Centro Italiano Ricerche Aerospaziali

Hydrogen propulsion systems for aviation

ANTONIO PAGANO

CONTENT

- Hydrogen for use in aviation: pros & cons
- Hydrogen propulsion systems for aviation
  - Fuel cell-based
  - Hydrogen fueled turbines
- Hot research topics on hydrogen for aviation
- Ongoing research at CIRA
- Aviation as hard-to-abate sector

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PROS

- Abundant even if combined with many elements
- High energy density (142 MJ/kg vs 46MJ/kg of kerosene).
- Lower fuel weight than kerosene.
- Used in fuel cell-based propulsion systems and hydrogen direct combustion engines.
- Fuel cell-based systems is suited for distributed electric propulsion.
- Combustion of H_2 produces no CO_2 and limited NO_x.
- No secondary emissions such as soot, CO, volatile organic compounds.
- Usage of the cryogenic heat sink can increase turbofan engine thermal efficiency substantially.
- Wide combustion range and flammability limit.
- In the event of a leakage and/or fire, it evaporates and rises away quickly
- Less prone to combustion instabilities when compared to other fuels.
- It can be made by renewable energy sources.

CONS

- Poor volumetric energy density (70.8 kg/m^3 for LH2 vs. 750 kg/m^3 for kerosene).
- Increased storage space compared to conventional jet fuels.
- The fuel cannot be stored in the wings but only in the fuselage or in underwing pods.
- LH2 storage requires cryogenic or pressurized tanks.
- LH2 has an extremely low boiling temperature (20.3 K); therefore, it requires very effective insulation to keep the fuel cool.
- Embrittlement. Hydrogen can damage the structural integrity of certain materials.
- The fuel cost is higher than the conventional kerosene.
- The production capacity for ”green” hydrogen is still inadequate.
- The airport logistics are quite difficult.
- Emission of water vapor increases and may be critical at higher altitudes (>8 km) because of contrails formation and in their further development to cirrus clouds
- Hydrogen has a propensity to leak.
- Hydrogen has a tendency to flashback during the combustion process in a gas turbine.
- Safety of operations and usage in an airport environment is challenging.
- The energy efficiency for electrolysis and liquefaction is around 50%.
- Psychological concerns from the disaster of the airship “Hindenburg” in 1937 in which 36 people died.

BASICALLY, FOR THE SAME ENERGY CONTENT…

Hydrogen | Kerosene

1 : 2.8

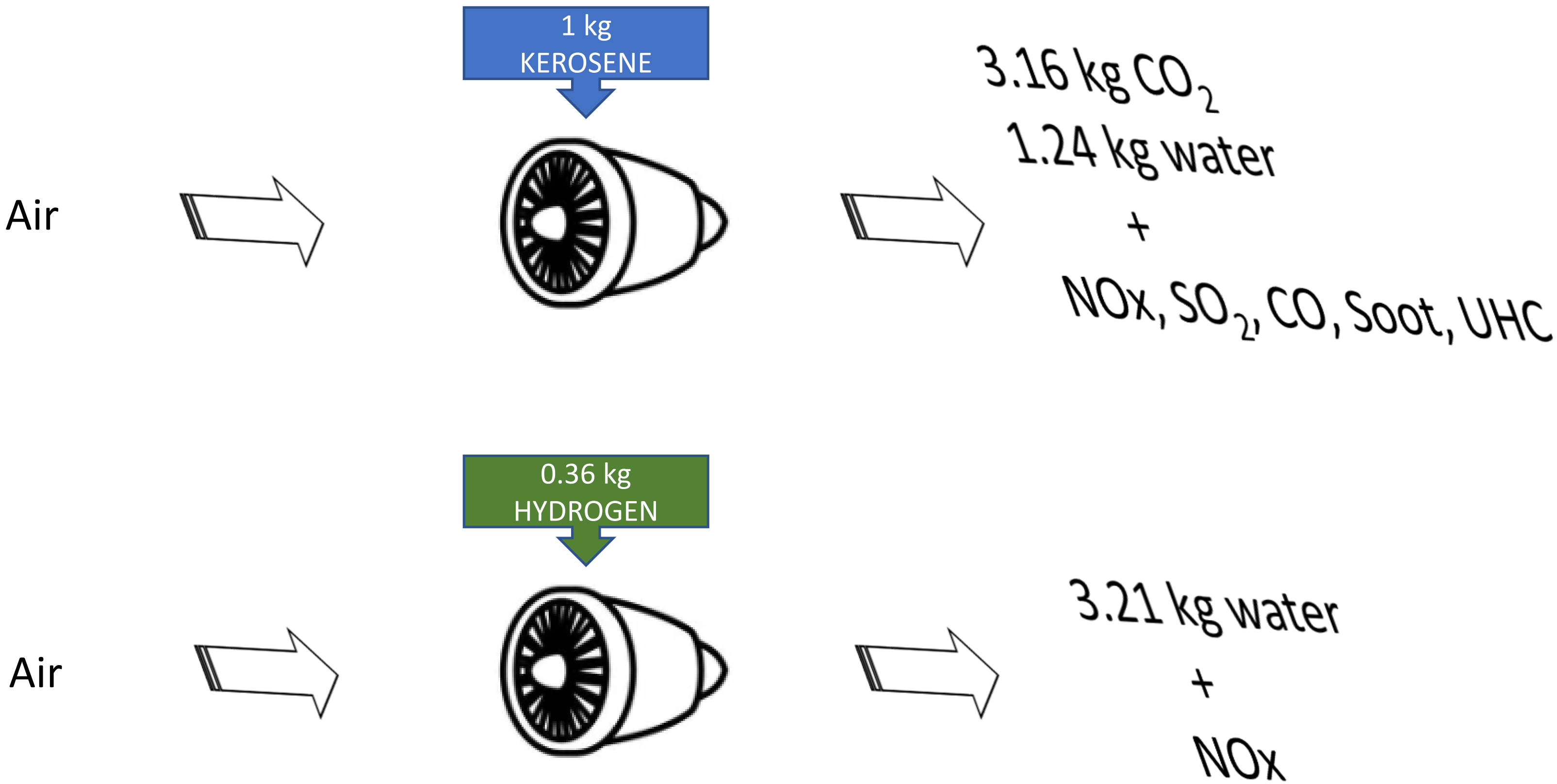
… but tank mass, fuel system

LH2 tank gravimetric index=0.15→0.35
CH2 tank gravimetric index=0.06→0.13

4 : 1

… and spherycal-cylidrical tank cryogenic system, a/c config.

