Global Development of Hydrogen-Powered Aviation Propulsion

Keynote lecture

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Outline

1. Why hydrogen? The decarbonisation problem
2. The physics: energy, mass and range
3. Two propulsion pathways
4. Storage and aircraft integration
5. Europe: Airbus, Rolls-Royce, start-ups
6. North America
7. China: a combustion-first strategy
8. Brazil: Embraer, Eve and the ethanol-to-hydrogen plant
9. Global comparison and timelines
10. The bottlenecks
11. Our work: fuel-cell flow fields, topology optimisation, Nektar++
12. Outlook, and a new textbook

Central message

Hydrogen propulsion has moved from concept to hardware. Engines have run on 100 % hydrogen at full take-off power. A megawatt-class hydrogen turboprop has flown in China. The limiting factors are now storage, certification and the hydrogen supply chain, not the propulsor itself.

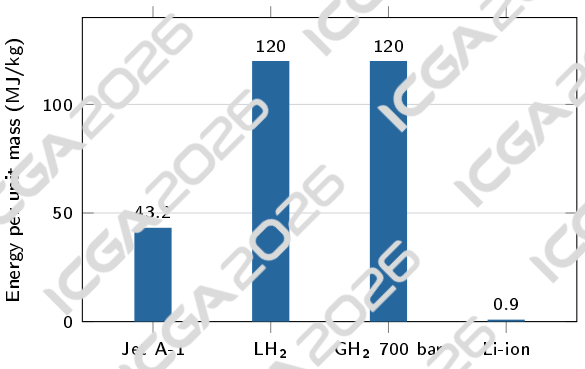
Why hydrogen? The decarbonisation problem

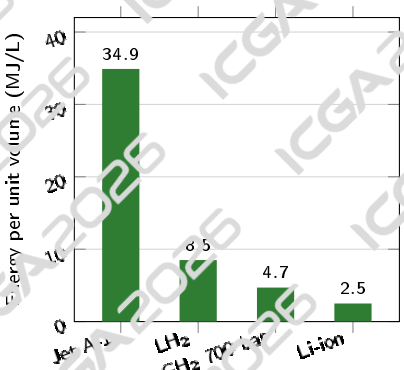
- Aviation emits roughly 2.5 % of global CO_2. Its total climate forcing is larger, about 3.5 %, because of contrails and NO_x.
- Traffic grows at 3 to 4 % per year. Efficiency gains of 1 to 2 % per year do not close the gap.
- ICAO and IATA target net zero CO_2 by 2050.
- Three technology routes:
  - **Sustainable aviation fuels (SAF)**: drop-in, scarce, costly.
  - **Batteries**: clean, but heavy. Limited to small aircraft and short ranges.
  - **Hydrogen**: zero CO_2 at the aircraft. Needs new aircraft, new engines and new airports.

Where hydrogen fits

- Batteries: up to about 9 to 19 seats, under 300 nmi.
- Hydrogen fuel cells: regional, up to about 100 seats, under 1000 nmi.
- Hydrogen combustion: single-aisle and above.
- SAF: long haul, for decades.

The physics: specific energy and energy density





- Hydrogen carries 2.8 **times** the energy of kerosene per kilogram. This is its great advantage.
- Liquid hydrogen needs **4 times** the volume of kerosene for the same energy. Gaseous hydrogen needs 7 times.
- Batteries sit two orders of magnitude below. Hence the hydrogen route for anything beyond commuter aircraft.

Lower heating values; Li-ion pack at about 250 Wh/kg; tank mass excluded.

The physics: what the range equations say

Combustion aircraft (Breguet)

$$R = \frac{V}{g\,\mathrm{TSFC}}\,\frac{L}{D}\,\ln\frac{m_{\mathrm{initial}}}{m_{\mathrm{final}}}$$

Hydrogen lowers TSFC by a factor of 2.8 in mass terms.

Fuel cell electric aircraft

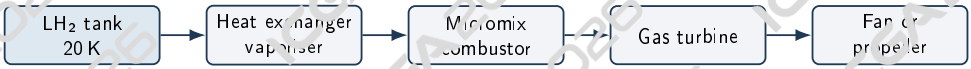
$$R = \frac{e^{*}\,\eta_{\mathrm{tot}}}{g}\,\frac{L}{D}\,\frac{m_{\mathrm{b}}}{m}$$

e^{*}: specific energy of the store, m_{b}/m its mass fraction. For hydrogen the store is tank plus fuel, so the **tank gravimetric index** enters directly.

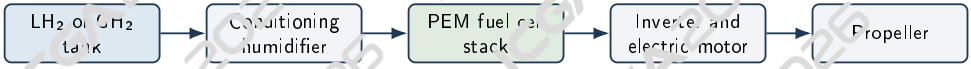
- A liquid hydrogen tank of gravimetric index 0.35 gives an effective e^{*} of about 42 MJ/kg. That is kerosene parity, before conversion efficiency.
- A fuel cell converts at 50 to 55 %, a small gas turbine at 30 to 40 %. The electric chain multiplies by about 0.9.
- A fuel-cell regional aircraft can therefore match a turboprop on energy, if tank, fuel cell and cooling stay light.
- **Specific power** of the whole powertrain, in kW/kg, becomes the decisive number. Today it is about 1 to 1.5 kW/kg. The target is 2 to 3 kW/kg.

