ZEROAVIA

SCALING HYDROGEN–ELECTRIC PROPULSION FOR LARGE AIRCRAFT

WHITEPAPER

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Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), hopes of limiting global climate change below 1.5 degrees Celsius before the end of the century are fading fast. Where have things gone wrong? With 140 countries signed up to net-zero goals, covering about 88 percent of global emissions, shouldn't we be on track?

In recent times, we have seen both huge commitments to spending on the green transition, and signs of some governments reversing commitments as tougher economic conditions bite on voters. The IPCC has also made clear that steep reductions in carbon emissions are needed this decade, as well as post-2030.

Aviation is in a precarious spot. Attractive solutions, including hydrogen-electric propulsion, are emerging to tackle the full climate impact of smaller aircraft. ZeroAvia plans to have the first commercial aircraft — between 10–20 seats — flying with its ZA600 engines as early as 2025. The company has also started working on a more powerful engine, the ZA2000, for 40–80 seat aircraft. But if we are to solve aviation's climate problem, we will need far-reaching solutions that strike at the bulk of flight emissions — those produced by large commercial jets.

Even to make the leap between Part 23 and Part 25 aircraft (the smaller and larger certification categories for these aircraft), some significant engineering challenges need to be overcome. Powering 40+ seat aircraft with true-zero emission, hydrogen-electric engines is not possible without improving specific power (the amount of power delivered per unit of mass of the engine) and improving fuel storage efficiency in terms of both mass and volume of hydrogen (i.e. by shifting from gas to liquid hydrogen). So far, no certified airframe has flown using liquid hydrogen.

This paper sets out a pathway for scaling hydrogen-electric engines into larger regional turboprops, regional jets and narrowbody aircraft. Accomplishing this goal would tackle the majority of emissions in aviation while improving economics so that flight can continue to grow and connect more of the world.

While sub-100 seat flights represent ~20% of global flights, they represent only 6% of global CO2 emissions.[1] Can hydrogen-electric engines — using fuel cells and hydrogen fuel to create electricity and power electric motors, with just water vapour emissions — power narrowbody aircraft like the Boeing 737 or Airbus A320 families, and thus tackle more than half of the global aviation industry's greenhouse gas contribution? Or is our only option to rely on combustion of either sustainable aviation fuel (SAF) or hydrogen? Or is there a place for hybrid-hydrogen engines, combining fuel cells and combustion engines?

It is no secret, ZeroAvia's view is that every commercial aircraft can eventually be fuel cell-powered. The company is pursuing hydrogen-electric propulsion for all aircraft types and sizes.

It is the farthest-reaching green solution, fully tackling CO2, NOx, particulate matter and other non-CO2 emission. Hydrogen-electric also brings the additional benefits of maintaining air quality at airports, reducing aircraft engine noise for residents, and offering operators improved economics.[2] The rapid pace of engine development for regional aircraft has taken many industry players by surprise, with few anticipating prototype systems flying 10+ seat aircraft by now, as well as active certification applications underway in commercially relevant segments.

ZeroAvia's confidence in the technology is based on our:

- in-depth analysis of fuel cell and electrification technology trends
- technology development roadmap that charts the innovations that will deliver the required performance
- validation of the feasibility of these solutions through the regional jet segment with our OEM partners[3]

But we don't have all the answers, and there is more research and technology development to be done. The learnings of two world-first flight test campaigns are a reminder that every development we make will change how we think about the future's larger aircraft.

This paper seeks to stimulate industry debate by investigating the technological requirements and feasibility of fuel cell propulsion above the imminent entry in service for sub-20 seat aircraft, right through to narrowbody, single aisle aircraft like Airbus' A220 through to the A320 class and Boeing's B737 family.

We welcome all feedback, inputs and challenges to the ideas presented herein. Further, we understand that the specific power and volume requirements for hydrogen-electric powered narrowbody aircraft look challenging with present day performance and components. But where jet power has benefited from 80 years of continuous R&D, hydrogen-electric power in aviation is just getting started. With time and effort, the trajectory and potential of fuel cell systems and cryogenic hydrogen storage looks promising.

In 1903 the New York Times wrote that man was a million years away from powered flight, just a few weeks before the Wright brothers made history at Kitty Hawk, NC. If we have the vision and a starting point, we will deliver the change that can enable the industry to grow and deliver on net-zero promises targeting 2050.

This white paper seeks to provide that starting point and to create debate that will spur on both ourselves and other innovators, and help airlines, OEMs, lessors, airports and government agencies plan for a clean flight future.

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[1] ICCT — CO2 Emissions from Commercial Aviation https://theicct.org/wp-content/uploads/2021/06/CO2-commercial-aviation-oct2020.pdf

[2] https://zeroavia.com/wp-content/uploads/2023/03/Zero_Avia_A4_Brochure_DIGITAL-2022-11-28.pdf

[3] ZeroAvia News—MHIRJ technical study — https://zeroavia.com/mhirj-initial-technical-study/

Section One: Large Regional Turboprops

The regional turboprop market (40–80 seat aircraft) is an important target for two big reasons.

Firstly, it has potential for a renaissance based on the cleaner, more cost-efficient operations that fuel cell propulsion can offer. Regional turboprops are recognised for their relatively good fuel efficiency in spite of no major new clean sheet airframe design for nearly half a century. Retrofit of electric propulsion systems in existing designs can improve the economics of regional turboprops, and catalyze development of entirely new designs specifically for zero-emission propulsion systems.

Secondly, many of the underlying technologies that will power future larger aircraft will be first put to work in the regional turboprop segment. This makes it a critical breeding ground for innovation and learning right across the aviation industry ahead of delivering larger, more complex and more costly zero-emission jet aircraft of similar and larger sizes.