EMISSIONS FROM FUEL MASSES OF SAME ENERGY CONTENT



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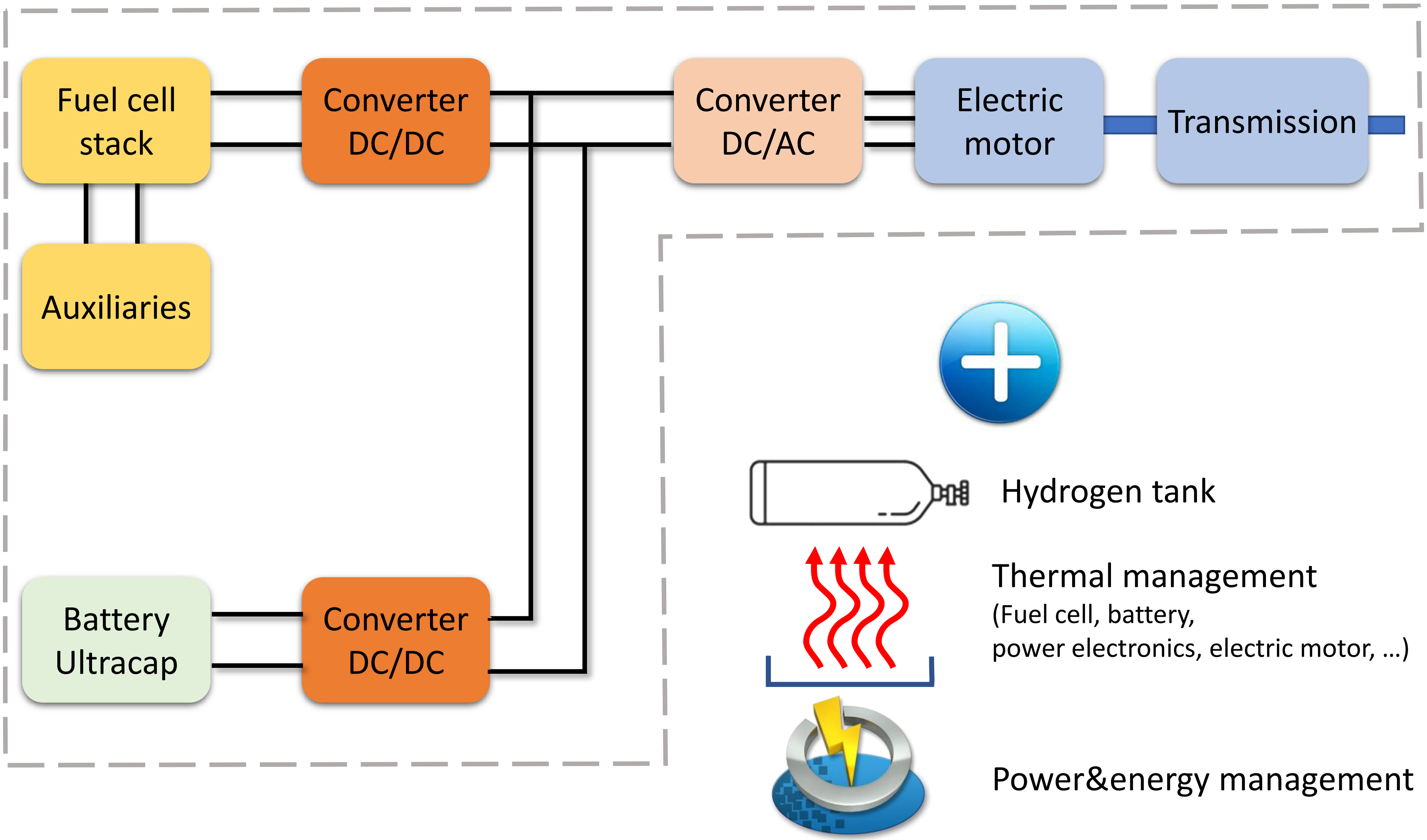
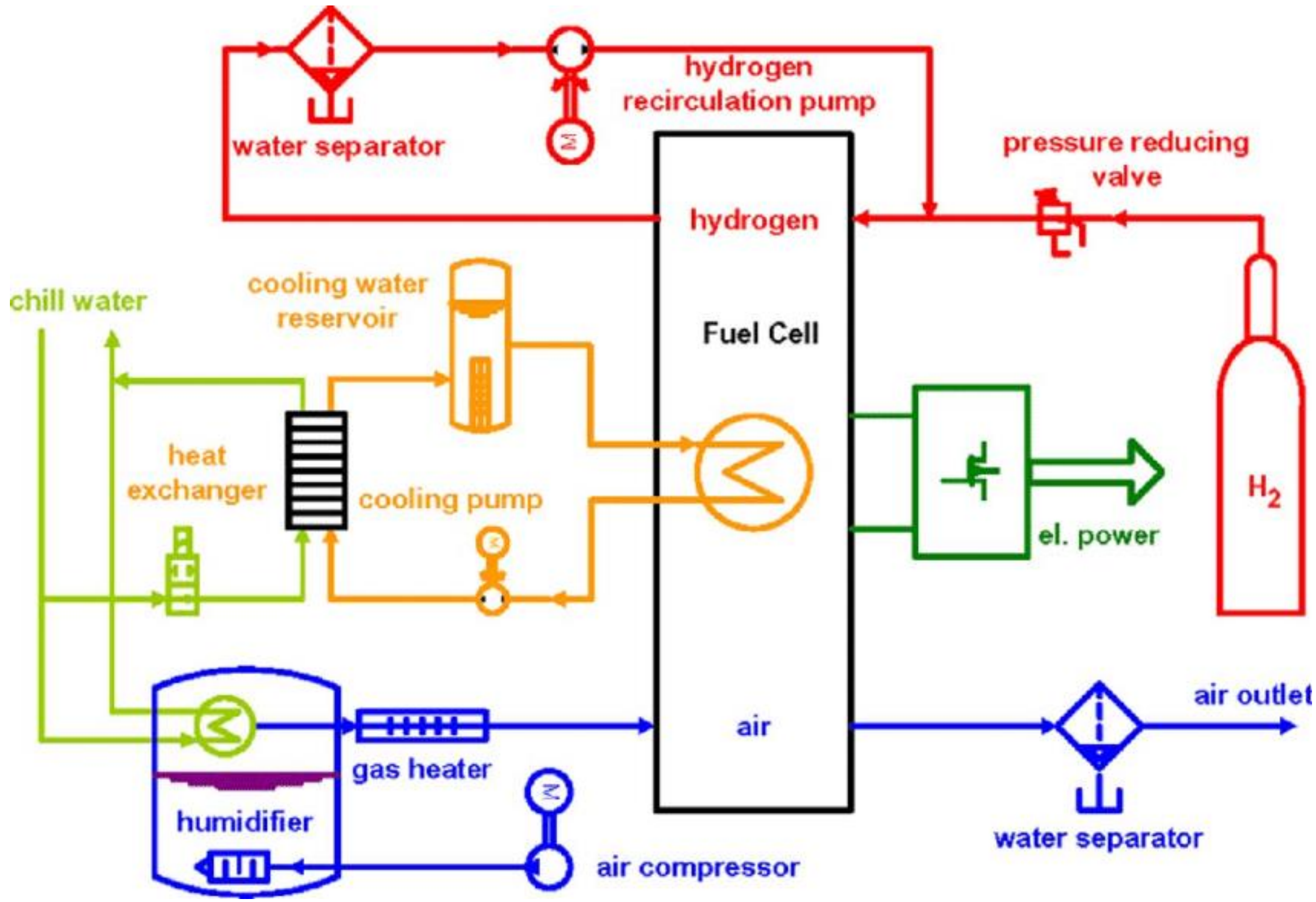
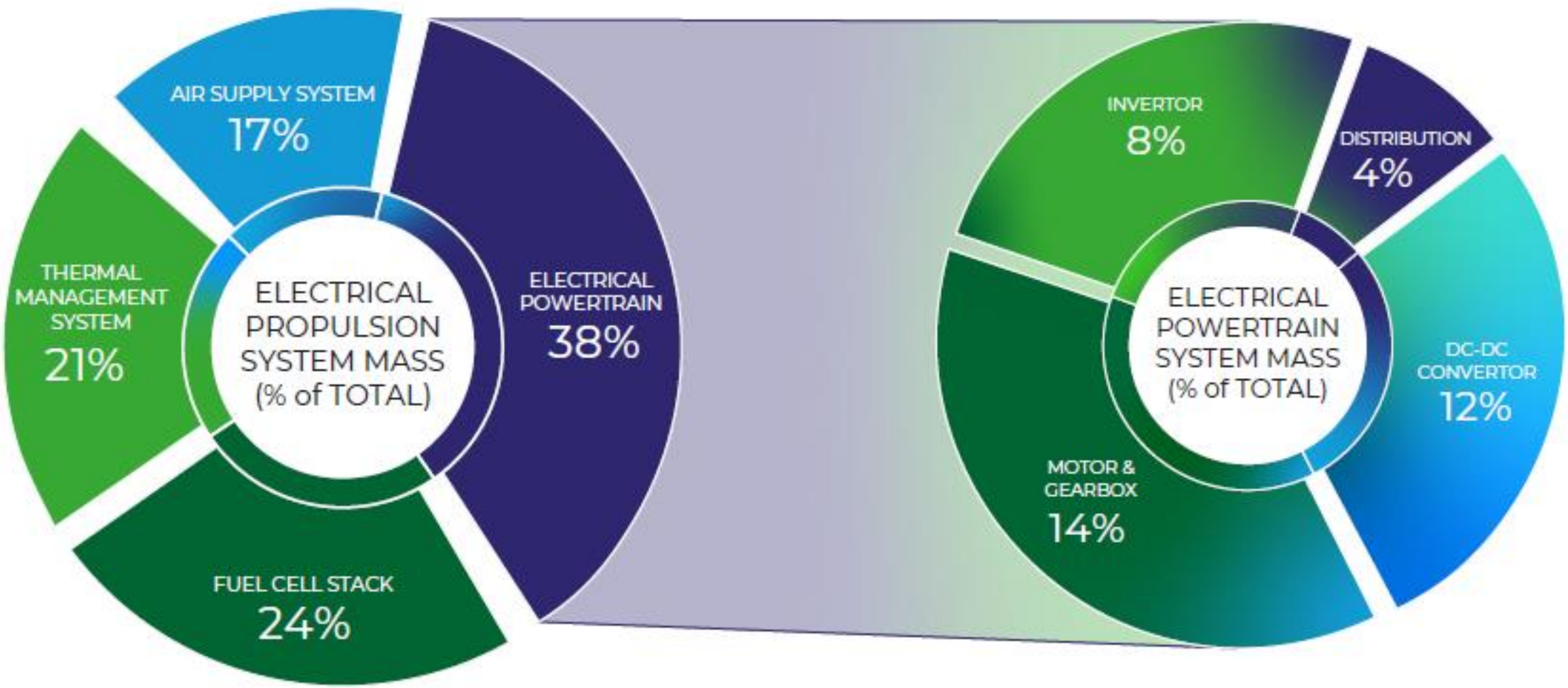
HYDROGEN FUEL CELL-BASED PROPULSIVE SYSTEM



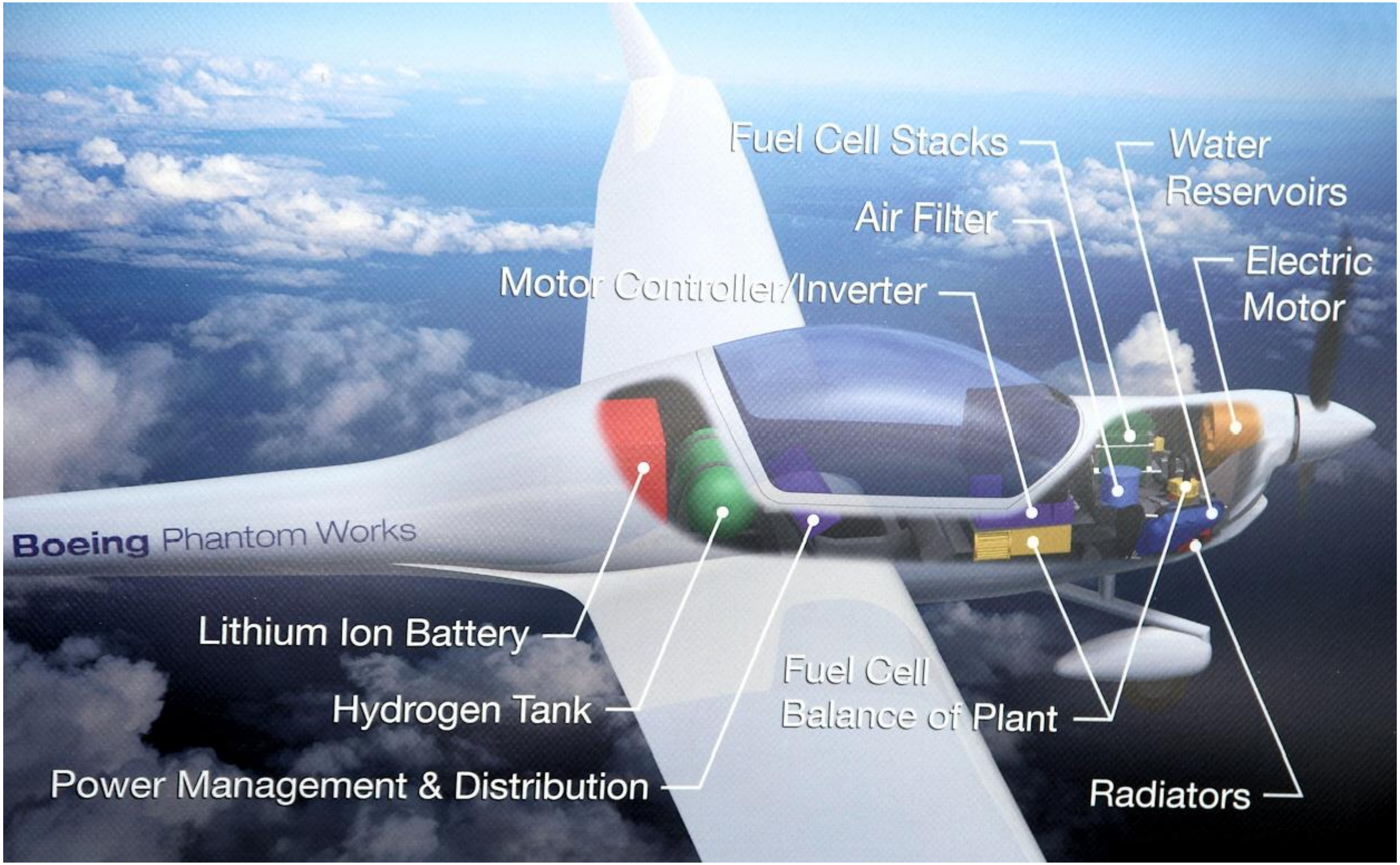


Grasser, F., & Rufer, A. A Fully Analytical PEM Fuel Cell System Model for Control Applications. Industry Applications, IEEE Transactions on. 43. 1499 – 1506, 2007.