Two propulsion pathways

Hydrogen combustion



Hydrogen fuel cell



Combustion: retains the gas turbine. Scales to single-aisle power. Must manage NO_x, flashback and water in the exhaust.

Fuel cell: highest efficiency, zero NO_x. Limited by stack specific power, thermal management and altitude derating.

Hydrogen combustion: what changes inside the engine

- Laminar flame speed about 3 m/s, eight times that of kerosene. Flashback becomes a design driver.
- Wide flammability limits (4 to 75 % by volume). Lean operation is easy. Lean-premixed burners risk flashback, so **micromix** injection with many small diffusion flames is the preferred route.
- Adiabatic flame temperature slightly higher than kerosene. Thermal NO_x must be controlled by short residence time and lean mixtures.
- The exhaust carries **2.5 times** more water per unit energy. No soot, so fewer ice nuclei, but more vapour. Contrail effects remain an open question.

Combustor design choices

- Micromix (hundreds of mm scale jets)
- Lean direct injection
- Steam injection (P&W HySIITE) to cut NO_x by up to 80 %
- Hydrogen cold sink used for intercooling and condensation

Key fact

A modern aero engine has now run on 100 % hydrogen through a full simulated flight cycle (Rolls-Royce, 2026).

Fuel cells for aviation: the numbers that matter

- Low-temperature PEM is the aviation workhorse. Operates at 60 to 90 °C. Efficiency 50 to 60 % at part load.
- **Specific power** of the installed system, including compressor, humidifier, cooling and power electronics: about 1 kW/kg today. Automotive stacks alone reach 4 kW/kg, but aircraft need the whole system.
- **Heat rejection** is the hidden problem. At 55 % efficiency, 45 % of the fuel energy leaves as low-grade heat at 80 °C. Radiator drag can exceed 5 % of aircraft drag.
- **Altitude**: air density at 25 000 ft is 45 % of sea level. Compressors must be sized for cruise. Stack power falls unless pressurised.

System	Power	Status
Airbus ZEROe FC engine	1.2 MW	ground demo, 2026
ZeroAvia ZA600	600 kW	flown 2023 to 2024
H2FLY H2F-175	175 kW	flown (LH_2), 2023
Beyond Aero BYA-1	6 × 400 kW	PDR, 2026
Tsinghua / easyh2power	30 kW +	UAV flights

Research levers

High-temperature PEM (160 °C) for smaller radiators; cryogenic cooling from LH_2; topology-optimised flow fields for uniform reactant distribution (our work, later in this talk).

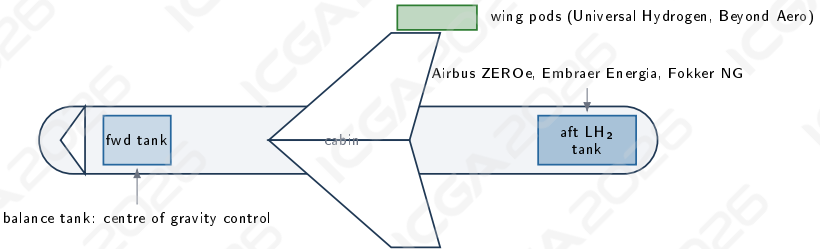
Storage: the cryogenic tank is the real aircraft problem

- Liquid hydrogen at 20 K and about 70 kg/m^3. Insulation must hold boil-off below roughly 0.1 to 1 % per hour.
- **Gravimetric index** $= m_{\mathrm{H_2}}/(m_{\mathrm{H_2}} + m_{\mathrm{tank}})$. Metallic tanks: 0.2 to 0.3. Target for airliners: above 0.5. Space-stage tanks reach 0.7, but they are single-use.
- Cylindrical or spherical shapes are compulsory for pressure and insulation. Wing tanks are therefore difficult. Fuselage tanks displace payload.
- Gaseous hydrogen at 700 bar: simpler, no boil-off, heavier. Beyond Aero chose this route for an 8-seat jet.

Tank programmes in 2026

- Airbus ZEDC (Bristol, Stade, Nantes, Madrid): metal and composite cryotanks.
- Cranfield CH2i: "type VI" composite cryogenic tank, flight trials planned 2026.
- Clean Aviation fLHYing tank: 1000 L vacuum-insulated composite tank, UAV flight 2026.
- Netherlands consortium (NLR, TU Delft, Toray, KVE): thermoplastic welded composite tanks.

Aircraft integration: where the hydrogen goes



- Aft fuselage tanks are the industry default. They stretch the fuselage by 10 to 20 % and move the centre of gravity aft as fuel burns.
- Every design so far accepts a 5 to 15 % energy penalty from extra wetted area and tank mass. The payoff is zero CO_2.
- Safety: hydrogen rises and disperses. Ventilation, leak detection and crash-worthiness drive the certification basis.

