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DESIGN AND ECONOMIC ASSESSMENT OF A 19-SEAT HYDROGEN FUEL CELL AIRCRAFT FOR REGIONAL AVIATION

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Abstract This paper summarises the results from the MAHEPA project, which investigated the technological and economic feasibility of 19-seat hydrogen fuel cell aircraft and their potential deployment towards 2050. It assesses the key requirements necessary to enable their operation and long-term viability. The analysis is structured in three parts. First, it addresses the required infrastructure and safety measures for hydrogen-based regional aviation, including production and distribution. Second, it evaluates the development needs of critical technological components such as fuel cells, hydrogen storage systems and propulsion integration. Third, it examines the economic feasibility, where the direct operating costs are linked strongly to the aircraft mass characteristics. The economic results for the 2030–2050 horizon indicate potential cost competitiveness under favourable hydrogen pricing and continued technology development, supporting hydrogen fuel cell aircraft as a viable option for regional aviation.

Keywords
fuel cell aircraft, hydrogen aircraft, regional aviation, MTOM estimation, direct operating costs, 19-seat aircraft

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1 Introducton

Due to the increasing environmental concerns associated with greenhouse gas emissions, significant efforts have been undertaken within the European Union in both the political and research domains to reduce dependence on combustion engines and transition towards alternative energy sources. This transformation spans multiple sectors, from energy production to energy consumption. One of the most critical sectors in this context is transportation, which contributes a substantial share of global greenhouse gas emissions. Consequently, strategies are being developed, both to reduce the transportation demand (e.g., car sharing and public transport), and to enable a transition towards alternative propulsion systems, particularly electrification.

A clear example of this transition can be observed already in the automotive industry, where coordinated EU-funded initiatives have supported the development of charging infrastructure, technological maturity of electric vehicles, and economic viability through subsidies. As a result, electric vehicles now offer a competitive range (typically 300–500 km), acceptable charging times via fast-charging networks, and increasingly comparable purchase and operating costs. Consequently, their market penetration is increasing steadily and rapidly (EEA, 2025).

The key question is whether other transport sectors can follow a similar trajectory. Among these, the aviation sector represents one of the greatest challenges, due to its rapid growth, high emissions and significant technological constraints (EASA, 2025). In particular, the high specific energy requirements of flight make battery-electric solutions feasible only for very small aircraft with limited passenger capacity. Unless substantial breakthroughs in battery energy density occur, batteries are unlikely to provide a viable solution for regional aviation (Prapotnik Brdnik et al, 2019).

Alternative pathways include hydrogen-based propulsion and sustainable aviation fuels (SAF), including synthetic fuels. While synthetic fuels, produced through carbon capture and fuel synthesis processes, offer compatibility with existing infrastructure, their current production costs remain high, limiting the near-term economic feasibility (Cabrera and de Sousa, 2022). Hydrogen, on the other hand, offers a high gravimetric energy density, making it a promising candidate for aviation applications. However, it introduces significant challenges, including low volumetric energy density, complex storage requirements and safety considerations due to flammability (Adolf et al, 2017).

This study investigates the potential of hydrogen-powered regional aviation, and evaluates whether such systems can become a feasible future solution. The analysis is structured around three key aspects: (i) ground infrastructure readiness, (ii) technological readiness, and (iii) economic feasibility.

2 Ground infrastructure and hydrogen supply chain

Hydrogen is a tasteless, colourless, odourless, non-toxic and highly flammable gas. It is found in its pure form in nature rarely, but can be produced from various energy sources, such as natural gas and electricity (Adolf et al, 2017). Therefore, hydrogen should not be considered a primary energy source, but rather an energy carrier and storage medium. Its main advantages are its low mass and the wide range of production pathways available. However, its high flammability and the fact that, as the lightest element, it can leak easily through materials and cause embrittlement of certain metals, represent significant challenges (ISO, 2015). The hydrogen supply chain consists of four main steps: (a) production, (b) compression or liquefaction, (c) transportation, and (d) storage.