Weight and volume concerns

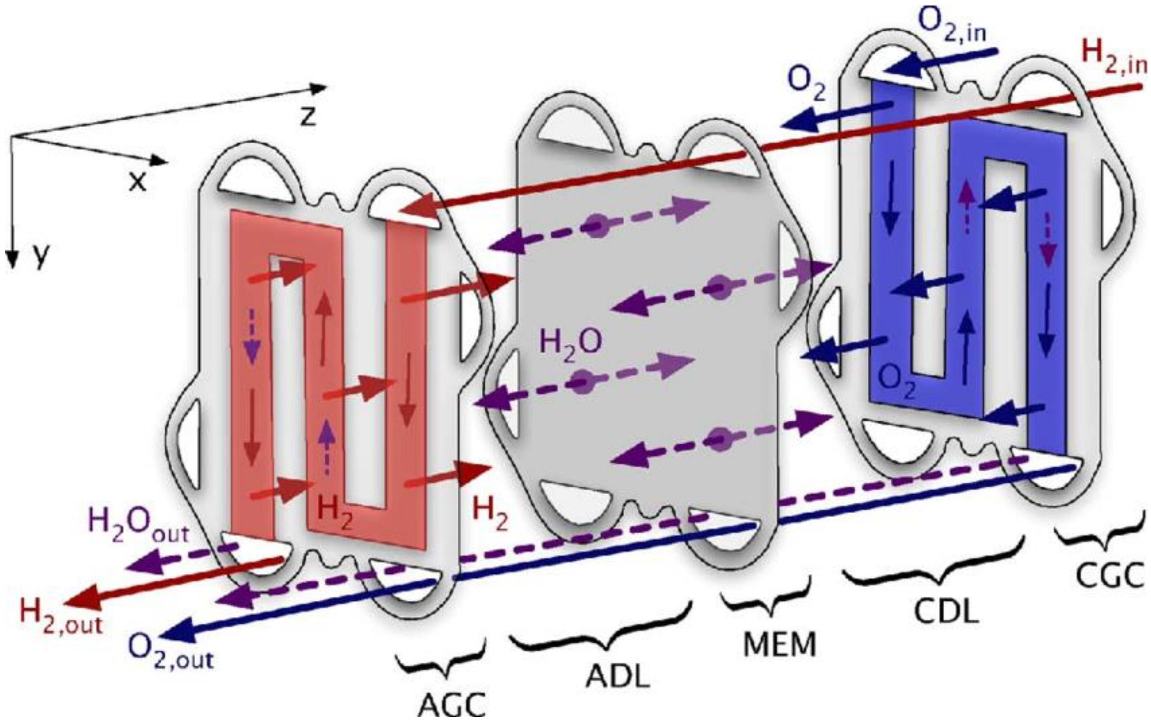


ATI, Electrical propulsion systems, project flyzero, F*ZO-PPN-COM-0030, March* 2022

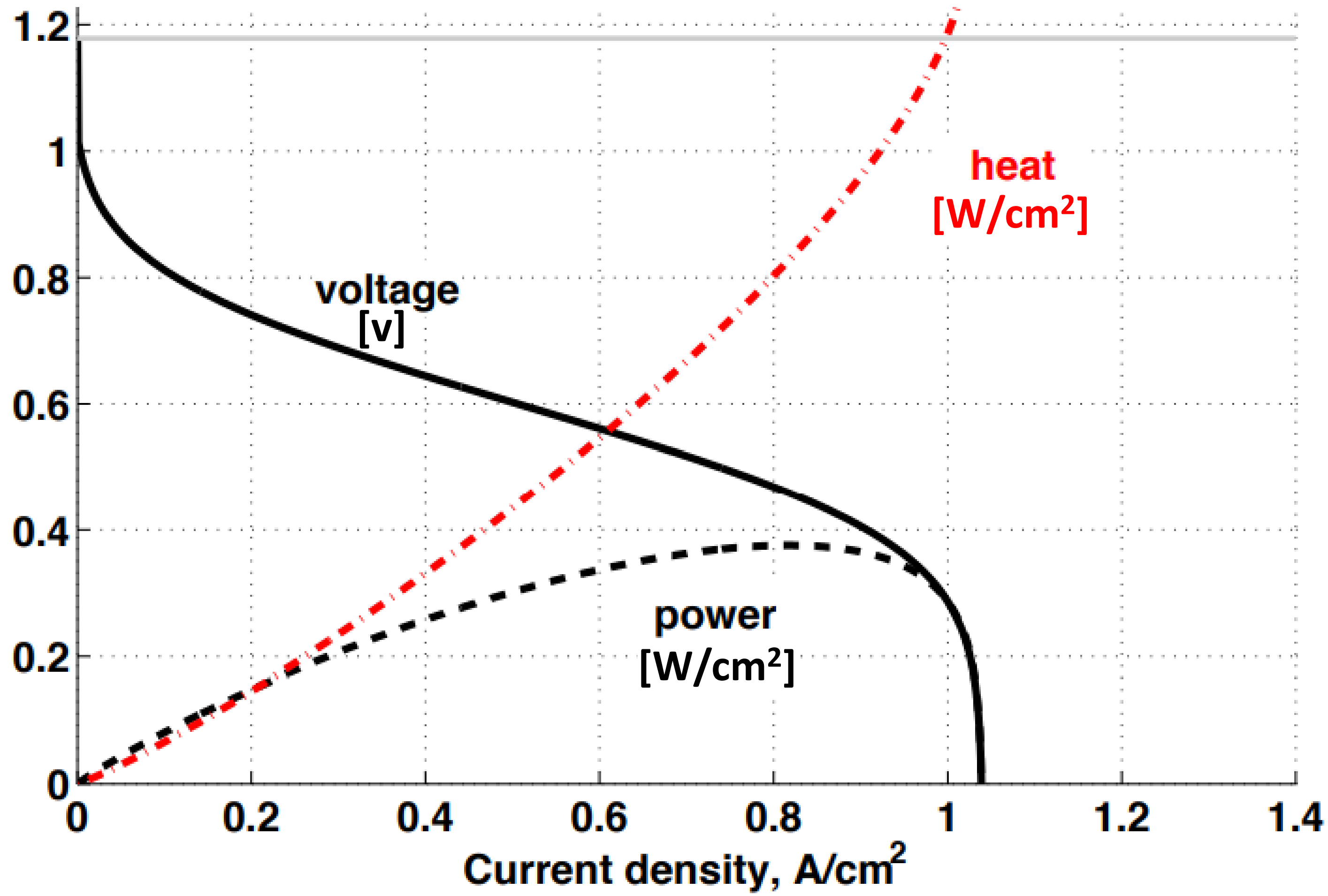


https://www.flugzeuglexikon.com/ILA%20-%20Luftfahrtausstellung/Sportflugzeuge/Diamond%20Super%20Dimona%20-%20Brennstoffzellen/diamond%20super%20dimona%20-%20brennstoffzellen.html

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Anode: $2H_2 \rightarrow 4H^+ + 4e^-$
Overall: $2H_2 + O_2 \rightarrow 2H_2O$ + Energy



A hydrogen fuel cell uses the chemical energy of hydrogen to produce electricity


1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
heat
[W/cm²]
voltage
[v]
power
[W/cm²]
Current density, A/cm²

LTPEM VS HTPEM FUEL CELLS

Parameter	LTPEM	HTPEM	Comments
Temperature Range	≤ 80 C	140-180 C	Significantly broader temperature range
Electrolyte	Water	Phosphoric acid	No water management problems, but more corrosive conditions
Humidity control	Critical	Unnecessary	HTPEM permits short overheating and overcurrent – more reliable in an emergency
Impurity Tolerance	CO – ppm levels	CO – several percent	Enhanced tolerance for HTPEM for other impurities also. Lower operational cost
Membrane chemistry	Fluorocarbon – higher cost	Hydrocarbon – lower cost	Lower capital cost
Durability	5,000-10,000 h	5,000-20,000 h	20,000 hours achieved in a lab
Stack design	Standard	Simplified	No gas humidification, simpler cooling system

https://ecofriend.com/enfica-fc-s-rapid-200-fc-electric-aircraft-sets-speed-and-endurance-records.html

https://www.flugzeuglexikon.com/ILA%20-%20Luftfahrtausstellung/Sportflugzeuge/Diamond%20Super%20Dimona%20-%20Brennstoffzellen/diamond%20super%20dimona%20-%20brennstoffzellen.html

	Based on	Aircraft	FC power (kW)	Year
Boeing	HK 36 Super Dimona	Motorglider	20	2008
ENFICA-FC	Rapid 200	Ultralight	20	2010
DLR	Antares 20E	Motorglider	3x11	2009-2012
H2FLY	Pipistrel Taurus G4	Twin-fuselage 4 seats	4x11	2016
ZeroAvia	Piper M350	Light (6 pax)	100 (?)	2020

https://aviationweek.com/aerospace/aircraft-propulsion/deutsche-aircraft-h2fly-partner-fuel-cell-dornier-328

https://www.thetimes.co.uk/article/are-zero-emission-flights-ready-for-take-off-gflbf70zc

	Based on	Aircraft	FC power (kW)	Maiden flight
Fresson project	Britten-Norman BN2	9 pax (CS23)	2x250	2025
ZeroAvia (?)	Dornier 228	19 pax (CS23)	2x600	2024
H2FLY	Dornier 328	40 pax (CS25)	1500	2030
Flyzero project	-	75 pax (CS25)	-	2030

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Tu-155 experimental aircraft – first fligth 1998

https://web.archive.org/web/20130218231656/http:/www.tupolev.ru/English/Show.asp?SectionID=82

- ❑ New combustors
- ❑ Cryogenic H2
- ❑ Fuel system
- ❑ Large tank
- ❑ Fuselage modification

Klug, H.G., CRYOPLANE – Hydrogen Fuelled Aircraft, 2001

https://www.enableh2.eu/

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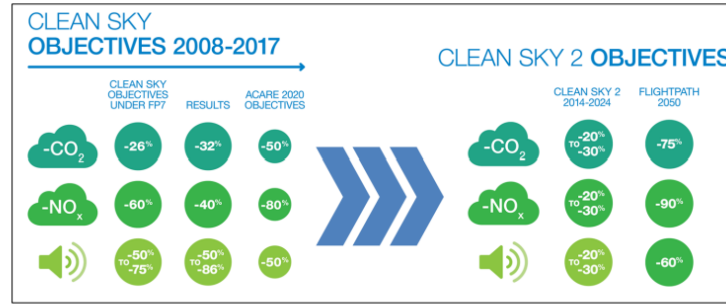
CLEAN SKY 2 ENHANCEMENTS



SRIA (Strategic Research and Innovation Agenda)

CLEAN AVIATION

- The Clean Aviation JU will develop disruptive new aircraft technologies to support the European Green Deal, and climate neutrality by 2050. These technologies will deliver net greenhouse gas (GHG) reductions of no less than 30%, compared to 2020 state-of-the-art.
- The technological and industrial readiness will allow the deployment of new aircraft with this performance no later than 2035, enabling 75% of the world's civil aviation fleet to be replaced by 2050.
- The aircraft developed will enable net CO_2 reductions of up to 90% when combined with the effect of sustainable 'drop-in' fuels, or zero CO_2 emissions in flight when using hydrogen as energy source.

