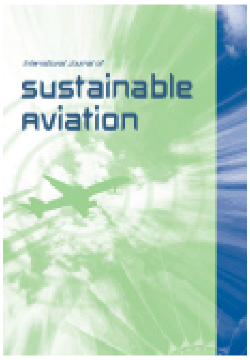

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A steady-state model-based evaluation of performance characteristics and feasibility analysis of retrofit hydrogen-powered aircraft configurations

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A steady-state model-based evaluation of performance characteristics and feasibility analysis of retrofit hydrogen-powered aircraft configurations

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Abstract: In the current study, in light of the zero-carbon emissions targets, the potential of hydrogen-powered propulsion aircraft is evaluated. The analysis of the aircraft power performance is carried out based on a comparison of jet-fuelled propulsion against the characteristics of that powered by hydrogen. A regional aircraft type ATR 72-600 was chosen for the study. It was configured with three propulsive retrofits: jet-fuelled, direct hydrogen combustion, and hydrogen fuel cell. A computational environment was created in Simulink to model the aircraft's power requirements, fuel consumption, propulsion efficiencies and emissions. Both direct combustion and fuel cell hydrogen propulsions demonstrated performance capabilities within key operational parameters with the benefit of reduced fuel consumption in terms of mass, and, thus, better thrust specific fuel consumption. A fuel mass drop of 50% and 80% were obtained for the hydrogen fuel cell and direct combustion, respectively. A weight penalty, however, remains a major drawback in the implementation of hydrogen technology.

Keywords: aircraft design; aircraft performance; aircraft weight; hydrogen; fuel cell; propulsion; fuel combustion; propulsive efficiency.

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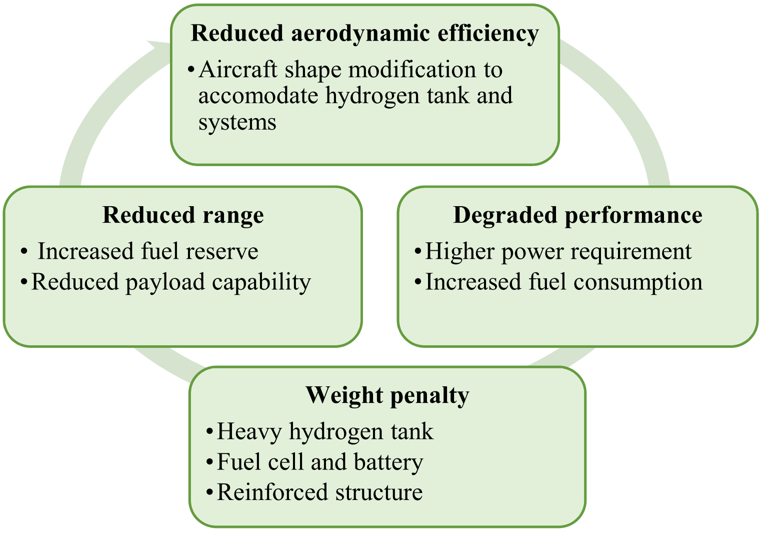
1 Introduction

Sustainable aviation is a long-term strategy that sets out the collective approach of academia and the industry to tackle the challenge of ensuring cleaner, quieter, smarter aircraft. Electrical and hydrogen propulsion technologies for aircraft have a significant potential to reduce the climate impact of aviation and contribute to decarbonisation objectives. CO_2 emissions generated by current aircraft technology amount to more than 900 million tonnes per year (2–3% of worldwide emissions) (Graver et al., 2020), and given the 4% growth rate in aviation, emissions are expected to more than double by 2050 (ATAG, 2020). Previous and current aviation technology programmes have established the need and roadmap to achieving sustainability in aviation through green technology invention and/or implementation.

Electrical and hydrogen-powered propulsions for aviation seems to have gained significant attention in recent years owing to the reduced or zero-carbon emissions involved. A number of design approaches have emerged to demonstrate and evaluate the performance characteristics of aircraft powered by non-hydrocarbon fuel. The ZeroAvia (ZeroAvia, 2023) hydrogen aircraft and the ZEROe Airbus (Airbus, 2023) initiatives, with the possibilities of retrofitting existent single aisle passenger aircraft with alternative propulsion, are examples of accelerated zero-carbon design. However, successful conventional aircraft design is strictly led by aerodynamic efficiencies that provide a benchmark for performance and operational requirements. Any foreseeable zero-carbon design will require a change or modification of an aircraft bulk components' shape, size and, ultimately, weight. The worsening of aerodynamic characteristics seems an early sign of the challenges that aircraft designers and, perhaps, aircraft operators are facing ahead of any viable new technology delivery (Figure 1). Some of the challenges that are currently reviewed in many designs and performance analyses are that hydrogen-powered aircraft will have shorter ranges, there will be less seating capacity, a higher cost of operation will arise, there will be a need for new infrastructure (hydrogen production, refuelling facilities, etc.), and there will be health and safety and operational regulation implications.

Figure 1 Hydrogen technology impact on aircraft performance (see online version for colours)



There is an important gap in the knowledge regarding hydrogen design performance characteristics compared to conventional hydrocarbon-fuelled aircraft. Obtaining and evaluating critical data such as the weight, the power required for cruising, and fuel consumption, by means of numerical modelling, is sought to form a novel approach regarding the findings of this study. The objectives to be pursued in this study are: the development of a computational model to evaluate performance characteristics, to compare and evaluate the computed data between hydrogen and non-hydrogen (hydrocarbon) designs, and, finally, attest to the feasibility of the hydrogen-powered technology in the cruise flight envelope.

1.1 Hydrogen fuel cell design

Hydrogen-powered aviation, for instance, is achieved through the direct combustion of liquid hydrogen (LH2) in a gas turbine engine or as a fuel cell powertrain, of which the characteristics require consideration and an analysis of design at both the component and system level. The component-level consideration deals with hydrogen storage or fuel cell power generation. Meanwhile, the system-level consideration explores the performance of the powertrain or the direct combustion gas turbine in terms of output characteristics (energy consumption, power/thrust production, emissions, and life cycle). Moreover, the performance characteristics of the design will be largely affected by enabling technologies, such as the fuel cell stack, fuel cell system, hydrogen fuel storage, etc. Apart from these design and technological considerations, the adaptation of the aerodynamic design of the aircraft to encompass the new non-hydrocarbon design criteria is thought to pose yet another significant challenge. The implications of such a challenge concern the aircraft's reduced performance capability and its downgraded efficiencies.