Innovators have made incredible advances to make existing fuel cell transportation technology aerospace-worthy and ready for flight. Low-temperature fuel cells can deliver sufficient specific power for commercial operations of sub-20 seat aircraft. Gaseous hydrogen, with clever engineering, can be stored in sufficient quantities to enable up to 300NM routes, tackling more than 95% of routes operated by these aircraft.[4]

However, higher-temperature fuel cells, space- and weight-saving liquid hydrogen fuel storage and advanced electric motor and inverter technology are needed to offer commercially relevant performance for larger regional aircraft in the 30–90 seat category. These are at a lower technological maturity, but they are the underlying technologies that can scale to support narrowbody aircraft.

In its own right, the 40–80 seat regional turboprop segment is an important market. There are approximately 6,000 of these aircraft in service or storage around the world today, with flight operations on 5,800 unique routes. This represents 170 million seat movements per annum.

Tackling totals emissions across the entire segment would represent a 171.5 Mt CO2e saving, equivalent to the annual emissions of The Netherlands. As we will see in Section Three, this is dwarfed by the CO2e emissions impact of narrowbody aircraft, but this market is the critical stepping stone to maturing the technologies which will ultimately solve the challenge in this segment. By contrast, sustainable aviation fuel (SAF) will only be able to offer a sliver of the required reductions.

The shortest commercial route in this aircraft segment is 10NM, and the longest regularly operated routes is ~950NM. ATR 72 and Dash 8-400 have a full passenger capacity (PAX) range in excess of 800NM, yet over 90% of routes flown are less than 400NM, allowing room for a reduction in operating range with a switch to hydrogen fuel.

Regional turboprops represent 8% of global flights, but, according to analysis by NASA, the improved operating costs offered by zero-emission propulsion could stimulate a big uptick in demand for retrofit and linefit aircraft.

Propulsion innovators have promised entry in service within the next five years, so how can the technology be ready to address this segment?

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[4] ZeroAvia analysis of Cirium market data based upon ZA600 designs.

System Requirements and Technology Pathways

Hydrogen Storage

As is well documented, hydrogen is a significantly better fuel than kerosene in terms of gravimetric energy density, but far poorer when it comes to volumetric energy density (see figure below[5]).

For small aircraft systems, around 60–70kg of gaseous hydrogen at 350 bar will need to be stored to support up to 300NM range. These Hydrogen Management Systems will weigh around 450kg when empty. Here, the systems will be similar to the large cylindrical tanks currently used in heavy duty road applications. These gaseous storage tanks can offer up to 12% mass efficiency within the next 3–4 years, possibly extending to ~14% thereafter.

To support an 80-seat turboprop over 500NM, around 600kg of gaseous hydrogen would be needed, requiring more than 30% of the fuselage to be dedicated to fuel storage. The system would also effectively weigh 4,300kg, impractical for flying these aircraft commercially.

Storage of hydrogen as a liquid increases its volumetric density, and is therefore essential for 30+ seat applications.

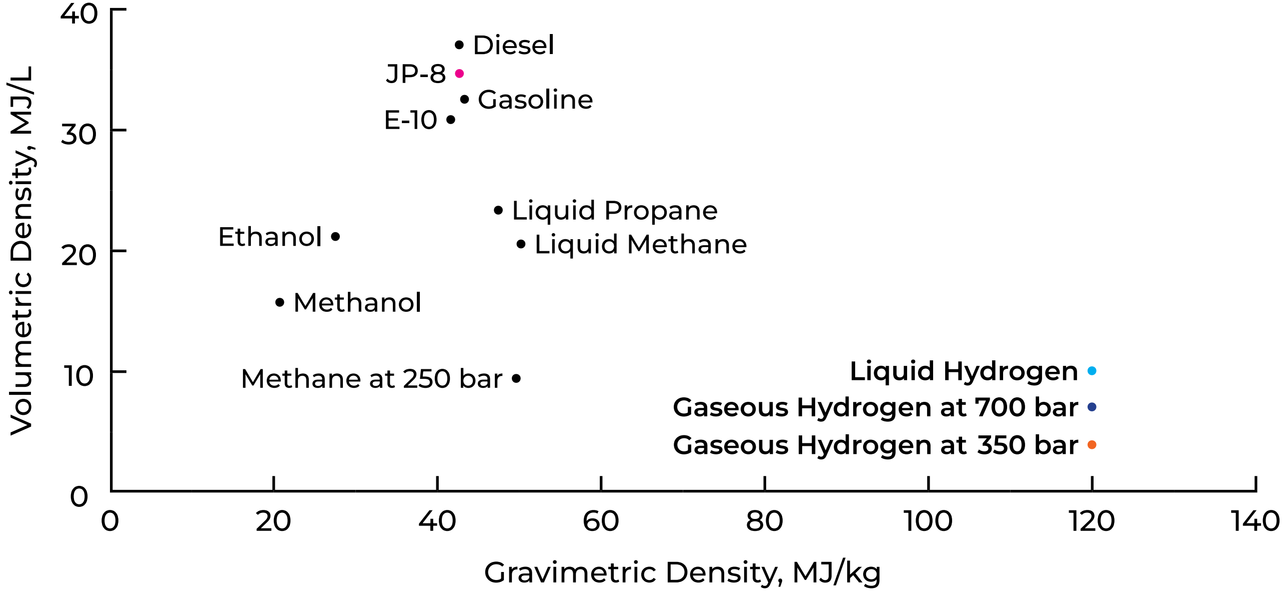
The theoretical volumetric density of liquid hydrogen (LH2) is 70g/L at the boiling point of hydrogen stored as a saturated liquid (−253°C) and atmospheric pressure, whereas it is 24g/L and 40g/L for compressed hydrogen at 350 and 700 bar, respectively, at room temperature.[6]

It is therefore necessary to move to cryogenic hydrogen for these systems. Liquid hydrogen (LH2) tanks can offer 50%+ mass efficiency potential, resulting in higher energy density. An 80-seat regional turboprop would require a cryogenic tank capable of storing 8,450L of LH2, equivalent to around 600kg in gaseous form. Cryogenic hydrogen storage tanks are normally double-walled vessels with a vacuum providing thermal insulation between the inner and outer walls.