Clean Hydrogen Partnership

- Facilitate the transition to a greener EU society through the development of hydrogen technologies.
- Fit for 55, greenhouse gas emissions reduction to at least 55 % below 1990 levels by 2030, and climate neutrality at the latest by 2050
- Strengthen the competitiveness of the Union clean hydrogen value chain, with a view to supporting, notably SMEs, accelerating the market entry of innovative competitive clean solutions;
- Stimulate research and innovation on clean hydrogen production, distribution, storage and end use applications.

- HPA – Hydrogen-Powered Aircraft
  - Direct Combustion of Hydrogen in Aero-engines (fuel injection system, H2 combustion chamber sizing and design, and the fuel delivery systems)
  - Multi-MW Fuel Cell Propulsion System for Hydrogen-Powered Aircraft (Power level 2-4MW, efficiency >0.45, power density >2kW/kg)
  - Large Scale Lightweight Liquid Hydrogen Integral Storage Solutions (150 kg LH2 content, integral and conformal/non-conformal, g.i.>=35%)
  - Near Term Disruptive Technologies for Hydrogen-Powered Aircraft (HIPS flight ready, power level 0.5MW, cryo TM, integral tank 100kg)
- HER – Hybrid-Electric powered Regional aircraft
- SMR – Short/short-Medium Range aircraft
- TRA – Transversal

- ❑ Reneable hydrogen production
- ❑ Hydrogen storage and distribution
- ❑ Hydrogen end uses: transport applications
  - Development and optimisation of a dedicated Fuel Cells for Aviation: Development of dedicated stack (100s kW) with the objective of MWs full system
    (Stack power >250kW, power density > 1.5kW/kg at a power level of at least 1 MW)
  - Development of specific aviation cryogenic storage system with a gauging, fuel metering, heat management and monitoring system
    (50-150kg LH2, g.i.=0.16-0.35)
  - Development and optimisation of a dedicated Fuel Cells for Aviation: disruptive next-gen high temperature Fuel Cells technology for future aviation
    (system size 1.5MW, system level > 1.5 kW/kg, stack level > 3 kW/kg)
- ❑ Hydrogen end uses: clean heat and power
- ❑ Cross-cutting
- ❑ Hydrogen valleys

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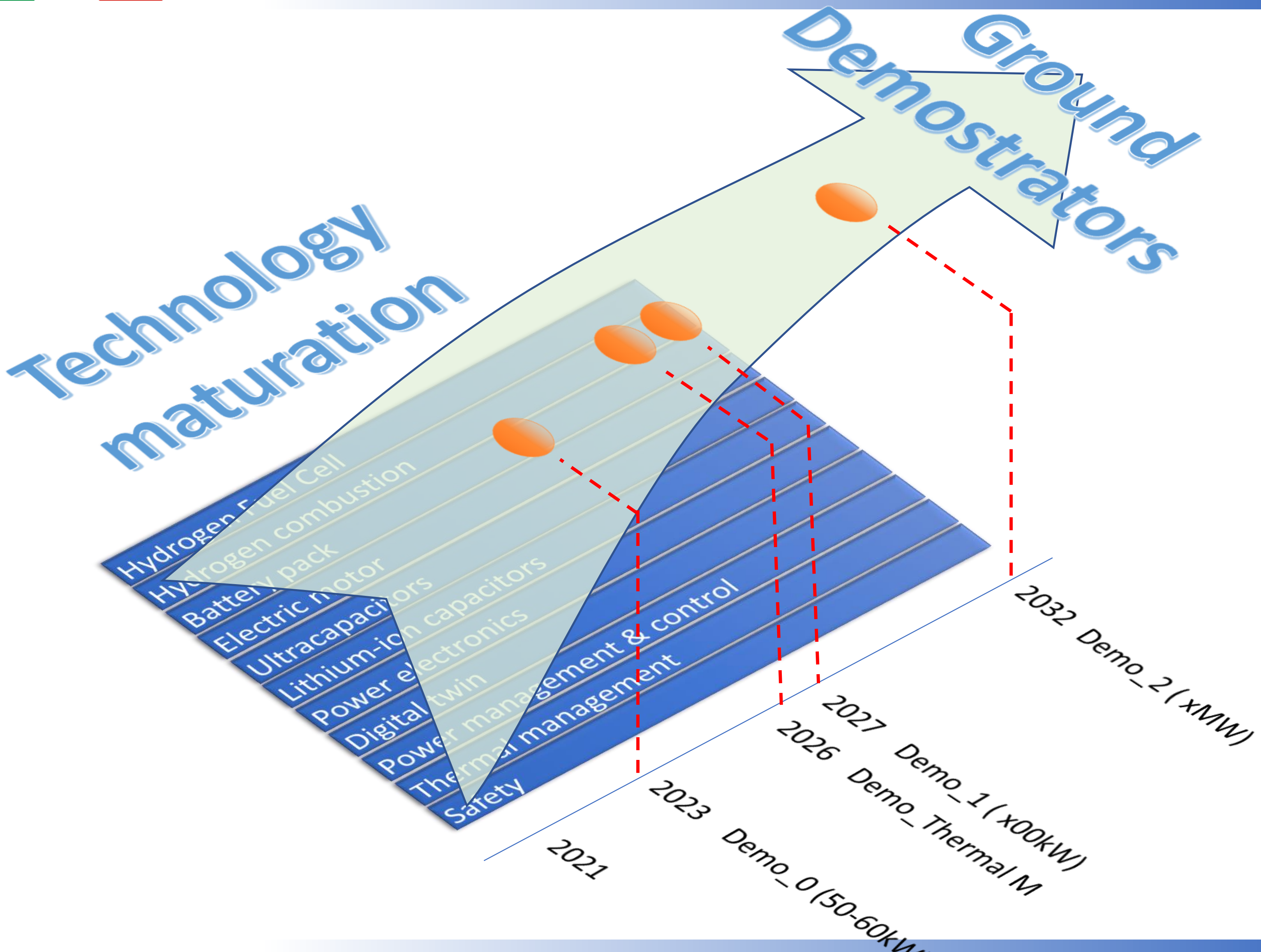
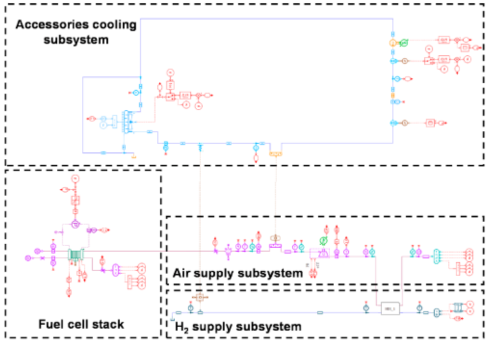
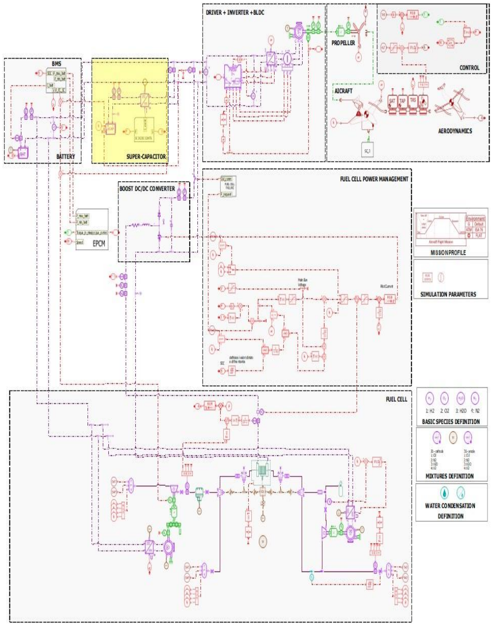
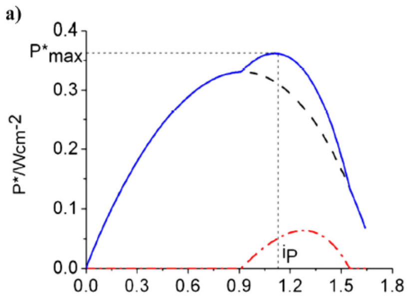

Technology maturation
Ground Demostrators
Hydrogen Fuel Cell
Hydrogen combustion
Battery pack
Electric motor
Ultracapacitors
Lithium-ion capacitors
Power electronics
Digital twin
Power management & control
Thermal management
Safety
2021
2023 Demo_0 (50-60kW)
2026 Demo_Thermal M
2027 Demo_1 (x00kW)
2032 Demo_2 (xMW)

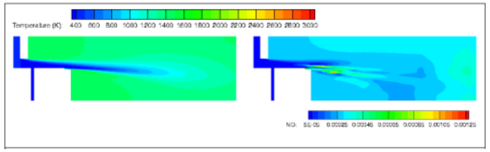
ONGOING RESEARCH ACTIVITIES AT CIRA

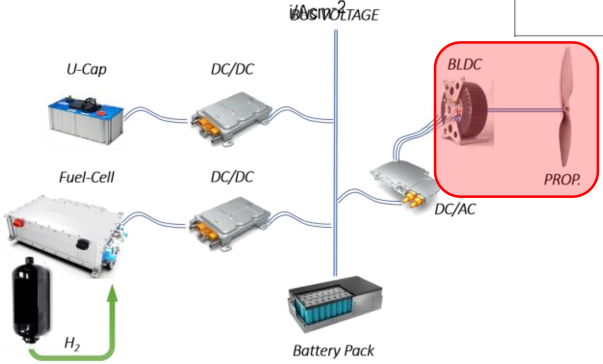
- Fuel cell systems by simulation
  - Energy sources modeling
  - Digital Twin
- Thermal management systems
  - Conventional
  - Innovative (for cryogenic H_2)
- Hydrogen direct combustion
  - Micromix combustor
- Fuel cell system by demonstration
  - 50-60 Kw Ground Demo

