Agenda

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
Opening Question: 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
Technology Landscape:
Low carbon solutions for aviation
Although different technology options exist – Hydrogen is the only viable low emission option for large-scale commercial aviation

**Batteries**
- Li-ion

- **Unviable**
  - Very small planes only

  “Assuming for a moment that we’d be able to rely on **batteries 30 times as energy dense as that** [from 100wh/kg to 3,000], a B737 or 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, CTO Airbus, 2019

**E-fuels**

- 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 (10 x kerosen)

**Fuel Cells with LH2**

- Viable mid term

  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” → Too heavy

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

- Viable for limited range and performances

- 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.
Technology Roadmap Snapshot 2020 shows diverse maturity across use cases – aviation mass-market readiness not to be expected on the short- to mid-term

<table>
<thead>
<tr>
<th>Hydrogen Use Cases</th>
<th>Industry Feedstock and applications</th>
<th>Grid balance</th>
<th>Heating</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Readiness Levels:</td>
<td>Feedstock for production of ammonia fertilizers &amp; steel</td>
<td>A gap-filler between variable production &amp; demand</td>
<td>A progressive substitute to fossil fuels used for heating</td>
<td>A new energy vector for mobility applications</td>
</tr>
<tr>
<td>9</td>
<td>Qualified system with proof of successful use – product</td>
<td>Petrochemical</td>
<td>Storage</td>
<td>Buses, Cars, Forklifts</td>
</tr>
<tr>
<td>8</td>
<td>Qualified system with proof of functional capability in area of use – product</td>
<td></td>
<td>Heating</td>
<td>Trains, Trucks</td>
</tr>
<tr>
<td>7</td>
<td>Prototype in use – demonstration almost to scale in the operational environment</td>
<td></td>
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<td></td>
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<tr>
<td>6</td>
<td>Prototype in operational environment – technical feasibility demonstrated in the area of application</td>
<td></td>
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<tr>
<td>5</td>
<td>Experimental setup in operational environment – key technology elements tested in a relevant environment</td>
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<tr>
<td>4</td>
<td>Experimental setup in lab environment – key technology elements tested</td>
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</tbody>
</table>

Hydrogen Use Cases:
- Trains
- Trucks
- Cars
- Forklifts
- Heating
- Buses
- Petrochemical
- Storage
- Propeller aircraft
- Jet

IAC Partners
Immense public (and private) investments in H2 projects across the world push towards a global Hydrogen ecosystem – with positive impact on scale effects

<table>
<thead>
<tr>
<th>Country</th>
<th>Date</th>
<th>Budget</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>June 9th 2020</td>
<td>€1.5 billion</td>
<td>Development of a carbon-neutral aircraft by 2035 (Prototype between 2026 &amp; 2028)</td>
</tr>
<tr>
<td>France</td>
<td>September 2019</td>
<td>£12 billion</td>
<td>Deployment of a 4GW floating wind farm for hydrogen production in the early 2030s.</td>
</tr>
<tr>
<td>South Korea</td>
<td>June 2019</td>
<td>$17 billion</td>
<td>Develop fuel cell industry and H2 mobility supply chain by 2023.</td>
</tr>
<tr>
<td>Germany</td>
<td>June 10th 2020</td>
<td>€9 billion</td>
<td>Ramp up Hydrogen production capacity to 5 GW by 2030 and 10 GW by 2040</td>
</tr>
</tbody>
</table>

No major public announcement so far: $64 million announcement for green hydrogen production (2020).

Private sector (such as Nikola) is investing massively in H2.
Use Cases:
Hydrogen propulsion in civil aviation
We see 3 evolutionary steps to reduce CO$_2$ emission using H$_2$ until 2040

<table>
<thead>
<tr>
<th>2025 - 2030</th>
<th>2030s</th>
<th>2040s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Synthesis Kerosene – E-Fuels</strong></td>
<td><strong>Fuel cells as auxiliary power unit</strong></td>
<td><strong>Hydrogen fuel cells as propulsion</strong></td>
</tr>
<tr>
<td>Synthesized from CO2 and Hydrogen</td>
<td>Electrification of auxiliary systems by Hydrogen based fuel cells:</td>
<td>Existing small planes prototypes</td>
</tr>
<tr>
<td>No impact on the aircraft design</td>
<td>Electrical wheel drive</td>
<td>Radical rethink of the design for small aircraft (e.g. distributed electric propulsion)</td>
</tr>
<tr>
<td>Compatible with current engines</td>
<td>Main engine start</td>
<td>ZeroAvia 6 seaters</td>
</tr>
<tr>
<td>Higher fuel cost than H$_2$</td>
<td>Water mgt., Pressurized air</td>
<td>Could appear earlier than fuel cells for mid-size carriers</td>
</tr>
<tr>
<td></td>
<td>Cabin and systems electric power</td>
<td>Early 2000 Cryoplane project</td>
</tr>
<tr>
<td></td>
<td>APU position</td>
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</table>
Ability to scale-up aviation use cases needs to balance trade-off between weight and operating range.
Fuel cells are the substitute of choice within a certain load (size) and performance (range) 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 – the natural playground of commercial aviation
Question remains: What are the prerequisites for large-scale usage of H₂ jets in commercial aviation?
Outlook:
Challenges towards large-scale deployment of 100% hydrogen civil aviation
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*
**H2 Aircraft**

