INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 50 (2024) 772–783

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Assessment of hydrogen gas turbine-fuel cell powerplant for rotorcraft

Rafael Baena Mejías [a], *Chana Anna Saias* [a,*], *Ioannis Roumeliotis* [a], *Vassilios Pachidis* [a], *Marko Bacic* [b]

[a] *Propulsion Engineering Centre, School of Aerospace Transport and Manufacturing, Cranfield University, Bedfordshire, MK43 0AL, UK*
[b] *Rolls-Royce Plc, P.O Box 31, Derby, DE24 8BJ, UK*

HIGHLIGHTS

- Design space exploration of hybrid hydrogen-fueled powerplant for UAM rotorcraft.
- Hybrid-electric rotorcraft compared against the hydrogen-fueled counterpart at different hybridization degrees.
- Performance and environmental assessment conducted at payload-range and mission level.
- Effects of gas turbine scaling with hybridization and fuel cell pressurization are quantified.
- Fuel cell technology level sensitivity analysis is conducted.

ARTICLE INFO

Article history:
Received 28 September 2022
Received in revised form
30 May 2023
Accepted 8 July 2023
Available online 17 August 2023

Keywords:
Hybrid propulsion
VTOL
Hydrogen
Fuel cells
UAM

ABSTRACT

Conventional turboshaft engines are high power density movers suffering from low efficiency at part power operation and producing significant emissions. This paper presents a design exploration and feasibility assessment of a hybrid hydrogen-fueled powerplant for Urban Air Mobility (UAM) rotorcraft. A multi-disciplinary approach is devised comprising models for rotorcraft performance, tank and subsystems sizing and engine performance. The respective trade-offs between payload-range and mission level performance are quantified for kerosene-fueled and hybrid hydrogen tilt-rotor variants. The effects of gas turbine scaling and fuel cell pressurization are evaluated for different hybridization degrees. Gas turbine scaling with hybridization (towards the fuel cell) results in up to 21% benefit in energy consumption relative to the non-scaled case with the benefits being more pronounced at high hybridization degrees. Pressurizing the fuel cell has shown significant potential as cell efficiency can increase up to 10% when pressurized to 6 bar which translates to a 6% increase in overall efficiency. The results indicate that current fuel cells (1 kW/kg) combined with current hydrogen tank technology severely limit the payload-range capability of the tilt-rotor. However, for advanced fuel cell technology (2.5 kW/kg) and low ranges, hybrid powerplant show the potential to reduce energy consumption and reduce emissions footprint.

* *Corresponding author.*
E-mail address: chana-anna.saias@cranfield.ac.uk (C.A. Saias).
https://doi.org/10.1016/j.ijhydene.2023.07.076

Nomenclature

Acronyms/Abbreviations

BEW	Baseline Empty Weight
UAM	Urban Air Mobility
VTOL	Vertical Take-Off and Landing
EW	Empty Weight
MTOW	Maximum Take-Off Weight
HDPE	High Density Polyethylene
LH2	Liquefied Hydrogen
CGH2	Compressed Gaseous Hydrogen
LHV	Low Heating Value
PEM	Proton Exchange Membrane
BOV	Bleed-Off Valve

Roman Symbols

HP	Degree of Hybridization by Power (%)
NO_X	Nitrogen-oxides
P_{max}	Maximum installed power (kW)
p_{FC}	Fuel cell power density (kW/kg)

Table 1 – Hydrogen and kerosene main properties [6,15].

Parameter	H_2	Jet-A
Low heating Value [MJ/kg]	120.0	42.8
Density Liquid [kg/m^3]	71	~0.811
Density at 273 K, 1 atm [kg/m^3]	0.09	~0.811
Boiling point at 1 atm [K]	20.27	40–539
Heat capacity [J/g K]	9.69	1.98
Flammability limits [vol%]	4.0–75.0	0.6–4.7
Min. Ignition energy [MJ]	0.02	0.25
Diffusion velocity [m/s]	< 2.00	< 0.17
Burning velocity [m/s]	265–325	18
Flame temperature $\varphi = 1$ [K]	2318	2200

1. Introduction

UAM has gained interest in recent years as a way of decongesting urban ground transportation. Currently, almost half of the population lives in cities, and it is expected to increase in the following years, contributing to traffic congestion [1]. In the European Union, traffic congestion was estimated to cost 100 billion annually, predicted to triple in the next twenty years [2]. To comply with current sustainable goals, set by the aviation industry UAM application is envisioned to be powered by alternative to kerosene-fueled gas turbines.

The multi-rotor configuration of UAM vehicles is naturally suited to distributed electrical powertrain, with batteries only and hybrid configurations being the main technologies of current interest [3–5]. This is due to the fact that hybrid configurations offer greater flexibility, increased redundancy and capability to reduce the need for engine oversizing [3]. These benefits come at a cost of increased Empty Weight (EW) and complexity of the propulsion and control systems [3,5]. Current state-of-the-art lithium-ion batteries limit the degree of hybridization if fixed payload-range capacity is to be assumed [5]. Thus, fully electric or hybrid-electric Vertical Take-Off and Landing (VTOL) architectures suffer from very low endurance and range for practical payloads. To negate this disadvantage, novel propulsion technologies may have to be introduced that could potentially allow reducing the carbon footprint while maintaining practical payload-range capability.

Various fuels are investigated as an alternative to fossil fuels, which currently represent more than 85% of the global energy systems [6]. Hydrogen is one of the main alternatives and is expected to contribute significantly to the goals set by the European Commission [7] and NASA [8] for sustainable aviation [9]. It should be noted that to achieve this goal, hydrogen must be produced by water electrolysis powered by renewable energy, which currently represents only 5% of the total hydrogen production, the rest produced by hydrocarbons reforming [6].

Table 1 presents the main properties of hydrogen (H_2) and kerosene (Jet-A) fuels. The major problem of hydrogen for aircraft applications is its low volumetric density. At room temperature and pressure, the volumetric density of hydrogen is 0.09 kg/m^3 [6,10], while the volumetric density of Jet-A is 800 kg/m^3 [6]. Even though the Low Heating Value (LHV) of hydrogen is around three times higher than the LHV of kerosene, the energy density of hydrogen under room conditions is 3000 times lower than the energy density of Jet-A at room temperature. Two different current state-of-the-art configurations are being considered in the industry for hydrogen storage, all focused on increasing its volumetric density [11]; Compressed Gaseous Hydrogen (CGH2) and Liquefied Hydrogen (LH2) option. LH2 requires storage under cryogenic conditions which requires a robust thermal management system for hydrogen pressurization and heat up prior to combustion resulting in a complex design [11,12]. LH2 storage requires a boil-off to ensure safe performance, as due to the heat exchange with the environment, part of the liquid hydrogen would evaporate [12,13]. CGH2 tanks are a fully developed technology for the automotive sector, but their current gravimetric density efficiencies of 6% make such designs impractical for long-range applications [11,13,14].

Nevertheless, due to its high energy density, gaseous hydrogen storage-based propulsion systems may be a more suitable lighter alternative to battery-powered configurations for UAM configurations. According to Saias et al. [16], for a civil tilt-rotor configuration, storing hydrogen in its gaseous form at 700 bar results in better energy efficiency compared to the LH2 counterpart. This comes at an expense of a higher reduction in payload-range capacity compared to the LH2 storage option.

Hydrogen can be directly introduced into the gas turbine, adapting it for hydrogen characteristics or integrated with a fuel cell powering electric motors [17]. Burning hydrogen in a gas turbine instead of kerosene can potentially have several advantages in emissions, durability, and efficiency due to non-carbon content, wider combustion stability, lower flame temperatures, and higher reaction rates [6,7,11]. Fuel cells on the other hand can convert chemical energy stored in fuel into electric energy through an exothermic electrochemical reaction [18–20] at higher efficiencies compared to the current small turboshaft engines.