2.1 Hydrogen production

As already mentioned, hydrogen can be produced in various ways (Adolf et al, 2017). Currently, the most common production method is steam methane reforming. Hydrogen produced by this process is referred to as *grey hydrogen*. If carbon capture and storage technologies are incorporated into the process, the resulting product is known as *blue hydrogen*. Alternatively, hydrogen produced through water electrolysis powered by electricity generated from renewable sources is referred to as *green hydrogen*. At present, the production cost of green hydrogen is significantly higher than that of blue or grey hydrogen. However, several studies suggest that green hydrogen will become the dominant production pathway by 2030 (IRENA, 2020). Therefore, this study considers only green hydrogen as the energy source.

2.2 Hydrogen preparation

Before distribution, the hydrogen is purified and either compressed or liquefied. Due to the high mass of pressurised storage tanks, only liquid hydrogen is considered suitable for aviation applications (Prapotnik Brdnik et al, 2019). Hydrogen liquefaction is typically achieved using the Linde cycle. Since liquefaction equipment is expensive, the process becomes economically viable only at large production scales. Consequently, liquefaction at centralised production facilities prior to delivery appears to be the most suitable solution (Marksel et al, 2019).

2.3 Hydrogen delivery

Hydrogen can be delivered in three principal ways: by truck in pressurised vessels, by cryogenic truck in liquid form, or through pipelines in gaseous form. Delivery using pressurised vessels is feasible only for short distances and relatively small quantities of hydrogen. Pipeline transport requires substantial initial investment, but offers very low transportation costs once the infrastructure is established. Therefore, for very large quantities and long transportation distances, pipelines represent the most suitable solution. Cryogenic truck transport is generally the most economical option for medium distances and moderate quantities of hydrogen (Yang and Ogden, 2007).

According to (Marksel et al, 2019), in 2017 there were approximately 150 European airports operating aircraft with capacities between 9 and 19 passengers. More than 90% of these airports handled three or fewer such aircraft movements per day, while the busiest airport operated approximately nine to ten aircraft of this category daily. Most of these flights covered distances between 100 and 500 km.

Assuming that the energy efficiency of a hybrid fuel-cell aircraft is comparable to that of a conventional aircraft, a 19-seat aircraft would require approximately 200 kg of hydrogen for a 500 km flight. This suggests that the hydrogen demand at regional airports would be relatively modest. Approximately 80% of all airports would require less than one tonne of hydrogen per day. If all regional aircraft with capacities of up to 70 passengers were powered by hydrogen, approximately 90% of airports would require less than 10 tonnes of hydrogen per day, while the largest airport would require approximately 40 tonnes per day (Marksel et al, 2019, Marksel et al, 2022).

Since a cryogenic truck can transport approximately 4 tonnes of liquid hydrogen, centralised liquefaction combined with cryogenic truck delivery appears to be the most suitable solution for regional aviation, at least during the initial phase of hydrogen adoption. In the longer term, if larger aircraft also transition to hydrogen propulsion, on-site hydrogen production at airports could become an attractive alternative.

2.4 Hydrogen storage

Based on the estimated hydrogen demand, dedicated long-term storage facilities at airports may not be necessary. Instead, direct aircraft refuelling from delivery trucks could represent the most efficient and cost-effective solution (Marksel et al, 2022).

2.5 Airport ground infrastructure

Although an extensive hydrogen storage infrastructure may not be required at airports, dedicated ground infrastructure is nevertheless necessary (Marksel et al, 2022). Due to the specific safety challenges associated with hydrogen handling, operational procedures must be defined clearly and followed strictly.

In this regard, the relevant ISO Standard, (ISO, 2004), although currently withdrawn, still provides useful guidance on the requirements for airport hydrogen infrastructure. Furthermore, the existing ISO Standards concerning hydrogen safety can be used as a reference for the development of operational procedures and safety measures (ISO, 2015).

According to these guidelines (ISO, 2004), the airport infrastructure should support several key operations, including: (a) warm refuelling (initial refuelling, or refuelling after an extended ground stay), (b) cold refuelling following a flight, (c) defuelling, and (d) boil-off gas management.

From a safety perspective (ISO, 2015), airport facilities should be equipped with appropriate warning signs and physical barriers to prevent unauthorised access to hydrogen-handling areas. Whenever possible, hydrogen-related operations should be conducted outdoors to minimise the accumulation of leaked hydrogen. In addition, hydrogen leak detection systems and flame detection equipment should be installed in all the relevant operational areas. Finally, all hydrogen-handling procedures should be performed exclusively by specially trained and qualified personnel in accordance with established safety protocols.

