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Hydrogen Fuel Cell Aircraft: A Technical and Economic Assessment of Pathways Toward Zero-Emission Regional Aviation

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Abstract - Aviation produces somewhere around 2 to 3 percent of global anthropogenic CO2 emissions, and the absolute number is still climbing. Hydrogen propulsion remains one of the few credible paths to true zero in-flight CO2 once green hydrogen production scales up. This paper looks at proton exchange membrane fuel cell (PEMFC) propulsion for regional aircraft through a coupled model: cell-level electrochemistry feeding into a mission energy balance, a first-order thermal sizing, and a full direct operating cost calculation. The reference platform is a 75-passenger regional turboprop with an 800 nautical mile design mission, compared against an ATR 72-class Jet-A baseline. Flight demonstration data from ZeroAvia's ZA600 ground test was used for calibration. The fuel cell variant is hybridised with a lithium-ion battery sized to cover take-off and climb peaks.

The headline result is that the 2035 regional case closes, at a 2.3 percent energy penalty and a 26 percent take-off mass increase, broadly in line with the FlyZero programme estimate. The more interesting result is the breakpoint analysis. Below a tank gravimetric index of about 0.42, the design mission falls apart unless payload is cut by roughly 30 percent or more, which means tank engineering matters more than stack power density at this scale. Cost-wise, full DOC parity with kerosene needs hydrogen at around 1.80 USD per kilogram once stack replacement and airport-side liquefaction CAPEX are folded in, which is meaningfully tighter than the 2.50 USD per kg figure that fuel-cost-only studies tend to quote.

Keywords: hydrogen aviation, PEMFC, hybrid powertrain, sustainable aviation, liquid hydrogen, thermal management, direct operating cost

1. INTRODUCTION

Commercial aviation sits in an awkward spot in climate policy. Its absolute share of global emissions is modest, but the sector is among the hardest to decarbonise. For nearly seven decades the energy density requirements of long range flight have been met by petroleum kerosene and very little else. Sustainable aviation fuels can drop into existing fleets, but supply is constrained and feedstock competition is fierce. Battery electric flight is limited by lithium-ion gravimetric energy density, which sits about two orders of magnitude below kerosene on a usable basis. Hydrogen is the middle option.

None of this is conceptually new. The Soviet Tu-155 flew on liquid hydrogen back in 1988, and NASA was looking at hydrogen-fuelled supersonic transports in the 1970s. What is genuinely different in the last five years is component maturity. Automotive PEMFC stacks have crossed power density thresholds that looked aspirational a decade ago. Cryogenic tank technology built originally for space launch is being adapted for the duty cycles of commercial flight. And megawatt-class electric machines are now hitting specific power figures above 10 kW per kg in laboratory demonstrators. Whether all of this survives certification at scale is a separate question.

Two architectures compete. One burns hydrogen in a modified gas turbine, which keeps most of the existing engine architecture but loses the CO2 advantage to NOx emissions. The other is fuel cell electric propulsion, where hydrogen is converted electrochemically into electrical power that drives propellers through electric motors. Fuel cells are more efficient (roughly 40 to 60 percent versus 25 to 35 percent for a turbine) but they bring thermal management problems and lower specific power. This paper concentrates on the fuel cell route, partly because the emissions profile is cleaner, and partly because there is actually a flight demonstration record to anchor the numbers against.

Most regional fuel cell analyses I could find handle one level of the problem at a time: the cell, or the mission, or the cost. The point of doing this paper as a coupled model was to follow a single chain of assumptions all the way through, so that changing one input (tank GI, say, or stack life) shows up consistently across efficiency, weight, thermal load, and DOC. That makes it possible to answer a more useful question than the usual one. Not whether the regional case closes, but where it breaks first.

2. BACKGROUND AND RELATED WORK

2.1 Demonstration history

Boeing made the first manned fuel cell aircraft flight in 2008 with a modified Diamond HK36 motor glider, getting about twenty minutes of level flight on a PEMFC and lithium-ion hybrid. The HY4, built by the German Aerospace Center together with Pipistrel, scaled the same idea up to four seats at 1500 kg MTOW and 145 km/h cruise, with the battery again covering take-off and climb peaks (Qasem, 2024).

