PRELIMINARY ASSESSMENT OF HYDROGEN POTENTIAL AS ALTERNATIVE FUEL FOR REGIONAL AIRCRAFT

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ABSTRACT

Pollution and environmental impact are at the core of recent European Commission policies, which have imposed stringent regulations on the emissions of greenhouse gases. At this purpose, several companies in the transportation sector, as well as aeronautical sector, started to look for alternative propulsion systems and fuels with specific R&D activities. This paper explores the feasibility of using hydrogen on board of regional airlines planes Taking into account that hydrogen has a significant gravimetric energy density (120 MJ/kg), but at the same time, a low density (0.0899 kg/m^3), making its storage and transportation heavy and complex. To assess the potential of hydrogen as an alternative fuel for regional air transport, this paper analyzes the possibility of using hydrogen as a fuel on a typical aircraft for such applications, the ATR 72-600. This paper research focuses on evaluating the weights to be carried on board the aircraft, targeting to replace traditional propulsion systems with four different plant architectures (thus also targeting mixed architectures not yet explored in literature): hydrogen-fuelled gas turbine, electric propulsion powered by a gas turbine and fuel cells in parallel, fully electric propulsion using only fuel cells, and finally, an electric hybrid configuration with fuel cells combined with a battery. The paper benchmarks all of them also looking at potential future technological evolution and trends as well as at the need of EU regional aviation potential hydrogen demand.

1 INTRODUCTION

Nowadays, the transportation sector has a strong impact on final energy consumption, accounting for about 112 Exajoules (EJ), representing nearly 27% of the total worldwide at the end of 2021. The largest part of the sector is powered by fossil fuels, by oil products which have the largest contribution (102 EJ) according to International Energy Agency data (2024), with a strong impact in terms of pollutants and greenhouse gas (GHG) emissions. Flights departing from EU27+EFTA represented 16% of global aviation's CO_2 emissions in 2018. In 2019, all departing flights from Europe were accountable for 5.2% of the total EU27+EFTA greenhouse gas emissions (an increase from 1.8% in 1990) and 18.3% of emissions from the transport sector, making aviation the second largest source of emissions in the transport sector after road [EASA, 2024]. The EU's European Green Deal envisions slashing transport emissions by 90% by 2050, compared with 1990 levels [EC, 2024], to do so aviation sector has been introduced to Emission Trading System (ETS) since 2013, while other initiatives are promoted by EC towards emissions reduction [EC, 2024]. In 2019, aircraft operators covered 22% of their CO_2 emissions by purchasing allowances under the EU ETS. The ETS has not fully mitigated the growth in CO_2 emissions due to the growth in emissions from flights outside its applicability scope [Shinsiong and Mu-Chen, 2023] [Fageda and Teixidó, 2022], furthermore in order to achieve above mentioned targets, it is clear that alternative fuels to kerosene have to be considered, as reported by ICAO in a report published on 2022 on the feasibility of a long-term aspirational goal (LTAG) for international civil aviation CO_2 emission reductions [ICAO, 2022].
To reach the above-reported ambitious targets (as currently done for maritime sector as well [Elkafas et al. , 2023]), it is mandatory to reduce the use of fossil fuels and promote low and zero-carbon fuels [Blakey et al., 2011] in the aviation sector (what called Sustainable Aviation Fuels or SAF [Kurzawska, 2021] [Cabrera and de Sousa, 2022]) and high-efficiency technologies for propulsion, also considering

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turbine/jet-engine enhancements [Liu et al., 2017], aircraft design alternative solutions [Bravo et al. , 2022], electrification [Talwar et al., 2023] and hybridization [Kuśmierek et al., 2023] of propulsion systems, also foreseeing the utilization of fuel cells [Farsi et al., 2023] [Collins and McLarty, 2020]. In this framework, the use of hydrogen as alternative fuel has attracted many researchers, thanks to its zero-emission nature, both foreseeing its use in gas turbines [Maningandan et al., 2023] and in fuel cells [Kadyk et al., 2018], the latter ones particularly for application in regional aircrafts [Sparano et al., 2023].
Hydrogen fuel cells setup for regional aircraft applications have been already studied quite intensively [Palladino et al., 2021] [Eissele et al., 2023] and also Clean Aviation Joint Undertaking considers regional application as the most relevant one [Clean Aviation JU, 2022], promoting to mature and demonstrate all relevant systems ready to be integrated into future aircraft: *liquid hydrogen storage on-board, fuel distribution system, fuel cell based propulsion drive trains or direct combustion of hydrogen into turboprop or turbofan engines*. As mentioned, liquid and high pressure compressed hydrogen as well as LT-PEM and HT-PEM fuel cells are considered the most relevant enabling technologies for regional aircraft application as analysed in previous literature [Kazula et al., 2023] where ATR-72 has been often used as reference aircraft for the sector [Palladino et al., 2021], also considering that ATR-72 hosted the first hydrogen fueled flight by Universal Hydrogen (2023).

