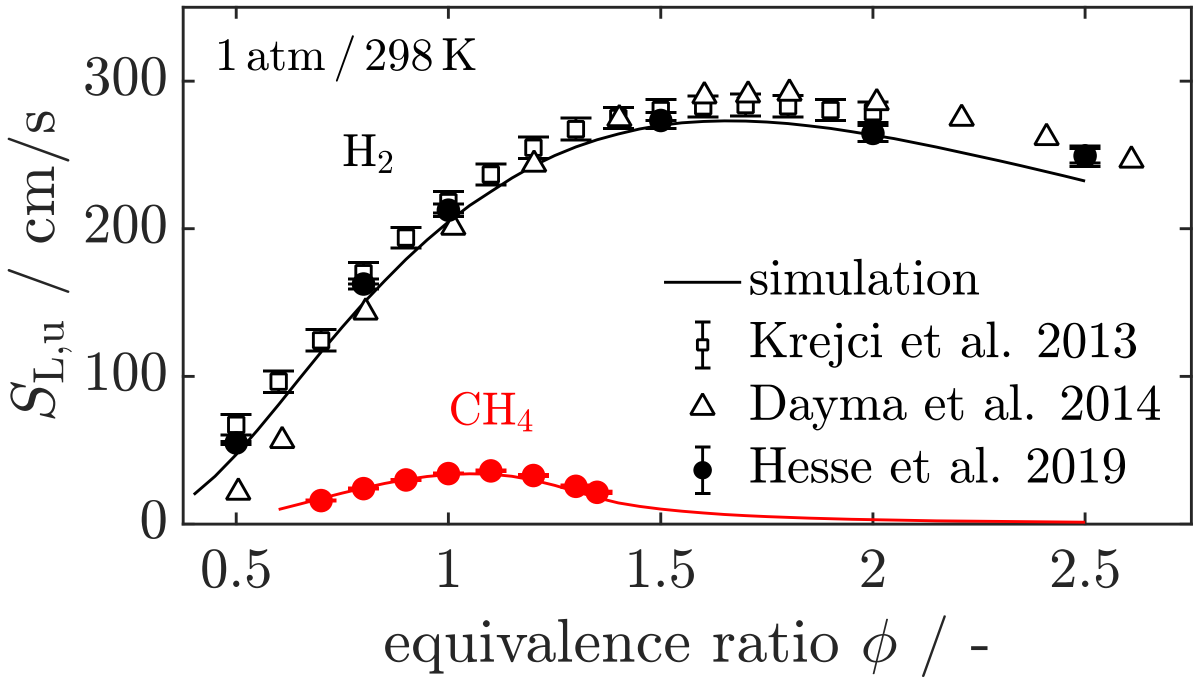
Design mission: 325 PAX, 10,000 km range, cruise speed Mach 0.85

- **2 LH_2 tanks** in front and back of PAX cabin - added weight: 52 tons
- **H_2 turbines** generating propulsion power

Energy demand[1]	+42%
CO_2 reduction	100%
Climate impact reduction	40-50%
Additional cost	40-50% CASK[2]
Entry into service	20-25 years
Propulsion power	H_2 turbine
MTOW[3]	+23%

1. Major assumptions: 38% gravimetric index of LH_2 tank, 92% useable LH_2 fuel, 50% H_2 turbine cruise efficiency, 80% fan efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

- Flame Speed: Laminar burning velocities S_L



- Stoichiometric burning velocity for hydrogen 650% higher than for methane!