Europe: Airbus ZEROe, from 2035 to the 2040s

- 2020: four concepts (turboprop, turbofan, blended wing, later a fuel-cell aircraft). Target entry into service 2035.
- 2023: first ZEROe fuel-cell engine powered on. Investment in ZeroAvia.
- February 2025: programme delayed by five to ten years. Reasons: slow hydrogen ecosystem, regulation, technology maturity. The A380 testbed is shelved. Fuel cells chosen as the primary route.
- Early 2026: feasibility of the **100-seat, 1000 nmi** concept confirmed. Four 2.4 MW fuel-cell engines, TRL 3. A 1.2 MW demonstrator is under test in Germany.
- February 2026 annual press conference: no revised entry-into-service year published.

Reading the Airbus decision

- The technology work continues at full pace. The commercial launch waits for the fuel.
- Airbus now talks of 2040 to 2045.
- Near-term focus moves to a SAF-burning next-generation single aisle.
- Hydrogen Hubs at Airports programme keeps growing.

Source: FlightGlobal, Mar 2026; Airbus annual press conference, 19 Feb 2026.

Europe: Rolls-Royce and easyJet, 100 % hydrogen at full take-off power

- November 2022: first run of a modern aero engine (AE 2100) on hydrogen, Boscombe Down.
- 2023: full annular combustor on 100 % hydrogen at take-off conditions, Loughborough and DLR Cologne.
- **April 2026**: a modified Pearl 15 ran on 100 % gaseous hydrogen at full take-off power at NASA Stennis. The test covered start-up, take-off, cruise and landing, including fault cases.
- August 2026: Rolls-Royce and TCS complete the four-year programme with a full simulated flight cycle.

What was proved

A narrowbody-class engine, scalable, can burn hydrogen safely across the whole mission. Combustion, fuel system and control technologies were validated.

What was not proved

No flight test. No liquid hydrogen on board. No service timeline. Rolls-Royce feeds the results into UltraFan and future studies.

Lesson: in Europe, hydrogen combustion is a technology bank. Fuel cells carry the near-term product plans.

Sources: Rolls-Royce and easyJet, 29 Apr 2026; TCS, Aug 2026.

Europe: Clean Aviation, universities and start-ups

EU Clean Aviation and national programmes

- fLHYing tank: composite LH_2 tank flown on a UAV, TRL 5 in 2026.
- COCOLIH2T (with Pratt & Whitney): onboard LH_2 storage.
- UK ATI: ZeroAvia, Cranfield CH2i, Rolls-Royce.

Fokker Next Gen (Netherlands)

- Fokker 100 retrofitted with hydrogen-burning engines. First flight planned 2028.
- Clean-sheet regional jet with LH_2 combustion targeted at 2035. MoU with airBaltic.

Beyond Aero (France)

- BYA-1: 8-seat hydrogen-electric business aircraft. 800 nmi at 300 kt.
- Preliminary design review passed, March 2026.
- Six 400 kW fuel cells, 950 kW shaft power, twin pusher propfans (ducted fans dropped).
- Gaseous hydrogen at 700 bar in external over-wing tanks. Refuelling in 30 minutes.
- Acquired the assets of Universal Hydrogen after its 2024 closure.
- Part 25 certification with EASA special conditions. Service entry targeted for 2030.

ZeroAvia: the furthest along, and the most exposed

- 2020: six-seat Piper M on gaseous hydrogen, Cranfield.
- 2023: 19-seat Dornier 228 with the 600 kW ZA600 powertrain on one wing. Twelve flights, campaign ended April 2024.
- Late 2025: UK CAA Design Organisation Approval, the first for a hydrogen-electric powertrain developer.
- **March 2026**: FAA publishes special conditions for the 600 kW electric engine (ZA601), effective 18 March. The first regulatory text written for hydrogen-electric flight.
- July 2026: partnership with Safran.

Reality check, early 2026

- Workforce halved on funding constraints.
- Plan reset: certify the **fuel-cell system alone** in 2027. Full ZA600 powertrain 12 to 24 months later.
- ZA2000 (40 to 80 seats) slips to the early 2030s.
- No test flights for 12 to 18 months. Next Dornier 228 campaign early 2027.
- Fuel-cell production site near Glasgow still planned.

Lesson: certification pathways now exist. Capital is the scarce resource.

Source: FlightGlobal, Jan 2026; Runway Girl Network, Apr 2026; FAA Federal Register, Mar 2026.

H2FLY and Joby: liquid hydrogen in the air

H2FLY (Stuttgart, DLR spin-off, owned by Joby)

- HY4: four-seat fuel-cell aircraft, first flight 2016 on gaseous hydrogen.
- **September 2023**: first piloted flight on cryogenic liquid hydrogen, Maribor. One flight exceeded three hours. Range roughly doubled by the switch from gas to liquid.
- H2F-175 fuel-cell system: full power at altitude, designed for commercial use.
- Partners: Air Liquide, Pipistrel, DLR, EKPO.

Joby Aviation (California)

- June 2024: a converted battery eVTOL flew 523 miles (842 km) on liquid hydrogen, landing with 10 % fuel remaining.
- Tank of 40 kg LH_2 at 22 K, built by Joby. Fuel cell by H2FLY. Small battery for take-off and landing.
- Three times the range of the battery version, same airframe.

Significance

Liquid hydrogen has been handled, stored and flown in piloted and VTOL aircraft. The step from 175 kW to megawatts is engineering, not science.