Within the ENFICA-FC programme (Environmentally Friendly inter-city aircraft powered by fuel cells – FC), Romero et al. (2012) have carried out a preliminary design of a 10-30-seat aircraft that is powered by hydrogen FC. The configuration of such a design for short-term technology readiness indicated a shortfall in performance capability compared to that of a non-hydrogen design. The increased take-off weight of up to 11.5%, reduced range and maximum cruise speed are examples of such shortfalls. Nicolay et al. (2021), on the other hand, have studied the performance characteristics of a design concept for a hydrogen fuel cell-powered aircraft in tandem with multidisciplinary design optimisation (MDO). The MDO was used to investigate the impact of the hydrogen fuel system on the aircraft's geometry, ultimately comparing the performance capabilities to that of a conventional design (a general aviation aircraft). Efficient configuration was implemented to component-level design, which included components such as a hydrogen tank, FC, and electric motors, as well as passenger seats and a cargo hold. The integration of the fuel cell system and a liquid hydrogen tank was a targeted challenge throughout the design process, one which set the design apart from previous retrofit designs. The design criteria for the aircraft were compared with a conventional one of a similar size, and it was found that a hydrogen fuel cell design was deemed to be feasible and, most importantly, produced no CO_2 emissions. Other examples of hydrogen fuel cell design include, but are not limited to, the Boeing fuel cell demonstrator that is a retrofit design of a two-seat Diamond motor glider (Lapena-Rey et al., 2010), and an HY4 fuel cell-powered aircraft developed and tested by DLR (the German Aerospace Centre) (Aerospace Technology, 2023). While many of the developments remain as concepts and feasibility studies, there is widespread evidence of significant milestones being reached in establishing design criteria and practical measures in materialising hydrogen-powered aviation (Clean Sky2, 2020). However, what will still be a challenge to overcome in hydrogen-based design will depend on several key enabling technologies, such as the fuel cell stack, the fuel cell system, the hydrogen fuel storage/tank, and a safe hydrogen-refuelling and handling infrastructure.

1.2 Direct combustion hydrogen design

The direct combustion of liquid hydrogen (LH2) in aviation propulsion has also been a subject of research and investigation in recent years. A direct hydrogen combustion aircraft design has been investigated and compared to conventional counterparts in a study conducted by Mukhopadhaya et al. (2020). The design was evaluated and optimised using the open-source platform SUAVE (Botero et al., 2016; Lukaczyk et al., 2015). The aerodynamic characteristics of the design were analysed using a low-fidelity concept (Lukaczyk et al., 2015) to assess the compatibility of the design and the level of efficiency that can be achieved. Studies from NASA (Brewer and Morris, 1976) and the Airbus Cryoplane project (Westenberger, 2007) have already attested to the feasibility of LH2 as a fuel for direct combustion in aviation propulsion (gas turbine). Given that hydrogen has a gravimetric energy density of 33.3 kWh/kg compared to kerosene with 12 kWh/kg, it is considered a reasonable alternative as an energy supply (Winnefeld et al., 2018). Depending on the flight mission (range, cruise speed, passenger number, payload, etc.), however, the consideration for a tank design in terms of size, shape, weight, and ultimately adequate integration into the aircraft, externally or internally, becomes a constraining factor. Attempts have been made to propose appropriate tank design to comply with aircraft mission configurations (Brewer, 1991; Mills et al., 2012; Winnefeld et al., 2018; Gomez and Howard, 2019). For a hydrogen design, the maximum take-off weight (MTOW) of an aircraft will be significantly affected by the design and integration of the LH2 storage and fuel system as liquid hydrogen has about four times the volume of jet fuel. This would lead to an increased weight of the storage/fuel system in particular, and the aircraft weight in general. Hence, one should study and analyse the different storage solutions available for minimal weight impact. For the foreseeable future, a direct combustion design may not result in a viable superior alternative compared to that of a hydrocarbon design (jet fuel combustion). This is due to the high mass of fuel storage, normally in the form of a cryogenic tank, that is measured by achievable gravimetric indices (0.2 to 0.35) (Mukhopadhaya et al., 2020). Nevertheless, the potential to achieve (full) decarbonisation seems to be significant. Along with the technical aspects of the hydrogen design, the costs of hydrogen fuel, the health and safety rules and regulations, and the certification and airworthiness of an operating hydrogen-powered aircraft will form another set of challenges that require thorough consideration. They are the adjusting key factors to the economic feasibility of the hydrogen aircraft design and operation, without which the entire hydrogen design concept would be invalidated. A Tupolev 155 (a modified Tu-154 trijet airliner that flew on LH2 in 1988) (Tupolev, 2012), a pioneering large aircraft to be tested for LH2 combustion, ended in facing hurdles on multiple fronts (technological, safety, and costs, etc.). But the important achievement of such a test was that the feasibility of the LH2 as a fuel-for-jet-propulsion aircraft was demonstrated and proved, while also advancing the knowledge regarding a hydrogen fuelling infrastructure (Reiman, 2009). All of these have become the subject of extensive research in the academic and industry fields.

2 Methodology

The feasibility analysis of hydrogen-powered aircraft design was largely based on a comparison of key performance parameters with conventional aircraft models (with conservative design attributes). The selection of such conventional models should, to a large extent, represent a major proportion of the aviation traffic measured by revenue passenger kilometres (RPKs) above 50%. Usually, this is the regional and short-to-medium haul market. Based on studies conducted by Bogaert (2015) and Eissele et al. (2023), it was found that the aircraft model that would best satisfy the feasibility and validation criteria is the short-haul single aisle turboprop commuter plane. Based on the high volume-to-weight ratio of hydrogen, in the current study, the selection criteria of a model aircraft involved meeting the requirements for MTOW and range. Given the hydrogen fuel and tank systems weight constraint, the performance characteristics were expected to be confined to a passenger number of 50–100, with a range of less than 1,000 NM, and a flight time of up to three hours. The ATR 72-600 (ATR, 2023), with technical data presented in Table 1, has been found to be the most prominent model used in a range of research straddling the academic spectrum. This seems to be the most promising class of aircraft for the implementation of hydrogen technologies in the short and medium term (Cantú et al., 2022).

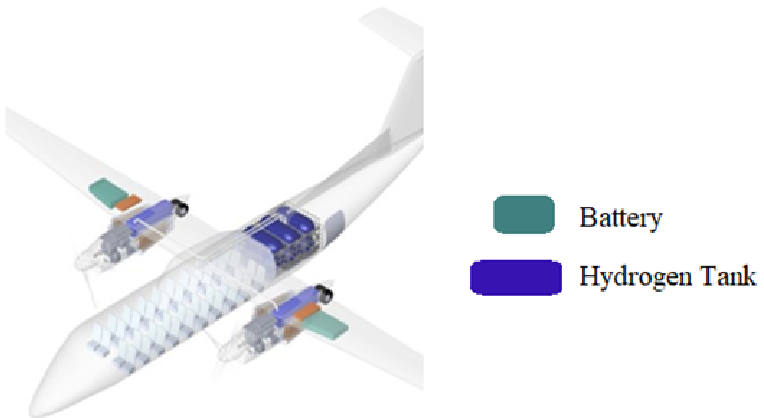
In this study, the model aircraft performance is studied in three power configurations: namely jet fuel-powered, fuel cell hydrogen-powered, and direct LH2 combustion-powered flight. The hydrogen-powered configuration (fuel cell/direct combustion) has a peculiar weight penalty as discussed earlier; thus, the current study will assess the performance of the aircraft in light of the mass (weight) and range constraints in the cruise phase. Although the design of the tank and fuel systems are beyond the scope of this study, a weight estimate of the tank and fuel is made to be incorporated into the computational environment. And given that the aircraft is retrofitted with hydrogen-based propulsion, the study assumes that the tank is internally integrated into the fuselage (Figure 2), and that no significant changes have been made regarding the overall shape, size and aerodynamic layout of the aircraft (except the weight). It is understood that the placement of a heavy hydrogen tank in the aft section of the fuselage will inevitably have implication on the CG and, hence, the stability and control of the aircraft, the impact of which is not considered nor assessed in the current study.