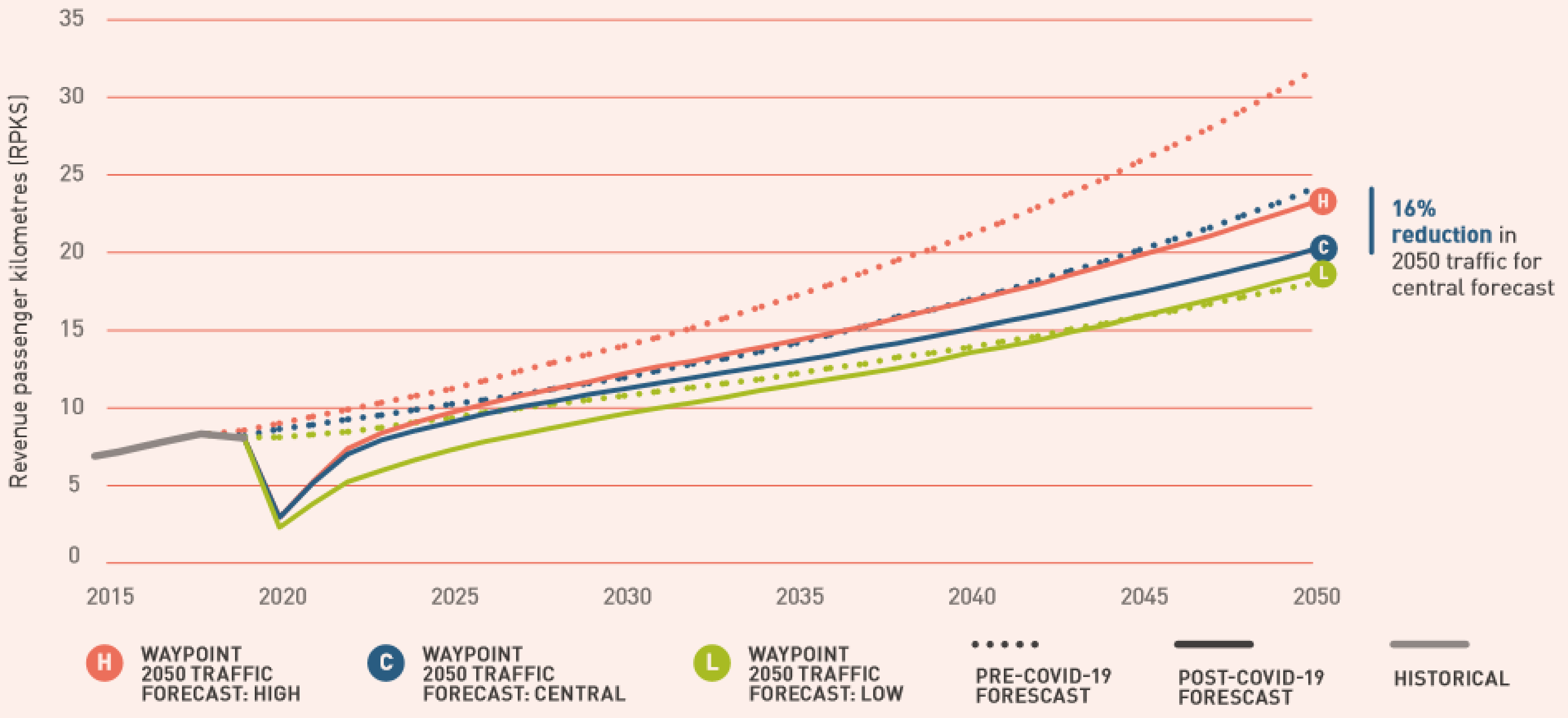
- What causes the difference?
  - Transport → Small Lewis number
    - ΔS_L = 43%
  - Thermodynamics → High flame temperature of H2
    - ΔS_L = 27%
  - Chemistry → Radical balance (chain branching)
    - ΔS_L = 350%

[1]Measurements at ITV, RWTH Aachen University
[3]G. Dayma et al., Combust. Flame 161 (2014), 2235-2241
[2]M.C.Kreji et al., J.Eng. Gas Turbines Power 135 (2013), 021503
[4]M.Reyes et al., Int. J. Hydrogen Energy 41 (2016), 2064-2074

COVID19 impact

Global air passenger traffic forecast comparison, pre- and post-Covid[20]

Comparison between the traffic forecasts used before Covid-19 hit and those used in the Waypoint 2050 report: the deep impact of Covid-19 on passenger traffic, as well as the long recovery will mean a 16% reduction in traffic in the central scenario in 2050.



Aviation segments

COMMUTER <19 seats <500 km

REGIONAL 20-80seats <2000 km

SHORT-RANGE 80-165 seats <4500 km

MEDIUM-RANGE 166-250 seats <10000 km

LONG-RANGE >250 seats >10000 km