Hydrogen-driven Proton Exchange Membrane (PEM) fuel cells have been long considered for automotive applications due to their compact design and high efficiency [21]. For the same reasons, PEM fuel cells have been recognized as potential candidates for aerospace applications [17,19,20,22]. Although relatively high fuel cell efficiency (50%+) can be attained in comparison to small gas turbines (~30%), fuel cells have the disadvantage of relatively lower system level power density (1–1.5 kW/kg) [22] compared to 3 kW/kg + for a typical 1 MW small gas turbine. Moreover, stack efficiency is highly dependent on operating conditions (pressure, temperature, humidity) and thus, power extraction and fuel cell sizing must be optimized with respect to each flight phase as reported in Ref. [20]. Consequently, a compromised solution with high-efficiency hydrogen fuel cells in a hybrid system powertrain with high power density gas turbines can contribute to reducing fuel consumption and emissions while improving flexibility, redundancy, and potential reduction of engine oversizing for rotorcraft [22,23] at an expense of increased weight.

Extensive studies on hydrogen-fueled gas turbines are being carried out to maturate the technology, create a synergy between systems and overcome the challenges of weight, thermal management and operability [22–24]. The focus of the studies are towards non-hybrid hydrogen-fueled large civil aircraft applications with studies on smaller general aviation applications highlighting the importance of designing hybrid-electric systems with fuel cells [25]. However, limited studies are found on hydrogen propulsion on VTOL with current literature focusing on hybrid fuel cells and battery-powered rotorcraft [24,26].

Even though gas turbines are considered high power density prime movers, they lack low efficiency, especially at part-load operation. Moreover, although the emissions related to hydrocarbons are eliminated when burning hydrogen, Nitrogen-oxides (NO_X) emissions may be produced. In light of the research presented in existing literature, hydrogen fuel combined with fuel cells for future rotorcraft applications have not yet been evaluated in the literature. This paper aims to contribute to the literature by assessing the feasibility of parallel hybrid hydrogen-fueled gas turbines with PEM fuel cells for future VTOL aircraft. A design space exploration is conducted and key performance metrics are quantified for both the investigated hydrogen-fueled and conventional kerosene-fueled rotorcraft. Optimum hybrid configurations are developed and compared against the kerosene-fueled and hydrogen-fuel VTOL at payload-range and mission levels. The effects of gas turbine scaling enabled by hybridization and fuel cell pressurization targeting improved efficiency on overall performance are quantified.

2. Simulation methodology

A validated rotorcraft performance analysis framework [5,27] was used to assess the performance of the VTOL. This framework is coupled with Simcenter Amesim, a dynamic simulation platform used herein for modelling of powerplant architectures considered. A tank sizing methodology is employed and verified [16]. Next, a design space exploration of the hydrogen storage system is carried out to calculate the gravimetric density to size the hydrogen tanks. The integrated VTOL–Amesim platform is used to assess the hybrid hydrogen gas turbine – fuel cell powertrain at aircraft and mission levels.

2.1. Tilt-rotor performance

The rotorcraft performance model is a Cranfield in-house software for performance analyses of rotorcraft at aircraft and mission levels. It comprises models for the different aspects of rotorcraft aerodynamics and flight dynamics, with a set of aerodynamic models for each rotorcraft component. The rotor is modeled using a steady-state non-linear blade element momentum theory approach comprising different inflow models for axisymmetric and non-axisymmetric flight conditions. The aerodynamic performance of the rest of the rotorcraft components is obtained using experimentally derived look-up tables. The deployed individual modelling theories are validated using experimental and flight test data as presented in Ref. [5]. The aerodynamic components are integrated with a trim model where the control and fuselage angles that ensure equilibrium of forces and moments are obtained using a Newton-Raphson approach. The developed methodologies are integrated within a numerical procedure to enable analysis at mission level or payload-range mode [5]. A detailed description has been provided by Saias et al. [5,27].

2.2. Powerplant performance (Amesim)

Amesim is a multi-domain simulation platform for the modelling and analysis of mechatronic engineering systems. The platform consists of a suite of different models used to simulate and analyze the performance of different mechatronics systems. These models are defined based on non-linear analytical equations that correspond to the component hydraulic, thermal, electric, or mechanical behaviour. The models are grouped in libraries by common applications, including a gas turbine library and a fuel cells library. The gas turbine library allows generating any engine model and has been used for turboshaft engine modelling for helicopters as presented in Ref. [3]. This library offers a set of different components that can be combined with other libraries such as electrical and thermal that enable modelling unconventional engines. For the PEM fuel cell stack, an electrochemical model is employed in Amesim. The model can account for fuel cell air inlet conditions such as temperature, pressure and humidity required for this work.

2.3. Integration of VTOL framework with Amesim

The integration of the different models presented in this section is shown in Fig. 1. The in-house VTOL performance framework [5,16] allows defining the mission flight path and power requirement for any specified mission. With these two inputs in tabulated form, Amesim extracts the altitude, velocity, and power at each time step of the mission evaluates the engine inlet conditions and hence, calculates the fuel, energy, and heat loads. A power management system was integrated with the system to control the power split between the fuel cell and the gas turbine. For the design point, the tank

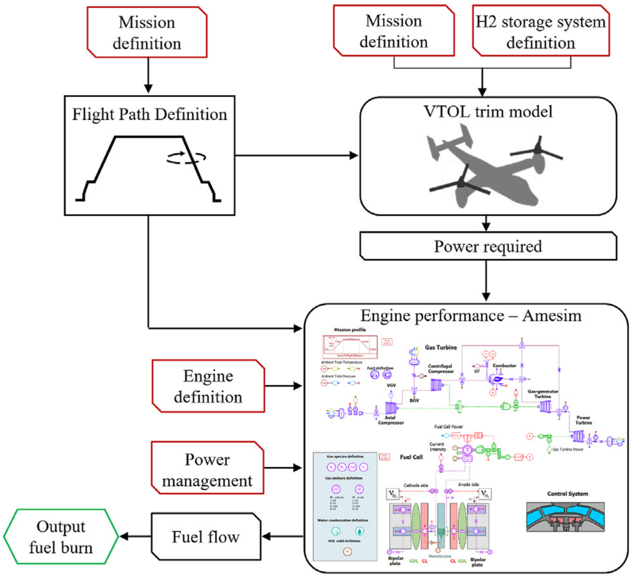

Fig. 1 – Integrated rotorcraft performance—Amesim framework.

sizing methodology is used to calculate the mass of the tank to store the maximum mass of hydrogen defined and obtain the EW of the aircraft is updated.

2.4. *Hydrogen storage system*

A sizing methodology based on Colozza [28] and Glanglоff [29] was developed to size the tank of hydrogen. Two main constraints for the storage systems can be identified: the hydrogen tank weight and volume. These parameters are often addressed as gravimetric density and volumetric density of the tanks, respectively. The former shows the relation between the mass of hydrogen that can be stored in the tank and the weight of the tank. The latter is a relation between the volume of hydrogen that can be stored in the tank and the volume of the tank. The tank sizing methodology is coupled with a design space exploration module targeting the evaluation of the gravimetric and volumetric density of the configuration of interest accounting for both weight and volumetric constraints.

For the rotorcraft considered in this paper, CGH2 storage was selected due to the simpler design, integration, thermal management system, and lack boil-off requirement [12,13,16]. In addition, wider UAM markets are predicted on point-to-point transport (including rural areas) which precludes the installation and use of complex LH2 hydrogen storage infrastructure. The tank sizing methodology was verified against data in Ref. [28].

The most common storage technique in the industry is compressing hydrogen at pressures up to 700 bar and storing it in high-pressure tanks. Under these conditions, hydrogen has a volume density of 36 kg/m^3. At least 13% of the hydrogen energy content (LHV) is required for the compression process [11].