*Liquid H₂ aircrafts require a significant update of the technology architecture*

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

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

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

- **Integration of large cylindrical tanks, preferably above the passenger cabin**
Cost Impact
3 colors of Hydrogen exist – with significantly different cost / eco-footprint

<table>
<thead>
<tr>
<th>Conversion Type</th>
<th>Production Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermochemical</td>
<td>Coal + Grid, Natural gas + Grid, Biomass + Grid</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>Water + Grid, Local renewables + Grid</td>
</tr>
<tr>
<td>Biochemical conversion</td>
<td>Biomass + Microorganisms</td>
</tr>
</tbody>
</table>

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*
  - Grid electrolysis

- **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 will be key for the future

Almost CO₂-free aviation is technically possible

Emission & cost impact balance*

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>CO₂ Emission (kg)</th>
<th>Ticket Cost Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>12</td>
<td>0%</td>
</tr>
<tr>
<td>Grey H₂</td>
<td>15</td>
<td>20%</td>
</tr>
<tr>
<td>Grey with CCS</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Blue H₂ Electrolysis</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Green H₂</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

- Calculation based on the French energy mix with 58 gCO₂/kWh
- Cost impact on a Boeing 737 or A320 block-hour cost for a 3,000km flight
Electricity Production *Mass market ready end user vehicles are just the start, significant infrastructure upgrades will be necessary to scale-up*

**Atlanta Airport**

- **Kerosene**
  - 7,200 t Kerosene need by day

- **H2 Propulsion**
  - 2,600 t $H_2$ need by day
  - 6.5 GW Power needed to produce $H_2$ by electrolysis

**What do these 6.5 GW represent?**

- **NUCLEAR**
  - Nuclear plant: 1,65 GW
  - 4 EPR reactors
  - $16 bn Capex Cost*

- **SOLAR POWER**
  - Solar farm: of 130 km²
  - 87 M 300 watt solar panels
  - $50 bn Capex Cost

*Based on a cost estimation of $4bn*
Supply Chain
The race is on – but no supply chain convergence on the short-term

**H2 Production**
- Coal + Grid
- Natural gas + Grid
- Biomass + Grid
- H2O + Grid
- H2O + Local renewables
- Biomass + Microorganisms

**Conditioning**
- Thermochromical conversion
  - Electrolysis
  - Biochemical conversion

**Distribution**
- Compression
  - GH2
  - 350 / 700 bars
- Liquefaction
  - LH2
  - -252°C, 1 bar
- Fluids
  - LOHC*, Ammonia, Methanol
- Absorption
  - Solids
  - Hybrids

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

**Deconditioning**
- Dehydrogenation
- Gasification/liquefaction

**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

<table>
<thead>
<tr>
<th>Key player</th>
<th>Their vision of hydrogen</th>
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</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>TOTAL sees hydrogen as a green fuel (potential threat to the fossil fuel market)</td>
</tr>
<tr>
<td>AIR LIQUIDE</td>
<td>AIR LIQUIDE sees hydrogen as a molecule and wants to remain a world leader in gaseous/liquid molecules production &amp; distribution</td>
</tr>
<tr>
<td>ENGIE</td>
<td>ENGIE considers hydrogen as a clean source of electricity / a useful buffer for renewable energy production</td>
</tr>
<tr>
<td>NEL</td>
<td>NEL sees itself as an hydrogen conversion specialists</td>
</tr>
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<table>
<thead>
<tr>
<th>Oil &amp; Gas players</th>
<th>Production &amp; Conditioning</th>
<th>Storage</th>
<th>Distribution</th>
<th>Dispensing</th>
<th>Conversion to energy</th>
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<tbody>
<tr>
<td>Gas Suppliers</td>
<td>TOTAL</td>
<td></td>
<td></td>
<td>TOTAL</td>
<td>Fuel Cells</td>
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<tr>
<td>Acquisition</td>
<td>NEL</td>
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<td></td>
<td>NEL</td>
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<tr>
<td>PROTON cars</td>
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Chronological Move
Take aways, Q&A

1. **H₂ aircraft** has proved to be feasible, however a long development and certification phase is to be expected.

2. ‘Zero’-carbon aviation is technically achievable with H₂. Today, its production is mostly “grey” and more polluting than burning kerosene.

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

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

5. 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.

6. E-fuels might play a role as a short-mid term solution, esp. for the already existing fleet, despite significant production costs.
Thank you – and let’s stay in touch

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