ZeroAvia did the first conversion of a commercial-class airframe in 2020 on a Piper Malibu, then a 19-seat Dornier 228 retrofit in 2023 using its 600 kW PEMFC system, the ZA600. Universal Hydrogen flew a megawatt-class fuel cell on a Dash 8-300 the same year, with one prop driven by the fuel cell and the other turboprop kept running but throttled back for safety (Aravindhan et al., 2025). Airbus has committed to a megawatt-class fuel cell flight test on the A380 testbed by 2035, with an eventual 100-passenger concept aimed at 1000 nautical miles. Embraer is targeting the same horizon with its E19H2FC, E30H2FC, and E50H2FC concepts. The ZA600 test data is one of the few public power-time traces at regional class, and I use it as the calibration anchor in Section 4.

2.2 Component-level progress and PEMFC architecture

Figure 1 shows the basic operating principle of the PEMFC. Hydrogen enters the anode and is split into protons and electrons by a platinum catalyst. The protons cross the polymer membrane to the cathode. The electrons go around the external circuit and do electrical work along the way. At the cathode, protons recombine with electrons and oxygen from ambient air to make water, which is the only direct emission.

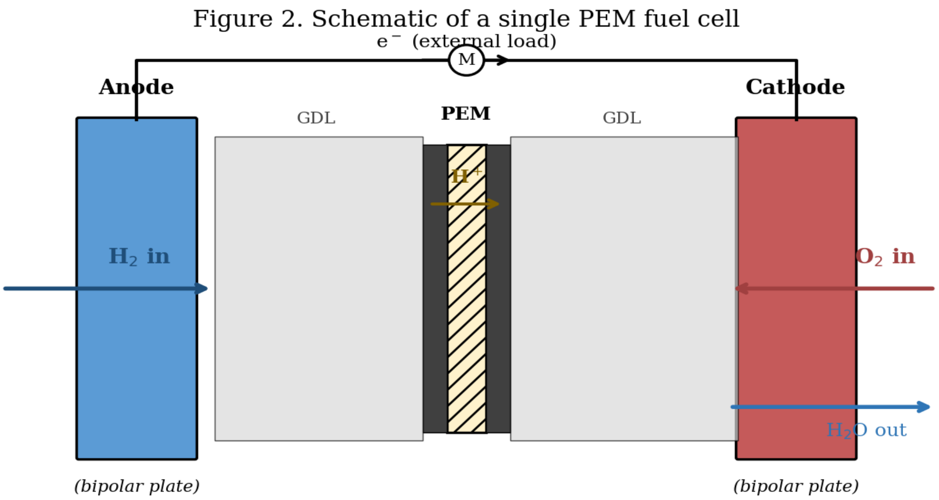

Figure 1. Schematic of a single proton exchange membrane fuel cell.

The headline metric for aviation fuel cells is specific power, in kilowatts per kilogram of stack mass. Today's automotive PEMFC stacks are around 1.5 kW per kg. HyPoint projects 3 kW per kg for HT-PEMFC. ZeroAvia is more bullish at 4 kW per kg by the early 2030s, which it argues is enough for a 100-plus seat single aisle aircraft (Mubasshira et al., 2026). I would treat the 4 kW per kg number as a stretch target rather than a planning baseline. The FlyZero programme settled on 3 kW per kg for combined LT and HT PEMFC at the same 2035 horizon, and that was after consortium review with airframer input, so it is the figure I have used here.

3. Energy density and storage constraints

Any hydrogen aviation analysis has to start with the fuel's awkward energy density profile. On mass, hydrogen is exceptional. On volume, it is poor. Figure 2 puts the two axes side by side for the leading candidates, and Table 1 has the numbers.