Source: H2FLY, Sep 2023; Joby Aviation, Jul 2024.

North America: engine makers and NASA

Pratt & Whitney (RTX)

- **HySIITE**, ARPA-E funded: hydrogen combustion with steam injection and water recovery. Targets: NO_x down 80 %, fuel burn down 35 %. Rig tests met targets. Closed December 2024.
- **HyADES** (Canada, INSAT): PW127XT turboprop adapted to burn hydrogen. Study phase to 2026, demonstrator to follow.
- COCOLIH2T with EU Clean Aviation: onboard LH_2 storage.

GE Aerospace and CFM

- GE Passport converted to hydrogen for the Airbus A380 testbed. The flight test was cancelled with the ZEROe delay. Ground work continues.

NASA and universities

- CHEETA (Illinois, Boeing, GE): cryogenic LH_2 with superconducting electric propulsion.
- NASA Stennis hosted the Rolls-Royce hydrogen tests.

FAA

- Special conditions for the ZeroAvia engine, March 2026. A template for future applicants.

A warning from the market

Universal Hydrogen flew a Dash 8 on fuel cells in 2023, the largest fuel-cell aircraft to date. It closed in 2024. Policy headwinds in 2025 and 2026 have cut funding for several start-ups.

China: the first megawatt-class hydrogen turboprop flight

- **4 April 2026, Zhuzhou, Hunan.** The AECC **AEP100** hydrogen turboprop powered an unmanned cargo aircraft of about 7.5 t.
- Liquid hydrogen fuel, burned directly in the gas turbine.
- Flight profile: climb to about 300 m, 36 km flown at about 220 km/h, 16 minutes, stable throughout.
- Described by AECC as the world's first flight of a megawatt-class hydrogen-fuelled turboprop.
- AECC states that China now holds a "complete technological chain" from core components to full engine integration.

Why this matters

- Europe has run hydrogen turbines on the ground. China has flown one, with liquid hydrogen on board.
- The cargo-UAV route avoids passenger certification and lets the engine accumulate hours quickly.
- A combustion-first strategy, in contrast with the fuel-cell-first strategy of Airbus.

Source: Xinhua and AECC, Apr 2026; Hydrogen Insight, Apr 2026.

China: general aviation and uncrewed systems

Liaoning General Aviation Academy, Shenyang

- RX4E: four-seat battery-electric aircraft. CAAC type certificate under CCAR-23, 29 December 2024. China's first.
- **RX4HE**: the same airframe with a hydrogen *internal combustion* engine. Validation flight March 2023, prototype first flight 29 January 2024.
- Engine from FAW: turbocharged direct injection, 120 kW in test, thermal efficiency above 43 %. 4.5 kg of gaseous hydrogen. Cruise 180 km/h.
- A third hydrogen pathway: the piston engine for light aircraft.

AVIC Chengdu and Tsinghua University

- 50 kg fuel-cell sailplane UAV: 30-hour flight, April 2025, a national endurance record.
- March 2026: first flight of a "three-in-one" UAV combining solar cells, hydrogen fuel cells and lithium batteries.

Fuel-cell supply chain

- easyh2power (Tsinghua spin-off): first aviation 30 kW liquid-cooled stack with NWPU, 2020. Supplier to COMAC. New funding in 2026.

China: policy, industry structure and the low-altitude economy

- Hydrogen is written into national energy law. The Energy Law in force since January 2025 lists hydrogen among the energy sources to be developed.
- China is the world's largest hydrogen producer and the largest market for fuel-cell vehicles. Stack costs have fallen by an order of magnitude in a decade.
- The **low-altitude economy** is a national priority since 2024. Cargo UAVs, eVTOL and general aviation give hydrogen propulsion a certification-light entry market.
- State-owned champions cover the whole chain: AECC (engines), AVIC (airframes, UAVs), COMAC (airliners), CAS institutes (materials, cryogenics).

The Chinese pattern

1. Fly early on uncrewed platforms.
2. Use automotive fuel-cell cost curves.
3. Pursue combustion, fuel cells and hydrogen pistons in parallel.
4. Build the hydrogen supply first, then the aircraft.

Open questions

Crewed certification under CAAC rules; liquid hydrogen logistics at airports; integration into COMAC's future narrowbody plans.

Brazil and the rest of the world

Embraer: the Energia programme

- 2021: four concepts. 2022: focus on 19 and 30 seats, hybrid-electric and fuel-cell.
- 2024: scope widened to 50 seats with a **dual-fuel** Jet-A and hydrogen turbine option.
- November 2024: fuel-cell aircraft readiness moved from 2035 to "towards 2040".
- June 2026: fuel-cell rig tests starting. Zero-emission aviation is one of six innovation verticals. No programme launched.

Why Brazil matters for hydrogen aviation

- Over 85 % renewable electricity. Among the lowest green hydrogen costs forecast worldwide.
- Ethanol as a hydrogen carrier: reforming on the ground, or ethanol fuel cells. A route studied at RCGI.
- Embraer as the natural integrator for regional hydrogen aircraft.

Elsewhere

- Japan: Kawasaki liquid hydrogen tanks and supply chain; JAXA hydrogen combustor research.
- Korea: Hanwha and KAI fuel-cell UAV and eVTOL work.