In this paper, different hydrogen fuelled aircraft propulsion architecture are studied to be applied on board of an ATR-72 for regional flight application looking at the impact that the integration on board of Hydrogen technologies (storage and propulsion system) would have on the payload (number of passengers) also looking at different distances to be covered by the flight. The goal and the novelty of the paper, which starts from previous R&D results, is the benchmark of the proposed low-emissions architectures one each other both in current and future technological scenarios (thus foreseeing enhancement from a component performance point of view). The results of the analysis would show the effective feasibility of the potential transition to hydrogen of EU regional aircraft, also enabling an evaluation of the overall amount of hydrogen that the sector would require.

2 METHODOLOGY

2.1 Reference aircraft and flight journey features

The study considers the propulsion retrofitting of regional aircrafts, taking as reference an ATR-72-6000, a high-wing turboprop aircraft powered by two engines and capable of carrying 72 passengers. The original version of this aircraft dates to 1988, but the updated version first flew in 2009 [ATR, 2022]. The ATR 72-600 is equipped with two Pratt & Whitney engines, specifically PW127XT-M, which produce a power of approximately 2 MW. The company states that with this type of propulsion, it emits 69 g CO2 per seat/km. Some relevant data of the ATR 72-600 analysis are : i) Maximum takeoff weight: 23,000 kg; ii) Empty weight (OWE): 13,600 kg; iii) Maximum passenger weight: 7,400 kg; iv) Fuel weight: 2,000 kg.
The single PW127XT-M engine has a weight of 494.7 kg, to which the following weights must be added: (i) Propeller, used to create thrust, 141 kg; (ii) Gearbox, due to the difference in RPM between propeller and fuel system, 148 kg; (iii) Nacelle, which is the covering over the engine, 125 kg; (iv) other systems for the proper functioning of the engine, such as the starting system, the engine and propeller control system, total weight 107 kg.

Summing up all the aforementioned items, the total weight of a single engine is 1015.7 kg. Considering the presence of two engines, the total weight of the propulsion system is 2031.4 kg. With the empty weight of the ATR 72-600 (13,600 kg) available, the weight of the engines has been subtracted from it.

$$\text{Empty weight of the aircraft without the engines} = 13600 - 2031.4 \text{ [kg]} = 11568.6 \text{ kg} \quad (1)$$

At this point, to maintain the aircraft's power unchanged, the maximum takeoff weight had to be set equal to that of the traditional aircraft, which is 23000 kg. From this mass, the weight of the aircraft without engines from Eq.1 was subtracted (Eq.2), thus obtaining the available weight capacity, which

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is the mass that can be considered as available once evaluating the possibility to integrate a different propulsion system, along with its storage system.

$$\text{Available weight capacity} = 23000 - 11568.6 \text{ [kg]} = 11431.4 \text{ kg} \quad (2)$$

Above value will be the threshold for the new propulsion system components to be studied and for the passengers' payload that could be calculated via Eq.3

$$\text{Passengers' payload capacity} = \text{Available weight capacity} - \text{New propulsions system components [kg]} \quad (3)$$

Once the passengers' payload capacity is obtained, to find their number, the weight value can be divided by the average estimated mass of a passenger, which is 95 kg (weight of a person being 75 kg and baggage 20 kg). Therefore, the final output is the number of passengers that the aircraft can carry for a given flight mission.