For aerospace applications, Type IV tanks are one of the most promising compressed tanks. Type IV tanks have a plastic liner, required to avoid hydrogen leakage, usually High Density Polyethylene (HDPE), fully over-wrapped by a composite fiber [30]. The tank storing efficiency is measured using a gravimetric density. Up to now, gravimetric efficiencies of up to 13% have been reported by Züttel [11] and Gong et al. [19].

3. Powerplant design

3.1. *Test case: baseline VTOL – powerplant*

The baseline VTOL aircraft is a tilt-rotor modeled after the NASA XV-15 [31,32]. The aircraft was modeled using the Cranfield University in-house VTOL performance analysis framework [5]. The VTOL performance framework developed was validated against experimental rotor isolated data and flight test data [33,34] and has been extensively described in Refs. [5,27].

The tilt-rotor is equipped with two turboshaft engines to power the propellers. The baseline turboshaft is modeled in Amesim after the General Electric T700-GE-700. The gas-generator turbine is mechanically attached to the axial and centrifugal compressors. The T700 compressor and turbine performance maps are integrated into the Amesim platform. In the control system, the fuel mass flow is calculated to match the shaft power with the power requirement. The control system also regulates the VGVs and BOV signals [35]. The baseline model is developed by Roumeliotis et al. [3] and validated against experimental data [35]. The model was then adapted to burn hydrogen in the combustor instead of kerosene.

3.2. *Hydrogen tank sizing*

For the tilt-rotor considered, the tanks are assumed to be integrated within the VTOL as cargo. The kerosene tanks were assumed to be kept fixed to ensure that the mechanical integrity of the wings is not affected significantly. The volumetric constraints are accounted for in the decision of the tank placement as discussed in Ref. [16].

To ensure that the tanks fit in the aircraft and that they are accessible, the tank diameter is limited to 1.55 m and the length of the tank must be lower than 3 m. Applying the verified tank sizing methodology, a design space exploration was performed including the volumetric constraints of the tilt-rotor.

Fig. 2 shows the CGH2 tank gravimetric density as a function of the tank outer diameter. The numbers next to the first and last point of each configuration show the maximum length (first point), and minimum length (last point) of each configuration. It is observed that based on current technology levels, the gravimetric densities vary from 11 to 13%.

As shown in Fig. 2, the aircraft will be able to store a maximum mass of hydrogen of 300 kg without violating the maximum diameter or length limits. The baseline XV-15 requires around 675 kg of kerosene to reach the maximum range for the design mission. By assuming the same overall efficiency, mission profile and power requirements, the mass of hydrogen required can be calculated. Assuming an LHV of

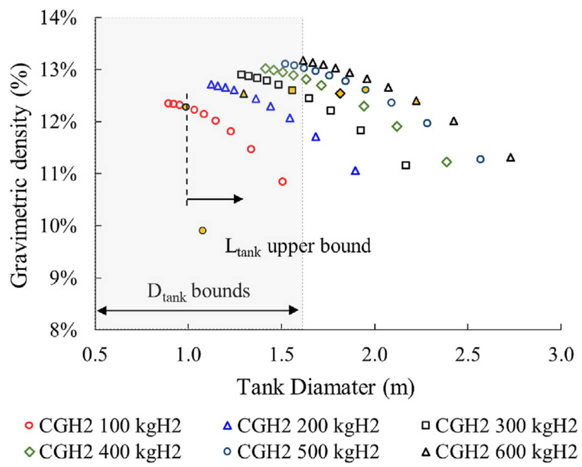

Fig. 2 – CGH2 tank design space exploration.

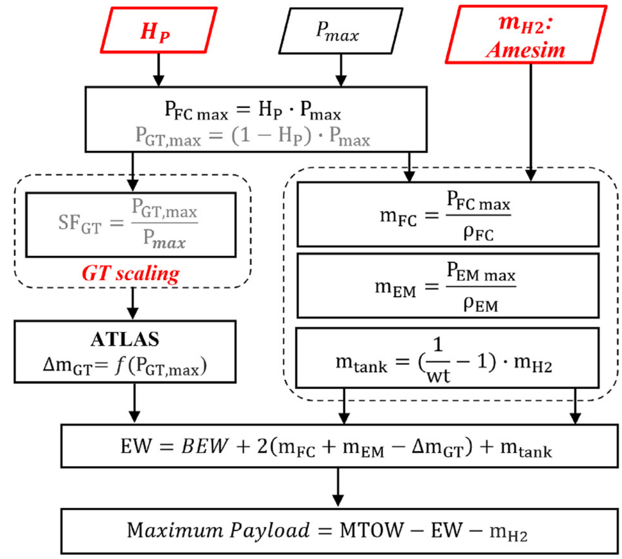

Fig. 3 – Hybrid powerplant design exploration flowchart.

kerosene of 43.12 MJ/kg and a hydrogen LHV of 120 MJ/kg, the mass of hydrogen required for this mission would be close to 240 kg which is less than the maximum mass of hydrogen allowed for the CGH2 tank.

3.3. *Hybrid-electric powerplant design and sizing*

The chosen hybrid powertrain configuration is a parallel architecture where both the gas turbine and the electric motor powered by the fuel cells are mechanically connected to the prop-rotor shaft through a gearbox. Both engines can be operated simultaneously or separately. The electric motor can be used to compensate for peak loads in-flight segments with high power requirements. Fuel cells were selected due to their high efficiency, which can be translated into fuel savings, and their zero emissions produced. The fuel cell operation efficiency can be close to 55% when operating at maximum power. This is around twice the efficiency of typical turboshaft engines for rotorcraft. However, fuel cells come with a penalty of reduced power density. Specifically, current technology level fuel cells have a specific power of 1 kW/kg [21,24] and are expected to rise to 2.5 kW/kg in the future [36], whereas small turboshaft engines have densities of the order of 4–7 kW/kg [35].

Fig. 3 displays a flowchart of the methodology followed to parametrically size the hybrid powertrain and hydrogen tank. The design variables selected are the Degree of Hybridization by Power (%) (*HP*) (Eq. (1)) and the design mission which will define the amount of energy and hence, hydrogen fuel must be stored. Given the HP and the maximum installed power (P_{max}) as defined by the baseline engine, the maximum power from the fuel cell ($Pmax_{,FC}$) and the new $Pmax_{,GT}$ is calculated using Eqs. (1) and (2).

$$HP = \frac{P_{max,FC}}{P_{max}} \tag{1}$$

$$P_{max,GT} = (1 - HP)P_{max} \tag{2}$$

With the calculated values of maximum power, the gas turbine scaling index can be calculated to ensure constant power ratings relative to the baseline cycle. The scaling is done assuming the same cycle and scaling the design inlet mass flow. The effect of scaling on gas turbine weight is accounted for using a Cranfield University in-house software ATLAS [38]. The weight of the fuel cell and the rest of the electrical components is calculated based on the power density of those (Table 2).

Once the mission is defined, both in terms of range, mission flight path, and power requirement, the mass of hydrogen to be stored can be calculated. With this hydrogen requirement, the mass of the tank was obtained using an assumed value of the gravimetric density of a CGH2 storage system, based on the hydrogen tank design exploration.

The empty weight was calculated subsequently. The new design EW is equal to the baseline XV-15 Baseline Empty Weight (BEW) [4], plus the additional weight due to introducing the hybrid system powertrain and the hydrogen tanks.

The hybrid system configuration was compared with the H2-fueled gas turbine configuration. The integrated system is designed based on the sizing mission of the baseline tilt-rotor operating at maximum payload. The take-off weight of the rotorcraft is equal to the Maximum Take-Off Weight (MTOW).

The maximum payload for each design range, or mass of hydrogen stored, can be calculated as described in Fig. 3. In this case, the new EW accounts for the difference in the weight of the propulsion system.

Table 2 – Power density assumptions [21,24,37].