Controlled management of boil-off is a key challenge. Onboard cryogenic tanks would need to minimize boil off for periods where the aircraft is not in operation. In all phases of flight, the extracted hydrogen fed to the fuel cell needs to counter the boil-off within the tank caused by the heat flow from the fuel cell system itself and the surrounding environment. If this cannot be achieved, the storage system would require active cooling systems or enhanced insulation, both adding weight. The most critical periods would be holding times on the ground pre- and post-flight, and these could establish the design requirements of the storage system.[7] Fortunately, air traffic management is geared to constant optimization of holding times.

There are several evolving liquid hydrogen tank concepts that are promising for aviation applications, including evaporatively cooled liquid hydrogen storage tanks that can meet many of these above needs are in development with industry leaders in storage technology.

Cryogenic fuel storage will have the significant advantage of improving thermal management system efficiency (further improving overall system-level specific power) and phase change augmentation of the system (such as being used as a thermal 'battery' for takeoff heat absorption).



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[5] U.S. Department of Energy — https://www.energy.gov/eere/fuelcells/hydrogen-storage

[6] Langmi et al — https://www.sciencedirect.com/topics/engineering/compressed-hydrogen-storage

[7] Kadyk et al — https://www.mdpi.com/1996-1073/11/2/375#B17-energies-11-00375

Power Generation Systems

The main challenge around H2-electric propulsion today, as developed for ZeroAvia's ZA600 product, is comparatively low overall specific power, partly driven by the cooling requirements for low-temperature proton exchange membrane (PEM) technology.

Advances in power density are predicted by Kadyk et al., but with a tradeoff in efficiency, which then ultimately has impacts on hydrogen volume required and thus storage (tank) weight.[8] The goal for this technology is increasing power density while minimizing efficiency reduction. Mitigations such as limiting load factors or oversizing the fuel cells obviously create specific challenges in an aviation context. The academic literature suggests that for designing the fuel cell, the whole propulsion system needs to be taken into account due to these interdependencies.

ZeroAvia's LTPEM SuperStack designed for up to 20-seat aircraft propulsion systems, developed in conjunction with PowerCell, offers high fuel cell stack power density to support a system level power density of 1.5kW/kg. The largest regional turboprops will require a significant improvement in stack-level specific power to around 3.5kW/kg, or just above 2kW/kg specific power at a system level. This analysis is derived from an assessment of operator load and mission profiles to establish acceptable operating parameters.

The solution to improving the specific power, as with jet engine development over many decades, is to raise the operating temperature and pressure inside the fuel cell. Importantly, however, in the case of fuel cells, this will not mean combustion of fuel and hence increased pollutants. High temperature proton exchange membrane (HTPEM) technology can operate efficiently at higher temperatures, eliminating components from the fuel cell system, reducing cooling drag and increasing Balance of Plant efficiencies to enable commercially relevant payload and range.

Technological breakthroughs are already being made in the application of High-temperature PEM (HTPEM) fuel cell systems for aviation. ZeroAvia is developing pressurized HTPEM fuel cell systems. In our HTPEM fuel cell stack innovations, innovative coatings enable the use of lightweight aluminum bipolar plates, even in highly aggressive HTPEM environments. Novel approaches to advanced membrane electrode assembly (MEA) are also contributing to improvements in cell performance, contributing to increases in specific power.

High-temperature proton exchange membrane (HTPEM) offers several clear advantages over Low-temperature proton exchange membrane (LTPEM) that make 40+ seat aircraft commercially viable with zero-emission propulsion for the first time:

	LTPEM	HTPEM	Key Advantage of HTPEM over LTPEM
Operating Temperature	65–95°C	130–200°C	• Lighter cooling system • Lighter and more efficient air compression system • Direct air cooling is possible
Electrolyte	Water	Phosphoric acid	• No water management problems • Permits overheating — more reliable in an emergency
Impurity Tolerance	Low	High	• Multiple fuels (methanol for instance) are acceptable • Can operate in polluted air conditions (like airports)
Membrane Chemistry	Fluorocarbon	Hydrocarbon	• Lower capital cost
Durability	5,000 to 10,000 h	Up to 20,000 h	• Lower cost in use

Electric Propulsion Systems

Scaling hydrogen-electric systems for up to 80-seat regional turboprops requires the most advanced power electronics and electric motor technology to ensure the most efficient translation of power into shaft torque, and thus enabling the propellers to generate enough thrust.

For ZeroAvia's planned 600kW hydrogen-electric engine (up to 20 seat turboprops), inverters will provide up to 800kW continuous power, with specific power density of 20kW/kg. The corresponding electric motor will offer max power of around 660kW at around 5kW/kg. It will be capable of delivering in excess of 3,000NM of torque with a max speed of around 2,500 rpm.