Table 1 ATR 72-600 specifications (ATR, 2023)

Aircraft	*ATR 72/600*
Powerplant	2×PW127XT-M
Maximum power (kW)	3,908
MTOW (kg)	23,000
Range (NM)	740
Fuel load (kg)	5,000
Ceiling (ft)	25,000
Wingspan (m)	27.05
Wing surface (m^2)	61
BSFC (g/kWh)	279
Cruise speed (knots)	280
CO2	62 g/pax/km
Max payload (kg)	7,400
Seating	72
Crew	4
Propeller diameter (m)	3.93

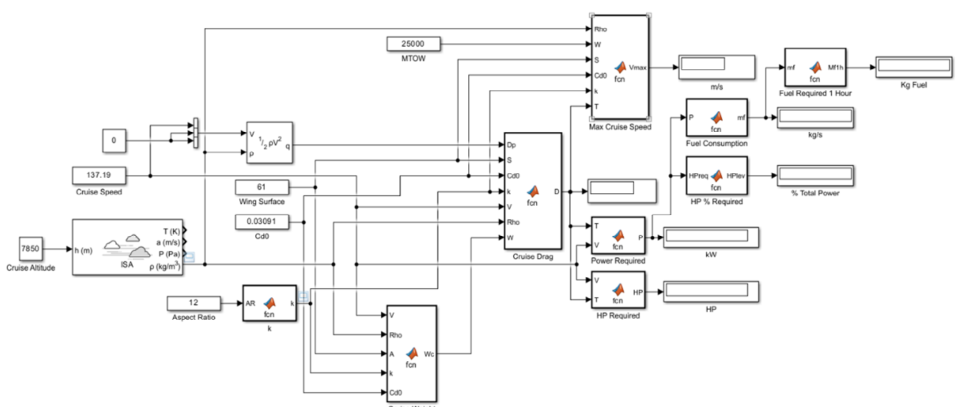
A computational model based on a Simulink platform (MathWorks) has been developed that incorporates aerodynamic and performance equations. These equations include design quantities such as wing area, wing loading, MTOW, volume for energy, re-engineering, to model the aircraft flight characteristics (Figure 3). Such a model allowed for an accurate and more convenient approach to numerically evaluating performance characteristics of a flight configuration. Quantities that are computed by the model are thrust and power required, fuel mass, fuel consumption, efficiency indicators, and maximum cruise speed. The power requirement and scalability of hydrogen propulsion with increased MTOW or modification to aerodynamics can be obtained concurrently. The modelling of flight physics is based on the classic aerodynamic model that is also used for validation purposes (Anderson, 1999). A quasi-steady flight configuration comprising only the cruise phase was used in the modelling. It is worth noting that aircraft usually spend most of their flight in cruise configuration, hence it is important to initially evaluate and/or assess the performance characteristics of the model aircraft retrofitted with hydrogen-powered propulsion in steady cruise conditions. As such, when modelling the flight envelope, a constant RPM of the rotor/propeller system, and a constant speed at constant altitude are considered as the main boundary conditions to the modelling procedure.

Figure 2 Tank and passenger cabin layout for the hydrogen-powered turboprop (see online version for colours)



Source: Universal Hydrogen (2023)

Figure 3 Selected diagram of Simulink cruise modelling programme (see online version for colours)



2.1 Model equations and constraints

The mathematical model describing the aircraft's characteristics considers different types of constraints and key indicator factors. The aircraft mass and propulsive specification must ensure the feasibility of the flight at the given configuration; i.e., flight altitude, atmospheric conditions, minimum thrust/power required, speeds, etc. In the following sections, the characteristic equations used to model the flight mission are presented with a focus on the implication of the weight constraint due to the propulsion retrofit imposed on the mission parameters.

2.1.1 Weight

The total mass of the aircraft entering the cruise phase must be below the MTOM (at take-off), as shown in equation (1):

$$m_0 + m_p + m_f < MTOM \tag{1}$$

where m_0 is the aircraft's gross mass, m_p is the mass of the propulsion system, and m_f is the mass of the fuel system (which includes the fuel, storage, and fuel delivery systems). Estimating the mass and/or weight of the aircraft MTOM/MTOW, propulsion and fuel storage systems for the hydrogen retrofit is based on the methodology given by NACA (Wells et al., 2017). For a gravimetric index (GI) of 0.35, the model aircraft with hydrogen retrofit will have an increased weight of approximately 10%. The GI accounts for the lump weight of hydrogen storage and delivery systems (tank, heat exchanger, pipes, pumps, seals, valves). A GI of 0.35 (equation (2)) is an assumed and required value to achieve specific energy parity between hydrogen and jet fuel at the system level.

$$GI = \frac{Mass\ of\ stored\ fuel}{Mass\ of\ stored\ fuel\ +\ Mass\ of\ the\ entire\ fuel\ system} = 0.35 \tag{2}$$

The MTOW of the model aircraft is used to compute the flight mission at maximum fuel and payload (including passengers) capacity, and to evaluate the impact of the weight penalty due to the hydrogen retrofit technologies.

2.1.2 Cruise aerodynamics and power quantities

During the cruise phase, the aircraft should satisfy the thrust requirement at a given altitude and speed. In a steady state cruise, the forces acting on the aircraft produce no excess forces, the lift is equal to the weight and the thrust is equal to the drag. For the quasi-steady analysis in this study, in spite of the weight being decreased due to fuel burn, the cruise mission configuration was set up for a range of a one-hour flight, where the condition in equation (3) was applied:

$$T = D = \frac{W}{Cl / Cd} \tag{3}$$

where W is the weight of the aircraft in cruise and Cl/Cd is the aerodynamic efficiency or glide ratio of the aircraft. From the classic aerodynamic theory, the drag D is estimated by equation (4) (Anderson, 1999):

$$D = \frac{1}{2}\rho_\infty V_\infty^2 S C_{D0} + \frac{2kS}{\rho_c V_c^2}\left(\frac{W}{S}\right)^2 \tag{4}$$

where values for C_{D0}, atmospheric conditions (density), and k (induced drag factor) are entered into the modelling as the initial/boundary quantities. The available power of the turboprop aircraft during cruise is then obtained by equation (5):

$$P_A = \eta_{pr} P = T.V \tag{5}$$

where p is the shaft power required, and η_{pr} is propeller efficiency (a value of 0.85 is considered (Anderson, 1999)). At maximum cruise speed and cruise weight, the required shaft power is provided by equation (6):

$$P = \frac{1}{\eta_{pr}} \frac{T}{W} .W.V_{max} \tag{6}$$

For the hydrogen fuel cell design, the power/thrust is generated by a propeller which is powered by an electric motor (engine). The shaft power of the propulsion system is found by using equation (7):