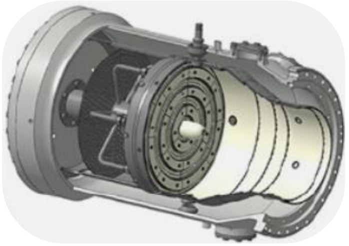




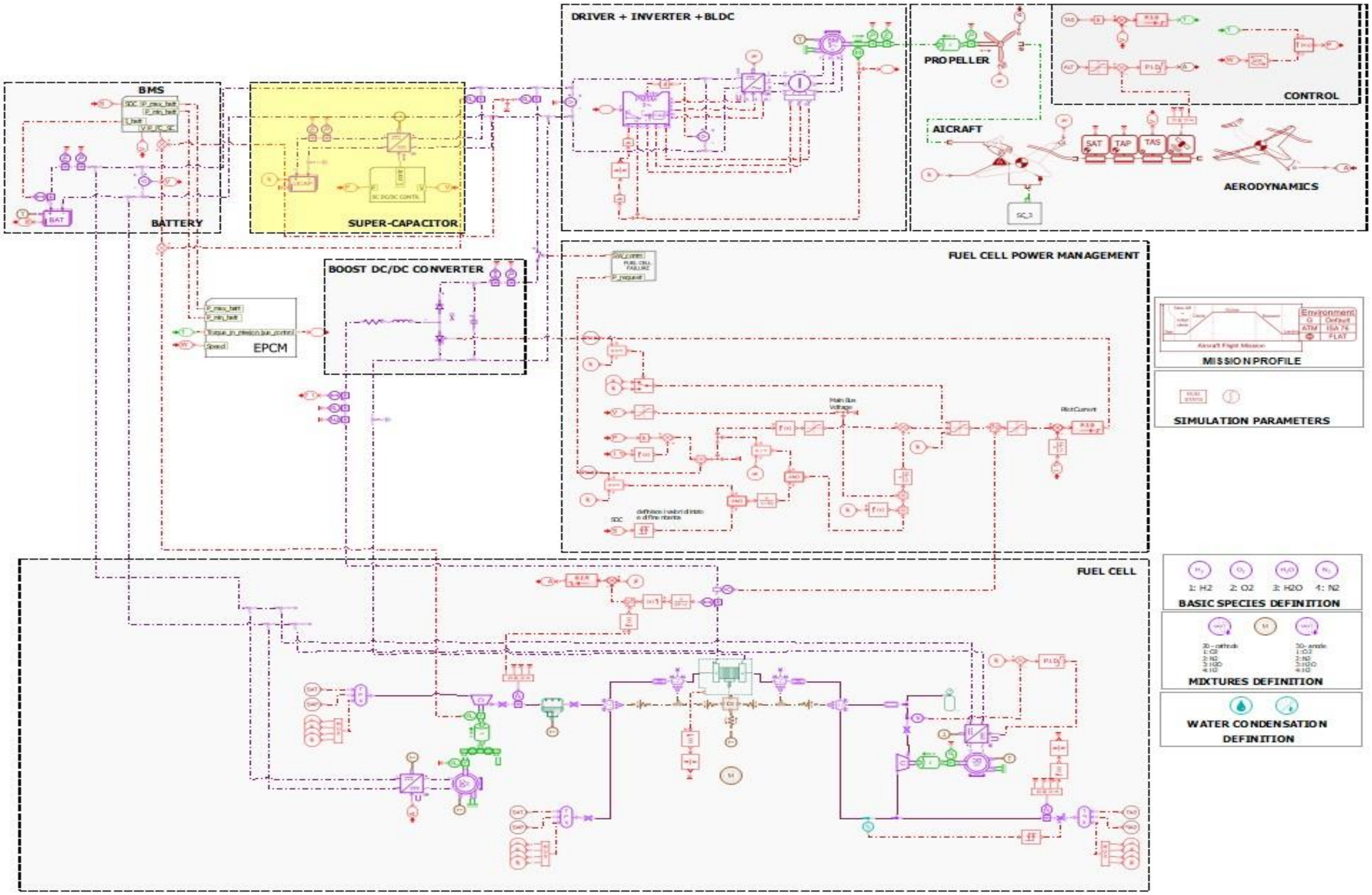




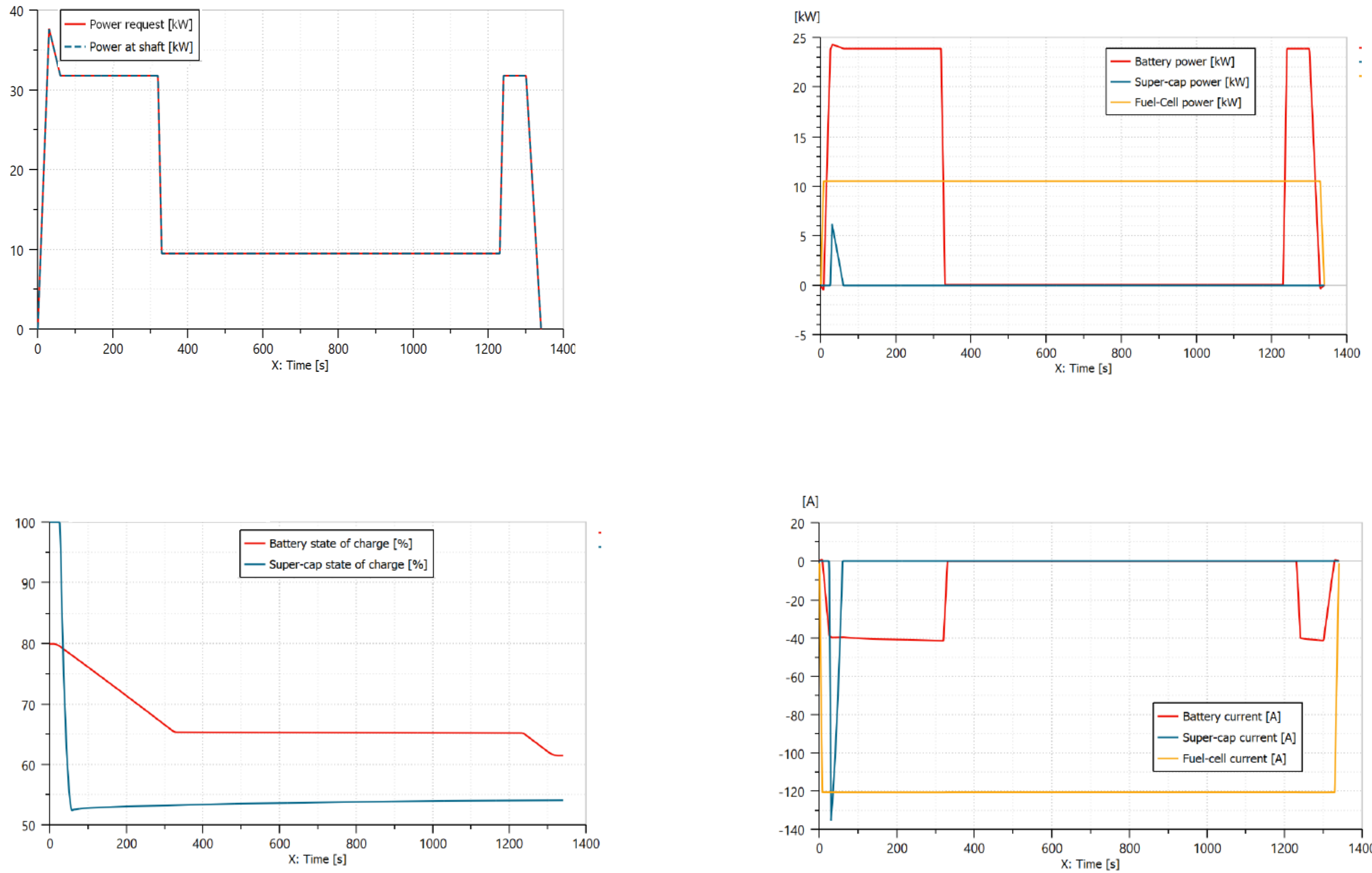




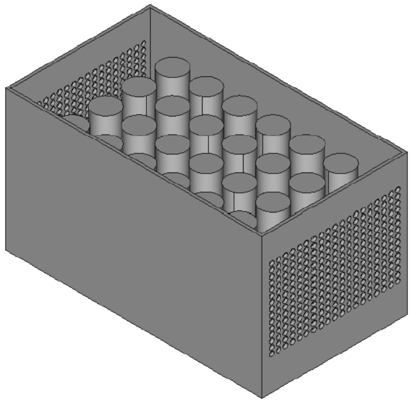
FUEL CELL SYSTEM BY SIMULATION: OVERALL MODEL