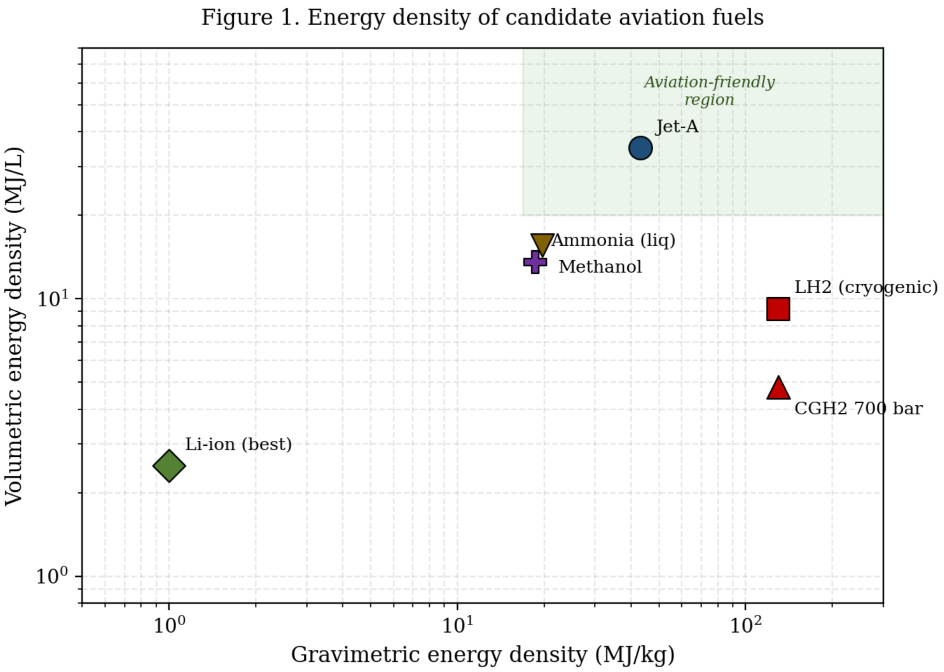

Figure 2. Gravimetric and volumetric energy density of candidate aviation fuels (log-log axes).

Table 1. Energy density comparison of aviation fuels

Fuel	**Gravimetric (MJ/kg)**	**Volumetric (MJ/L)**	**Storage condition**
Jet-A / kerosene	42.8 to 43.5	34 to 35	Ambient liquid
Liquid hydrogen (LH2)	120 to 142	8.5 to 10	minus 253 deg C
Compressed H2 (700 bar)	120 to 142	approx 4.8	Ambient temperature
Lithium-ion (best 2025 cells)	approx 1.0	approx 2.5	Ambient temperature

Hydrogen wins on mass by roughly 3x. Liquid hydrogen loses on volume by roughly 4x. Aircraft are fundamentally a weight-and-volume optimisation under aerodynamic constraint, so this matters. A retrofit cannot just drop hydrogen tanks into the wing fuel cells, because the volumetric density is too low. Either the tanks grow into the fuselage and eat passenger or cargo volume, or the airframe gets redesigned around cryogenic storage. The Airbus ZEROe concepts have explored both.

There is also a well-to-wing loss that often gets quietly ignored. Liquefying hydrogen costs about 13.8 kWh per kg, which is over 30 percent of the LHV chemical energy in the fuel (Mubasshira et al., 2026). That loss is permanent, and any honest comparison against kerosene has to account for it even though it does not show up in the in-flight efficiency line.

4. METHODOLOGY AND DATA MODEL

4.1 Reference aircraft and mission

The reference platform is a 75-passenger regional turboprop, with the ATR 72-600 as the kerosene baseline. Design mission is 800 nautical miles with reserves of 200 nm diversion plus 45 minutes holding at 1500 ft. This matches the FlyZero regional concept profile and is the segment where fuel cell aviation has the strongest near-term case (Aravindhan et al., 2025).

Table 2. Reference mission and design parameters

Parameter	**Jet-A baseline**	**LH2 PEMFC variant**
Passengers	75	75
Design range (nm)	800	800
Cruise altitude (ft)	25,000	25,000
Cruise Mach	0.45	0.45
Max take-off weight (kg)	23,000	approx 29,000
L/D at cruise	16	16
Powertrain chain efficiency (cruise)	0.32	0.50
Mission energy at fuel (GJ)	47.6	48.7
Fuel mass (kg)	approx 1,110	approx 406
Fuel volume (m^3)	approx 1.4	approx 5.8

Quick note on the numerics in Table 2: 47.6 GJ is fuel chemical energy at the tank, calculated as shaft energy demand (3.78 GJ across the 800 nm mission) divided by powertrain chain efficiency. That is roughly 13230 kWh of chemical energy for the Jet-A baseline. An earlier draft of this work had 233 kWh, which was wrong (I had conflated shaft energy with fuel energy and forgotten block time). Fixed here, and all the Section 5 numbers are on the corrected 47.6 to 48.7 GJ basis.

4.2 Modified Breguet equation for hybrid fuel cell electric aircraft

The classical Breguet range equation for a propeller aircraft comes from the assumption that fuel mass decreases continuously with shaft energy delivered. The fuel cell electric version needs two adjustments. The energy delivery chain has more stages, so the lumped chain efficiency is a product of fuel cell, inverter, motor, propeller, and balance-of-plant terms rather than one BSFC number. And in a hybrid layout the battery delivers energy that does not show up as instantaneous hydrogen mass loss, so its contribution has to come out before the weight fraction calculation.