$$SHP = \frac{VI\eta}{746} \tag{7}$$

where *SHP* is the output power in horsepower, *V* is the input voltage, *I* is the input current and η is the electric motor efficiency. FC provide maximum-rated power in kW. Based on the commercially available P-stack fuel cell (PowerCell Group, 2022), a fuel cell can supply up to 125 kW of electrical energy per stack. The total current consumption of the system is estimated based on 230V and a motor efficiency of 0.9, as shown in equation (8):

$$I = \frac{746.SHP}{230\ .0.9} \tag{8}$$

The total required power in kW is found by the product of voltage and current proved by equation (9):

$$P_{stack} = I.V \tag{9}$$

It is also possible to determine the amount of cell stacks for the given power output. P-stack FC can be paired in either a series or parallel configuration. Finding their total number was achieved by dividing the total required power by the maximum power provided per stack, given by equation (10):

$$n_{fuel\ cell\ stacks} = \frac{P_t}{P_{stack}} \tag{10}$$

2.1.3 Fuel consumption

2.1.3.1 AVTUR (aviation turbine fuel)

The metric for fuel consumption of a conventional jet-fuelled turboprop is given as (BSFC). This metric represents the mass of fuel required to generate one kW of power per unit of time. It is a key efficiency indicator of the propulsion system, and for maximum-rated power it is found using equation (11) (Gudmundsson, 2014):

$$BSFC = \frac{\dot{m}_f}{P} \tag{11}$$

from which the fuel mass flow rate is followed by equation (12):

$$\dot{m}_f = P.BSFC \tag{12}$$

For the fuel consumption during the cruise phase for the turboprop *AVTUR*, the *BSFC* is considered constant per given cruise power, as shown in equation (13):

$$\dot{r} = \left(\frac{P_{cruise}}{P_{max}} \right).100.BSFC \tag{13}$$

Converting the above results into a standard unit and multiplying it by the given cruise time, the total fuel mass is obtained for the flight mission. Cruise time is given by t_c; hence, the required fuel mass is obtained by equation (14):

$$m_{fuel} = \dot{m}_f .t_c \tag{14}$$

2.1.3.2 Hydrogen fuel cell

Fuel consumption for the hydrogen fuel cell design is not a direct relationship to aircraft power. Any proposed hydrogen-based fuel systems usually include batteries to smooth out the power (Hartmann and Nøland, 2022). This means that the load on the FC is not always constant or proportional to the total power required. A P-stack system (PowerCell Group, 2022) that contains 455 cells and weighs 42 kg was implemented in the retrofit technology. The hydrogen consumption per stack was found based on the manufacturer's data, the chemical properties of hydrogen and a given run time. Equation (15) is based on the total power produced by the FC with a lower heating value of the fuel.

$$\dot{m}_{H_2} = \frac{P_{stack} t.3600}{\eta.LHV_H} \tag{15}$$

where P_{stack} is the total power of hydrogen per fuel cell stack, t is the run time in hours, η is the efficiency of the fuel cell and LHV_H is the lower heating value of hydrogen. Taking this fuel consumption as the 125 kW rated output power, the fuel consumption per kW is calculated by equation (16):

$$\dot{m}_{H_2/kW} = \frac{\dot{m}H}{P_{stack}} \tag{16}$$

where P_{stack} is the total power provided by one stack rated at 125 kW. The hydrogen fuel consumption per fuel stack is calculated by equation (17):

$$\dot{m}_{H_2c} = \frac{\dot{m}H}{kW} n \cdot P_{req} \tag{17}$$

where n represents the required number of fuel cell stacks and P_{req} is the minimum power required in cruise. Factoring the cruise time into the hydrogen fuel cell, the total flight mission fuel mass is found by equation (18):

$$m_{H_2t} = t.\dot{m}_{H_2c} \tag{18}$$

The BSFC for a hydrogen fuel cell is given by equation (19) (Gudmundsson, 2014):

$$BSFC_{Hcell} = \frac{\dot{m}_{H_2c}}{P_{cruise}} \tag{19}$$

2.1.3.3 Direct hydrogen combustion

Calculating the fuel consumption for the direct hydrogen combustion will require a different approach. First, the total amount of energy of the AVTUR fuel that is used by the turboprop engine is found from equation (20), with the known AVTUR energy content value being 43.147 MJ/kg (Annamalai and Puri, 2006):

$$E_{AVTUR} = LHV_{AVTUR}.\dot{m}_f \tag{20}$$

where LHV_{AVTUR} is the lower heating value of the *AVTUR* expressed in MJ/kg, and $\dot{m}_f$ is the mass of fuel flow for the turboprop engine found previously at maximum power. The previous fuel flow calculations based on BSFC are applied again in equation (21). Now, with the minimum power required for the hydrogen combustion, BSFC was kept constant at the initial value.

$$\dot{m}_{P\ combustion} = P_{H_2 combustion}.BSFC \tag{21}$$

where $\dot{m}_{P\ combustion}$ is the mass of fuel flow for the minimum power required for the direct hydrogen combustion configuration, and $P_{H_2 combustion}$ is the minimum cruise power. The energy of the amount of fuel burnt is calculated by equation (22):

$$E_{AVTUR\ cruise} = LHV_{AVTUR}.\dot{m}_{Pcombustion} \tag{22}$$

As the hydrogen power requirement was taken into consideration, the quantity of hydrogen needed to generate the same calorific value can be found. As shown in equation (23), this was achieved by dividing the required energy $E_{AVTUR\ cruise}$ by the lower heating value of hydrogen LHV_{H_2}.

$$\dot{m}_{H_2} = \frac{E_{AVTUR\ cruise}}{LHV_{H_2}} \tag{23}$$

From here, the same steps were applied as for the *AVTUR* fuel. The units were all converted into the standard international. The fuel consumption in kg/s was then multiplied by the cruise time (in seconds) to find the total fuel mass using equation (24):

$$m_{H_2 fuel} = \dot{m}_{H_2}.t_{cruise} \tag{24}$$

2.1.4 Propulsive and thermal efficiency

The propulsive efficiency of the turboprop AVTUR engine was found from equation (25) (Spakovsky, 2006). This was sequentially coded in the modelling environment after thrust, and where the atmospheric and velocity quantities were known for the given configuration.

$$\eta_p = \frac{2}{1+\sqrt{\dfrac{T}{A_{disc}v^2\dfrac{\rho}{2}}+1}} \tag{25}$$

where v is the cruise speed in m/s and A_{disc} is the area of the propeller disc. The ATR 72-600 has a propeller of 3.93 m in diameter, resulting in a disc area of 12.13 m^2.

The propulsive efficiency of the turboprop running on hydrogen is based on the presumption of power generated by a motor in terms of consumed heat energy. With imperial units in mind, equation (26) states:

$$\eta_p = \frac{3600\ .550.P_{shaft}}{HhJ} \tag{26}$$

where P_{shaft} is the engine power measured at the output shaft in horsepower, H is the calorific value of the fuel in BTU/lb (British thermal unit/lb), and h is the fuel consumption rate in lb/hr. J is the mechanical equivalent of heat equal to 778.24 ft.lb/BTU. For hydrogen, the calorific value is 18850 BTU/lb.