In this study, no specific analysis was conducted regarding the volumes and distribution of weights on the aircraft, focusing solely on the masses related to the propulsion systems. The most important parameter used for comparison in these analyses relates to the number of passengers transportable by each configuration for three different distances: 200, 400, and 600 nautical miles (NM). To dimension the new components specifically for the ATR 72-600, a reference flight mission was used, exposing the power, speed, and altitude values for each segment of the flight. The reference profile is the one proposed in [Hartmann et al., 2022], as depicted in Fig. 1.

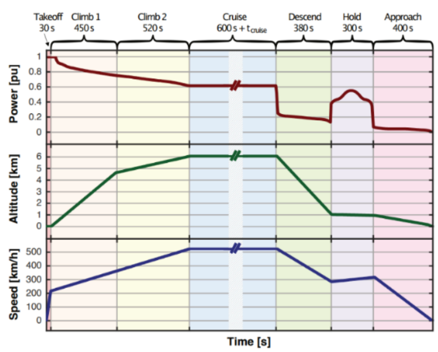

Fig. 1 Reference flight profile [Hartmann et al., 2022]

As Fig. 1 shows, the power required for takeoff is the maximum that the engines can deliver. In the case of the ATR 72-600, the power for takeoff has been set at 4 MW (2 MW per engine). In hybrid configurations (described in §2.2), the maximum power for takeoff will be obtained by summing the powers that both systems can provide, totaling the required 4 MW.

This power is used to size all components of the system (via mass/weight functions defined in §2.3) because even though the power during subsequent flight phases is lower, it is necessary to ensure the ability to deliver sufficient power to take off. As observed, the power for takeoff is used only for a short time span (the time required to lift the aircraft off the runway), and subsequently, the power gradually decreases until reaching cruise flight conditions. This power profile and duration over the various flight phases affect the amount of fuel carried for the mission and consequently the weight of the tank.

After the takeoff and the climb phase, the aircraft reaches cruise altitude, where the power stabilizes and, barring weather conditions during the mission, remains constant throughout the flight until the landing maneuvers are initiated. In Fig. 1, the duration of the cruise flight is not indicated because it can vary depending on the distance between the departure and arrival points. In this study, the distances considered are 200, 400, and 600 NM, so knowing the cruise speed and the distances covered during the takeoff, climb, and landing phases (derived from the flight time and the speeds required to perform these operations), it has been possible to determine the time required to complete the three flight missions and therefore to estimate the amount of fuel to be stored.

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Finally, the last phase of the flight is the landing, where the required powers decrease. In cases where landing at the destination airport is not immediately possible due to weather or safety reasons, the aircraft must have the capability to execute a reserve mission. The European Union Aviation Safety Agency (EASA) sets regulations regarding the amount of fuel to be carried for each flight mission. In situations where landing at the destination airport is not possible, it is specified that the aircraft should be able to fly for at least another 30 minutes at normal cruise altitude [EASA, 2012]. This requirement affects the sizing of the tanks, which must be larger and heavier.
Additionally, fuel required for aircraft movements on the airport runway has been estimated, assuming a total timing, including pre- and post-flight maneuvers, of 8 minutes. All these guidelines are useful for determining the fuel required for the mission at hand and have been derived using equation (4), summing the fuel needs in the different phases of the journey.

$$m_{H2} = \frac{\sum_i P_i * T_i}{\eta * LHV} \qquad \text{(Eq.4)}$$

The three flying journey distances considered for the study (200, 400, and 600 NM) were chosen as regional aircrafts are usually used to connect airports over short to medium distances. Additionally, turboprop aircraft, such as the ATR 72-600, are more efficient at lower speeds and altitudes, thus typical of this type of journeys.

2.2 Analysed low emissions propulsion architectures

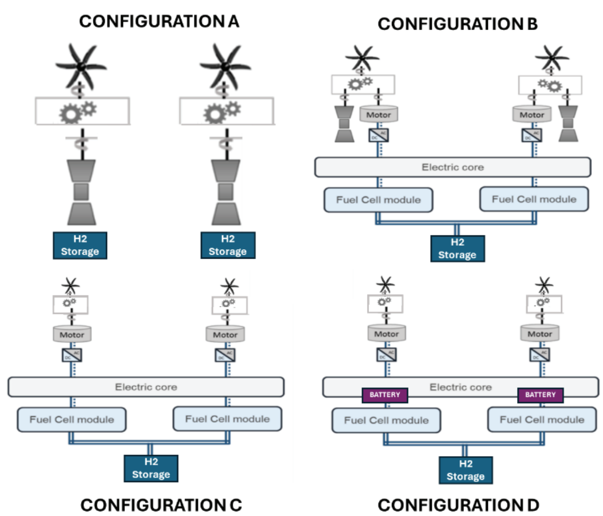

Fig. 2 Analysed low emissions propulsion architectures

In this paper, to replace the traditional propulsion system, four different configurations of hydrogen-powered engines were studied (Fig.2):

a) Gas turbine powered entirely by hydrogen.