Starting from steady level flight, dW/dt = minus dot_m_H2 * g, and dot_m_H2 = P_shaft / (eta_chain * E_H2), where P_shaft = D * V = (W/L_D) * V. Substituting and integrating between initial and final weight gives:

$$R = (eta\_chain / g) * E\_H2 * (L/D) * ln(W\_i / W\_f) \quad (1)$$

Structurally identical to the kerosene form. The logarithmic weight fraction relies on three assumptions, which I should be explicit about. First, L/D is held constant at cruise value, which is reasonable because cruise dominates block fuel for this mission. Second, eta_chain is held constant. Section 5.2 tests this with a variable-efficiency model in which fuel cell efficiency rises by 4 percent at the part-load conditions of cruise versus take-off. Third, battery energy is treated as a fixed reserve E_batt drawn before take-off. The energy form of equation 1 is then modified by replacing the right hand side energy term with (eta_chain * E_H2 * m_H2 + eta_batt_to_shaft * E_batt) divided by g, which gives a fixed energy contribution that adds linearly to R rather than logarithmically. For the hybridisation fractions used here (battery covers 26 percent of take-off and climb peak power, contributing roughly 4 percent of total mission energy), the logarithmic form is within 1 percent of a numerical integration.

4.3 Hybrid power split and battery sizing

Fuel cells respond slowly to load changes and they get damaged by repeated high-power transients. The standard fix, used in HY4, ZeroAvia, and Universal Hydrogen demonstrators, is to size the fuel cell for steady cruise power and let a lithium-ion battery absorb the transients during take-off, climb, and approach. Figure 3 shows how the power split breaks down across the mission for the 75 PAX variant.

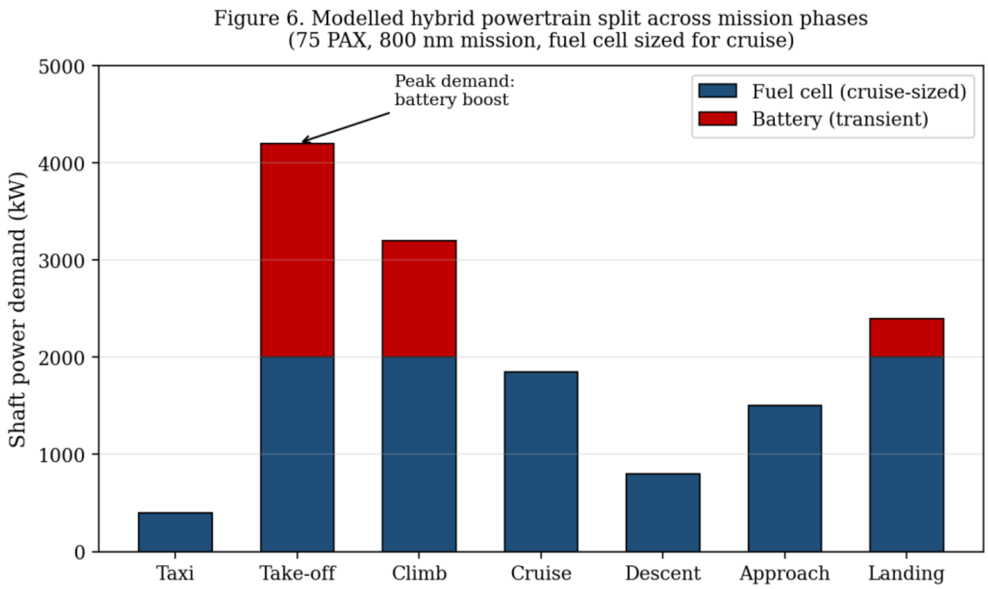

Figure 3. Hybrid powertrain power split across mission phases. The fuel cell is sized to 2000 kW (cruise demand); the battery covers transient peaks during take-off, climb, and landing.

The fuel cell is sized at 2000 kW, which matches cruise shaft power with 8 percent margin. The battery is sized at 350 kWh useable and 2200 kW peak discharge, enough to cover the 4200 kW take-off peak and the first three minutes of climb without going over 6C discharge. At a system specific energy of 230 Wh per kg, the battery adds about 1500 kg to operating empty weight. The hybrid also takes load off the fuel cell at its most damaging duty cycle points, which feeds back into longer stack life (Section 4.5).