In the case of a hydrogen fuel cell design, an electric motor is used to drive the propeller system. According to the literature (Deisenroth and Ohadi, 2019) the (target) efficiency of high-power electric motors powered by FC and recommended for aviation will have an efficiency value of 80–90%. This should not be confused with the fuel cell conversion efficiency of 55%. Schmelcher and Häßy (2022) have expressed the propulsive efficiency of fuel cell-powered propulsion system as shown in equation (27):

$$\eta_p = \frac{F_N.U}{P_{shaft}} \tag{27}$$

where F_N is the net thrust, and U is flight velocity.

Thermal efficiency is pertinent to internal combustion propulsions. The thermal efficiency was calculated only for the AVTUR and hydrogen combustion retrofits (equation (28)). In the case of the AVTUR conventional engine, Dinc and Gharbia (2020) stated that thermal efficiencies in the range of 25%–35% are common. Less certain data is available for the hydrogen combustion, however, with Hosseini and Butler (2019) stating values of 20–25%.

$$\eta_{th} = \frac{(1+f)u_e^2 - u^2}{2\dot{m}_f \cdot LHV} \tag{28}$$

And overall efficiency is expressed as the product of thermal and propulsive efficiency given by equation (29):

$$\eta_o = \eta_p \cdot \eta_{th} \tag{29}$$

2.1.5 Emissions

Calculating the NO_x emissions of an internal combustion jet engine was performed on the basis of propulsive efficiency, rate of fuel consumption, the flight time and the type of fuel used, as shown in equation (30):

$$AE_{NO_x} = EF_{NO_x}.Q \tag{30}$$

AE_{NO_x} is the amount of NO_x emissions, EF_{NO_x} is the coefficient of NO_x emissions of the fuel type and Q is the heat per time. The total heat Q is an input that is calculated from equation (31):

$$Q = F_{max}.LHV_{AVTUR}\cdot_{AVTUR}.t_c\cdot\frac{1}{\eta_p.10^6} \tag{31}$$

where F_{max} is the maximum fuel usage in cruise, LHV_{AVTUR} and ρ_{AVTUR} are the lower heating value and density, respectively, of AVTUR, t_c is the cruise time and η_p is the propulsive efficiency.

Carbon oxide emissions (CO_2) are calculated based on an industry standard emission factor. As shown in equation (32), the emission factor when multiplied by the fuel used provides an approximate estimate of CO_x emissions for the given burnt amount of fuel. In the case of *AVTUR*, this constant e_{AVTUR} is equal to 3.125. That is, for every 1 kg of *AVTUR* burnt, 3.125 kg of CO_2 are released to the atmosphere (United States Environmental Protection Agency, 2014).

$$CO_{xemissions} = M_{fuel}.e_{AVTUR} \tag{32}$$

3 Results and discussion

The modelling environment was developed in Simulink (MathWorks) and excel. power characteristics, fuel consumption and efficiencies were modelled for cruise performance, where the weight estimates were performed for the design MTOW in three propulsive configurations (factoring in the weight of the tank/fuel system). The model aircraft used for this study was the ATR 72-600. It is a regional airliner that seems to be the most studied for hydrogen technology. Also, it is the most promising type/class of aircraft for hydrogen technology implementation in the short and medium term.

3.1 Weight characteristics

The results were obtained for the cruise phase of the flight mission, as it is usually the longest segment and accounts for most of the flight's used fuel and produced emissions. The aircraft enters this phase with a weight of 90% MTOW as 10% of the fuel would have been used during take-off and climb. For the hydrogen retrofit, structural considerations are necessary due to the heavy LH2 tank and the fuel cell stacks. The fuel required for the aircraft's entire flight mission in terms of LH2 is 1,754.38 kg. In terms of energy content/release, this amount of LH2 is equivalent to 5,000 kg of AVTUR in the conventional configuration (hydrocarbon design). For a GI of 0.35, the mass of the LH2 storage system and balance of plant (BoP) combined are of a value of 3,257.4 kg. In the case of a fuel cell retrofit, for the defined flight mission, 28 hydrogen fuel cell stacks of a total weight of 1,176 kg would be required (42 kg per stack). The weight of batteries and electric motors are 4,000 and 800 kg, respectively. The selection of the batteries and electric motor is based on energy characteristics, whereby modern Li-Ion batteries boast an energy density of 250 kW/kg (Xie et al., 2021). At maximum thrust, the electric power of 2 MW is required; this would be supplied by batteries with an output of 4 MWh. These specifications resemble that of the Airbus E-Fan project that was designed to use a Siemens 2MW electric motor rated at 5.2 kWh/kg (Fehrm, 2017). Based on the thrust to weight ratio, a mass of 400 kg per motor was used for the modelling. The electric motor runs on a 2-tonne battery; therefore, for the two motors used for the model aircraft, a battery weight of four tonnes was added to the MTOW. Summing up all the weight components (including the LH2) a total mass of 31,071 kg for the aircraft with fuel cell hydrogen technology was determined.

For the direct hydrogen combustion configuration, however, where there are no electrical components (batteries, motors, etc.) used, a total mass of 25,011 kg was estimated, of which 5,011 kg was the weight portion of the fuel storage system, including LH2 of 1,754.38 kg. By contrast, the AVTUR fuel system (including jet fuel of 5,000 kg) would weigh 7,300 kg.

Table 2 summarises the initial boundary conditions for the modelling. These conditions represent a typical flight mission of the ATR 72-600 that is cruising at an altitude of 7,850 m with a cruise speed of 137.19 m/s. The max possible cruise speed is verified by equation (33) (Anderson, 1999):

$$V_{\max} = \sqrt{\frac{\left[(T_A)_{\max}/W\right]\left(W/S\right)+\left(W/S\right)\sqrt{\left[(T_A)_{\max}/W\right]^2-4C_{D_o}K}}{\rho_\infty C_{D_o}}} \tag{33}$$

Table 2 Initial boundary conditions

	Conventional	*Fuel cell electric*	*LH2 combustion*
MTOW (kg)	25,000	31,071	25,011
Cruise mass (kg)	22,500	27,963	22,509
Fuel mass (kg)	5,000	1,754.38	1,754.38
Wing surface (m^2)	61		
C_{D0}	0.03091		
Cruise altitude (m)	7,850		
Cruise time (s)	3,600		
Wing aspect ratio	12		
Cruise speed (m/s)	137.19		

3.2 Power and thrust characteristics

Power characteristics for the fuel cell electric motor and direct hydrogen combustion propulsion are obtained based on the maximum thrust produced by the propeller during the cruise phase. In the case of the fuel cell retrofit, a cell voltage of 230 V was considered, and from equations (8–9), the continuous current draw of 4.5 kA and a total power requirement of 2.172 MW per motor were determined. Based on the power requirement for the fuel cell system, a minimum amount of 28 PowerCell P-stacks (PowerCell Group, 2022) was established.

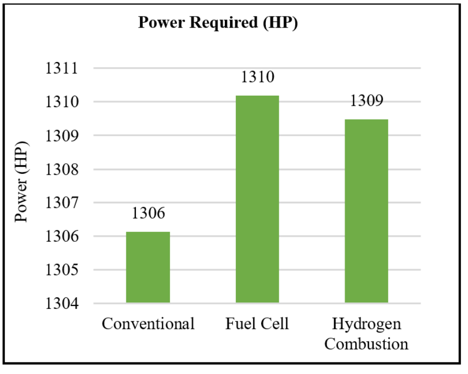
Since for the steady flight a constant RPM on the propeller system is needed, the electric motor output should be constant too. As such the voltage is constant, and the variable considered for controlling power is current that is being calculated by the numerical model.