In this first configuration, the same type of propulsion as the reference aircraft was considered, just changing the fuel from a fossil one to hydrogen. Due to these aspects some parts, such as the combustion chamber and the fuel delivery system are not identical to the reference case: it was supposed that from a weight perspective, this new H_2-combustion-enabled engine is identical to that of the ATR 72-600.
COMPONENTS TO BE CONSIDERED FOR OVERALL WEIGHT ASSESSMENT: Gas Turbine Engine, Nacelle, Mechanical Connection, Propeller, Fuel Tank,

b) Gas turbine powered by hydrogen with a parallel PEM fuel cell system.

The second configuration analyzed features a hybrid engine with both a gas turbine and fuel cells, both fuelled by hydrogen, towards an electric propulsion. This technology comprises an electrical component (fuel cell) and a thermal component (gas turbine). The use of a hydrogen-powered gas turbine certainly results in lower pollutant emissions compared to the initial case, while utilizing hydrogen in a fuel cell maximizes the system's efficiency and thus reduces the onboard fuel requirement despite significant

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NOx production. In this configuration, in addition to the gas turbine and fuel cells, all components necessary for electrical power supply are present, including a DC bus, a DC/AC converter, an electric motor, and all related cables with their respective power switches for system safety. Finally, unlike the previous case, there is a gearbox with dual inputs and a single output.

COMPONENTS TO BE CONSIDERED FOR OVERALL WEIGHT ASSESSMENT: Gas Turbine Engine, Nacelle, Mechanical Connection, Propeller, Fuel Tank, PEMFC, Compressor, Radiator, Humidifier, DC Bus, DC/AC, Cables, AC Motor, Gearbox

c) Electric propulsion through hydrogen fuel cell

This configuration is fully electric. In this full electric propulsion architecture, the same electrical components as the architecture presented in point b) are present, with the difference that in this setup, they have been sized to cover the entire power and mission of the flight. In this study, a battery has not been included to assist in transients because it was assumed that PEMFCs could meet such load deviations quickly (even if this is not an optimal architecture due to stress that the PEMFC should suffer from the aircraft journey). Additionally, the output voltage of the fuel cell might not be compatible with the voltage required to optimize the downstream components' operation. To ensure the correct operation of all electrical components and thus greater efficiency of the entire powertrain, a DC bus has been included, which also acts as a voltage regulator. This component certainly increases the weight of the system, but by maintaining a higher powertrain efficiency, it is advantageous to include it.

COMPONENTS TO BE CONSIDERED FOR OVERALL WEIGHT ASSESSMENT: Nacelle, Propeller, Fuel Tank, PEMFC, Compressor, Radiator, Humidifier, DC Bus, DC/AC, Cables, AC Motor, Gearbox

d) Electric hybrid propulsion with fuel cell and lithium-ion battery

In this last configuration, it is proposed to hybridize the electric architecture described in architecture c) through a parallel configuration with both a PEMFC and a lithium-ion battery, which can provide power simultaneously. To ensure that both components can operate at their maximum efficiency, their voltages must be different. Therefore, in this configuration, like in architecture c), the DC bus is a fundamental component. The terminal part is analogous to the previous type, with an inverter, a gearbox, and finally the propeller, which transforms mechanical energy into thrust energy for the aircraft. The presence of the battery allows for a reduction in the amount of hydrogen required, with lighter tanks, as it is charged before the flight mission.

COMPONENTS TO BE CONSIDERED FOR OVERALL WEIGHT ASSESSMENT: Nacelle, Propeller, Fuel Tank, PEMFC, Compressor, Radiator, Humidifier, DC Bus, DC/AC, Cables, AC Motor, Gearbox, Battery

For each of these configurations, the possibility of onboard hydrogen storage was evaluated both in liquid form and compressed at 700 bar.