When examining the trajectory required to scale this into larger applications, we see a step change in performance is needed. While similar state-of-the-art power electronics can be integrated to support these higher power systems, the combined integrated package would need to offer in excess of 10kW/kg in power density.

To support an ATR 42 aircraft, a 1.9MW engine would be required, whereas an ATR 72 would be in excess of 2.1MW. The higher-powered Dash 8-400 would require around 3MW+, and ideally in excess of 3.5MW.

Of the required technology developments to support the delivery of zero-emission engines for 30–80 seat aircraft, electric propulsion systems are the most advanced. ZeroAvia has groundtested a 1.8MW configuration of its HyperCore motor stack with the stock Dash 8-400 engine gearbox and propeller. This configuration consists of two "HyperCore" motor modules, each a high-power, high-speed 900kW permanent magnet radial flux machine which operates at 20,000 rpm, matching the typical turbine engine speeds, and providing an unprecedented 15kW/kg motor power density.

Crucially, HyperCore's modular design enables the technology to address applications ranging from 900kW up to 10MW, meeting a number of regional turboprop and regional jet requirements.

The development and testing program will enable the understanding and measurement of system dynamics, calibration of physical and electrical models, and validation of thermal management systems. The company has developed world-class silicone-carbide power electronics to ensure hyperefficient and controlled connection of fuel cell power generation output (DC) into AC power for electric motors.

Propulsors

Envisaged propulsion systems are designed to work with existing propeller technology to deliver the required thrust and support operator performance needs.

However, advances in composite propeller technology design and manufacturing techniques can further enhance the appeal of a next-generation regional turboprop, when coupled with hydrogen-electric, zero-emission propulsion. Reduced weight and efficiency is promised by thermoplastic composites and enhanced integrated propeller controls, especially for new, responsive propulsion systems such as electric powertrains.

Furthermore, with the dramatic reduction of engine noise of hydrogen-electric systems, the resultant noise effects will be from the airframe itself and the propellers. Projects are underway to significantly enhance propeller design to reduce noise. The Clean Aviation IRON Project led by Leonardo and Dowty Propellers, for example, targets a 6 dB near-field noise reduction without significantly impacting fuel burn.

For clean sheet design in the regional category, there are some interesting concepts already in circulation. The Aerospace Technology Institute's wide-ranging Fly Zero study envisages a fuel cell-propelled aircraft using distributed propulsion.[9] The concept aircraft (which uses the ATR 72-600 as its reference point) is designed to bridge the regional turboprop and jet market and, as we will unpack below in the section looking at regional jet propulsor concepts, there is already convergence given propfan development.

The Fly Zero regional aircraft is designed for 800NM range, thus covering 92% of the full regional aviation market (regional turboprops and regional jets within the US scope clauses). The concept features six distributed propellers, which means that a one-engine inoperative scenario does not affect the system sizing case.

Similarly, Airbus' fuel cell-powered ZeroE regional turboprop concept, revealed in December 2020, envisages a similarly distributed propulsion architecture and targets a 1,000NM range.[10]

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[8] https://www.mdpi.com/1996-1073/11/2/375#B17-energies-11-00375

[9] ATI Fly Zero — Zero-Carbon Emission Aircraft Concepts - https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

[10] Airbus — https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe

Configuration

Retrofit

In terms of configuration for retrofit of leading regional turboprops, a possible location for fuel tanks will be in fairings above the fuselage. One other avenue being explored is for tanks to be installed in the rear of the fuselage, with some resulting reduction in seat capacity of around 20%. This would still enable typical load factors to be maintained and offer a simpler integration solution.

The electric propulsion systems will be housed in existing or modified engine nacelles, with fuel cell capacity potentially integrated.

Clean Sheet Designs

Returning to the ATI FlyZero study and its regional turboprop concept, the design involves an increase in diameter of the fuselage to make the hydrogen storage more efficient.[11] In this architecture, the bulk of the power generation systems (fuel cells) are located under the cabin floor in an unpressurized zone, with extension of the landing gear fairings to provide sufficient room. Liquid hydrogen tanks are located aft fuselage, behind the cabin.

The improvements that new aircraft designs will bring can be seen in FlyZero's assessment of potential dry wing benefits:

— *The wings are dry (they do not contain any fuel) with the fuel stored in the fuselage, and this offers a potential performance benefit as the structure can be optimised for wing bending moment and aeroelastic purposes. The flap mechanisms can be located within the wing structure rather than requiring external fairings. There is also an opportunity to relocate some systems within the wing, though this has not been investigated by FlyZero*

Section Two: Regional Jets

With over 4,000 regional jets in commercial service, and many thousands more similar airframes operating in business and private aviation, this segment represents a substantial opportunity for further cleaning up aviation's climate impact. It also provides the challenge for technology development of operating on a relatively similar-sized platform to a regional turboprop, but with enhanced power requirements.

The underpinning technologies for scaling into regional turboprop remain the same in regional jet, and the expansion of these capabilities further underlines their applicability to narrowbody class with continued iteration and performance improvements. In addition, in replacing jet engines with either open rotor designs or electric ducted fans, the regional jet application will go some way in proving out the development path for narrowbodies, stimulating investment and signaling to airframe OEMs and the wider market that hydrogen-electric fuel cells are viable for larger jet aircraft.

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[11] ATI Fly Zero — https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

Hydrogen Storage

For the regional jet application, liquid hydrogen storage would need to increase to accommodate up to one ton of H2 fuel for a retrofit aircraft, with the existing ~75 passenger count reduced to around 60, to provide a range above 500NM.[12] This equates to 15–16 cubic meters total tank volume for 1,000kg of LH2 storage.