3 Technological readiness

Hydrogen fuel cell aircraft require the following new key technological components: electric propulsion motors, a fuel cell system and hydrogen storage tanks.

3.1 Electric motors

Electric motors represent one of the least challenging components in hydrogen fuel cell aircraft, as electric motor manufacturing for a wide range of applications is already a well-established and mature industry (Marksel et al, 2019). Electric motors for hydrogen fuel cell aircraft must ensure high reliability, compatibility with the propulsion system, economic viability, and, above all, high power density. Currently certified or flight-tested electric motors achieve a specific power of approximately 5 kW/kg. However, research and development indicate significant progress in the coming decades, with expected increases in the specific power to approximately 13 kW/kg by 2026, 23 kW/kg by 2035, and up to 25 kW/kg or more beyond 2050, alongside efficiencies of up to 99%.

The most promising manufacturers of electric motors for regional electric and hydrogen-powered aircraft are currently developing solutions that are already undergoing flight testing and enable appropriate integration with propeller systems. Development is focused on increasing both the absolute power and specific power of electric motors, with the current solutions already reaching power levels on the order of several hundred kilowatts.

The development of regional aviation between 2023 and 2026 includes several demonstration projects of electric, hybrid-electric and hydrogen-powered aircraft with a capacity of approximately 19 passengers. The expected propulsion motor power ranges from 350 kW to 1 MW. The hydrogen fuel cell aircraft development projects foresee replacing conventional engines with electric motors of approximately 600 kW, powered by fuel cell systems.

3.2 Fuel cells

Among the different types of fuel cells, solid oxide fuel cells (SOFC) and proton exchange membrane fuel cells (PEMFC) are considered for aviation applications (Marksel et al, 2019). PEMFC technology is currently the most technologically mature option for aerospace and space applications, due to its high power-to-weight ratio, which, today, reaches approximately 2.9 kW/kg at stack level, and is expected to increase up to 8 kW/kg in future developments. PEMFC systems operate at low temperatures (60–80 °C), enabling fast start-up and relatively simple system integration.

PEMFC technology is already applied widely in the automotive sector, and benefits from increasing production scale and decreasing costs (Thompson et al, 2018). Key challenges for aviation application remain the reduction of system mass while, simultaneously, improving the reliability, lifetime and power output under demanding operational conditions. Future cost reductions are expected primarily through economies of scale, industrial learning effects and increased production volumes. Two main development pathways are foreseen: the adaptation of automotive fuel cell systems for aviation use, and the development of aviation-specific fuel cells with higher specific power, longer lifetime and optimised lightweight materials.

3.2 Cryogenic tanks

Liquid hydrogen storage systems represent one of the least mature subsystems in hydrogen-powered aviation, primarily because the existing ground-based cryogenic tank designs are not transferable directly to aircraft applications. Conventional storage systems are designed to minimise boil-off over several days of storage, which results in heavy insulation and structural designs that are unsuitable for aviation due to excessive mass. Aircraft applications, in contrast, require dedicated tank designs optimised for short-duration storage, typically limited to the flight time and a short pre-flight ground period of one to two hours, where controlled boil-off is acceptable or managed actively.

Verstraete (Verstraete et al, 2010) investigated the design requirements for liquid hydrogen tanks in regional aircraft, and highlighted the strong dependence of tank mass, insulation thickness and boil-off behaviour on ground time and operational constraints. His results showed that the gravimetric index of a liquid hydrogen tank system (the ratio between the mass of the fuel content and total mass of the storage system) can be expected to reach values of approximately 60–70%, depending on the structural materials, insulation concept and allowable boil-off conditions. Achieving values towards the upper end of this range requires optimised lightweight structures and highly efficient thermal insulation systems.