Source: Aviation Week, Jun 2026; FlightGlobal, Nov 2024.

Brazil in the low-altitude economy: the Eve eVTOL, under certification



Click the picture to open the Eve Air Mobility video online. Image: Eve Air Mobility.

Video link (Bing Videos, Eve Air Mobility channel)

Eve Air Mobility (Embraer subsidiary)

- Lift-plus-cruise: eight fixed lift rotors on four booms, pusher for cruise, fixed high wing. Battery-electric, fly-by-wire. Four passengers plus pilot. Range about 100 km.
- Full-scale prototype first flew on 19 December 2025. Fifty flights by April 2026. Transition flights scheduled for late 2026.
- **Under certification with ANAC**, Brazil's civil aviation authority. Airworthiness criteria published. Six conforming prototypes for the campaign. Type certificate and entry into service targeted for **2028**.
- Final assembly at Taubaté, São Paulo state. Letters of intent for about 2,700 aircraft.

Link to this talk

Battery-electric today. Joby and H2FLY showed in 2024 what liquid hydrogen does to the range of the same airframe.

Sources: Eve Air Mobility press releases, Mar to May 2026; Aerospace Global News, 7 May 2026; evtol.news.

Brazil: hydrogen from ethanol, the USP pilot plant



The ethanol-to-hydrogen station at the USP campus bus terminal, São Paulo. Photo: RCGI-USP.

Why it matters for aviation

Ethanol is a liquid hydrogen carrier that already exists at scale in Brazil, and its network reaches every airport. A reformer of this size at a regional airport fuels a fleet of 19-seat hydrogen aircraft, with no hydrogen liquefaction or transport. This is our proposal for Brazil's entry into hydrogen aviation.

Sources: RCGI-USP and Jornal da USP, Feb 2025.

The first plant of its kind in the world

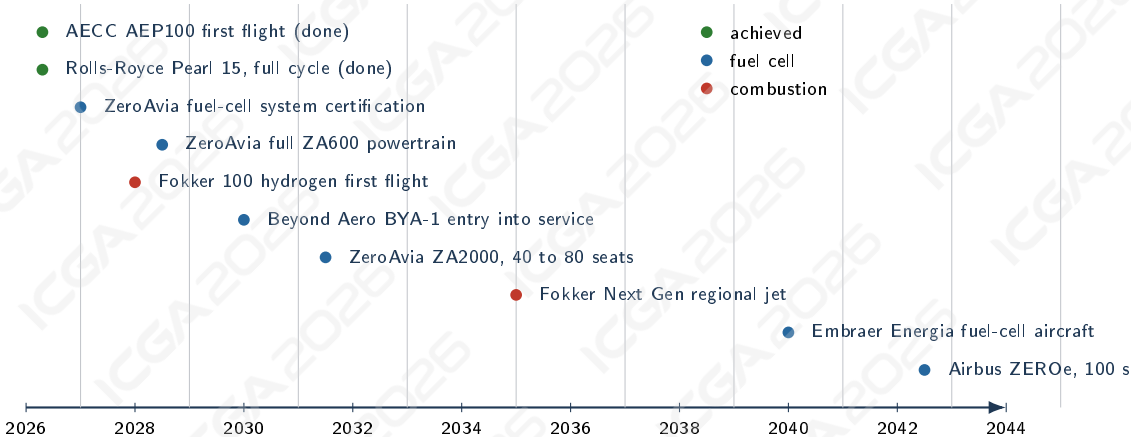
- Steam reforming of ethanol on the USP campus, São Paulo. Led by RCGI with Shell Brazil, Raízen, Hytron, SENAI CETIQT, Toyota, Hyundai, Marcopolo and EMTU. About R$ 50 million.
- Maximum capacity **100 kg of hydrogen per day**: three buses and two light vehicles in daily service on campus.
- Per kilogram of hydrogen: about **6.7 L of ethanol**, **30 L of water** and **2 kWh** of electricity. Electrolysis needs about 50 kWh. Here the energy comes from the ethanol, grown with sunlight.
- The CO_2 released is biogenic. With capture at the reformer the route becomes carbon-negative (BECCS).
- Tests began in February 2025, fuelling Toyota Mirai and Hyundai Nexo cars and fuel-cell buses.

Global comparison: who is doing what

Region	Actor	Pathway	Flagship hardware	Status (Oct 2026)
Europe	Airbus	Fuel cell, LH_2	1.2 MW FC engine; 100 seats	TRL 3, EIS 2040s
Europe	Rolls-Royce / easyJet	Combustion	Pearl 15 on 100 % H_2	Ground, full cycle
Europe	ZeroAvia	Fuel cell	ZA600 on Do 228	FC cert 2027
Europe	Beyond Aero	Fuel cell, GH_2	BYA-1, 8 seats	PDR, EIS 2030
Europe	Fokker Next Gen	Combustion, LH_2	Fokker 100 retrofit	Flight 2028
Europe	H2FLY / Joby	Fuel cell, LH_2	HY4; Joby eVTOL	Flown 2023 to 2024
N. America	Pratt & Whitney	Combustion	HySIITE; HyADES PW127XT	Rig; study
N. America	GE Aerospace	Combustion	Passport on H_2	Ground
China	AECC	Combustion, LH_2	AEP100 turboprop, 7.5 t UAV	**Flown Apr 2026**
China	LGAA / FAW	Piston ICE, GH_2	RX4HE, 4 seats	Flown 2024
China	AVIC / Tsinghua	Fuel cell	50 kg UAV, 30 h	Flown 2025
Brazil	Embraer	FC and dual fuel	Energia E19/E30	Rig 2026, EIS 2040

- Fuel cells lead in the West for products under 100 seats. Combustion leads in China and for the single aisle everywhere.
- Only three organisations have flown liquid hydrogen: H2FLY, Joby and AECC.