Similar tank technology to the regional turboprop applications could be deployed, but with expected performance and materials improvements by the earliest possible certification date (2029), more efficient and lighter composite tank technology can be expected.

Aluminum tank technology has a max gravimetric index up to 35% and has a high maturity (see for example the successful flight of H2Fly's HY4 demonstrator powered by liquid hydrogen[13]). Glass fiber-based composite tanks have a low maturity but are in extensive ground testing by innovators, including ZeroAvia's work with Element and Fabrum at Cotswold Airport. These glass fiber tanks promise an up to 45% weight efficiency. Carbon fiber-based composites in theory promise up to 65% weight efficiency, but functional working prototypes do not yet exist, making this solution a long way from deployment.

Based on progressing the application with a tank at 45% weight efficiency, there is likely a compromise in terms of passenger capacity to accommodate the required fuel storage. As noted above, a retrofit regional jet aircraft could be expected to support up to 60 passengers over 560NM range according to analysis by ZeroAvia.

Clean sheet design could open up the design space for accommodation of greater fuel, but with the ubiquity of narrowbody and with a resurgence in turboprops, new concepts in these categories are more likely.

Power Generation Systems

The first regional jet class applications will require a propulsion system energy density in excess of 2.4kW/kg, representing an approximate 15% improvement over the regional turboprop systems.

For the fuel cell systems, this would likely mean a stack-level performance of 4kW/kg possible by advancing HTPEM stack technology.

Ultimately, for the largest applications in the regional jet category, the system level-specific power would need to increase to around 3kW/kg.

To deliver these improvements, further advancement of HTPEM fuel cells will be necessary to increase cell performance and operating temperatures above 200C.

Electric Propulsion Systems

Overall, engine power will need to increase to above 10MW to support typical regional jet applications.

Electric motor power density will need to further improve to support regional jet class applications, extending to above 14kW/kg based on ZeroAvia analysis. According to the UK Aerospace Technology Institute's FlyZero analysis, reasonable targets for electric motor and inverter power density are 23kW/kg and 40kW/kg, respectively, by 2030.

Higher cooling efficiency will need to be engineered into the systems to support the improvement in power density.

Propulsors

In entering the jet market, electric solutions need to deploy novel propulsor concepts to overcome the loss of turbine thrust. Increased fan diameter is considered to compensate for loss of turbine core thrust, and there are a number of configurations that can seek to maximize efficiency of converting engine power to thrust. Of course, increasing fan diameter increases the area that needs to be ducted, meaning an increase in weight and drag that counters the promised efficiency gains.

Open-rotor (or propfan) design combines elements of both turboprop and turbofan design to produce a new type of efficient propulsor that can increase efficiency and overcome the loss of jet exhaust thrust. Open-rotor concepts typically consist of two stages of unducted contra-rotating propeller blades. These designs can offer a three times higher bypass ratio, increasing the thrust without increased fuel consumption.

While the concept of open rotor had a major false dawn in the 1980s when Boeing considered the concept as a way to power the ultimately shelved 7J7 project, the need to increase efficiency in order to address CO2 emissions, and indeed the prospect of electric motor driven propulsors, has brought the concept back into discussion. As early as 1987, a Gulfstream II demonstrator operated by Lockheed was flying with a nine-foot open rotor propulsor, with GE and Pratt & Whitney also testing unducted fan technology as they looked to support the doomed Boeing project.

The two chief barriers to adopting open rotor design in order to improve efficiency were historically noise and concerns about the maturity of gearboxes. In terms of noise, modern designs utilize reduced tip speed and decreased blade loading. Lower speeds are thought to potentially offer reduced community noise impact, creating advantages for the open rotor design.

More recently, however, Safran's clean sky project performed successful ground tests with a geared open rotor engine, ultimately leading to an extension of the CFM International Safran/GE joint venture to pursue the RISE program,[14] which plans flight testing of a single-stage, gear-driven propfan by 2025. With this testing, Safran and GE have seemingly solved the gearbox issues through innovation that removes the need for two contra-rotating fans, meaning that the one rotating fan (unducted single fan, or USF) can be powered by more traditional gearbox technology. This is achieved by second-stage swirling vanes behind the USF.[15]

CFM predicts that engine efficiency targets of 20% are realistic, and this has caught the attention of major OEMs. A second phase of flight tests will be performed from the Airbus flight test facility in Toulouse with the RISE open fan engine mounted under the wing of a specially configured and instrumented A380 testbed aircraft.[16]

Open fan designs could cruise at speeds of Mach 0.80,[17] a marked step above regional turboprops and similar to the Mach speeds on current narrow-body aircraft. However, regional turboprops have been evolving towards increased fan blades, with the concepts essentially converging.[18]

One complication of open rotor for existing airframe designs is that the tips of the fans create vortices which need to be kept away from the aircraft fuselage to avoid cabin noise and vibrations.[19] Rear-mounted engines are therefore preferable, making the concept interesting for the CRJ and ERJ regional jet families in particular. Changes would likely be necessary to accommodate the increased diameter, but the overall location could remain the same. The size and weight/drag of the pylons needed to support the open rotor propulsors would also need to be considered.

Configuration

In contrast to the regional turboprop systems, the regional jet model would most likely see fuel cell power generation systems located within the fuselage. Cryogenic fuel tanks could be stored either under the cabin forward and aft of the wing, or internally within the cabin behind a relocated pressure bulkhead.

Electric propulsion systems would be located where existing engines sit in respective leading regional jet platforms, with some alterations potentially needed to support new propulsor types with increased diameter (see above).