2.3 Mass functions used to calculate the weight of the different propulsion architectures

According to the above-mentioned architectures, the following components and their efficiency/weight functions values have been considered as reported in Table 1. For fuel cells, gas turbines and batteries, both current and future technological performances (based on future R&D trends achievement) have been reported to analyse both current and future scenarios of hydrogen transition of regional aircraft. At this purpose, while analysing PEMFC technologies, the possibility to apply HT-PEMFC (a technology currently at R&D edge for aviation [BASF, 2023]) will be considered in order to take advantage of higher efficiency and lower weight. Once referring to the weight of hydrogen storage, he above mentioned weight functions include not only the weight of the tank, but also the overall hydrogen management system.

Table 1: Weight and efficiency reference values

Component	***Weight***	***Efficiency***
Gas Turbine	Current: 4,04 kW/kg	Current: 0,37
	Future: 4,49 kW/kg	Future: 0,38
Li-On Battery	Current: 0,259 kWh/kg	-
	Future: 0,370 kWh/kg	-
LT-PEM Fuel Cell	1,5 kW/kg	0,52

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HT-PEM Fuel Cell	2,5 kW/kg	0,55
Liquid Hydrogen	13,33 kg_{tank}/ kg_{H2}	-
Compressed Hydrogen	17,54 kg_{tank}/ kg_{H2}	-

Other components of the architectures, defined in §2.2, are dependent on the sizing of the Fuel Cell, particularly the air compressor and the radiator whose power capacity and weight depend on the operating temperature too. Specifically, the compressor maintains the air pressure at the cathode constant, despite the change in altitude during the flight mission resulting in a variation in ambient air density. The compressor was sized using linear interpolation based on the results presented in [Sparano et al., 2023] and [Palladino et al., 2021], where the relationship between the mechanical power of the compressor and its weight is provided by Eq.5

$$m_{comp} = 0.0401\ P_{comp} + 5.1724 \qquad (5)$$

In parallel, the radiator has the goal to dissipate the residual heat of the PEMFC (around 35% of the input energy for LT-PEMFC). Part of this heat is used to bring the fuel to the correct temperature, allowing it to be fed into the FC. Since the temperature of pressurized hydrogen is much higher than that for cryogenic storage, two different calculations were carried out for the recovered heat (Eq.6), where in the case of liquid, the recovered portion is higher, allowing for a lighter radiator.

$$Q_2 = \dot{m}_{H2}\ \lambda + \dot{m}_{H2}\ C_p\ (T_{hot} - T_{cold}) \qquad (6)$$

Then, it is possible to obtain the actual heat to be dissipated through the radiator by calculating the difference between 35% of the input energy and heat calculated via Eq.5 to estimate the thermal energy needed to pre-heat the hydrogen. Subsequently, the temperature difference between the fuel cell and the ambient air leads to heat exchange sizing. If the temperature difference is high, the radiator can have reduced dimensions and mass, while, if the operating temperature differences are low, the radiator must have larger dimensions and higher weights. With the use of LT-PEM, the temperature difference is lower, resulting in a higher mass for the radiator. Conversely, in the case of HT-PEM, the temperature difference increases, allowing for easier heat dissipation.

Further than being affected by the type of PEMFC (LT or HT) the temperature difference can be increased if the fuel cell is used only for cruise or for all flight phases. In the former case, the ambient air temperature to be considered is around -58°C, while in the latter, it is 35°C, considering the worse operating condition for the FC (thus considering 35°C as "ground temperature" in take-off phase in an average summer period) for radiator sizing. All these parameters compete to calculate the specific heat rejection of the radiator (Eq.7), which is a crucial parameter to evaluate the weight of the radiator (Eq.8)

$$c = \text{Specific heat rejection} = \frac{\Delta T}{Q} \qquad (7)$$

$$m_{rad} = 40.29\ c + 5.10 \qquad (8)$$

3 RESULTS AND DISCUSSION

In the following paragraphs the analysis of the weights of the different architectures also varying the journey distance is presented, reporting per each configuration the maximum number of travelers allowed on board, calculated in accordance with the methodology introduced in §2.1

3.1 Architecture A (H_2 gas turbine propulsion)

In this configuration, the weights related to the gas turbine are kept as those ones for the reference aircraft, assuming that the mass of the gas turbine remains unchanged even if the combustion chamber is fueled by hydrogen. Table 2 reports the results obtained for the different flight distances.

