Hydrogen for Aviation
Webinar
1. Introduction

2. Comparison of low carbon solutions for aviation: battery, fuel-cell and hydrogen propulsion

3. Field of use of hydrogen propulsion in civil aviation

4. The 4 challenges for the large-scale deployment of 100% hydrogen civil aviation

5. Q&A
WHEN will the first H₂ mid-range aircraft appear?

WHEN will an H₂ powered mid-range aircraft fly?

H₂ aviation is not Sci-Fi and ecological transition puts it back in the spotlight...

TUPOLEV TU-155
- Switch to a single LH₂ engine during flight
- 1st LH₂ flight: April 15th 1988
- Cancelled: 1994

... But sector wide adoption of H₂ is a bigger challenge than flying a single aircraft
Hydrogen is the only viable low emission option for commercial aviation

Batteries
Li-ion

Unviable
Very small planes only

E-fuels

Viable mid term

kerosene-equivalent performance

Interoperable with kerosene, but limitations due to energy consumption during production:
- H2 production (electrolysis)
- CO2 capture systems
- Fuel synthesis systems ➔ High OPEX

Fuel Cells with LH2

Viable for limited range and performances

For an E175 aircraft (78 PAX)
“With experimental fuel cell densities potentially as high as only 2.2 kW/kg, the fuel cell system would require about 19,800 kg of equipment to generate the 43.7 MW of power output during the climb phase of the flight, compared to the 2364 kg total for two CF34-8E turbine engines on the aircraft today”

Ahmed F Ghoneim
MIT: Center for Energy & Propulsion Research, 2019

LH2 as propellant

Viable High ranges and performances

Increased aircraft weight and volumes:
For same energy
Fuel Weight / 2.8 vs kerosene
Fuel Volume x 4 vs kerosene

High autonomy requires a significant increase in the aircraft volume for LH2 storage.

“Assuming for a moment that we’d be able to rely on batteries 30 times as energy dense as that [from 100wh/kg to 3000], an A320 would be able to fly with half of its payload for one-fifth of its current range, 500nm max. So, assuming a battery which today does not exist … It doesn’t work, purely electrical will not work.”

Grazia Vittadini, Airbus, 2019
The interest of hydrogen & its use cases across its application segments

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- Industry Feedstock and applications: Feedstock for production of ammonia fertilizers & steel
- Grid balance: A gap-filler between variable production & demand
- Heating: A progressive substitute to fossil fuels used for heating
- Mobility: A new energy vector for mobility applications

Technology Readiness Levels:

- **9** System Ready: Qualified system with proof of successful use – product
- **8** Prototype in work: Qualified system with proof of functional capability in area of use – product
- **7** Experimental Tests: Prototype in use – demonstration almost to scale in the operational environment
- **6** Experimental Tests: Prototype in operational environment – technical feasibility demonstrated in the area of application
- **5** Experimental Tests: Experimental setup in operational environment – key technology elements tested in a relevant environment
- **4** Experimental Tests: Experimental setup in lab environment – key technology elements tested

Applications:

- **Industry Feedstock and applications**
  - Petrochemical
  - Storage

- **Grid balance**
  - Heating
  - Buses
  - Cars
  - Forklifts

- **Heating**
  - Heating

- **Mobility**
  - Trains
  - Trucks
  - Propeller aircraft
  - Jet
Major public investments in H2 projects across the world

- **Germany**
  - **Budget**: €9 billion
  - **Goal**: Ramp up hydrogen production capacity to 5 GW by 2030 and 10 GW by 2040
  - **Date**: June 10th 2020

- **France**
  - **Budget**: €1.5 billion
  - **Goal**: Development of a carbon-neutral aircraft by 2035 (Prototype between 2026 & 2028)
  - **Date**: June 9th 2020

- **United Kingdom**
  - **Budget**: £12 billion
  - **Goal**: Deployment of a 4GW floating wind farm for hydrogen production in the early 2030s.
  - **Date**: September 2019

- **South Korea**
  - **Budget**: $22 billion
  - **Goal**: Develop private-public industry ecosystem for hydrogen fueled vehicles by 2022.
  - **Date**: June 2018