4 Estimation of the direct operating cost

The economic perspective of hydrogen fuel cell aircraft is shaped primarily by the capital costs (CAPEX) and operating costs (OPEX). CAPEX includes aircraft development, certification, production and infrastructure investment, while OPEX refers to the recurring costs associated directly with operating the aircraft, such as hydrogen fuel, maintenance, insurance, etc…...Since aircraft development is expected to be supported largely by EU-funded programmes, the main economic challenge lies in reducing the direct operating costs. If these can be reduced to levels comparable to or lower than those of conventional aircraft, fuel cell aircraft could become a viable solution for future aviation applications.

The operating costs depend on several factors, the most important being aircraft mass. Therefore, before performing a cost analysis, an estimation is required of the fuel cell aircraft mass.

4.1 Estimation of the maximum take-off mass of the aircraft

In the literature several methods exist for estimating the maximum take-off mass (MTOM) of an aircraft, ranging from simple approaches requiring only basic input data such as passenger numbers and range, to highly detailed methods requiring full aircraft design specifications. Therefore, a dedicated model was developed that is sufficiently flexible to differentiate between aircraft with different performance characteristics, while remaining simple enough to estimate MTOM without detailed design data (Marksel and Prapotnik Brdnik, 2022).

Aircraft performance can be summarised by key parameters, such as passenger numbers, range, cruise speed, take-off and landing distance and manoeuvring capability (e.g., rate of climb). Most of these parameters, with the exception of range and passenger capacity, are influenced strongly by wing loading (wing area per unit of aircraft mass) and power loading (engine power per unit of aircraft mass). The developed model therefore incorporates the following input parameters: power loading, wing loading, range, passenger numbers and selected wing geometric parameters.

The model calculates the fuselage and wing dimensions using analytical relations, while other aircraft masses are estimated using a mass percentage breakdown approach (Kundu, 2010; Marksel and Prapotnik Brdnik, 2022). Validation has shown that the method provides good agreement with the existing conventional aircraft mass estimates. It has therefore been adapted for fuel cell aircraft applications.

In this adapted version, the electric motor mass is determined based on the required power, the fuel cell system mass is estimated using data from the automotive sector (Thompson et al, 2018), and the tank mass is derived using the Verstraete methodology for cryogenic hydrogen storage system estimation (Verstraete et al, 2010).

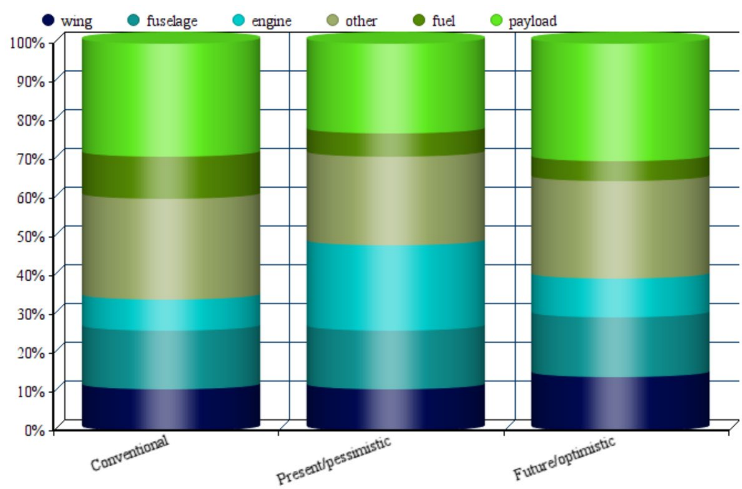

Figure 1: Breakdown of aircraft mass by subsystems
(Marksel and Prapotnik Brdnik, 2022)

4.2 Estimation of the maximum take-off mass of the aircraft

Currently in Europe, six 19-seat aircraft models are in operation: Aircraft Industries L410 NG, DHC-6 Twin Otter, Dornier 228 NG, Beechcraft 1900D, British Aerospace Jetstream, and Fairchild Swearingen Metroliner (Marksel and Prapotnik Brdnik, 2023). The first three models are still in production, while the latter three are no longer produced, although existing aircraft remain in service across Europe.

In total, 11 companies operate 19-seat aircraft fleets, ranging from 1 to 13 aircraft 19 seat aircraft per operator. The majority of these aircraft are used for domestic operations (without cross-border flights), with the exception of one operator providing services between the United Kingdom and France across the English Channel.