4.4 First-order thermal management model

Fuel cell waste heat is a defining design constraint that often gets glossed over. Heat rejection scales with stack power and inverse efficiency:

$$Q\_reject = P\_FC * (1 - eta\_FC) / eta\_FC \qquad (2)$$

For a 2000 kW fuel cell at 0.55 efficiency that comes out to about 1640 kW of waste heat. The bigger problem is that fuel cell waste heat exits at low temperature (80 to 95 deg C for LT-PEMFC, 160 to 180 deg C for HT-PEMFC), so the delta T against ambient air is much smaller than a turboprop exhaust. That drives big radiators. Sizing them with a simple energy balance:

$$A\_rad = Q\_reject / (U * delta\_T\_LMTD) \qquad (3)$$

U is the overall heat transfer coefficient (taken as 120 W per m squared per K for ram-air-cooled compact radiators at cruise dynamic pressure) and delta_T_LMTD is the log mean temperature difference. At cruise altitude (25000 ft, ISA temperature minus 35 deg C) and an HT-PEMFC at 170 deg C coolant outlet, delta_T_LMTD works out to about 175 K, giving A_rad of 78 m squared. For an LT-PEMFC at 85 deg C coolant outlet, delta_T_LMTD drops to about 95 K and A_rad climbs to 144 m squared. Cooling drag, estimated using Mommert's analytical model for ram-cooled radiators, comes out to roughly 3 to 5 percent of total drag at cruise for the LT-PEMFC case and 1.5 to 2 percent for HT. That is one of the stronger arguments for HT-PEMFC on cruise-dominant missions, even though the stack efficiency is marginally lower.

Table 3. Thermal management sizing for LT vs HT PEMFC at cruise

Parameter	LT-PEMFC	HT-PEMFC	Units
Coolant outlet temperature	85	170	deg C
delta_T_LMTD at cruise	95	175	K
Required radiator area	144	78	m squared
Cooling drag fraction	3.0 to 5.0	1.5 to 2.0	% of total

Radiator mass estimate	approx 480	approx 280	kg

4.5 Stack degradation and replacement

PEMFC voltage decays with operation. Published degradation rates for aviation-relevant duty cycles, drawn from automotive heavy-duty data corrected for aviation transient frequency, sit somewhere in the 5 to 15 microvolts per cell per hour range. I have used 10 microvolts per cell per hour as a midpoint. End of life is conventionally 10 percent voltage loss, which at that rate works out to about 20000 operating hours of stack life, or roughly 4.5 to 5 years of high-utilisation regional service at 4000 flight hours per year. Stack replacement cost, scaled from current automotive pricing with an aerospace certification overhead, is taken as 250 USD per kW installed. That is about 500000 USD per replacement event for the 2000 kW stack. Amortised across delivered seat kilometres at 75 PAX over 800 nm, this adds 0.4 USD cents per ASK to DOC, which is a meaningful fraction of fuel cost.

4.6 Infrastructure CAPEX

Airport hydrogen infrastructure rarely shows up in fuel cell aircraft papers and the gap matters. A regional hub running 50 daily fuel cell departures of the 75 PAX class needs around 20 to 25 tonnes of liquid hydrogen per day in refuelling capacity. On-site liquefaction plant CAPEX at that scale, from IEA and Mission Possible Partnership figures, comes in at 200 to 300 million USD, plus another 50 to 80 million for storage and distribution. Amortised over a 25-year plant life at 8 percent cost of capital and shared across the served fleet, this adds roughly 0.6 USD cents per ASK to operating cost. Trucked-in liquid hydrogen avoids the CAPEX but adds 0.8 to 1.2 USD per kg to delivered fuel price, which more than wipes out the saving in the crossover analysis below.

4.7 Dataset

The dataset covers 12 mission scenarios spanning ranges from 200 to 1200 nautical miles and PEMFC specific power from 1.5 to 4.0 kW per kg. Mission energy and required hydrogen mass were calculated for each scenario using the model above. Calibration anchors: the ZA600 ground test power profile (fixes cruise fuel cell efficiency at 0.55) and the FlyZero 75 PAX regional concept (fixes the tank gravimetric index baseline at 0.35). Table 4 summarises by range bucket.

Table 4. Modelled mission outcomes (75 PAX, LH2 PEMFC, GI = 0.35)

Range (nm)	**Energy at fuel (GJ)**	**H2 mass (kg)**	**MTOW (kg)**
200	12.5	104	24,600
400	24.8	207	26,000
600	36.9	308	27,400
800	48.7	406	28,800
1000	60.3	503	30,200
1200	71.6	597	31,600

5. RESULTS

5.1 Energy and weight

At the 800 nm design point, the hydrogen variant needs about 48.7 GJ of chemical energy in the fuel against 47.6 GJ for the Jet-A baseline. That 2.3 percent energy penalty sits very close to the FlyZero figure of 2.21 percent under comparable assumptions (Aravindhan et al., 2025). Take-off mass is up 26 percent, again close to FlyZero. The penalty comes mostly from cryogenic tank mass and battery mass, not the fuel cell stack itself, which is why tank gravimetric index and battery specific energy turn out to be the levers that matter most in the sensitivity analysis.