- **China**
  - **Budget**: $17 billion
  - **Goal**: Develop fuel cell industry and H2 mobility supply chain by 2023.
  - **Date**: June 2019

- **United States**
  - **Budget**: $64 million
  - **Goal**: Private sector (such as Nikola) is investing massively in H2
  - **Date**: June 2019

No major public announcement so far : $64 million announcement for green hydrogen production (2020).
3 steps to reduce CO$_2$ emission using H$_2$

**2025 - 2030**

*Synthesis Kerosene – E-Fuels*

- Synthesized from CO$_2$ and Hydrogen
- No impact on the aircraft design
- Compatible with current engines
- Higher fuel cost than H$_2$

*Lower CAPEX, Higher OPEX*

**2030s**

*Fuel cells as auxiliary power unit*

- Electrification of auxiliary systems by Hydrogen based fuel cells:
  - Electrical wheel drive
  - Main engine start
  - Water mgt., Pressurized air
  - Anti-ice
  - Cabin and systems electric power
  - APU position

**2040s**

*Hydrogen fuel cells as propulsion*

- Existing small planes prototypes
  - Radical rethink of the design for small aircraft (e.g. distributed electric propulsion)
  - ZeroAvia 6 seaters
  - Higher CAPEX, Lower OPEX

*LH2 for propulsion*

- Re-design of jet aircrafts
  - Early 2000 Cryoplane project
  - Could appear earlier than fuel cells for mid-size carriers
  - Higher CAPEX, Lower OPEX
Mapping of civil aviation

Range

100 km 1000 km 4000 km 7000 km 15000 km

PAX

1 2 3-4 4-8 8-12 12-20 20-100 100-500

Propulsion type

Jet aircraft
Propeller aircraft

Jet turbines

Propellers

A320 A321 A321 NEO B737 B787-8

Embraer ERJ 145 PZL M28 Skytruck

Bombardier DHC-8-401 Q400 ATR42

Cirrus SF50 Pilatus PC12

Socata TB 30 Epsilon

Extra 300

Pipistrel Panthera (Electric)

A350 B787

Jet turbines

A330 A332 B737

Pilatus PC12 Cirrus SF50

PZL M28 Skytruck

Bombardier DHC-8-401 Q400 ATR42

Cirrus SF50 Pilatus PC12

Socata TB 30 Epsilon

Extra 300

Pipistrel Panthera (Electric)
Fuel cells are relevant to replace within a certain load and performance limit.

Small sized jet turbines aircraft: could shift to fuel-cells depending on speed requirements.

Small-mid sized propeller aircraft: shift to fuel cells.

Light propellers and jet turbines
Shift to fuel cells propellers.
LH2 jet turbines are suited for larger aircraft and longer ranges.
4 key challenges of large scale H2 aviation

**H₂ aircraft** → New aircrafts have to be designed and certified
New, safe and robust solutions have to be developed including Storage tank, distribution, Venting, dispensing and purging

**Cost impact** → Lower emissions come at a higher price
Cost increase has to be offset either by carbon taxes of ~500€/ton of CO₂ or supported by the passenger

**Electricity production** → Widespread and sustainable H₂ requires more electricity supply
Full electrolyzed H₂ scenario requires a 35% increase of current global electricity generation

**Supply chain** → Massive H₂ storage & delivery capacities must be developed
40,000 airports have to go through a major overhaul of their infrastructure while maintaining dual capabilities during a 30-year transition period
LH2 Aircraft

What does the Liquid $H_2$ aircraft look like?

**System**
- **New Fuel System**: Tanks, Pipes, Valves, Pumps, Vents
- **New Fuel Control System**: Sensors, Control Box
- **Fire Protection features**: Sensors, Ventilation, Control Box

**Airframe**
- Tank support
- Local strengthening fuselage
- Fairings fuselage stretch to accommodate increased payload strengthening of wing structure

**Engine**
- High pressure Pump
- Heat Exchanger
- Fuel Flow Control Valve
- Combustion Chamber
- Control Box
- Oil Cooler

**Configuration**
- Integration of large cylindrical tanks, preferably above the passenger cabin
Cost Impact
First of all, 3 colors of Hydrogen

Different “shades of green”
CO₂ emissions from hydrogen production depends on technology and energy mix