Timelines: stated targets, October 2026



- Every airliner-class target has slipped by five to ten years since 2022. Sub-20-seat products have held close to 2027 to 2030.
- China publishes few dates. Its hardware milestones have come earlier than announced.

The bottlenecks

Technology

- Fuel-cell system specific power: 1 kW/kg today, 2 to 3 kW/kg needed.
- Cryogenic tank gravimetric index: 0.3 today, 0.5 or more needed, with 20-year fatigue life.
- Heat rejection at low temperature, and compressor power at altitude.
- NO_x and flashback control in hydrogen combustors across the flight envelope.
- Cryogenic valves, pumps, sensors and connectors with aviation reliability.

System

- **Green hydrogen cost**: 4 to 8 USD/kg today. Parity with kerosene needs about 1.5 to 2 USD/kg, plus liquefaction at roughly 30 % of the fuel's own energy.
- **Airports**: liquefaction, storage, refuelling trucks or hydrants, turnaround times, safety distances.
- **Certification**: no complete rule set exists. Special conditions are written case by case (FAA for ZeroAvia, EASA for Beyond Aero).
- **Capital**: start-ups have halved staff. Policy support in the US and parts of Europe weakened in 2025 to 2026.

The propulsor is no longer the pacing item. The fuel and the tank are.

Non-CO_2 effects: water, contrails and NO_x

- Contrails and contrail cirrus cause roughly half of aviation's total climate forcing. Hydrogen does not remove this problem by itself.
- Hydrogen combustion emits about 2.6 times more water per unit energy than kerosene. Contrails form more easily and at lower altitudes.
- However, no soot. Ice crystals nucleate on far fewer particles. Crystals are larger, fewer and fall out faster. Model studies suggest a reduced net forcing, but the uncertainty is large.
- Fuel cells emit liquid water or vapour at low temperature. Condensing and retaining water on board is possible at a weight cost.

Research needs

- In-flight measurements behind a hydrogen engine. None exist yet at full scale.
- Combustor NO_x characterisation at cruise, not only at take-off.
- Operational avoidance: hydrogen aircraft may need contrail-aware routing more than kerosene aircraft.

Note

Zero CO_2 is necessary, not sufficient. The climate case for hydrogen rests on the full set of effects.

Economics: the fuel decides the date

- Kerosene at 0.7 USD/L holds about 35 MJ. Hydrogen at 2 USD/kg holds 120 MJ. Energy-parity price for hydrogen is therefore about 2.4 USD/kg, before liquefaction and distribution.
- Liquefaction costs 10 to 12 kWh per kilogram, close to a third of the hydrogen's own heating value. Large plants and cheap renewable power are essential.
- A regional airport serving 50 hydrogen turboprops a day needs some 20 to 30 t of LH_2 daily. That is one mid-sized liquefier.
- Airbus's stated reason for delay was exactly this: the ecosystem, not the aircraft.

Where hydrogen will be cheap first

- North-west China and Inner Mongolia (wind and solar at scale).
- North-east Brazil (wind, solar, hydro backing).
- Chile, Australia, the Gulf, Namibia.

Implication

Hydrogen aviation will start on **point-to-point regional routes** between hubs with cheap hydrogen, not on global networks. China and Brazil are both well placed.

Research at the BUGA Lab and RCGI

Beihang-USP Green Aviation Laboratory

- High-order spectral/hp simulation of hydrogen and ammonia combustion with Nektar++. Wavy and micromix burner geometries. Flashback and NO_x at the resolved scale.
- PEM fuel-cell modelling in Nektar++: multiphysics transport in channels and gas diffusion layers.
- **Topology optimisation** of fuel-cell flow fields and bipolar plates. Adjoint sensitivities for uniform reactant distribution and low pressure drop.
- Low-speed aerodynamics of hydrogen aircraft: stretched fuselages, aft tanks, radiator integration and eVTOL.

RCGI, University of São Paulo

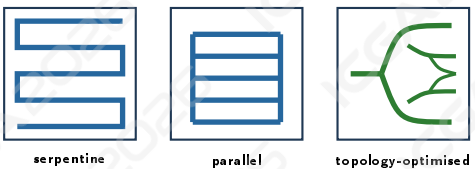
- Hydrogen production, storage and carriers, including ethanol reforming.
- Solid oxide and PEM fuel-cell programmes with topology-optimised components.
- Sustainable aviation fuel: joint laboratory with COMAC on SAF application.
- Carbon capture, greenhouse-gas accounting and policy.