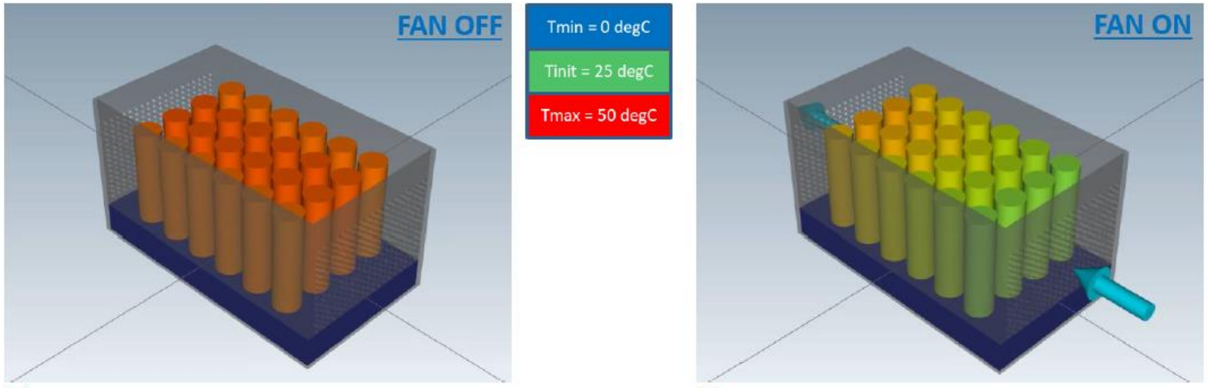


FUEL CELL SYSTEM BY SIMULATION: EXAMPLES OF RESULTS

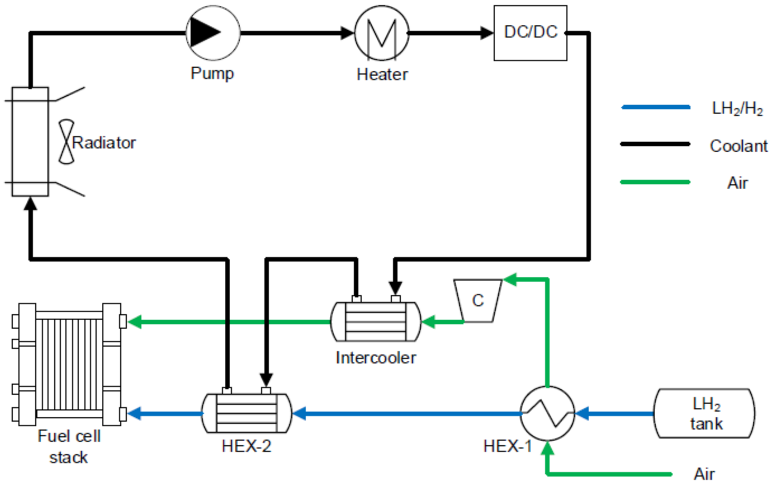


Battery pack cooling

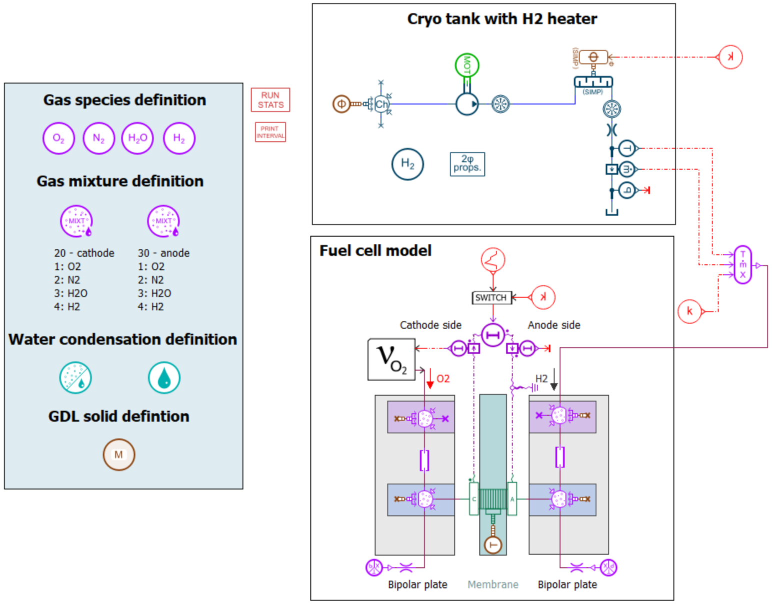




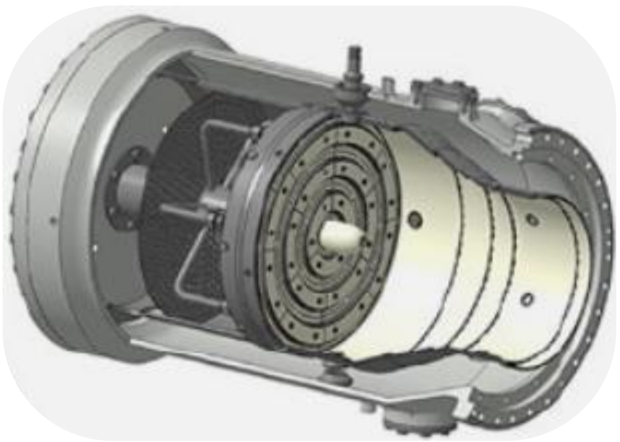
Regenerative sub-system for heat recovering to increase the cryogenic hydrogen temperature

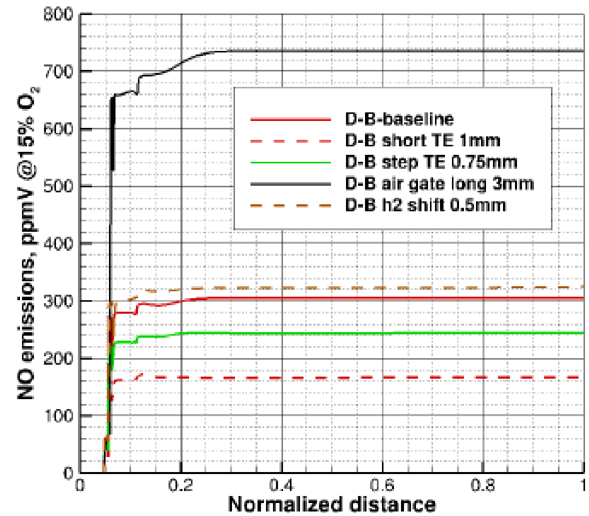


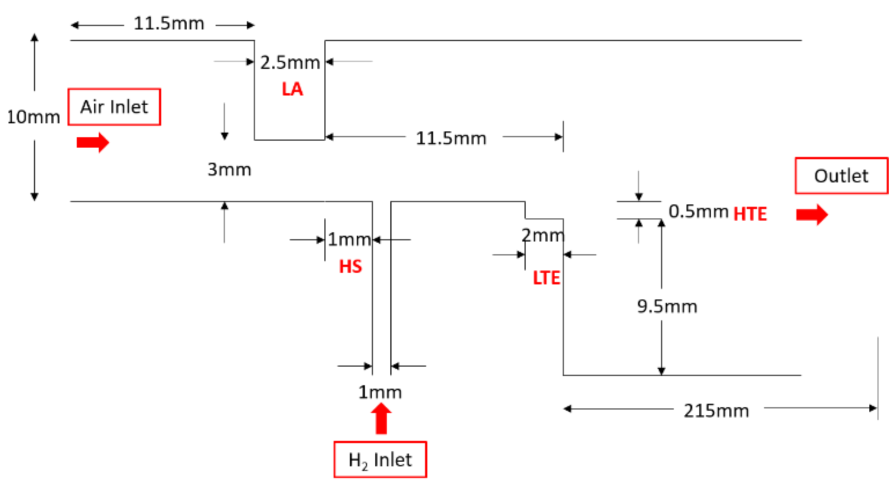
Yang, M. et al, On-Board Liquid Hydrogen Cold Energy Utilization System for a Heavy-Duty Fuel Cell Hybrid Truck, World Electr. Veh. J. 12(3) 2021.

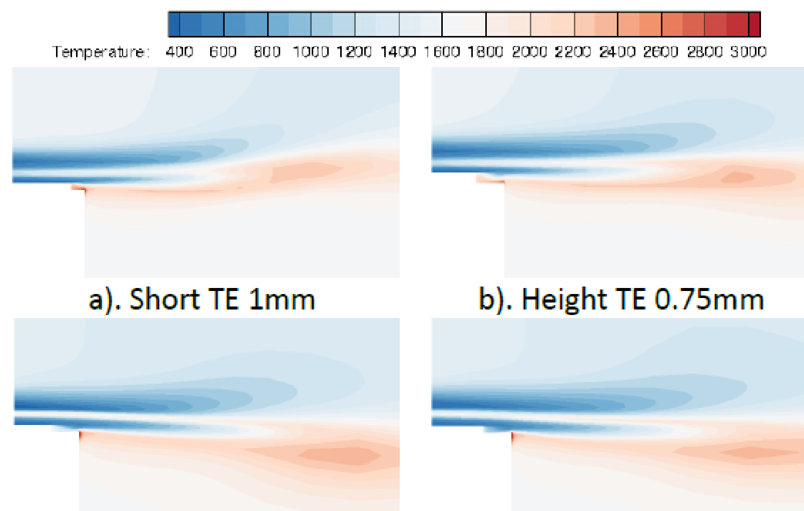


French, A., Mingione, G., Schettino, A., Roncioni, P., Vitagliano, P.L., Minervino, M,
Parametric Studies and Simulations of a Hydrogen Micromix Combustor ,
ASME Turbo Expo 2022, June 2022.

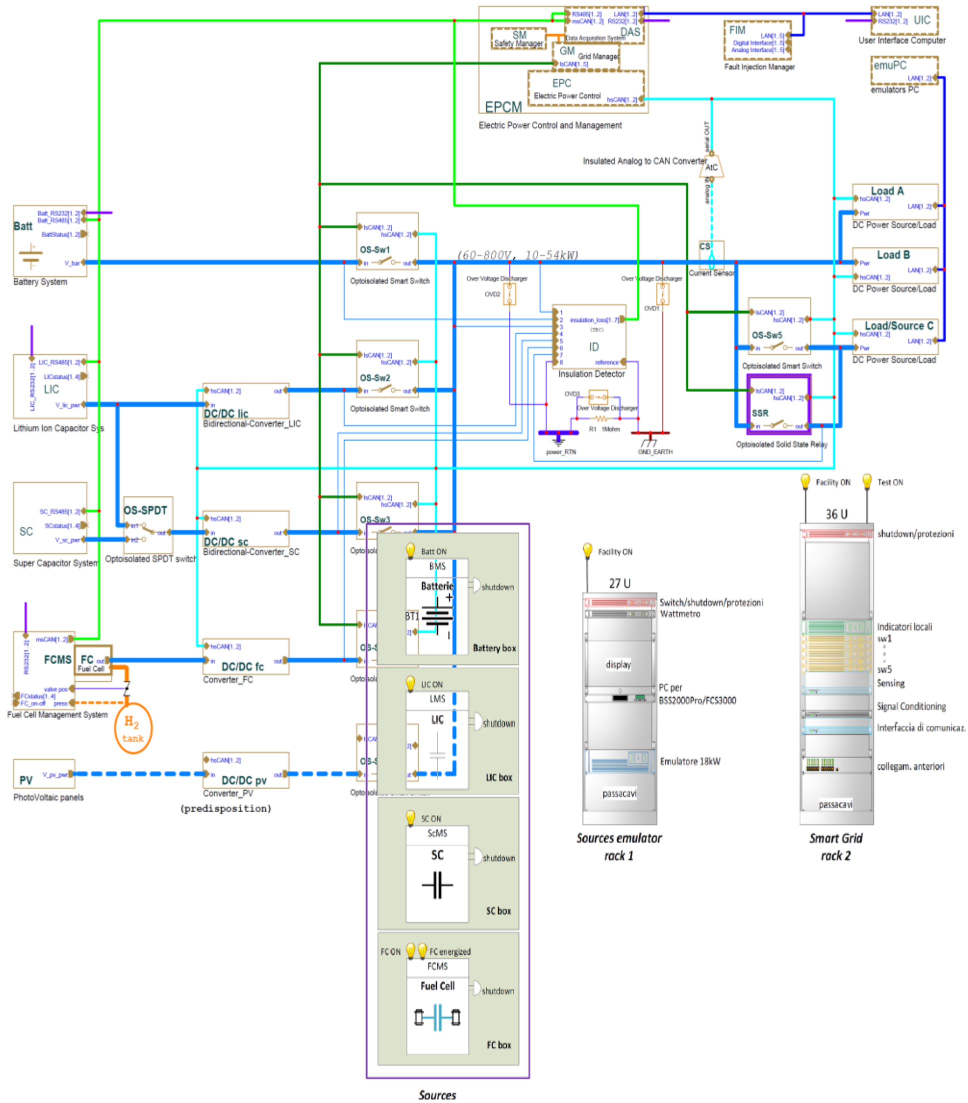








a). Short TE 1mm
b). Height TE 0.75mm
c). h2 channel shift 0.5mm
d). Air gate channel 3mm