Component	Parameter	Value
Fuel cell	Power density [kW/kg]	1.0–2.5
Motor	Power density [kW/kg]	7.0
Inverter	Power density [kW/kg]	11.0
Cooling system	Power density [kW/kg]	1.5

4. Results & discussion

4.1. *Hydrogen-fueled VTOL*

The VTOL performance framework was used to carry out payload-range performance analyses. The hydrogen-fueled VTOL variants and the baseline XV-15 performance are compared. Two different cases were studied for the hydrogen tilt-rotor variants.

- Hydrogen Case 1: VTOL capable of maintaining fixed maximum useful load as the baseline XV-15
- Hydrogen Case 2: VTOL capable of reaching the same maximum range as the baseline XV-15

Table 3 presents the maximum amount of fuel that the VTOL can store, the maximum payload, and the maximum range that it can fly. Fig. 4 depicts the payload-range performance comparison. One of the major benefits of hydrogen is its high LHV compared to other fuels. To cover the same range as the kerosene-fueled XV-15, the hydrogen-fueled XV-15 required a third of the mass of the kerosene baseline. However, to introduce hydrogen into the aircraft, the storage system must be considered. The result is that the saving in fuel mass by using hydrogen is lower than the increase in EW due to the addition of the hydrogen storage system. From Fig. 4 it is observed that if payload capacity is maintained fixed relative to the baseline (Hydrogen Case 1), the hydrogen-fueled VTOL must sacrifice 62% of its range capability. Similarly, for an aircraft that can cover the same range as the baseline tilt-rotor (Hydrogen Case 2), the hydrogen-fueled VTOL needs to sacrifice 60% of its maximum payload.

As the tilt-rotor would normally fly at various mission ranges, an analysis is carried out to account for off-design mission scenarios. Fig. 5 shows a comparison of the energy consumption between the hydrogen VTOL configurations and the baseline VTOL at various off-design mission ranges. For each variant, the payload was set to the maximum payload that the configuration can carry as presented in Table 3. As the Hydrogen Case 2 VTOL is designed at a lower payload than the other two coneations, the performance is quantified as energy consumed per useful load-km flown.

Although the short-range hydrogen VTOL (Hydrogen Case 1) results in lower fuel consumption relative to the baseline, an increase in energy per payload-range of the order of 8% is observed (Fig. 5). This increase is due to the fact the hydrogen VTOL is heavier throughout the mission due to the increased tank weight and the lower weight reduction rate of the hydrogen fuel relative to kerosene. It is highlighted that the energy penalty reduces as the mission range increases. On the other hand, if the hydrogen-fueled VTOL is sized for high range capability (Hydrogen Case 2), the penalty in payload due to the additional weight of the hydrogen storage system dominates leading to a significant increase in block energy per payload which is more pronounced at high mission ranges. In both cases, the heavy weight of the hydrogen storage system is the main factor driving the energy trends observed.

Fig. 6 shows the payload range performance of hydrogen VTOL variants with the tanks sized parametrically for

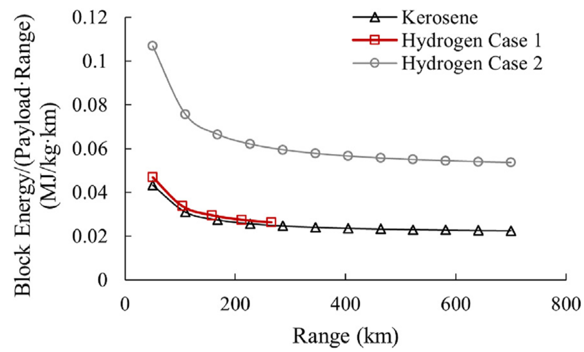

Fig. 5 – Energy consumption per payload and range for various mission ranges – Comparison of kerosene VTOL, CGH2 VTOL Case 1, CGH2 VTOL Case 2.

Table 3 – Comparison of hydrogen-fueled variants with baseline kerosene-fueled tilt-rotor.

	Fuel capacity [kg]	Payload [kg]	Range [km]
Hydrogen Case 1	107	1842	274
Hydrogen Case 2	248	796	753
Baseline	687	1842	753

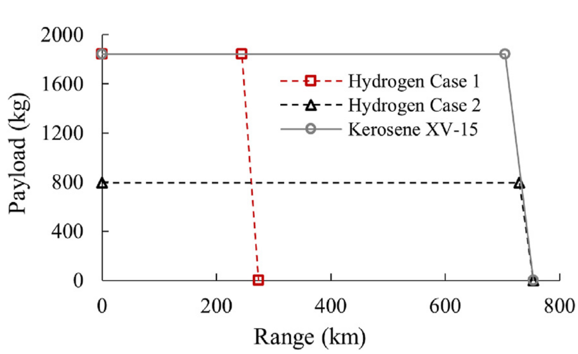

Fig. 4 – Payload-range performance comparison between hydrogen-fueled and kerosene-fueled VTOL.

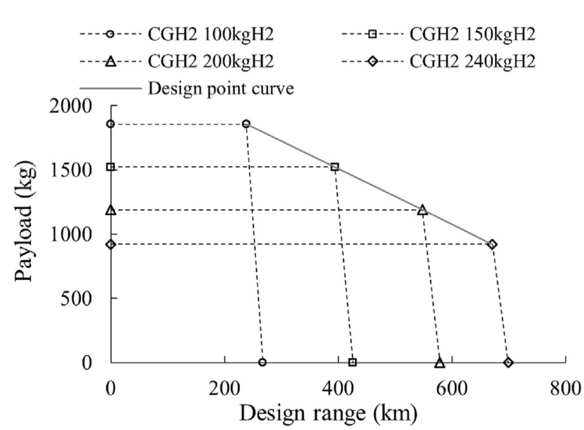

Fig. 6 – Payload-range trade-off design reference curve definition.

different levels of payload. Each point represents a different integrated tank and subsystems sized based on the maximum hydrogen capacity of the tilt-rotor. The line connecting all the maximum payload-maximum range points will be used as a reference for comparison of the hybrid powertrain configurations. The design of the above hydrogen variants across the different payload capacities is done in order to cover the design space.

4.2. *Hybrid hydrogen gas turbine – fuel cell VTOL*

The performance of the hydrogen VTOL is heavily dependent on the added weight of the storage system. A design exploration of hydrogen-fueled gas turbine combined with fuel cells in a parallel arrangement is employed and analysis is carried out at payload-range and off-design mission performance. The hybrid powertrain is sized based on the methodology explained in Section 3.3. For this design, the reduction of hydrogen fuel due to the increased efficiency of the hybrid system is traded-off with the added weight of fuel cells. The fuel cells are assumed to operate at constant power at their design peak efficiency. Thus, the power split between the gas turbine and fuel cell is variable and designated by the power extraction from the fuel cell. A power density of 1 kW/kg corresponding to current state of the art [21] was considered for this comparison.

After the hybrid powertrain is sized, payload-range and off-design mission analyses are performed for different degrees of hybridization. Fig. 7 shows the payload range trade-off design point curve at various degrees of hybridization and the mission energy per payload for off-design mission ranges. Table 4 outlines the hydrogen-fueled rotorcraft weight breakdown. The design at HP = 0 corresponds to the hydrogen-fueled variant without fuel cells. For all the hybrid configurations, the design process starts with the turboshaft assumed to remain fixed. Although the fuel cells come with increased efficiency, their added weight dominates, and penalties are observed as hybridization degree increases both at payload-range and energy level. Additionally, the energy per payload penalty increases with hybridization and range as the reduction in passenger capacity dominates.