To provide a constant voltage and hence constant power, and in line with the retrofit configuration the fuel cell stack was selected with given properties that matched the required power characteristics of the propulsion system in steady flight (cruise). The mass and volume of the fuel cell system as stack were considered for the weight modelling, and constant fuel cell voltage of 230 V was the input to the modelling environment.

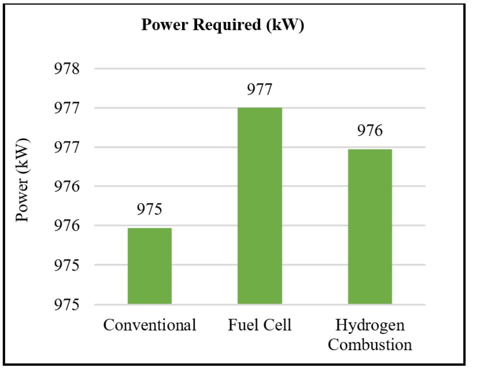
The results in Figure 4 illustrate the cruise power output of the shaft to the propeller. This means that the actual power produced by the motors needs to be higher to account for propeller deficiencies. The impact of the heavier weight on the power output is evident, though still compatible with a conventional counterpart.

The modelling programme also enabled an analysis of the scalability of the power characteristics in respect of the aircraft weight, as shown in Figure 5. The requirement for power is almost linearly proportional to the MTOW. One should note that any excess weight in the hydrogen design will inevitably lead to a higher requirement of power for the aircraft operation envelope.

Figure 4 Minimum cruise power required, (a) in horsepower (b) in kW (see online version for colours)

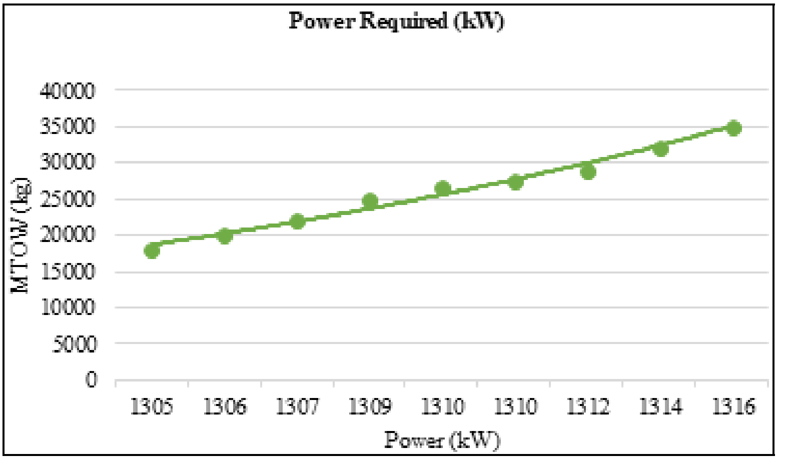


(a)



(b)

Figure 5 Required power scaling with MTOW (see online version for colours)

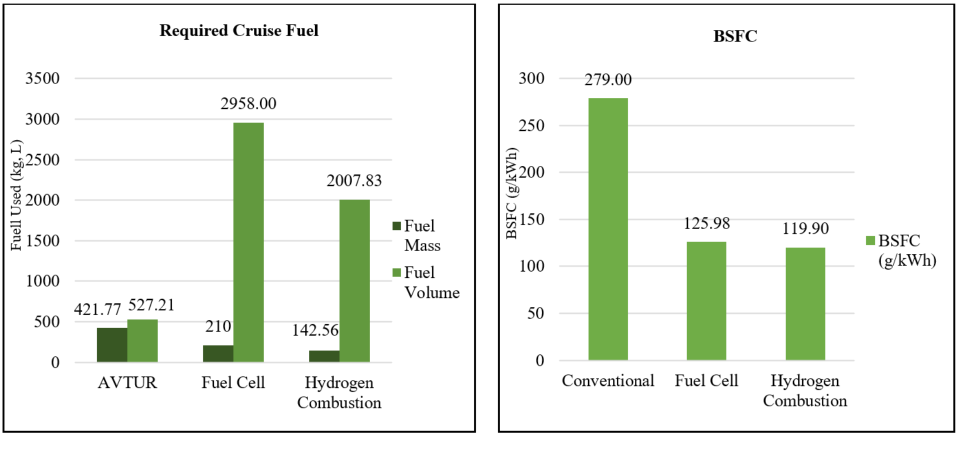


3.3 Fuel consumption

For the conventional propulsion of ATR 72-600, the manufacturer's declared value of BSFC along with propeller efficiency of 85% were used to perform the fuel consumption analysis in the modelling environment. From equation (12), and with the cruise power found in Section 3.2, a fuel flow of 117.157 g/s was obtained. With the prescribed one-hour cruise time, a total fuel mass of 421.766 kg, or a volume of 527.205 litres (based on the AVTUR density of 800 kg/m^3) was estimated.

Equation (15) was used to find the amount of hydrogen consumed per fuel cell. A fuel cell efficiency of 50% was assumed, along with the manufacturer's stated 125 kW per stack (PowerCell Group, 2022). Taking the lower heating value of the liquid hydrogen (LHVH) as 33.33 kWh/kg (Tretsiakova-McNally, 2016), the hydrogen consumption per stack was found to be 7.5 kg/h. Consequently, for the 28 stacks the total hydrogen mass required was 210 kg and based on the LH2 density of 71 kg/m^3 this mass of hydrogen is equivalent to a total volume of 2,958 litres. With the rated power output of 125 kW/stack, the fuel consumption per kW was found to be 60 g/kW. An approach of energy equivalence presumption was adopted for the direct hydrogen combustion. Given the fuel burn rate for the AVTUR propulsion was 117.15 g/s and considering the hydrogen energy content was approximately 2.85 times higher than that of kerosene, the fuel consumption rate of 39.6 g/s was found for the direct hydrogen combustion. For the one-hour cruise, the total required LH2 was 142.556 kg (2,007.83 litres). Knowing the fuel consumption and power output, the BSFC was calculated from equation (11) (Figure 6(b)).

Figure 6 Fuel consumption, (a) cruise fuel (b) brake specific fuel consumption (BSFC) (see online version for colours)

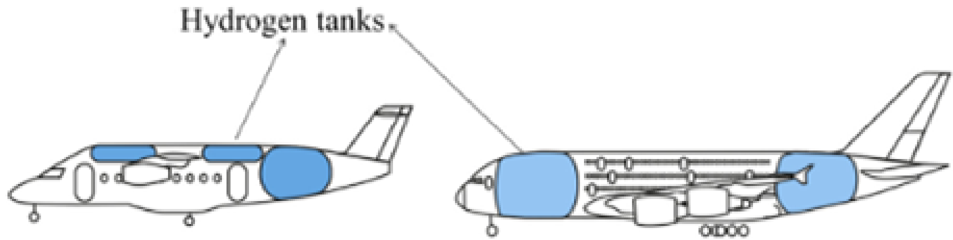


(a) (b)

The most significant and notable characteristic of hydrogen fuel compared to the AVTUR is the emerging higher volume (Figure 6(a)). The hydrogen fuel would, therefore, require a larger storage system. The implication of such a larger storage system is that there will be weight, shape and aerodynamic penalties imposed on the aircraft.