The annual utilisation of these aircraft varies significantly, ranging from approximately 200 to just over 1,300 flight hours per aircraft. The number of flights per year ranges from slightly above 400 to just below 8,000, corresponding to an average utilisation of approximately 1 to 22 flights per day per aircraft.

4.3 Estimation of the direct operating cost

The direct operating costs (DOC) are divided into annual depreciation, annual interest costs, annual insurance costs, annual fuel costs, annual maintenance costs, annual crew costs and annual airport and air navigation charges (Scholz, 2015). The detailed calculation is presented in (Marksel and Prapotnik Brdnik, 2023).

The annual depreciation, interest and insurance costs are estimated as a percentage of the aircraft purchase price. The purchase price is estimated using a mass-based cost model, in which the aircraft is decomposed into its major subsystems, the mass of each subsystem is determined, and the corresponding manufacturing and assembly costs are calculated. Depreciation is determined further by the expected operational lifetime of the aircraft.

The annual fuel costs depend on both the number of flights and the total distance flown. These costs are estimated by dividing each flight into its main phases–take-off, cruise and landing–and calculating the fuel consumption for each phase separately. Since the fuel consumption is strongly dependent on the aircraft mass, accurate mass estimation is an essential prerequisite for operating cost calculations.

The annual crew costs depend on the total flight hours, including block time, which accounts for ground manoeuvring before take-off and after landing. These costs are calculated using the hourly rates of the pilots and cabin crew.

The maintenance costs are determined by both the material costs and labour costs associated with the maintenance personnel and engineering specialists. For conventional kerosene-powered aircraft, detailed maintenance cost data are available from the existing operators (Aircraft Industries, 2023). For hydrogen fuel cell aircraft, the maintenance requirements for the airframe are assumed to be similar to those of conventional aircraft, while the propulsion system maintenance differs. In particular, maintenance is expected to focus on the fuel cell system and its periodic replacement, whereas electric motors and hydrogen tanks are anticipated to require mainly inspections and routine servicing (Thompson et al, 2018).

The airport-related costs include both air navigation charges paid to Eurocontrol and airport fees. These costs are among the most difficult to estimate, as charging schemes vary considerably between airports, both in terms of pricing and the services included.

The results indicate that the dominant cost category depends strongly on the aircraft`s utilisation. For operators with high annual flight activity, fuel costs represent the largest share of direct operating costs, whereas, for operators with low annual utilisation, depreciation becomes the dominant cost component. An example of the DOC breakdown for the Croatian airline Trade Air is presented in Figure 2.

The cost analysis shows further that hydrogen fuel cell aircraft are expected to have higher direct operating costs than conventional aircraft by around 2030. However, by 2050, the direct operating costs are projected to become lower than those of kerosene-powered aircraft. This trend is driven primarily by the expected increase in kerosene prices and the simultaneous decrease in hydrogen production costs. The projected evolution of the direct operating costs for the Croatian airline Trade Air is presented in Figure 3. The Figure shows that the annual direct operating costs of conventional aircraft are expected to increase substantially between 2030 and 2050, while the costs of fuel cell aircraft remain more stable. Although fuel cell aircraft may initially have comparable or slightly higher operating costs, they become increasingly cost-competitive over time. The widening gap between the two cost curves suggests that hydrogen fuel cell aircraft could offer long-term operational cost advantages, particularly if fossil fuel prices, carbon costs and environmental compliance costs continue to rise.

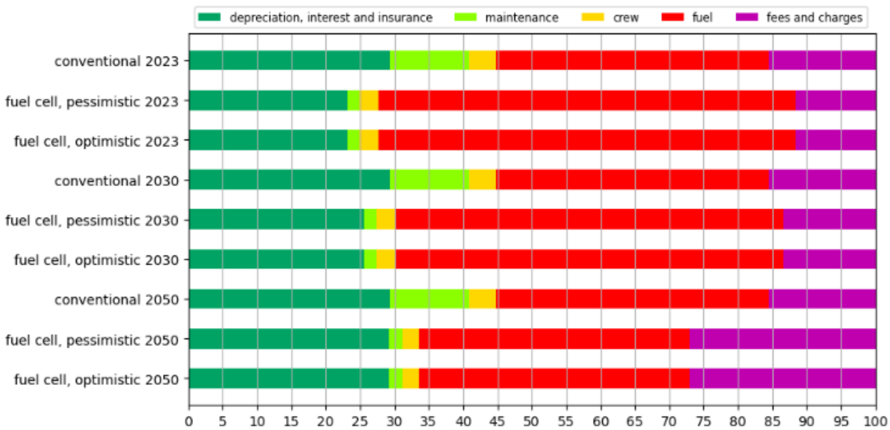

Figure 2: DOC breakdown for Croatian Trade Air airline
Source: (Marksel, 2023)