Ground demonstrator

Objective: experimental investigations on FC-based propulsion systems

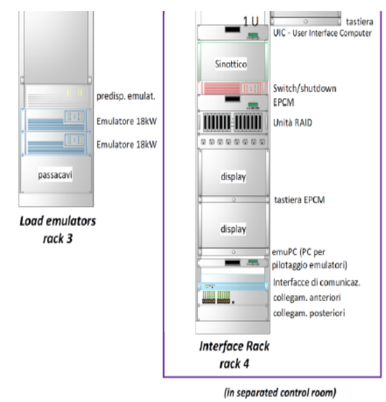
Power output: 50-60 kW

COTS assembly

Expandable modular architecture

Preliminary sizing

- Fuel Cell: 10-20kW
- Battery pack: ≈ 5kWh
- Ultracap:≈ 100Wh
- Motor: >60 kW (continuous)



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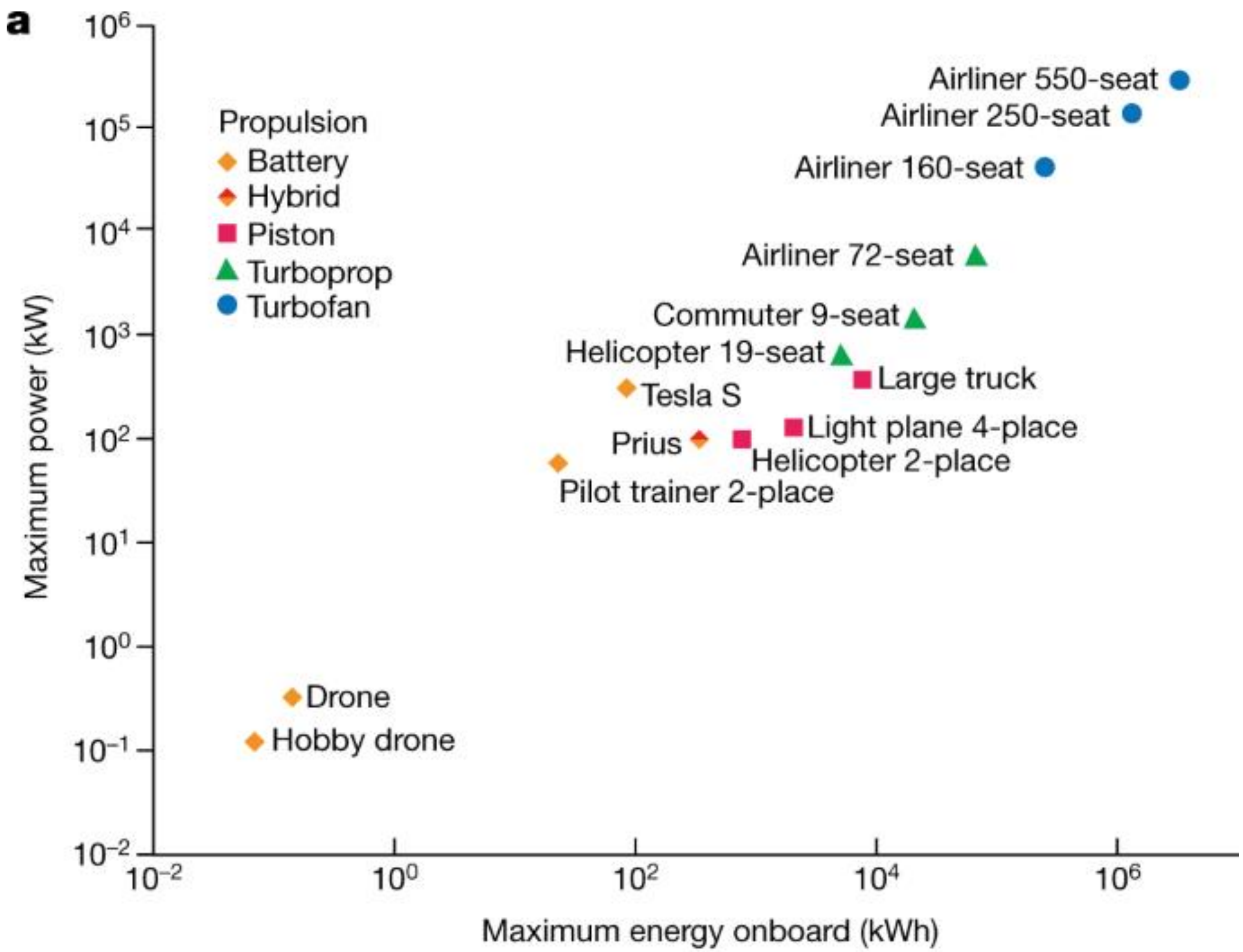
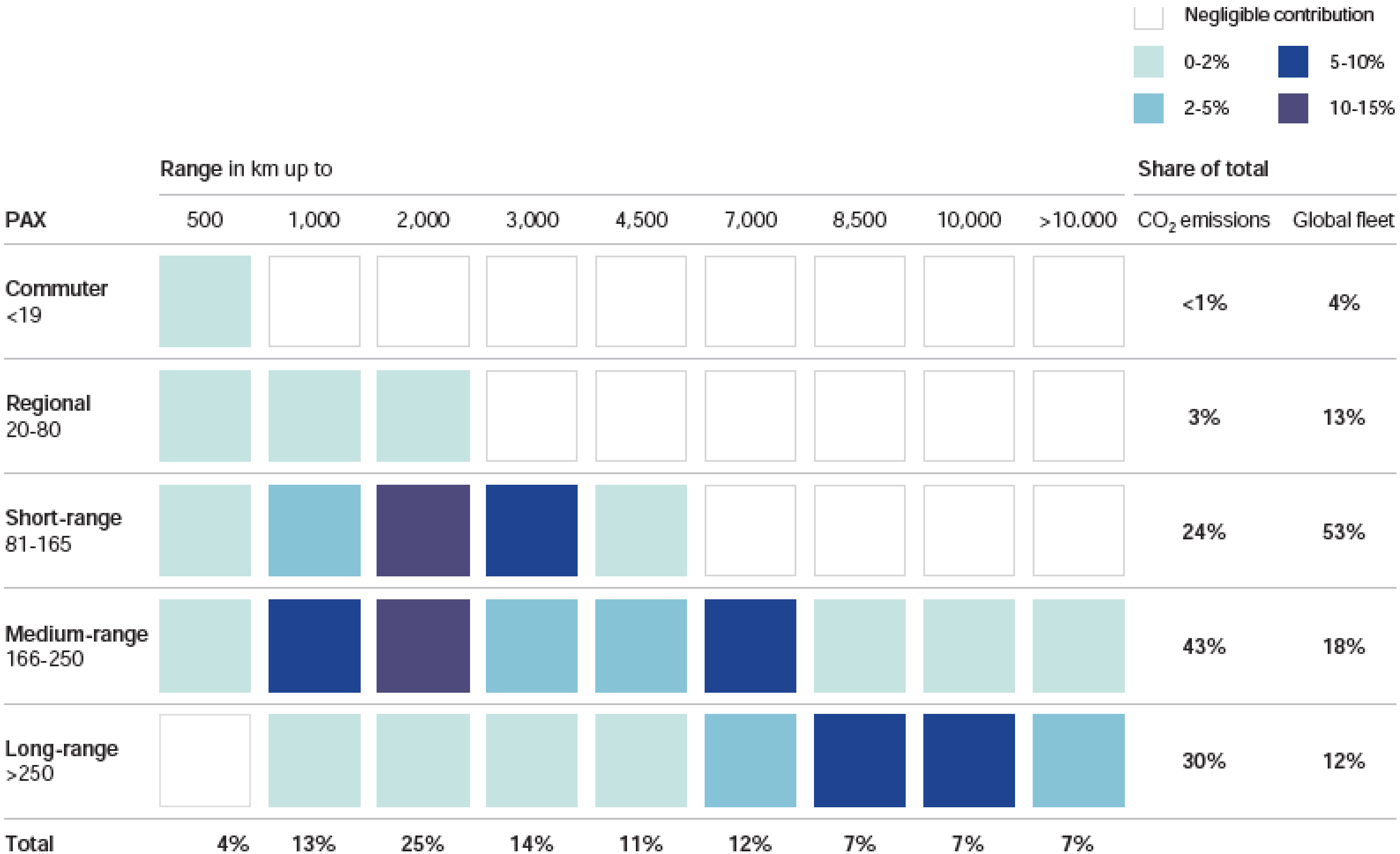


Viswanathan, V., Epstein, A.H., Chiang, YM. *et al.* The challenges and opportunities of battery-powered flight. *Nature* **601,** 519–525 (2022). https://doi.org/10.1038/s41586-021-04139-1