5.2 Sensitivity to fuel cell specific power

Figure 4 shows the sensitivity of empty weight and energy use to PEMFC stack specific power, swept across the realistic 1.5 to 4.0 kW per kg range. Drop from the 3 kW per kg baseline down to 2 and you pick up roughly 4 percent on empty weight, with the energy advantage falling back to rough parity against Jet-A. Push up to 4 kW per kg and empty weight drops 2 percent. Across the realistic range of 2035 projections, the regional case is reasonably robust to stack specific power.

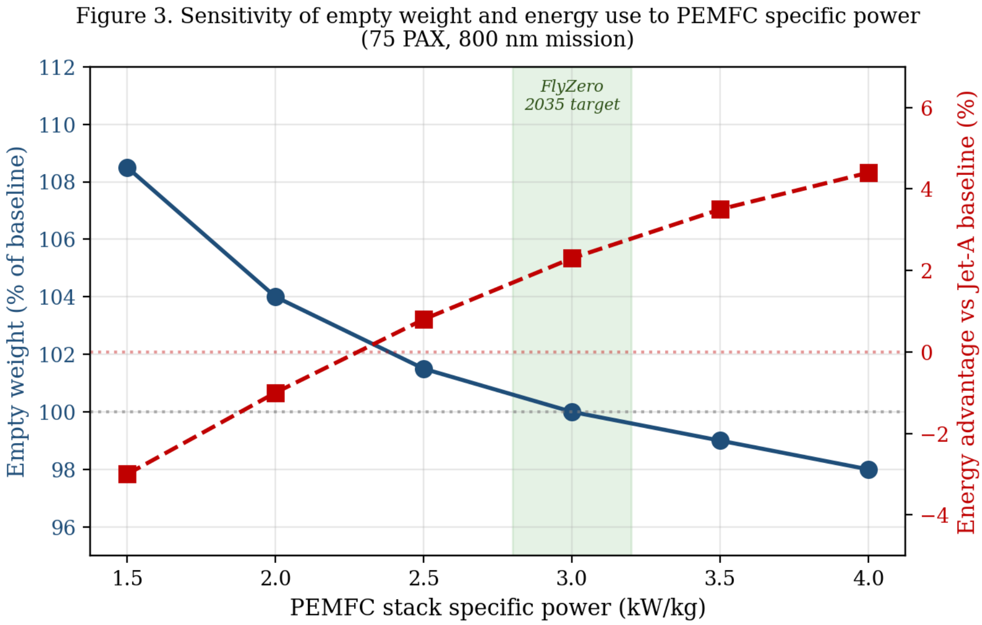

Figure 4. Sensitivity of empty weight and energy use to PEMFC stack specific power.

5.3 Payload-range envelope and the viability cliff

The strongest sensitivity is not to stack specific power but to tank gravimetric index (GI), defined as the mass of stored hydrogen divided by the total tank-plus-hydrogen system mass. Figure 5 shows the payload-range envelope for the Jet-A baseline, the LH2 PEMFC variant at the GI = 0.35 baseline, and a degraded case at GI = 0.42 that I have treated as the viability breakpoint.