Studies have suggested that integrating an LH2 tank will inevitably require modifications to the size, weight, and shape of the aircraft. Baroutaji et al. (2019) demonstrated the positioning of the hydrogen tank in three fuselage configurations: the forebody, top, and rear body (Figure 7). Modifying the shape of the aircraft by increasing its length or diameter, for example, may lead to deteriorated aerodynamic performance. Nicolosi et al. (2015) obtained simulation results for a zero-lift drag coefficient of the ATR 72 with a 10% and 20% increase in fuselage diameter that resulted in a 7% drag increment. This comes with a power requirement of up to 1,565.45 kW, a power penalty of 19.43%. The increase of the aircraft weight due to the hydrogen storage system has been reflected in the modelling environment as explained in Section 3.1.

Figure 7 Proposed hydrogen tank position inside the fuselage (see online version for colours)



Source: Baroutaji et al. (2019)

3.4 *Efficiency*

The overall efficiency of all three propulsive configurations are the functions of four key factors: namely propeller efficiency ($\eta_{propeller}$), propulsive efficiency (η_{prop}), powertrain efficiency ($\eta_{prowertrain}$), and thermal efficiency ($\eta_{thermal}$). For a turboprop aircraft like an ATR 72-600, the thrust is generated by the propeller, and the efficiency of the propeller is assumed to be 85% (Anderson, 1999). The propeller itself is powered by a jet engine in the case of an AVTUR and direct combustion propulsions, and by an electric motor in the case of a hydrogen fuel cell design. The propulsive efficiency of a jet engine-powered propeller is calculated using equations (25–26), where the energy density of the fuel is a dominant factor in the computational procedure. An energy density of 44.65 MJ/kg was used for conventional aviation fuel, and 120 MJ/kg for the hydrogen. The modelling of the propulsive efficiency for the conventional jet propulsion during cruise resulted in a value of 71.76%, which is well in agreement with the expected range of 70–85% reported by the literature (Raymer, 2018). Meanwhile, for the hydrogen combustion, a propulsive efficiency of 88.85% was obtained. The results of the efficiency modelling are illustrated in Figure 8. In Table 4, the efficiency characteristics are compared for the three propulsive retrofits.

For the electric motor, the efficiency value was adopted from the literature/research estimates. It was found that high-power electric motors run at efficiencies ranging from 80% to 98% (Deisenroth and Ohadi, 2019). An average value of 89% was used (Figure 8).

The powertrain efficiency considers the losses found in the power transfer system acting between the propulsive unit and the propeller. For a jet-powered propeller, the powertrain comprises a gearbox with an efficiency value of 95% (Anderson et al., 1984; Howe et al., 1988). In the case of a hydrogen fuel cell, the powertrain is fitted with batteries for power smoothing and redundancy. Modern Li-Ion batteries, which have an efficiency range of 75.6% to 97.9%, are used in powertrains (Samadani, 2015). An average of 90% battery efficiency was considered to be an adequate representation of the powertrain efficiency.

Figure 8 Propulsive efficiency (see online version for colours)

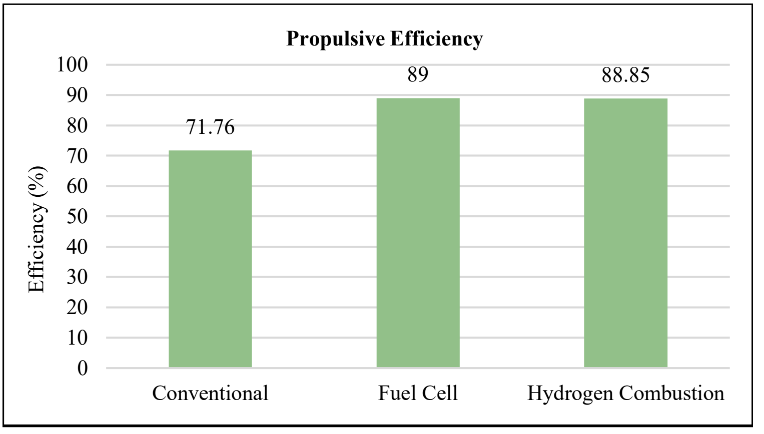


Table 4 Efficiency characteristics

	Conventional	*Fuel cell*	*LH2 combustion*
Propeller efficiency (%)	85	85	85
Propulsive efficiency (%)	71.76	89	88.85
Thermal efficiency (%)	25–35	40–60	20–25
Powertrain efficiency (%)	95	90	95
Overall efficiency (%)	18–25	35–53	18–22
Fuel consumption (g/s)	117.157	58.3	39.6

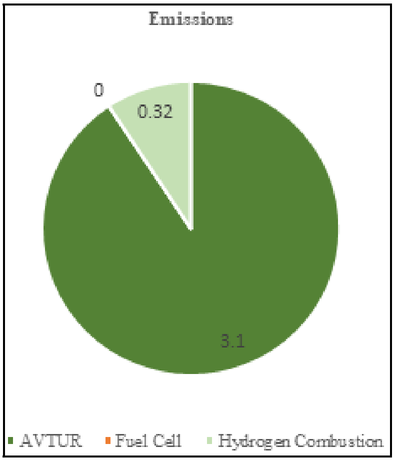
Thermal efficiency is another key factor in determining the feasibility of hydrogen propulsion technology. It refers to the amount of power an engine can extract from the fuel during combustion and/or a chemical reaction. It is calculated using equation (28). With a higher thermal efficiency, more heat and, therefore, more power is generated by the engine. AVTUR turboprop engines have a thermal efficiency of between 25% and 35% (Dinc et al., 2020), and according to Hosseini et al. (2019), in the case of hydrogen combustion, only a thermal efficiency between 20% and 25% is expected, theoretically. Retrofitting modern turboprop engines to run on hydrogen may lead to a decreased thermal efficiency performance. Energy efficiency is the equivalent of thermal efficiency in the case of fuel cell propulsion. It shows the amount of usable electrical energy the chemical oxidation process yields. Lu et al. (2022) and Ellis et al. (2001) place this energy efficiency in the range of 40% to 60%.

3.5 NO_x emissions

The NO_x and CO_x emissions produced by the ATR 72-600 in a one-hour flight in cruise are computed using equations (30–32). CO_2 emissions are functions of fuel-to-air ratio and combustion temperature. They are found based on an emission constant that is specific to each fuel type. For AVTUR, this constant is 3,125 (United States Environmental Protection Agency, 2014) that, when multiplied by the mass of fuel burnt during cruise, which is 421.77 kg, a total CO_2 emissions of 1,318 kg is obtained. To find the amount of NO_x compounds released into the atmosphere, equations (30–31) are used in the computational environment. The total NO_x emissions of 3,213 kg per hour of flight was found.