With no changes to the airframe externally, aerodynamics can be preserved, and block speed kept close to existing fossil fuel operations.

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[12] ZeroAvia/MHIRJ Initial Technical study https://zeroavia.com/mhirj-initial-technical-study/

[13] https://www.futureflight.aero/news-article/2023-09-13/h2flys-breakthrough-flight-demonstration-bolsters-case-liquid-hydrogen

[14] Leeham News — https://leehamnews.com/2021/06/14/cfm-announces-the-rise-engine-program

[15] https://leehamnews.com/2020/01/03/bjorns-corner-why-e-in-eplane-shall-stand-for-environment-part-3

[16] Airbus — https://www.airbus.com/en/newsroom/stories/2022-07-could-an-open-fan-engine-cut-carbon-emissions-for-more-sustainable

[17] CFM: RISE Program — https://www.cfmaeroengines.com/wp-content/uploads/2021/07/CFM_RISE_Whitepaper_Media.pdf

[18] Mentour Pilot — https://youtu.be/ojVNOj-q3SQ

[19] Leeham News — https://leehamnews.com/2020/01/03/bjorns-corner-why-e-in-eplane-shall-stand-for-environment-part-3

Section Three: A Zero-Emission, Hydrogen-Electric Narrowbody

While long-haul, widebody aircraft are per passenger and per aircraft bigger emitters, narrowbody aircraft have the greatest share of carbon emissions at a category level, with 43% of aviation's total. This is a reflection of the popularity of these workforce aircraft for short and medium-haul routes. Currently, aircraft in this category fly 85,000 unique route pairings globally, carrying 4.1 billion seats. There are over 20,000 aircraft flying.

Looking at the orderbook for both Airbus and Boeing, this is set to increase drastically, with narrowbody aircraft likely to support the bulk of increased passenger demand. With nearly 8.7 billion passengers predicted by 2037 — more than the world's population — and much of this increased demand coming from emerging middle class in countries like China and India — the proportion of passengers carried on narrowbodies is likely to increase. Low-emission propulsion solutions are needed for this segment to make a positive shift for the majority of aviation and outstrip the emissions increase that would otherwise be occasioned by demand growth.

The routes narrowbodies fly vary greatly in size, with the shortest scheduled service being 15NM and the longest over 3,500NM. Nominal range for narrowbody aircraft is as high as 4,000NM. With no new widebody aircraft currently planned by either Airbus or Boeing at the time of writing, airline operators seem happy to deploy narrowbody aircraft on progressively longer routes, including some long-haul flights.

With reduced range due to hydrogen's comparative volumetric energy density when compared to jet kerosene, delivering a powertrain for narrowbody aircraft would by necessity tackle the market by degrees, beginning at the lower end. However, the distribution of narrowbody operations sees the bulk of flights at the lower end, with 95% sub 1,750NM.

Another alternative for initial introduction would be as a single-fuel hybrid with a smaller gas turbine and electric propulsion hybrid drive, powered by fuel cells, with the combustion powering peak power output like take-off, and the fuel cells powering the majority of flight time in cruise, with drastic emissions reduction.

The emissions prize for this segment is enormous. It represents 1% of global carbon emissions on its own. Assuming steady share of the global aviation market, this would represent about 10% of human carbon emissions in 2050 without efforts to reduce.

As a drop-in (or near drop-in) fuel for narrowbody aircraft, SAF is seen by the majority of industry and policymakers as the near-term solution. But aviation needs between 25% and 30% of renewable fuel production capacity for SAF to be on the trajectory needed to reach net-zero carbon emissions by 2050. The ReFuelEU Aviation proposal would require that 32% and 63% of jet fuel consumed by flights departing from EU airports be SAF in 2040 and 2050, respectively. However, S&P Global Commodity Insights projects that SAF demand by 2050 could climb to 5.8% of global jet fuel demand.

As stated, carbon emissions make up only a portion of aviation's climate impact, with non-CO2 emissions thought to be as much as two-thirds of the overall climate warming effect. The NOx volume produced by the global narrowbody fleet would be unchanged by a move to SAF, and high-temperature water vapor exhaust would remain the same. In-flight carbon emissions would also remain, meaning that with scalability and residual emissions, it represents only a partial or bridge solution.

An electrically propelled A320 would require 27.6MW, according to a paper released in 2018 by Liu et al.[23]

According to analysis by Kadyk et al. in 2018, the state of fuel cell technology at the time would mean doubling the mass of the overall propulsion system to support an A320, clearly untenable. However, Liu et al. find that revolutionary technologies at vehicle level (such as laminar flow control, structure and gust load alleviation technologies and new structures and materials) could reduce this requirement to around 16.3MW. "Combining future aircraft technology with future fuel cell technology could lead to a mass reduction by 41%," write Kadyk et al.

Hydrogen Storage

For the narrowbody application operating purely on fuel cell power, liquid hydrogen storage would need to increase to accommodate around 64,000 liters of liquid hydrogen fuel for an aircraft in excess of 150 seats to provide a range above 2,400NM.[24]

Similar tank technology to the regional turboprop applications could be deployed, but with expected performance and materials improvements by the earliest possible certification date (2033), more efficient and lighter composite tank technology can be expected.

Aluminum tank technology has a max gravimetric index up to 35% and has a high maturity (see for example the successful flight of H2Fly's HY4 demonstrator powered by liquid hydrogen). Glass fiber-based composite tanks have a low maturity but are in extensive ground testing by innovators, including ZeroAvia's work with Element and Fabrum at Cotswold Airport. These glass fiber tanks promise an up to 45% weight efficiency. Carbon fiber-based composites in theory promise up to 65% weight efficiency, but functional working prototypes do not yet exist, making this solution a long way from deployment.