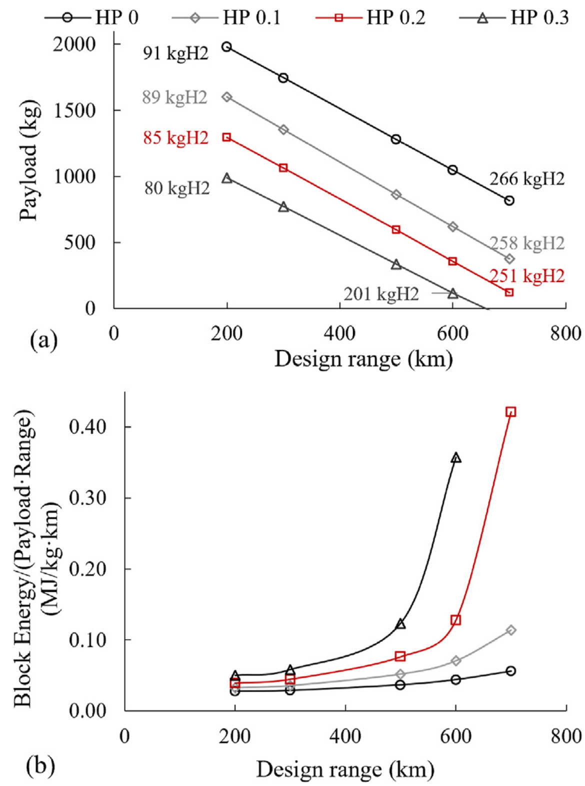

Fig. 7 – Performance comparison of the hybrid hydrogen-fueled VTOL designed at different ranges and a) Payload-range (fuel capacity annotated), b) Energy per payload-range.

Table 4 – Hybrid hydrogen-fueled propulsion system breakdown.

Weight [kg]	HP = 0	HP = 10%	HP = 30%
MTOW	6800	6800	6800
Fuel	267	241	194
Tank	1513	1366	1100
Fuel cell	0	270	810
Motor	0	34	101
Payload	806	709	475

4.2.1. *Effect of gas turbine scaling*

The introduction of a fuel cell enables the potential to avoid engine oversizing. This allows integration of a smaller turboshaft depending on the degree of hybridization while maintaining constant power ratings relative to the baseline herein, the effect of gas turbine scaling with hybridization is investigated. The scaling is done by using scaled maps for the gas path components. The engine weight reduction due to scaling was considered with ATLAS [38].

Fig. 8 reflects the impact of scaling on the performance of the VTOL. As expected, an important benefit both in terms of payload capacity at a fixed range and fuel consumption is achieved when the gas turbine is scaled. The benefits are more pronounced at higher degrees of hybridization. Specifically, the engine scaling for 30% hybridization results in an increase in payload of the order of 14% and a reduction of energy consumption per payload of 21%. This increase is attributed to the reduction of engine weight that allows for greater payload capacity and operation closer to the design point which is more pronounced at part-power. It should be noted that this results in improved fuel economy that translates into a lighter tank.

4.2.2. *Effect of fuel cell pressurization*

Pressurizing the fuel cell is shown to have an important benefit on fuel cell performance [20,39,40]. At higher pressure, the fuel cell Gibbs Energy is higher and hence, the ideal voltage is higher, leading to an improvement in the polarization curve.

For this reason, the effect of pressurization on VTOL performance is investigated. Two different ways of pressurizing the fuel cell are considered. The first one is through the utilization of bleed-off air from the engine and the second is the use of an air compressor powered by the gas turbine. The baseline turboshaft has a BOV in the fourth stage of the axial compressor, which is the point where the air is extracted to

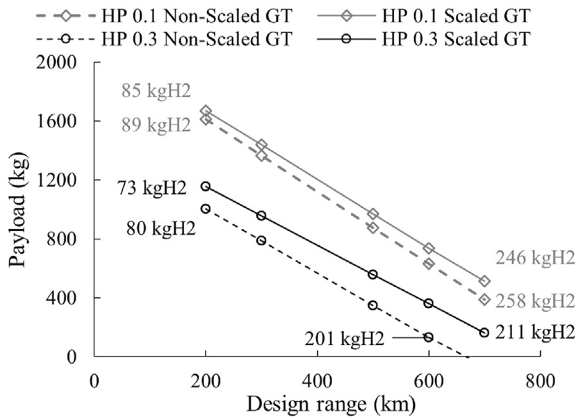

Fig. 8 – Impact of gas turbine scaling at payload-range and fuel (Fuel capacity annotated).

power the fuel cell. The BOV is installed to ensure operation within the compressor stability limits at low power settings away from the surge line. This air is also used for seals and auxiliaries. The bleed-off mass was obtained by considering the BOV schedule presented in Ref. [35].

For a range of 300 km and a degree of hybridization in the power of 10% and 30%, the bleed-off mass and the fuel cell mass flow requirement were plotted as a function of time as presented in Fig. 9. It is noticed that the bleed-off mass is only sufficient to supply the air required from the fuel cell only during the descent phase. It is thus realized that additional air needs to be extracted to reach the fuel cell airflow requirements, which will affect the efficiency of the gas turbine.

Three different cases were considered depending on the air supply system as shown in Table 5. The baseline is designed with an air compressor supplying air at 1.5 bar. Next, Case Study 1 considers that the air is introduced via the BOV of the gas turbine at approximately 6 bar, which is a value close to the design point, depending on the operating point. Finally,

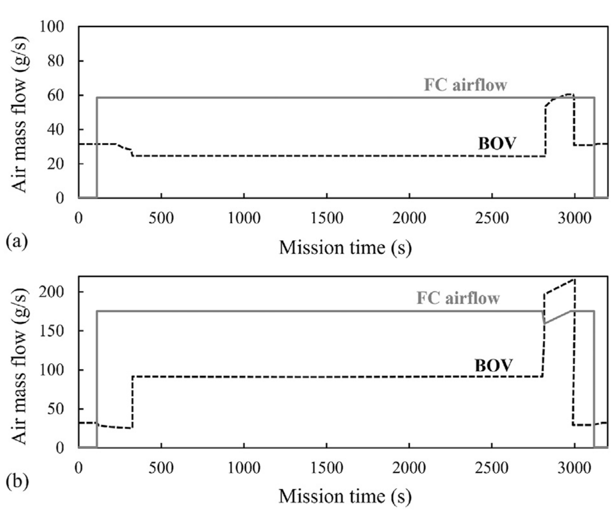

Fig. 9 – Comparison of gas turbine bleed-off air and fuel cell air flow requirement at a) HP = 10% and b) HP = 30% for 300 km mission.

Table 5 – Air supply case studies considered.

	FC operating pressure [bar]	Air boosting [–]
Baseline	1.5	Air Compressor
Case Study 1	~ 6	Turboshaft BOV
Case Study 2	6	Air Compressor

Case Study 2 assumes that the air pressure is fixed at 6 bar and is supplied to the fuel cell by an air compressor.

The results from the comparison of the three air supply systems at a payload-range level are presented in Fig. 10. Only the results at HP = 30% are illustrated in this figure, as the trends observed at lower degrees of hybridization are the same. Using the gas turbine to pressurize the fuel cell has a negative impact on the rotorcraft performance relative to the baseline non-pressurized case. This is since the engine operates at part load for the majority of the mission where the pressure at the BOV is lower and hence, the advantage of pressurization can only be seen at high power settings. The other disadvantage is that the increase of engine bleed-off to supply air to the fuel cell increases the compressor work and penalizes the gas turbine performance. It is thus concluded that for this arrangement, pressurization using bleed-off mass from the gas turbine cannot bring any benefit.

On the other hand, pressurizing the fuel cell with an air compressor has a benefit to the rotorcraft performance, both at payload-range and fuel economy level. Pressurizing the fuel cell from 1 bar to 6 bar can increase the efficiency at the cell level up to 10%. This translates into an increase of 4.6% in payload and a 9% reduction in fuel consumption at 200 km. The payload benefit increases at higher mission ranges. It is thus concluded that fuel cell pressurization can provide significant improvements in overall performance.