Table 2: Architecture A weight evaluation

		RANGE 200 Miles		RANGE 400 Miles		RANGE 600 Miles	
		LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]
CONF. A.	N° PAX	65.08	54.39	45.30	28.36	25.52	2.33

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Due to the introduction of hydrogen tanks, whether LH2 or CH2, a decrease in the number of passengers can be observed even for short distances such as 200 NM. The best configuration is the one that involves the use of liquid hydrogen storage. Additionally, concerning system efficiency, having a cold source like cryogenic hydrogen allows for an enhanced cooling of engine parts [Barcellona, 2022], [Khandelwal et al., 2013]. If the flight distance increases, the payload decreases, and this occurs with a rapid trend due to the low efficiency of the gas turbine propulsion system (here assumed to have an average value of 0.37 throughout the flight), which results in large quantities of fuel for longer distances. As can be seen from the diagrams in Fig. 3, the fuel tank and its management system have a very high weight on the overall system, constituting effectively, even for distances of 200 NM, the majority of the overall aircraft propulsion mass, up to almost 62% of the total.

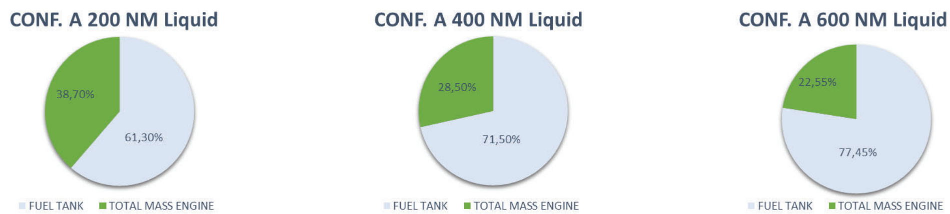

Fig. 3 Weight distribution in the propulsion system for architecture A

The charts refer to liquid hydrogen storage: if CH2 is considered, the portion relative to the weight of the fuel tank would be approximately 68% for 200 NM, reaching up to 82% for the longer distance. This configuration helps to understand how significant the storage system is in relation to the weights of the hydrogen propulsion system.

3.2 Architecture B (Coupling of H_2 gas turbine and PEMFC)

In this configuration the fuel cell is sized to cover the power needed for cruise period (Fig.1), with a power output of 2500 kW. The gas turbine, on the other hand, is coupled with the FC for takeoff and climb phases, which represent the phases with the highest power demand for flight. In this case, the radiator is sized with a temperature difference of 70°C at the FC anode and an ambient air temperature of 35°C because the FC is used for all flight phases. This type of sizing and use of the FC during the flight mission leads to a low temperature difference (between ambient air and operating temperature of the FC), necessitating the sizing of a radiator with significant mass. Tab.3 shows the number of passengers transportable for the three different flight missions. Despite the traditional propulsion system being coupled with a more efficient system (LT-PEM with $\eta = 0.52$), resulting in lower weight in terms of fuel and tank for completing the mission, the number of passengers still decreases due to the low power density of the fuel cell system if compared with the traditional GT system.
Once analysing configuration B, a different sizing and operative strategy can be imagined, foreseeing the use of the fuel cell exclusively for the cruise phase, thus maintaining the propulsion system more efficient and less polluting for the longest part of the journey, while the remaining parts of the flight (takeoff, climb, and landing) are performed by the gas turbine (Conf. B bis in Table 3).

Table 3: Architecture B weight evaluation

		200 NM		400 NM		600 NM	
		LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]
CONF. B	N. pax	37	27	23	9	9	0
CONF. B bis	N. pax	33	23	19	5	5	0
CONF. B future	N. pax	52	44	38	26	25	9

This approach can guarantee a larger temperature difference between the operating temperature of the FC and the ambient air, thereby allowing for easier heat dissipation and a lighter radiator as described

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in §2.3. However, the propulsion system is obviously oversized with a 4 MW gas turbine (required for takeoff) and a 2.5 MW fuel cell (required for the cruise phase), totaling 6.5 MW of power. The oversizing is carried out with the less efficient propulsion system, resulting in additional weight of fuel for the mission, as well as the obviously increased weight of the gas turbine. Consequently, one might expect Conf.B prime to have a higher weight, but as seen in Table 3, this is not the case, as the number of passengers transportable between the two configurations varies slightly. In Table 3, Conf. B and Conf. B-Bis are compared also with Conf. B future, where the use of HT-PEMFC and more efficient GT (as reported in Table 1) are foreseen.