CO_2 EMISSIONS PER SEGMENT AND RANGE



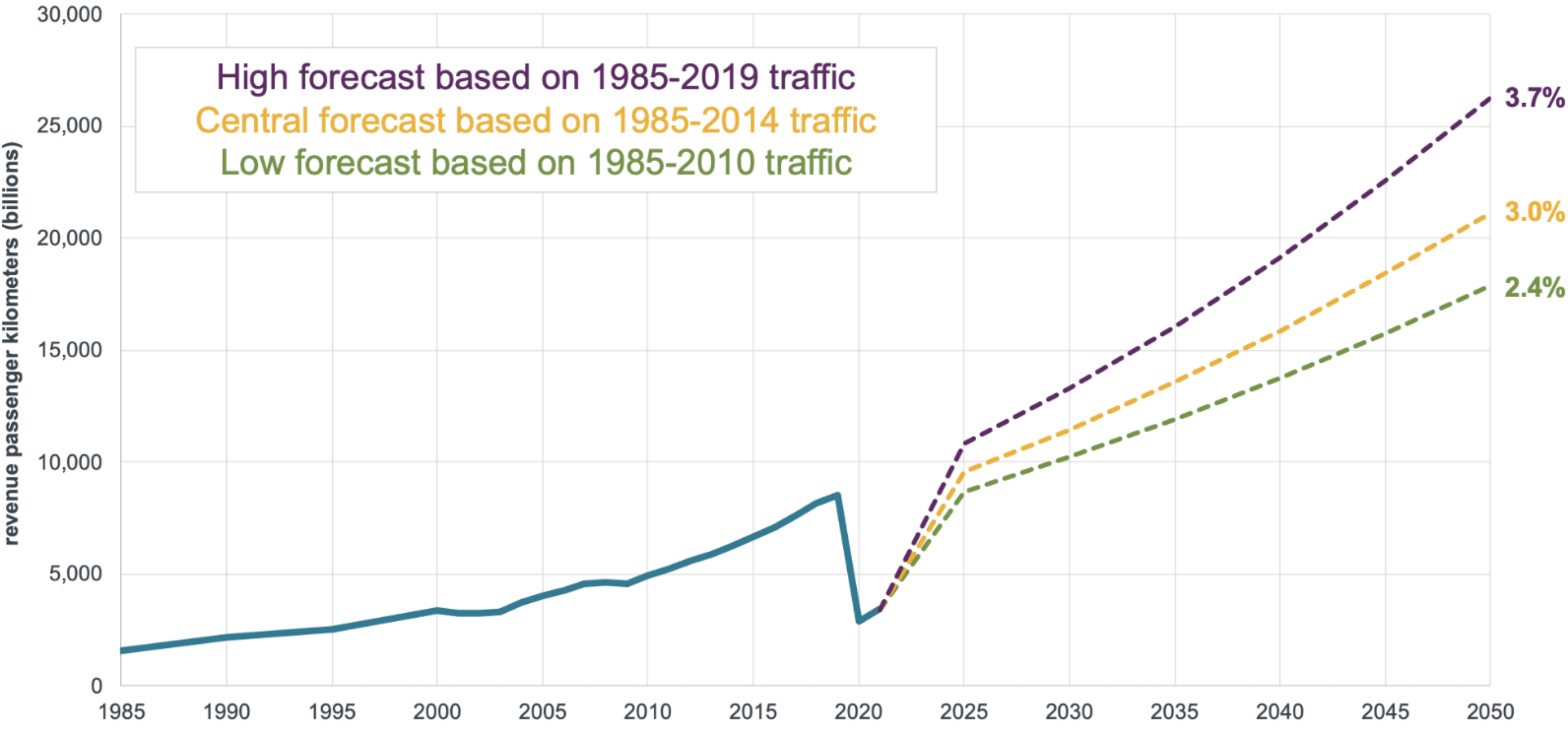
FCH, Hydrogen-powered aviation, May 2020

CO_2 EMISSIONS IN COMMERCIAL AVIATION

- Worldwide, flights produced **915 million tonnes** of CO_2 in 2019. Globally, humans produced over 43 billion tonnes of CO_2.
- The global aviation industry produces around **2.1%** of all human-induced CO_2 emissions
- Aviation is responsible for **12%** of CO_2 emissions from all transport sources (compared to 74% from road transport)
- Around **80%** of CO_2 emissions are emitted from flights of over 1500 km

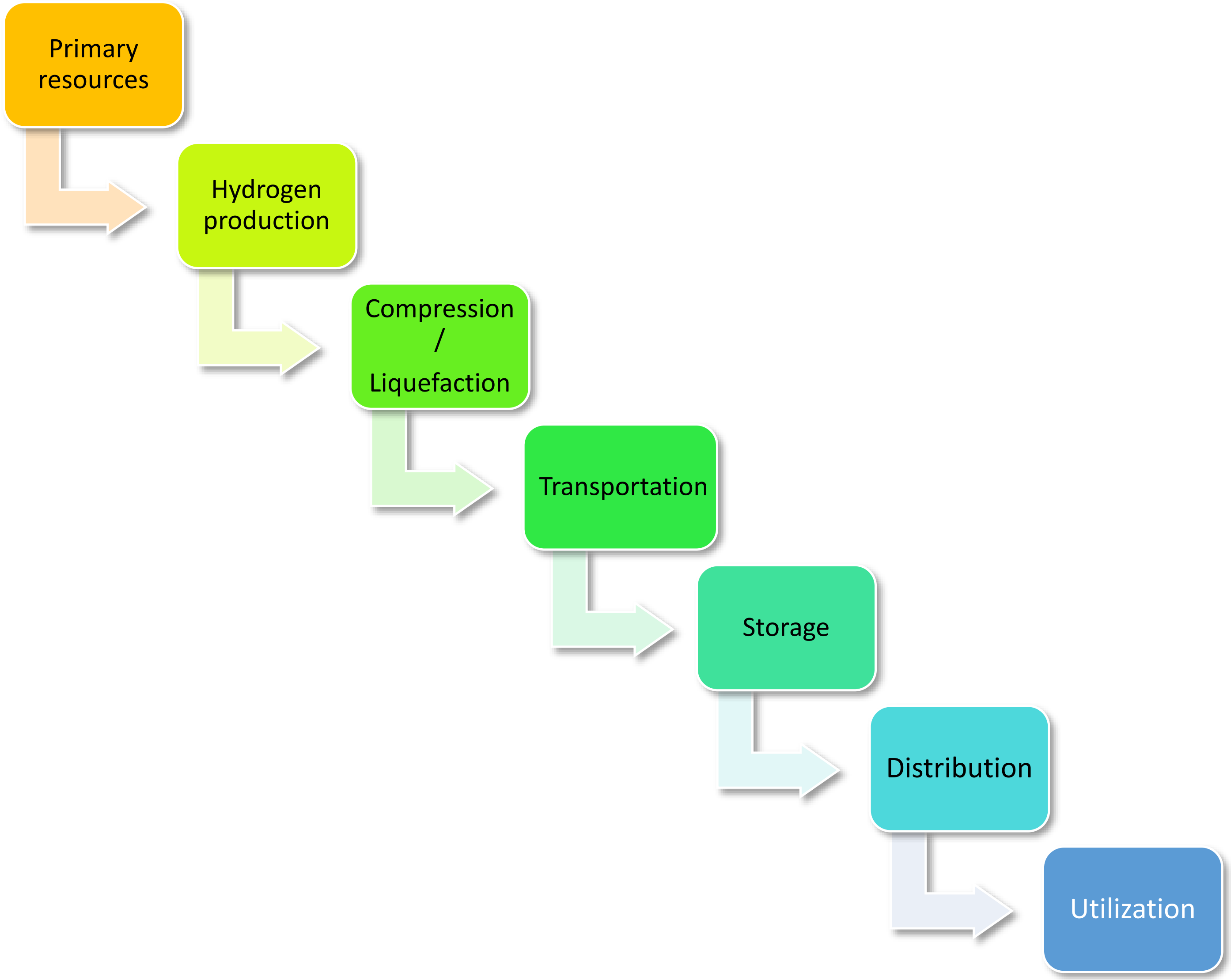
ATAG AIR TRANSPORT ACTION GROUP

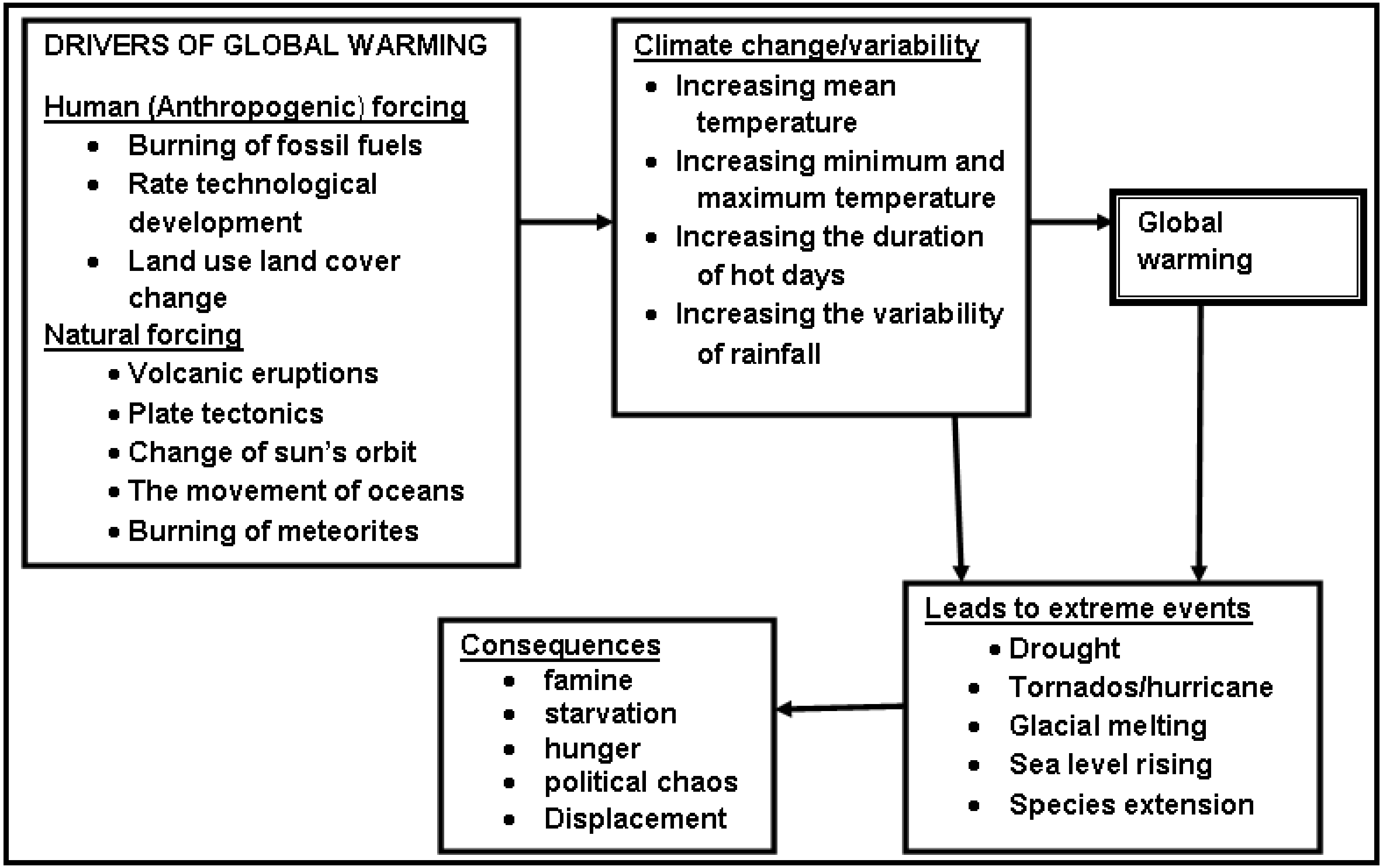
FORECAST ON TRAFFIC GROWTH



THE INTERNATIONAL COUNCIL ON Clean Transportation

… BEFORE UTILIZATION, MANY OTHER STEPS REQUIRE ENERGY





Berlie, Arega, Global Warming: A Review of the Debates on the Causes, Consequences and Politics of Global Response, Journal of Geography, 2018

Low carbon

Carbon neutral

Carbon-free

Carbon negative

Thanks for your attention.

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