In estimating and analysing NO_x emissions for hydrogen propulsion, the fuel (hydrogen)-to-air ratio is more delicate to adjust compared to AVTUR due to the high energy content of hydrogen. Methods of calculating NO_x emissions for hydrogen combustion, such as the Zeldovich mechanism (Zhang et al., 2017), and emission indices (EIs) (Khan et al., 2022), have been used to provide an estimate for the NO_x emissions for the one-hour cruise of the ATR 72-600 with hydrogen-powered propulsion. The NO_x emissions from hydrogen-fuelled aircraft were found to be one order of magnitude lower (0.3 kg) than in the AVTUR aircraft (3,213 kg). Overall, the total NO_x emissions were reduced in the hydrogen-fuelled aircraft by 86% compared to the AVTUR, which agrees with the existing literature, reinforcing the idea of liquid hydrogen being a fuel that has the potential to significantly offload the aviation impact on climate (Figure 9).

Figure 9 NO_x emissions (kg/h) (see online version for colours)



4 Discussion

Hydrogen technology has demonstrated the potential for revolutionising aviation towards net zero-carbon emissions. On a multitude of scales of technology, demonstrators are achieving performance targets while deficiencies and shortcomings have been improved and/or refined.

Numerical studies, including the current one, have been established to evaluate the design and performance characteristics of hydrogen propulsion technologies for aviation. Regional turboprop aircraft such as the ATR 72-600 have been widely used as a model to attest the feasibility of hydrogen technology. The computational techniques provide data on the effectiveness of the various hydrogen technology applications. The feasibility of hydrogen-powered aircraft in terms of performance requirements in comparison to conventional hydrocarbon design has been the focus of the current study. Such performance requirements have been shown to fit within the cruise flight envelope. Results from the ATR 72-600 cruise modelling have shown a more efficient hydrogen propulsive operation compared to the AVTUR, with an almost 50% reduction in fuel consumption. Although this would lead to a reduced on-board fuel load, the weight-saving benefit would be counter-balanced, or even superseded by the weight impact due to the heavy LH2 storage and fuel systems. Furthermore, adjusting the shape and size of the aircraft to accommodate heavy and bulky tanks would impact the seating and payload capacity and, perhaps, the range of the aircraft. Due to the low volumetric energy density of hydrogen, a high-mass storage system would still be an obstacle to maintaining compatible capability. Therefore, improvements in LH2 storage technology to increase GI would be a key factor in the feasibility consideration.

The development of a hydrogen combustion gas turbine is thought to be a cumbersome task, but as can be seen from the numerical results, the low fuel consumption of a hydrogen propulsion retrofit, and the high propulsive efficiency would warrant an improved aircraft performance capability. Higher flying range, more passengers and load to carry, lower running cost, etc. are examples of such a performance improvement (Godula-Jopek and Westenberger, 2016). Fuel cell technology, on the other hand, is constrained by the electric architecture, where the fuel cell system has a relatively high mass density. As such, to scale up the power output, there would be a significant weight penalty due to more fuel cell stacks and a bigger electric motor. The results obtained in this study have indicated the lower fuel mass needed, but the mass of the fuel cell stacks, and the electric motor negated the benefit of this lower fuel mass. Therefore, in the case of regional flight, there would be limitations in range if seating and payload are to stay unchanged.

Hydrogen fuel cell and combustion technologies have been shown to be able to perform as mainstream propulsion technology. All the modelled performance characteristics obtained in the computational environment have proven that the technology can meet the flight operation requirements, following compromises made in terms of weight, range, shape and size. CO_2 emissions, however, are advantageous when utilising either of the hydrogen architectures, which will make the technology a viable future for zero-carbon aviation.

5 Conclusions

In the current study, a numerical yet practical platform has been developed to evaluate the performance characteristics of hydrogen retrofit technologies in two different configurations. The performance characteristics of the hydrogen retrofit was compared to the original hydrocarbon design. The study had a particular focus on weight and volume constraints. A model aircraft of type ATR 72-600 was chosen to attest the feasibility of the technology.

The outcome of the modelling analysis results in the following key conclusions:

- Hydrogen retrofitted aircraft present worsening weight characteristics due to the higher hydrogen volume required to be encompassed in the appropriate tank system.

- Aircraft retrofitted with direct combustion hydrogen would result in a reduction in fuel consumption by almost a third of the original hydrocarbon design, while fuel cell technology has shown fuel consumption to be half of the original aircraft model.
- The power required in cruise configuration is almost the same for both direct combustion and fuel cell hydrogen retrofits, though they are both slightly higher than the original model.
- The propulsive efficiency of hydrogen technology, in general, was higher than the original model. This is partially due to the higher energy density of hydrogen. Higher overall efficiency, however, was demonstrated by direct combustion hydrogen technology.
- The output for emissions is evidence of the carbon-zero performance of hydrogen-powered aviation.

Further investigation should include modelling the power characteristics in unsteady flight configurations. Most notable unsteady flight configurations include, take-off and landing, climb rate, turn/bank, etc. In terms of hydrogen power requirements, during unsteady operation the requirements for power output will be increased in some configurations (take-off, climb) and decreased during descent/landing. As such the sizing/optimisation of fuel cell will be required in such performance evaluation.

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Nomenclature

TSFC	Thrust specific fuel consumption
LH2	Liquid hydrogen
ENFICA-FC	Environmentally friendly inter-city aircraft powered by fuel cells
ATAG	Air Transport Action Group
MDO	Multidisciplinary design optimisation
DLR	The German aerospace centre
NASA	National aeronautics and space administration
CG	Centre of gravity
MTOW	Maximum take-off weight
MTOM	Maximum take-off mass
RPK	Revenue passenger kilometres
BSFC	Break specific fuel consumption
GI	Gravimetric index
AVTUR	Aviation turbine fuel
LHV	Lower heating value
BTU	British thermal unit
SHP	Shaft horsepower
Symbols	
m_0	Gross mass of aircraft
m_p	Mass of the propulsion system
m_f	Mass of the fuel system
Cl/Cd	Aerodynamic efficiency (glide ratio)
W	Aircraft weight
D	Aircraft drag
C_{D0}	Base drag
k	Induced drag factor
p	Shaft power required
η_{pr}	Propeller efficiency
V	Input voltage

Nomenclature (continued)

Symbols	
I	Input current
η	Electric motor efficiency
t_c	Cruise time
$\dot{m}f$	Fuel mass flow
n	Number of fuel cell stacks
P_{req}	Minimum power required
$\dot{m}_{P\ combustion}$	Mass of fuel flow at minimum power
E_{AVTUR}	Fuel energy
v	Cruise speed (m/s)
A_{disk}	Area of propeller disc (m^2)
H	Calorific value of fuel
H	Fuel consumption rate
J	Mechanical equivalent of heat
FN	Net thrust
U	Flight velocity
η_{th}	Thermal efficiency
η_p	Propulsive efficiency
η_o	Overall efficiency
$\eta_{propeller}$	Propeller efficiency
$\eta_{prowertrain}$	Power train efficiency
Q	Total heat
ρ_{AVTUR}	Fuel density
ρ_∞	Freestream air density
F_{max}	Maximum fuel usage
e_{AVTUR}	Emission factor
T	Thrust
T_A	Thrust available
S	Wing planform area