Power Generation Systems

Overall system level-specific power needs to improve to in excess of 4kW/kg to support single-aisle narrowbody aircraft. ZeroAvia has stated that it believes achieving this energy density for its HTPEM stacks is possible in the early 2030s.

According to analysis by academics Kadyk et al., "a 5-fold increase in stack power density towards >10kW/kg seems a reasonable estimate for future development",[25] pointing to weight reductions of peripherals (end-plates, screws) and improvements in catalyst layers.

As we will examine below, an interim step could be single-fuel hydrogen hybrid systems, combining H2 gas turbine and fuel cells power.

Electric Propulsion Systems

Narrowbody aircraft like a 737 and A320 have a unit thrust per engine between 80 and 130 kilonewtons.[26] At cruise, 1kW shaft power will be equal to approximately 5.9N of thrust. Even with improvements in airframe design, the required shaft power to support these airframes with an electric powertrain will be in excess of 12MW (6MW per engine in a conventional two propulsors configuration), with a 15kW/kg electric motor power density.

According to the UK Aerospace Technology Institute's FlyZero analysis, electric motor power density is expected to go from around 23kW/kg to 25kW/kg between 2030 and 2050, while inverter power density could increase by 50% from 40kW/kg to 60kW/kg over the same period. At the 2030 targets, the electric propulsion systems would be well capable of flying 100+ seat aircraft, assuming sufficient power supply.

Propulsors

As outlined in the section examining regional jet propulsor concepts, novel systems will be necessary to support narrowbody, single aisle aircraft and open fan concepts are being actively explored by Airbus with testing planned.

While we explored the rationale and status of development for open fan concepts in some depth in the regional jet section, much of this is applicable to the narrowbody category, but with one caveat. The typical configuration of popular regional jet airframes is with rear-mounted engines, which negates the challenges of open rotor tips creating vortices. However, Airbus's testing plan with one of four A380 engines replaced with the prototype RISE engine will provide great data on the impact of this effect.

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[20] ICCT — CO2 Emissions from Commercial Aviation https://theicct.org/wp-content/uploads/2021/06/CO2-commercial-aviation-oct2020.pdf

[21] IATA — https://www.iata.org/en/pressroom/2023-releases/2023-12-06-02/

[22] S&P Global Commodity Insights — https://www.spglobal.com/commodityinsights/en/market-insights/blogs/oil/032222-sustainable-aviation-fuel-saf-2050

[23] Exploring Vehicle Level Benefits of Revolutionary Technology Progress via Aircraft Design and Optimization - Liu et al - https://www.mdpi.com/1996-1073/11/1/166

[24] ATI Fly Zero Report Zero Carbon Emission Concepts

[25] Analysis and Design of Fuel Cell Systems for Aviation, Kadyk, Winnefeld, Hanke-Rauschenbach Krewer Energies — Analysis and Design of Fuel Cell Systems for Aviation (mdpi.com)

[26] OEM Manual Data

Configuration

Retrofit

As outlined above, supporting retrofit of existing A320 or 737 would require advances in fuel cell propulsion system power to above 20MW according to the literature. Supporting this power would require 40 fuel cell stack modules at power density in excess of 4.5kW/kg.

While these technologies are all within the bounds of the possibilities considered in the academic literature, the development of these components is a major engineering undertaking, and reaching these levels will be achieved as the clock counts down on in-service narrowbody designs, making this market uncertain.

However, the major challenge remains in hydrogen volume. Tank technology mass fraction developments will significantly mitigate the weight penalty of hydrogen. According to Cambridge University's Aviation Impact Accelerator, "liquid hydrogen – which doesn't require the heavy, pressurized tanks that gaseous hydrogen does – could achieve a gravimetric energy density that is over twice that of jet fuel."[27]

But volume challenges are often cited as a chief concern, with liquid hydrogen's volumetric energy density more than three times poorer than that of kerosene. Academics at Cambridge University suggest that simply extending the fuselage of airframe designs can achieve the desired effect, without drastic redesign of the airframe concepts that are common today. Of course, any increase in fuselage length or size will have an impact on drag and weight, meaning that this is not a simple redesign and delivering new airframes is still a number of years away.

The Aviation Impact Accelerator concludes: "liquid hydrogen fuel offers significant potential for powering long-range aircraft if it can be designed for liquid hydrogen's low volumetric energy density."

Hybrid systems

As fuel cell specific power matures, an interim step that could enable earlier adoption of hydrogen-electric flight in the narrowbody category is a single-fuel hybrid hydrogen concept, with propulsors driven by a hydrogen gas turbine engine and electric motors (powered by fuel cells), using the same shaft.

This concept would enable higher overall efficiency by utilizing the gas turbine at peak power demand during take-off, and relying only on fuel cell power in cruise. It can thus eliminate CO2 impacts, and drastically reduce non-CO2, with only low-temperature water vapor emitted for the majority of the flight.

This concept would allow for optimum sizing of the power generation systems — a smaller turbine and smaller fuel cell for combined total power.

According to ZeroAvia's preliminary analysis, single-fuel hybrid could enable fuel cell adoption in the narrowbody segment earlier, reducing the requirements for fuel cell-specific power to between 4–5kW/kg compared to the 10kW/kg estimated for full narrowbody power generation from fuel cell systems alone. This reduced target would be close to the range required for the highest powered regional turboprops, which ZeroAvia targets its HTPEM system to support by 2027. A hybrid concept propulsion system could be ready by the early 2030s.