A Brazil-China bridge

Joint graduate course on Sustainable Aviation, taught at Poli-USP, RCGI and Beihang Hangzhou. The new textbook grew out of this course.

Why the flow field decides the fuel cell's specific power

- Bipolar plates are 60 to 80 % of the stack mass. Their channel layout fixes three things at once:
  - **reactant distribution**, hence current-density uniformity and peak power;
  - **pressure drop**, hence compressor power at altitude;
  - **water removal** on the cathode, hence flooding.
- Serpentine, parallel and interdigitated layouts are hand-drawn compromises.
- Our approach: let the governing equations draw the layout. This is **topology optimisation** of the flow field.



Aviation stakes

Lower cathode pressure drop at equal power saves compressor mass and energy at cruise. A more uniform current density raises the usable power of a given stack mass. Both move the stack towards 2 to 3 kW/kg.

The multiphysics model behind the design

One set of equations for channel and porous electrode (Brinkman form)

$$\frac{\rho}{\epsilon}(\mathrm{u}\cdot\nabla)\frac{\mathrm{u}}{\epsilon} = -\nabla p + \nabla\cdot\Big[\tfrac{\mu}{\epsilon}\big(\nabla\mathrm{u} + \nabla\mathrm{u}^{\top}\big)\Big] - \Big(\tfrac{\mu}{\kappa} + \tfrac{Q_m}{\epsilon^2}\Big)\mathrm{u}$$

Species (Maxwell-Stefan): $\nabla\cdot(\rho\,\omega_i\,\mathrm{u} - \rho\,D_{ij}\nabla\omega_j) = S_i$
Charge: $\nabla\cdot(\sigma_{\mathrm{el}}\nabla\phi_{\mathrm{el}}) = -j, \qquad \nabla\cdot(\sigma_{\mathrm{ion}}\nabla\phi_{\mathrm{ion}}) = +j$
Kinetics (Butler-Volmer):
$j = j_0\Big[\exp\big(\tfrac{\alpha_a F\eta}{RT}\big) - \exp\big(-\tfrac{\alpha_c F\eta}{RT}\big)\Big]$

Design variable $\psi \in [0,1]$ enters the drag term:

$$f(\psi) = -\Big[\alpha_{\mathrm{ch}} + (\alpha_{\mathrm{solid}} - \alpha_{\mathrm{ch}})\frac{1-\psi}{1+q\psi}\Big]\mathrm{u}$$

$\psi = 1$: open channel. $\psi = 0$: solid rib. Diffusivities and conductivities are interpolated likewise.

Why one domain and one density field

- No remeshing. Channel and rib are the two limits of a single material law.
- The porous electrode (GDL, catalyst layer) uses the same Brinkman equation with its own κ and ϵ.
- The objective is physical: cell power, current-density uniformity, or a weighted log-sum of power and pressure drop.

Covered: SOFC (700 to 900 °C, gas-phase species) and PEMFC (60 to 90 °C, with water transport).

Topology optimisation: adjoint sensitivities and 2D design of a 3D cell

The cost problem

- Design variables: one per mesh cell, $N \sim 10^5$ to 10^7.
- Finite differences: N extra solves per iteration. Hopeless.
- **Adjoint method**: one extra linear solve gives $\mathrm{d}J/\mathrm{d}\theta$ for all N at once.

$$\frac{\mathrm{d}J}{\mathrm{d}\theta} = \frac{\partial J}{\partial \theta} + \boldsymbol{\lambda}^{\top}\frac{\partial R}{\partial \theta}, \qquad \left(\frac{\partial R}{\partial \mathrm{u}}\right)^{\top}\boldsymbol{\lambda} = -\left(\frac{\partial J}{\partial \mathrm{u}}\right)^{\top}$$

Regularisation

- Helmholtz filter: minimum channel width, no checkerboards. Heaviside projection: crisp 0/1 ribs that can be machined or printed.

Design-variable propagation (Gonçalves et al., 2024)

The designer controls a **two-dimensional** density $\theta(x, y)$ on the plate surface. An auxiliary field $\psi(x, y, z)$ is extruded through the channel depth by an anisotropic Helmholtz equation,

$$\nabla\cdot(-\mathrm{C}\nabla\psi) = 0, \quad \psi = \theta \text{ on } \Gamma_{\mathrm{top}}, \quad C_x = C_y \ll C_z.$$

The physics stays fully 3D; the design variables stay 2D. The chain $\theta \to \psi \to \mathrm{u} \to J$ is differentiated link by link by the adjoint.

Optimisation statement

$\max_\theta\ J = (1 - w_J)\log J_{\mathrm{power}} - w_J \log(w_R J_{\Delta p})$ subject to the multiphysics state, the propagation equation, a length-scale constraint and $0 \le \theta \le 1$.

Gonçalves, Sá, Lopes, Meneghini, Silva, SMO 67:216 (2024); Razmara, Sá, Prado, Lopes, Meneghini, Silva, SMO (2024).

Results: optimised channel layouts for SOFC and PEMFC

Insert figure:
optimised SOFC channel layout
(Gonçalves et al. 2024, SMO 67:216)
`figs/sofc_layout.png`

SOFC, 3D cell, 2D design

- Layouts emerge as branching networks, not serpentines. Channels split to feed the far corners of the plate.
- Against a parallel reference, the optimised design raises power and evens the current density at lower pressure drop.