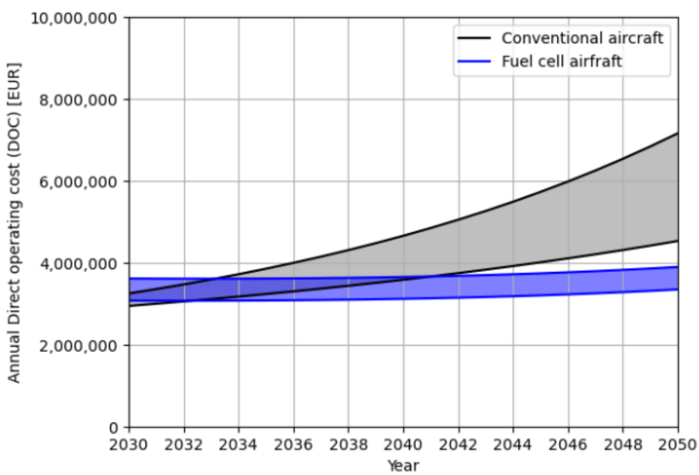

Figure 3: The projected evolution of direct operating costs for the Croatian airline Trade Air
Source: (Marksel, 2023)

5 Conclusion

Hydrogen fuel cell aircraft represent a promising alternative to conventional kerosene-powered aircraft, and have the potential to play an important role in the future decarbonisation of aviation. The analysis presented in this study indicates that ongoing technological developments in fuel cells, electric propulsion systems, and hydrogen storage technologies, could enable hydrogen-powered regional aircraft to become both technically and economically competitive in the coming decades.

Nevertheless, any long-term economic projections should be interpreted with caution. The large-scale adoption of alternative energy carriers, such as hydrogen, would likely influence global energy markets, and could affect the future prices of oil and petroleum-derived fuels significantly. As a result, the future evolution of both hydrogen and kerosene prices remains highly uncertain, making precise long-term predictions difficult.

Despite these uncertainties, the results suggest that hydrogen offers several important advantages, including the potential for low-emission operation, compatibility with renewable energy sources, and long-term sustainability. Consequently, hydrogen fuel cell technology appears to be a promising pathway towards more sustainable regional air transport.

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Povzetek v slovenskem jeziku

Načrtovanje in ekonomska analiza 19-sedežnega letala na vodikove gorivne celice za regionalni zračni promet. Prispevek povzema rezultate projekta MAHEPA, v okviru katerega so raziskovali tehnološko in ekonomsko izvedljivost 19-sedežnih letal na vodikove gorivne celice ter njihov potencial za uvedbo v uporabo do leta 2050. Obravnava ključne zahteve, potrebne za omogočanje njihovega obratovanja in dolgoročne vzdržnosti.

Analiza je razdeljena na tri sklope. Prvi obravnava potrebno infrastrukturo in varnostne ukrepe za regionalno letalstvo na vodik, vključno s proizvodnjo in distribucijo vodika. Drugi ocenjuje razvojne potrebe ključnih tehnoloških komponent, kot so gorivne celice, sistemi za shranjevanje vodika in integracija pogonskega sistema. Tretji sklop analizira ekonomsko izvedljivost, pri čemer so neposredni obratovalni stroški tesno povezani z masnimi značilnostmi letala.

Rezultati ekonomske analize za obdobje 2030–2050 kažejo, da bi lahko bila letala na vodikove gorivne celice stroškovno konkurenčna ob ugodnih cenah vodika in nadaljnjem tehnološkem razvoju, kar podpira njihov potencial kot izvedljivo rešitev za regionalno letalstvo.