4.3. *Optimal hybrid and pure hydrogen-fueled powertrain comparison*

The optimal hybrid powertrain is designed with a scaled gas turbine with hybridization and an air-boosted fuel cell with an air compressor as discussed in the previous section. A comparison between the optimal hybrid system powertrain and the pure hydrogen-fueled VTOL is performed for different degrees of hybridization in power.

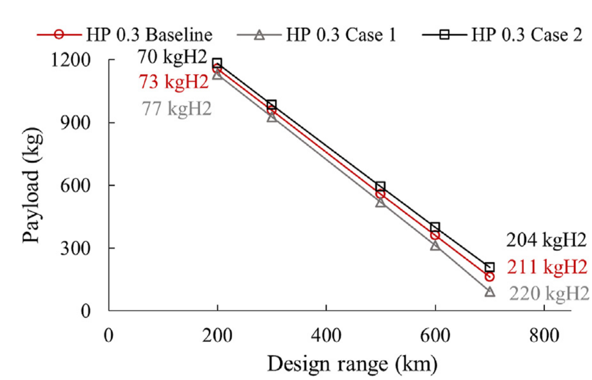

Fig. 10 – Payload-range comparison for the different air boosting configurations.

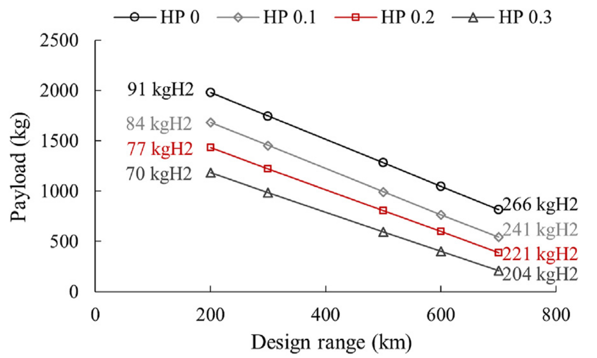

Fig. 11 – Payload-range trade-off of the hydrogen-based variants at different degrees of hybridization (p_{FC} = 1.0 kW/kg).

It is seen in Fig. 11 that the hydrogen-fuel gas turbine (HP = 0) results in greater payload capability at a fixed range. Although the gas turbine scaling and pressurization of the fuel cell increase its performance, the added weight still dominates. The energy consumed in the design range per kg of payload (maximum payload allowed in the aircraft) is presented in Fig. 12. It is observed that the optimized hybrid powertrain results in higher energy consumption per payload relative to the non-hybrid hydrogen-fueled VTOL. This effect becomes more pronounced at high design ranges and high degrees of hybridization. From Fig. 12 it is highlighted that the improvements of the hybrid powertrain relative to the hydrogen VTOL in fuel burn are outweighed by the high penalties in payload capacity.

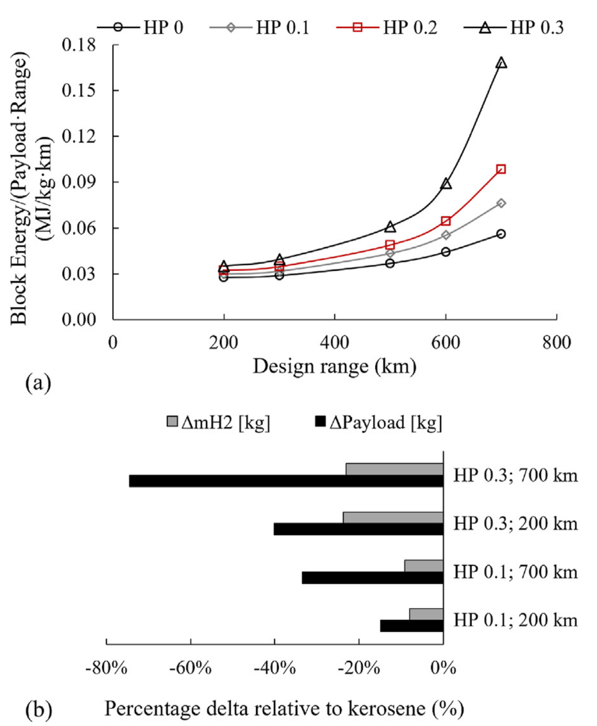

Fig. 12 – Comparison of a) block energy per payload for various mission ranges, b) effect of hybridization on payload and fuel burn for 200 km and 700 km mission ranges relative to the hydrogen-fueled VTOL (p_{FC} = 1.0 kW/kg).

It can be therefore concluded that the power density of the fuel cell is one of the key parameters for the observed trends. The fuel cell technology is assumed to improve in the following years. Considering a near-future technology level, a specific power of 2.5 kW/kg was assumed based on Ballard Power Systems [36] to perform the same analysis.

For this technology level, a significant improvement in the payload-range performance relative to current technology fuel cells can be attained as the difference between the pure gas turbine and the hybrid system is decreased substantially (Fig. 13). However, the hybrid powertrain still leads to a reduced payload for any design range. A break-even point in power density at which the hybrid configuration would result in constant payload capacity with respect to the hydrogen-fueled VTOL is calculated. For a design range of 200 km, the break-even point is at 8.0 kW/kg, 7.1 kW/kg and 6.6 kW/kg for hybridization degrees of 10%, 20% and 30%, respectively. At this point, the hybrid variants would be superior to the hydrogen-fueled configuration at energy efficiency, fuel consumption and payload capacity. At higher design mission ranges (700 km), the target payload is much lower and hence, the sensitivity of power density with hybridization degree is higher. At this design range, the break-even point is calculated at 7.5 kW/kg, 3.8 kW/kg and 3.3 kW/kg for HP = 10%, 20% and 30%.

Fig. 14 presents the energy comparison per payload capacity in off-design mission scenarios. It is observed that for degrees of hybridization above 10%, the hybrid hydrogen-fueled VTOL results in better energy consumption per payload capacity compared to the non-hybrid variant. This betterment in energy becomes more pronounced for high mission ranges where the fuel cell is utilized for a greater fraction of the mission. Additionally, for this technology level, the reduction in maximum payload due to added weight of the fuel cell is compensated with the amount of fuel saved by introducing the hybrid system powerplant configuration (Fig. 14a). This effect is increased as the degree of hybridization in power is increased.

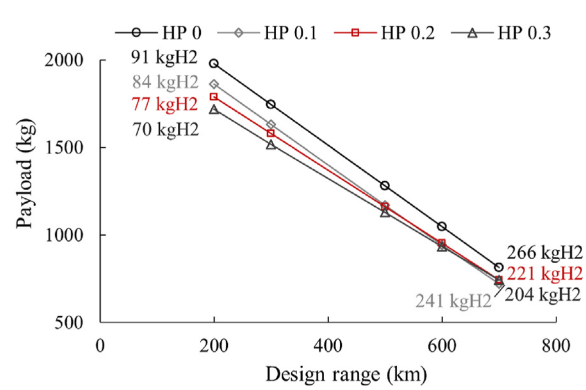

Fig. 13 – Payload-range trade-off of the hydrogen-based variants at different degrees of hybridization for improved fuel cell technology (p_{FC} = 2.5 kW/kg).