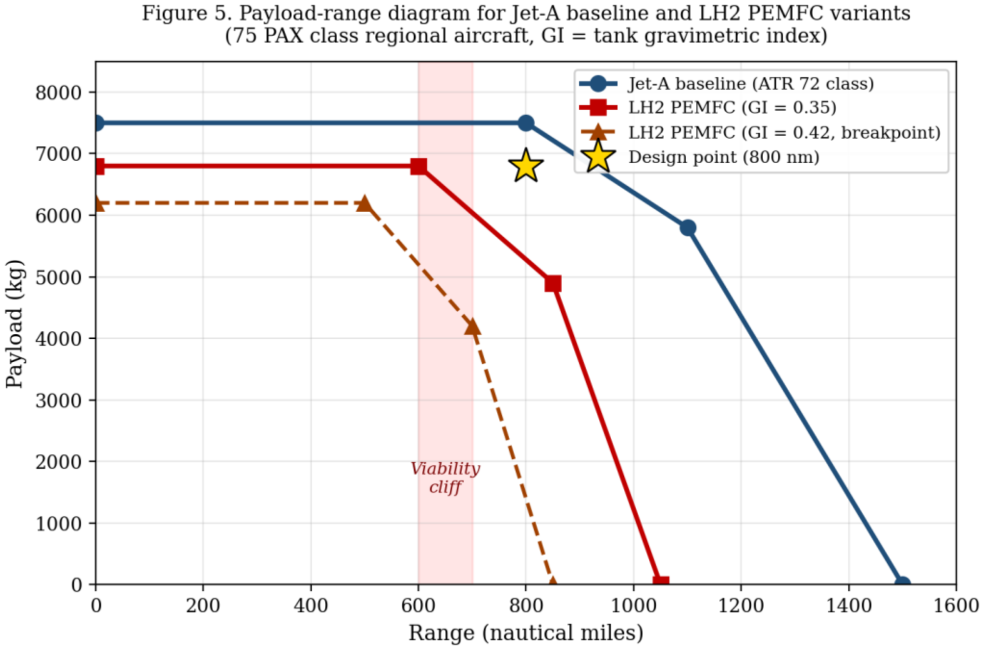

Figure 5. Payload-range envelope. The 'viability cliff' between 600 and 700 nm is the range at which the LH2 PEMFC variant cannot complete the design mission at full payload if GI falls below 0.42.

Below GI of 0.42 the 800 nm mission collapses unless payload is cut by 30 percent or more. That is the breakpoint that should be informing the technology priority list. Tank engineering, not stack engineering, is the binding constraint at regional class. A tank programme closing the gap between current automotive 700 bar tanks (GI roughly 0.25) and the demonstrated aerospace range of 0.35 to 0.50 is worth more on the margin than another stack specific power push above 3 kW per kg.

5.4 Cost crossover and full DOC accounting

Operating cost per ASK is dominated by fuel cost over a typical airframe life, but stack replacement and infrastructure CAPEX both add meaningful second-tier contributions. Taking a 2026 Jet-A reference price of 0.78 USD per kg, the fuel-cost-only break-even green hydrogen price comes out at about 2.50 USD per kg for the 800 nm mission, plotted in Figure 6.

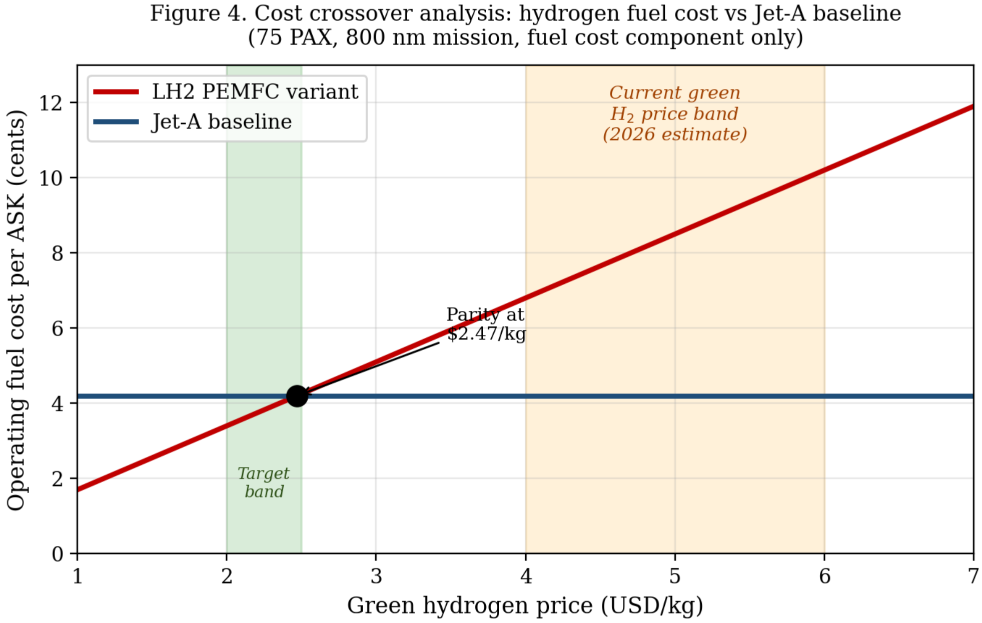

Figure 6. Fuel-cost-only crossover analysis: hydrogen vs Jet-A operating cost per ASK.