GREY H₂ – Fossil Fuel
- Gasification – coal / lignite
- Steam methane reforming

BLUE H₂ – Grey with CCS* or Grid electrolysis
- Fossil fuel production with Carbon Capture & Storage
- Electrolysis from grid yet not renewable sources

GREEN H₂ – From renewable energies
- Electrolysis from low-carbon renewables source

* Carbon Capture and Storage
Cost Impact
Finding the right balance between emissions and cost

Almost CO₂-free aviation is technically possible

Emission & cost impact balance*

- Kerosene
- Grey H₂
- Blue H₂ SMR with CCS
- Blue H₂ Electrolysis
- Green H₂

kg of CO₂ per H₂ equivalent kg « well-to-wheel »

12
15
5
3
2

• Calculation based on the French energy mix with 58 gCO₂/ kwh
• Cost impact on a Boeing 737 or A320 block-hour cost for a 3000km flight

20% ticket cost increase
0% ticket cost increase

Ticket cost increase
Electricity Production

Paris CDG airport turned 100% H₂ with state of the art technology

Paris Charles de Gaulle Airport

- 700 Take-offs / day
- 4 200 t Kerosene need by day
- 1 500 t H₂ need by day

What do these 4 GW represent?

- 4 GW Power needed to produce H₂ by electrolysis
- 2.5 EPR reactors
- €9 bn Capex Cost*
- 3 200 5MW-25% load factor Wind turbines
- €16 bn Capex Cost

Kerosene

H₂ Propulsion

*Based on initial cost estimation of €3.5 bn
Hydrogen value chain – Multiple production and supply patterns

**H2 Production**
- Coal + Grid
- Natural gas + Grid
- Biomass + Grid
- H20 + Grid
- H20 + Local renewables
- Biomass + Microorganisms

**Thermochemical conversion**
- Electrolysis

**Electrolysis**
- Compression
- Liquefaction
- Absorption

**Biochemical conversion**
- LOHC*, Ammonia, Methanol

**Conditioning**
- Fluids
- Solids
- Absorption

**Distribution**
- Underground / Pressure vessel
- Cryogenic tank
- Standard fuel tank
- Standard container

**Storage**
- Optional

**Deconditioning**
- Optional

**Dispensing & application**
- Power
- Fuel cells refueling
- Propellant refueler
- Transport
- Industry
- Building

*Liquid Organic Hydrogen carrier
Supply Chain

Positioning of the main actors in H2 supply chain is beginning to take shape

- **TOTAL** sees hydrogen as a green fuel (potential threat to the fossil fuel market)
- **AIR LIQUIDE** sees hydrogen as a molecule and wants to remain a world leader in gaseous/liquid molecules production & distribution
- **ENGIE** considers hydrogen as a clean source of electricity / a useful buffer for renewable energy production
- **NEL** sees itself as an hydrogen conversion specialists

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**Key player** | **Their vision of hydrogen** | **Oil & Gas players** | **Production & Conditioning** | **Storage** | **Distribution** | **Dispensing** | **Conversion to energy**
---|---|---|---|---|---|---|---
TOTAL | TOTAL sees hydrogen as a green fuel (potential threat to the fossil fuel market) | Gas Suppliers | Production & Conditioning | Storage | Distribution | Dispensing | Fuel Cells
AIR LIQUIDE | AIR LIQUIDE sees hydrogen as a molecule and wants to remain a world leader in gaseous/liquid molecules production & distribution | | | | | | | Air Liquide
ENGIE | ENGIE considers hydrogen as a clean source of electricity / a useful buffer for renewable energy production | | | | | | | ENGIE
NEL | NEL sees itself as an hydrogen conversion specialists | Acquisition | | | | | | NEL
Zero-carbon aviation is technically achievable with H₂. Today, its production is mostly “grey” and more polluting than burning kerosene.

Immediate focus should be on infrastructures and supply. An H₂ airplane without refueling capabilities is useless.

H₂ for aviation will benefit from a scale effect as many regions and industries are investing heavily.

Production ramp up will be a massive challenge since a large amount of energy will be needed to generate H₂: full H₂ scenario would need 35% of current worldwide electricity generation capacity.

E-fuels might play a role as a short-mid term solution, esp. for the already existing fleet, despite significant production costs.