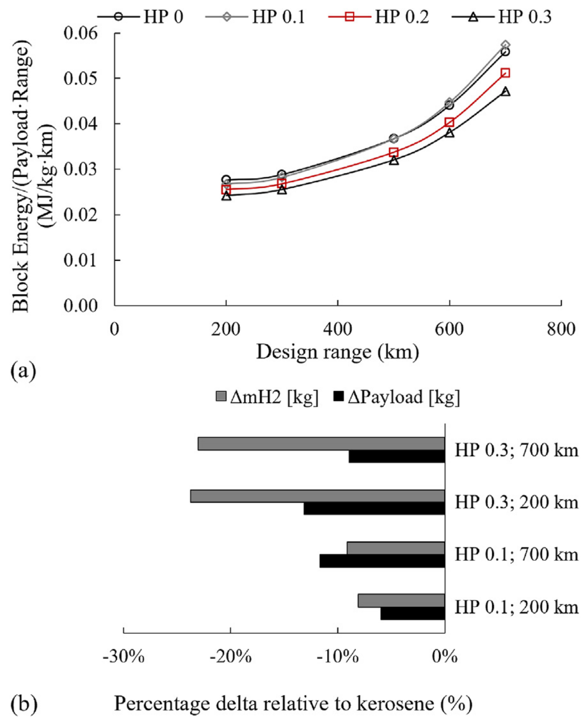

Fig. 14 – Comparison of a) block energy per payload for various mission ranges, b) effect of hybridization on payload and fuel burn for 200 km and 700 km mission ranges relative to the hydrogen-fueled VTOL (p_{FC} = 2.5 kW/kg).

Conclusions

This paper presented a comprehensive assessment of the feasibility of compressed gaseous hydrogen directly used in the gas turbine or through a parallel hybrid powerplant with fuel cells for VTOL air-taxi applications. An analysis has been performed to quantify corresponding trade-offs between fuel economy, energy efficiency, powerplant weight, hydrogen tank weight and rotorcraft weight. The performance benefits and associated penalties are quantified at payload-range and mission level. This was performed utilizing a multi-disciplinary framework that combines models for rotorcraft performance, novel powerplant performance, tank sizing, weight estimation and mission analysis. A tilt-rotor configuration was selected as a baseline.

The baseline tilt-rotor is used for retrofitting with hydrogen accounting for the volumetric constraints of the configuration. It was demonstrated that the hydrogen-fuel variant cannot maintain fixed payload-range capacity with current gravimetric efficiencies. It was demonstrated that if the hydrogen-fueled tilt-rotor is designed at maximum payload capacity of the baseline, 62% of the design range must be sacrificed. Alternatively, maintaining fixed range capability relative to the baseline can be achieved at a 60% reduced payload. It was found that at off-design mission ranges, the former design imposes significant energy penalties due to the relatively low payload capacity and hence, was excluded. The latter design results in better energy per passenger-km with penalties of the order of 8% at energy relative to the baseline kerosene rotorcraft and hence, selected for this study. It is however highlighted that it results in a 60% reduction in fuel relative to the kerosene counterpart. Introducing a hybrid powerplant coupled with a fuel cell in a parallel arrangement was found to increase penalties in payload-range capacity and block energy, especially at high degrees of hybridization relative to the non-hybrid hydrogen tilt-rotor. This was found to be highly dependent on the power density of the fuel cell. The flexibility encountered in the hybrid powertrain to reduce the engine size led to an improvement both in payload and fuel consumption but still penalties were reported relative to the hydrogen-fuel VTOL for 1 kW/kg fuel cell power density.

Fuel cell pressurization was recognized as a potential means to improve overall performance as at the design point it was found that cell efficiencies can increase up to 10% which translates into 6% in overall system efficiency. Although at cycle level this improvement was important, the pressurization using engine bleed-off was found to have an adverse effect on overall performance. On the contrary, fuel cell pressurization via an air compressor was found to provide benefits of up to 10% in payload capacity and 5% in block fuel relative to the non-pressurized design.

Current technology levels in tank gravimetric densities and fuel cell power densities allow for significant fuel burn improvements with high penalties penalty in payload-range capacity. Through a sensitivity analysis on fuel cell technology, it was found that with power densities of 2.5 kW/kg, the penalties in payload reduce significantly while also resulting in fuel burn benefit relative to the non-hybrid hydrogen rotorcraft for hybridization degrees above 10%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to express their gratitude to Rolls-Royce plc. for funding this research and for permission to publish the paper.

REFERENCES

[1] J. Holden, N. Goel, Fast-forwarding to a future of on-demand urban air transportation, White Paper, Uber.
[2] Nase A. Urban air mobility (UAM). (FEV). 2021. https://uam.fev.com/. [Accessed 8 September 2021].
[3] I. Roumeliotis, C. Mourouzidis, M. Zafferetti, D. Unlu, O. Broca, V. Pachidis, Assessment of Thermo-Electric Power Plants for Rotorcraft Application, J Eng Gas Turbines Power 142 (5), 51003. arXiv:https://asmedigitalcollection.asme.org/gasturbinespower/article -pdf/142/5/051003/6484291/

gtp_142_05_051003.pdf, doi:10.1115/1.4045103. URL https://doi.org/10.1115/1.4045103.

[4] R. A. Danis, M. W. Green, J. L. Freeman, D. W. Hall, Examining the conceptual design process for future hybrid-electric rotorcraft, technical report, NASA/CR-2018-219897.

[5] C. A. Saias, I. Goulos, I. Roumeliotis, V. Pachidis, M. Bacic, Preliminary Design of Hybrid-Electric Propulsion Systems for Emerging Urban Air Mobility Rotorcraft Architectures , J Eng Gas Turbines Power 143 (11), 111015. arXiv:https://asmedigitalcollection.asme.org/gasturbinespower/article-pdf/143/11/111015/6765892/gtp_143_11_111015.pdf, doi:10.1115/1.4052057. URL https://doi.org/10.1115/1.4052057.

[6] Cecere D, Giacomazzi E, Ingenito A. A review on hydrogen industrial aerospace applications. Int J Hydrogen Energy 2014;39(20):10731–47. https://doi.org/10.1016/j.ijhydene.2014.04.126. https://www.sciencedirect.com/science/article/pii/S0360 319914011847.

[7] CleanSky2. Hydrogen-powered aviation. A fact-based study of hydrogen technology, economics, and climate impact by 2050. Tech. rep May 2020. URL, https://www.fch.europa.eu/sites/default/files/FCHf%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf.

[8] Bonet, J. T., Schellenger, H. G., Rawdon, B. K., Elmer, K. R., Wakayama, S. R., Brown, D. L., Guo, Y., Environmentally responsible aviation (ERA) project - N+2 advanced vehicle concepts Study and conceptual design of subscale test vehicle (STV): final report, Technical Report NASA/CR-2011-216519.

[9] J. R. Smith, E. Mastorakos, An energy systems model of large commercial liquid hydrogen aircraft in a low-carbon future, Int J Hydrogen Energy. doi:https://doi.org/10.1016/j.ijhydene.2023.04.039. URL https://www.sciencedirect.com/science/article/pii/S0360.319923017469.

[10] Barthelemy H, Weber M, Barbier F. Hydrogen storage: recent improvements and industrial perspectives. special issue on The 6th International Conference on Hydrogen Safety (ICHS 2015), 19-21 October 2015, Yokohama, Japan Int J Hydrogen Energy 2017;42(11):7254–62. https://doi.org/10.1016/j.ijhydene.2016.03.178. https://www.sciencedirect.com/science/article/pii/S0360.319916305559.

[11] Züttel A. Hydrogen storage methods. Naturwissenschaften 2004;91:157–72. https://doi.org/10.1007/s00114-004-0516-x.

[12] Xu W, Li Q, Huang M. D design and analysis of liquid hydrogen storage tank for high-altitude long-endurance remotely-operated aircraft. Int J Hydrogen Energy 2015;40(46):16578–86. https://doi.org/10.1016/j.ijhydene.2015.09.028. https://www.sciencedirect.com/science/article/pii/S0360 319915300367.

[13] Brewer GD. Hydrogen aircraft technology. Boca Raton: CRC Press; 1991.

[14] Verstraete D, Hendrick P, Pilidis P, Ramsden K. H ydrogen fuel tanks for subsonic transport aircraft. hyceltec 2009 Conference Int J Hydrogen Energy 2010;35(20):11085–98. https://doi.org/10.1016/j.ijhydene.2010.06.060. https://www.sciencedirect.com/science/article/pii/S0360.31991001236X.