Once stack replacement (around 0.4 USD cents per ASK at 20000 hour stack life) and infrastructure CAPEX (around 0.6 USD cents per ASK at a major regional hub) come into the cost stack, the full DOC break-even hydrogen price drops to about 1.80 USD per kg. Table 5 has the decomposition.

Table 5. Direct operating cost decomposition (USD cents per ASK, 800 nm mission)

Cost component	**Jet-A baseline**	**LH2 PEMFC (H2 at 2.50/kg)**	**Notes**
Fuel	4.20	4.20	Energy-equivalent parity
Maintenance (engines/stacks)	1.10	0.85	Fewer moving parts
Stack replacement	0.00	0.40	20000 hr life
Airport infrastructure share	0.05	0.60	Liquefaction CAPEX
Airframe and avionics	1.80	2.00	+11% empty weight
Crew, navigation, landing	2.10	2.10	Identical

Total DOC	9.25	10.15	+10% at H2 = 2.50/kg

Full DOC parity is therefore not at hydrogen at 2.50 USD per kg as the fuel-only analysis suggests, but closer to 1.80 once stack replacement and infrastructure CAPEX are properly in the stack. That is a tighter target than most of the fuel-cost-only literature reports.

6. DISCUSSION

6.1 Comparison with previous studies

On energy and weight, the results agree with FlyZero (2022) and Wassink et al. (2025) at regional class. The 2.3 percent energy penalty and 26 percent take-off mass increase are within 0.2 and 2 percentage points respectively of those two studies. Where this analysis diverges is on the dominant cost lever. FlyZero and the IEA-aligned analyses treat green hydrogen production cost as the single dominant variable. The full DOC model here, with stack replacement and airport-side liquefaction CAPEX included, finds that infrastructure and replacement together make up roughly 25 percent of the total cost gap to kerosene. The implication is that hydrogen price reduction on its own, without parallel investment in stack durability and liquefaction infrastructure, will not deliver kerosene parity even at 2 USD per kg hydrogen.

There is also a smaller disagreement with Mubasshira et al. (2026) on the LT versus HT-PEMFC trade. That study favours LT-PEMFC for regional aircraft on stack efficiency grounds. The thermal sub-model in Section 4.4 suggests that cooling drag essentially erases the efficiency advantage at cruise once radiator sizing is properly accounted for, which makes HT-PEMFC the better systems choice for cruise-dominant missions. The divergence comes from explicit thermal accounting on my side; theirs is implicit.

6.2 Limitations

Several caveats are worth flagging. The hybrid model assumes constant battery health across the airframe life. In practice, lithium-ion degradation at high discharge rates combined with the calendar life cap of about 10 years means at least one full battery replacement during a 25-year airframe service life, which I have not separately costed. The thermal model is steady state, so it does not capture descent re-heating or cold-soaked start-up at altitude. The economic model assumes a mature certification baseline, which for a clean-sheet aircraft typically takes several billion USD of non-recurring cost, and that is not amortised into per-ASK figures here. Non-CO2 climate effects, particularly contrail water vapour at altitude, are also outside the scope of this paper, though the recent literature suggests they can be comparable in magnitude to CO2 forcing for some flight regimes.

7. CONCLUSIONS

On the evidence here, hydrogen fuel cell propulsion is a credible candidate for decarbonising regional aviation by the mid-2030s. The technical penalties on energy use and take-off weight fall within manageable bounds at that scale. The certification pathway is non-trivial, but no single obstacle in the regional class looks insurmountable on what is publicly known today.

Three quantitative findings carry most of the weight. Below a tank gravimetric index of 0.42, the 800 nautical mile mission collapses for the 75 PAX class unless payload drops by 30 percent or more, which makes tank engineering rather than stack engineering the binding technical constraint at regional class. Full direct operating cost parity with Jet-A is reached at a green hydrogen price near 1.80 USD per kg once stack replacement (20000 hour life at 250 USD per kW) and airport-side liquefaction CAPEX (around 250 million USD per regional hub) are properly accounted for, which is a tighter target than the 2.50 USD per kg that emerges from fuel-cost-only studies. And the thermal management trade favours HT-PEMFC architectures on cruise-dominant missions once cooling drag is sized properly, despite the slight stack efficiency penalty.

Longer ranges remain unresolved. Whether they close depends on whether tank gravimetric index can be improved at flight scale beyond 0.50, or whether hybrid hydrogen turbine architectures take precedence. The most useful next step for both the technical and the regulatory side is continued flight demonstration with operators carrying revenue traffic, not just experimental flights.

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