In theory, adoption here would enable advances for the hydrogen fueling industry and supply chain given it would soften the exponential growth curve in fuel needs between regional turboprop operation and narrowbody by providing a use case for a more limited number of flights.

Hydrogen volume again could be the major hurdle, with the gas turbine portion of the system requiring more volume-intensive fuel when in operation when compared to the fuel cell. While the majority of the flight profile would operate powered by fuel cells, this will still have an impact on the payload and range. In addition, with turbines running on the ground ahead of take-off, it would not alleviate NOx impacts on air quality, which a fully electrified system powered by fuel cells would. However, the climate impact could be huge.

Blended wing body

The blended wing body (BWB) concept for airframe design has been a popular idea for those looking to radically improve upon the trusty tube and wing designs that we have relied upon for nearly a century.

The basic concept of the blended wing body aircraft is to make the entire aircraft a flying wing, so that the whole bottom surface is generating lift, as opposed to just the wings that are then carrying the tube. The airfoil-shaped body thus increases efficiency and reduces fuel consumption. According to a US Air Force review, a blended-wing-body design "increases aerodynamic efficiency by at least 30% over current air force tanker and mobility aircraft, and enables dramatically greater fuel offload at range to ensure strike capabilities in a contested environment".[28]

In addition, it allows for increased interior volume, which could either carry more passengers or accommodate the extra space required for hydrogen fuel.

Key barriers for the innovation have been the impact on public confidence in safety that a radically differently shaped airframe might create initially, and, as ever, cost of development.

Now, however, a range of concepts are coming to the fore driven by the climate crisis, with the development dovetailing with hydrogen propulsion system innovation. Both technologies could be symbiotic enablers of each other.

When Airbus revealed its ZEROe concepts a couple of years ago, the one that captured the imagination most prominently was the 200+ seat BWB design with a 2,000NM target range.[29] While the initial concept is focused on hydrogen gas turbine, maturation of fuel cell-specific power could make this a preferred propulsion concept given the efficiency and overall environmental improvements.

Airbus ZEROe BWB - The Blended Wing Body's exceptionally wide interior opens up multiple options for hydrogen storage and distribution. Here, the liquid hydrogen storage tanks are located underneath the wings. Two hybrid-hydrogen turbofan engines provide thrust.

Another prominent development is the US Air Force, NASA and FAA-supported JetZero project (not to be confused with the UK Government's JetZero Council). JetZero is developing the ultra-efficient BWB concept, which plans a 2030 launch, initially on SAF, but with design looking to accommodate a transition to hydrogen fuel storage. While a new company, the founder, Mark Page, has been working on the blended wing concept for over 30 years. The company plans to be ready to adopt fuel cell propulsion as and when it becomes available.[30]

ZeroAvia is working with Natilus, a clean sheet developer focusing on a BWB design for the cargo market.[31] The Natilus Kona is designed to offer increased volume for hydrogen storage, potentially transforming the air cargo delivery industry to one with low-cost, low carbon emissions, while also extending flight range. Natilus plans to combine fuel cell propulsion with its unique design to create a scalable, long-range, and zero-emission air cargo delivery solution for the entire industry. Natilus validated the performance of the BWB design with flight testing of a quarter-scale Kona prototype aircraft in 2023, following three years of extensive wind-tunnel testing.

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[27] True Target Zero — Aviation Impact Accelerator https://aiazero.org/wp-content/uploads/2022/07/180227_Target_True_Zero_Report.pdf

[28] US Air Force climate action plan, as reported in Flight Global — https://www.flightglobal.com/fixed-wing/us-air-force-to-test-blended-wing-logistics-aircraft-by-2027/150501.article

[29] Airbus, ZEROe — https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe

[30] Robb Report — https://robbreport.com/motors/aviation/this-blended-wing-x-bwb-1-jet-airborne-1234884595

[31] Natilus and ZeroAvia partnership — https://zeroavia.com/natilus-partnership

Conclusion

This paper has sought to examine the trajectory of fuel cell propulsion systems beyond the Part 23, small turboprop aircraft, where the systems are not just proven in flight test, but in some cases are now undergoing regulatory approvals.

Fuel cell-powered commercial aviation is a certainty this decade, but detractors still level criticism about the long-term scalability of the systems. This paper has taken a step-by-step review of each segment sequentially, examining the required power, power-to-weight ratio, fuel storage and configuration requirements to establish theoretical viability.

As readers will note, the certainty around designs is much more crystallized within the regional category, with narrowbody aircraft requiring some substantial gains in component performance, as well as more uncertainty about potential configurations, particularly in the light of volumetric fuel challenges presented by hydrogen.

Fundamentally, however, we can begin to see that the roadmap is there to evolve fuel cell technology for the vast majority of the global fleet and thus provide a stronger footing to unlock a net-zero aviation system by tackling the majority of emissions for the majority of flights.

Widebody applications are not considered here, as we have decided that the knowledge base is not yet strong enough to address this question.

However, what a future we can look forward to if and when we can definitively establish the technical and commercial viability of a fuel cell-powered narrowbody aircraft. At this stage, the next — most daunting — challenge will then be within reach.

The largest aircraft may not be powered by truly clean propulsion systems before 2050, but if progress can continue as envisioned here and beyond, electrification can ultimately be delivered for the entirety of aviation, with hydrogen as the energy storage vector, within the lifetime of many reading this white paper. This should be a source of inspiration to all those working on tackling aviation's climate impact today.

We need to plan for adopting large hydrogen-powered aircraft today, right up to the 200-seat airframes, while we look ahead to a future where all aircraft can be powered by a fuel produced from just two ingredients — renewable energy and water.