[15] Klell M. Storage of hydrogen in the pure form. Ch. 1. John Wiley & Sons, Ltd; 2010. p. 1–37. https://onlinelibrary.wiley.com/doi/abs/10.1002/9783527629800.ch1.

[16] Saias CA, Roumeliotis I, Goulos I, Pachidis V, Bacic M. A ssessment of hydrogen fuel for rotorcraft applications. Int J Hydrogen Energy 2022;47(76):32655–68. https://doi.org/10.1016/j.ijhydene.2022.06.316. https://www.sciencedirect.com/science/article/pii/S0360 319922030099.

[17] Petrescu RVV, Machín A, Fontánez K, Arango JC, Márquez FM, Petrescu FIT. Hydrogen for aircraft power and propulsion. Int J Hydrogen Energy 2020;45(41):20740–64. https://doi.org/10.1016/j.ijhydene.2020.05.253. https://www.sciencedirect.com/science/article/pii/S0360 319920321108.

[18] Perry ML, Fuller TF. A historical perspective of fuel cell technology in the 20th century. J Electrochem Soc 2002;149(7):S59. https://doi.org/10.1149/1.1488651.

[19] Gong A, Verstraete D. F uel cell propulsion in small fixed-wing unmanned aerial vehicles: current status and research needs. Int J Hydrogen Energy 2017;42(33):21311–33. https://doi.org/10.1016/j.ijhydene.2017.06.148. https://www.sciencedirect.com/science/article/pii/S0360 31991732503X.

[20] Schröder M, Becker F, Kallo J, Gentner C. O ptimal operating conditions of pem fuel cells in commercial aircraft. Int J Hydrogen Energy 2021;46(66):33218–40. https://doi.org/10.1016/j.ijhydene.2021.07.099. https://www.sciencedirect.com/science/article/pii/S0360 319921027634.

[21] T. Kadyk, C. Winnefeld, R. Hanke-Rauschenbach, U. Krewer, Analysis and design of fuel cell systems for aviation, Energies 11 (2). doi:10.3390/en11020375. URL https://www.mdpi.com/1996-1073/11/2/375.

[22] Baroutaji A, Wilberforce T, Ramadan M, Olabi AG. C omprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. Renew Sustain Energy Rev 2019;106:31–40. https://doi.org/10.1016/j.rser.2019.02.022. https://www.sciencedirect.com/science/article/pii/S1364 032119301157.

[23] Husemann M, Glaser CK, Stumpf E. Assessment of a Fuel Cell Powered Air Taxi in Urban Flight Conditions. AIAA Scitech 2019 Forum, 7-11 January 2019, San Diego, California. https://doi.org/10.2514/6.2019-0812, https://arc.aiaa.org/doi/abs/10.2514/6.2019-0812.

[24] Ng W, Datta A. Hydrogen fuel cells and batteries for electric-vertical takeoff and landing aircraft. J Aircraft 2019;56(5):1765–82. https://doi.org/10.2514/1.C035218.

[25] Nicolay S, Karpuk S, Liu Y, Elham A. C onceptual design and optimization of a general aviation aircraft with fuel cells and hydrogen. Int J Hydrogen Energy 2021;46(64):32676–94. https://doi.org/10.1016/j.ijhydene.2021.07.127. https://www.sciencedirect.com/science/article/pii/S0360 319921027920.

[26] Datta A, Johnson W. Requirements for a hydrogen powered all-electric manned helicopter. 2012. https://doi.org/10.2514/6.2012-5405. 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, 17 - 19 September 2012. URL https://arc.aiaa.org/doi/abs/10.2514/6.2012-5405.

[27] C. A. Saias, I. Roumeliotis, I. Goulos, V. Pachidis, M. Bacic, Design Exploration and Performance Assessment of Advanced Recuperated Hybrid-Electric Urban Air Mobility Rotorcraft, J Eng Gas Turbines Power:https://asmedigitalcollection.asme.org/gasturbinespower/article-pdf/doi/10.1115/1.4052955/6786755/gtp-21-1262.pdf, doi:10.1115/1.4052955. URL https://doi.org/10.1115/1.4052955.

[28] Colozza AJ, Kohout LL. Hydrogen storage for aircraft applications overview. Tech Rep September 2002. NASA/CR-2002-211867.

[29] J. Gangloff, John J., J. Kast, G. Morrison, J. Marcinkoski, Design Space Assessment of Hydrogen Storage Onboard Medium and Heavy Duty Fuel Cell Electric Trucks, Journal of Electrochemical Energy Conversion and Storage 14 (2), 21001. arXiv:https://asmedigitalcollection.asme.org/electrochemical/article- pdf/14/2/021001/6034750/jeecs_014_02_021001.pdf, doi:10.1115/1.4036508. URL https://doi.org/10.1115/1.4036508.

[30] E. Rivard, M. Trudeau, K. Zaghib, Hydrogen storage for mobility: a review, Materials 12 (12). doi:10.3390/ma12121973. URL https://www.mdpi.com/1996-1944/12/12/1973.

[31] P. B. Harendra, M. J. Joglekar, T. M. Gaffey, R. L. Marr, V/STOL tilt rotor Study - volume V: a mathematical model for real time flight simulation of the bell model 301 tilt rotor research aircraft, NASA Contract NAS 2-6599 (Report 301-099-001).
[32] Ames Research Center and U.S. Army air mobility R&D laboratory, NASA/Army XV-15 Tilt Rotor Research Aircraft Familiarization Document, January 1975.
[33] S. W. Ferguson, A mathematical model for real time flight simulation of a generic tilt-rotor aircraft, NASA Contractor Report (CR-166536).
[34] Johnson W, Branch A. Ndarc — NASA design and analysis of rotorcraft. Validation and demonstration. In: American helicopter society aeromechanics specialists' conference; 2010. San Fransisco, CA.
[35] M. G. Ballin, A high fidelity real-time simulation of a small turboshaft engine, NASA Technical Memorandum 100991.
[36] High Performance Fuel Cell Stack. Innovations in Proton exchange Membrane fuel cell stack design. Ballard Power Systems Inc.; 2021. https://www.ballard.com/docs/default-source/default-document-library/high-performance-fuel-cell-stack-white-paper-14-september-2020.pdf. [Accessed 4 April 2021].
[37] Winnefeld C, Kadyk T, Bensmann B, Krewer U, Hanke-Rauschenbach R. Modelling and designing cryogenic hydrogen tanks for future aircraft applications. Energies 2021;11(1). https://doi.org/10.3390/en11010105. URL, https://www.mdpi.com/1996-1073/11/1/105.
[38] Lolis P. Development of a novel preliminary aero engine weight estimation method. PhD Thesis. Cranfield University; 2014.
[39] Hoeflinger J, Hofmann P. A ir mass flow and pressure optimisation of a pem fuel cell range extender system. Int J Hydrogen Energy 2020;45(53):29246–58. https://doi.org/10.1016/j.ijhydene.2020.07.176. https://www.sciencedirect.com/science/article/pii/S0360 319920327841.
[40] Yan Q, Toghiani H, Causey H. S teady state and dynamic performance of proton exchange membrane fuel cells (pemfcs) under various operating conditions and load changes. J Power Sources 2006;161(1):492–502. https://doi.org/10.1016/j.jpowsour.2006.03.077. https://www.sciencedirect.com/science/article/pii/S0378 775306005878.

2023-12-11

Assessment of hydrogen gas turbine-fuel cell powerplant for rotorcraft

þÿB a e n a   M e j 1 a s ,   R a f a e l

Elsevier

Mejías RB, Saias CA, Roumeliotis I, et al., (2024) Assessment of hydrogen gas turbine-fuel cell powerplant for rotorcraft. International Journal of Hydrogen Energy, Volume 50, Part B, January 2024, pp.772-783

https://doi.org/10.1016/j.ijhydene.2023.07.076