Insert figure:
radial PEMFC flow field and water saturation
(Razmara et al. 2024, SMO)
`figs/pemfc_radial.png`

PEMFC, radial flow field, water management

- Radial cells feed at the centre and exhaust at the rim. The objective combines power with liquid-water removal from the cathode.
- The optimiser widens channels towards the rim, where water accumulates, and keeps fine ribs near the inlet.

Point for the aviation audience

The same adjoint machinery applies to any objective. For aircraft: **power per unit stack mass at cruise altitude**, with pressure drop charged at the compressor's cost.

Nektar++ for fuel cells: high-order multiphysics at BUGA Lab

Why a spectral/hp solver

- Nektar++ (Imperial College and partners): open-source spectral/hp element framework. Exponential convergence in the polynomial order P.
- Fuel cells are multiscale: a 200 µm gas-diffusion layer under a 1 mm channel. High order resolves thin layers cheaply.
- Clean adjoint sensitivities need an accurate primal.
- Azimuthal Fourier expansion for radial cells.

Programme at BUGA Lab and RCGI

1. PEMFC solver in Nektar++: Navier-Stokes and Brinkman flow, species, charge, Butler-Volmer kinetics, membrane water transport. Validated on polarisation curves. First paper in preparation (with H. Varela).
2. Aviation operating points: altitude pressure, cold start, load following.
3. Adjoint topology optimisation of the flow field in the same framework.
4. Shared infrastructure with the hydrogen and ammonia combustion solver for the Beihang swirl-burner experiments.

Open invitation. The codes are open. We welcome collaboration on test cases, validation data and aviation operating conditions.

Cantwell et al., Comput. Phys. Commun. 192 (2015); Karniadakis and Sherwin, Spectral/hp Element Methods for CFD (2005).

Outlook: what to expect by 2035

Likely

- Certified fuel-cell powertrains in 9 to 19-seat aircraft by 2028 to 2030.
- An 8-seat hydrogen business aircraft in service around 2030.
- Hydrogen cargo UAVs in routine operation in China before 2030.
- Liquid hydrogen flight demonstrators at megawatt scale in Europe, China and North America.

Unlikely before 2035

- A 100-seat hydrogen airliner in revenue service.
- Hydrogen combustion on a single-aisle jet in revenue service.
- A global hydrogen airport network.

Two strategies to watch

Europe: fuel cells first, combustion as a technology bank. China: fly combustion early on uncrewed platforms, build the fuel supply, then scale. The next five years will show which path reaches passengers first.

A new textbook: Low-Speed Aerodynamics and Sustainable Aviation



- **Springer Nature**, Springer Aerospace Technology series. Hardcover and eBook due **2 April 2027**. About 420 pages.
- Graduate textbook for a 36-hour course: half classical low-speed aerodynamics, half sustainable aviation.
- Developed at the Beihang-USP Green Aviation Laboratory. Worked examples, exercises and real-world cases.
- Scan the QR code to pre-order: `link.springer.com/book/9783032424594`

Central thesis of the book

Decarbonised flight is an energy problem. The range equation $R = (e^* \eta_{\mathrm{tot}}/g)(L/D)(m_{\mathrm{b}}/m)$ links aerodynamics, propulsion and the energy carrier in a single statement.

Inside the book: sixteen chapters in five parts

Part I. Foundations of Low-Speed Aerodynamics

- Aerodynamic fundamentals; governing equations
- Inviscid flow over airfoils; thin-airfoil theory
- Boundary layers, transition, turbulence
- Separated flows and vortex shedding

Part II. Flight and Aircraft Performance

- Finite wings, downwash, induced drag
- Flight envelope; range laws for jet, propeller, electric and fuel-cell aircraft
- Stability and flight dynamics

Part III. Propulsion

- Gas turbines and the energy baseline
- Electric and hybrid-electric propulsion

Part IV. Green Energy Carriers and Fuel Cells

- **Hydrogen and ethanol as aviation energy carriers**: production, liquefaction, cryogenic storage, combustion
- **Fuel cells for aviation**: PEM and SOFC, specific power, thermal management, altitude

Part V. Computational Design, eVTOL and Capstone

- Sensitivity analysis and topology optimisation of flow fields
- eVTOL and low-altitude aircraft design
- Capstone design project

For instructors: slides and a solutions manual accompany the book.

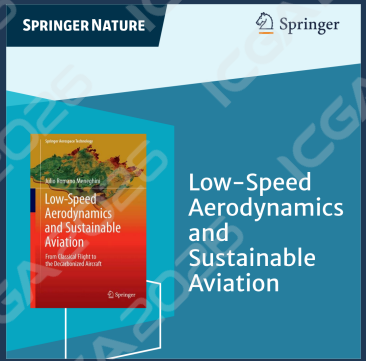
Thank you

Hydrogen propulsion has flown. The fuel, the tank and the rules now set the pace.

Julio Romano Meneghini
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Textbook: *Low-Speed Aerodynamics and Sustainable Aviation*, Springer, April 2027

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