A deeper analysis of configuration B highlights two main aspects:

- the relevance of the radiator's weight which in terms of mass is almost equal to the weight of the additional sizing of the gas turbine and the weight of the enlarged tank due to the increased demand for fuel in configuration B-bis. A future scenario for architecture B was also analysed where LT-PEM could be replaced by HT-PEM, showing higher efficiency, higher power-to-weight ratio, and higher operating temperature, which results in a lower radiator mass (Table 1). In addition to the fuel cell replacement, an improvement in gas turbine technology was also supposed as reported in Table 1, assuming a weight reduction of the system by about 10% and an efficiency improvement from 37% to 38%. The data reported in Table 3 show a significant improvement in the payload values for all proposed distances once analysing Conf. B Future.
- the integration of a more efficient propulsion system, such as PEMFC, allowed for less fuel consumption during flight missions, resulting in a shallower curve compared to case A. The longer the distance, the greater the influence of efficiency can be highlighted. In fact, for the 600 NM distance, it can be observed that both Conf. B Future and Conf. A allow the same passengers payload, while the two B configurations (current and future) have a slightly different trend, caused by the slightly higher efficiency of HT-PEM compared to LT-PEM (Fig.4)

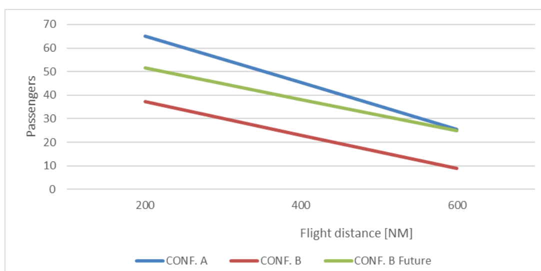

Fig. 4 Passengers number against flight journey distance for different configurations

3.3 Architecture C (Full electric propulsion driven by PEMFC)

Configuration C features a fully electric motor powered by a PEMFC. The PEMFC, being the sole energy system supplying electricity to the motor/propulsor, is sized at 4 MW to provide the required power for the whole flight mission. While this component exhibits better efficiency compared to the traditional case, the low power-to-weight ratio of the fuel cell system (stack and balance of plant) results in an increase in the total weight of the propulsion system, strongly reducing the payload capacity (Fig. 5), with no possibility to allow passengers on board: the only flight allowing passenger transport is the one corresponding to the 200 NM distance, allowing for only about a dozen passengers.

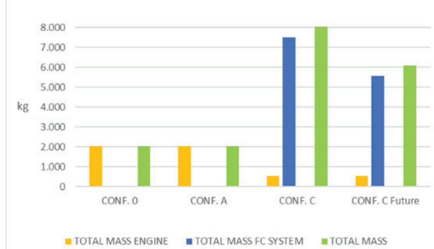

Fig. 5 Mass comparison of the different architectures

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This configuration was also analyzed in a future scenario (Table 4), foreseeing HT-PEM installation: however, the number of transportable passengers approaches remains low. This finding highlights that configuration B is more favorable in the current state of the art compared to a future, and thus uncertain, perspective of propulsion based solely on FCs. For this reason, the application of fuel cells in the aerospace sector as the sole propulsion choice currently presents significant challenges and complexities, despite being environmentally more sustainable due to the complete absence of NOx emissions in the exhaust. Nevertheless, R&D on HT-PEMFC particularly looking at increasing power/weight ration and efficiency could open significant horizons in this sense.

Table 4: Architecture C weight evaluation

		200 NM	
		LIQUID	COMPRESSED [700 bar]
CONF. C	N. pax	12	0

		200 NM		400 NM		600 NM	
		LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]
CONF. C Future	N. pax	34	26	20	8	7	0

3.4 Architecture D (full electric propulsion with PEMFC and batteries)

As mentioned in Section 2, this last configuration involves the integration of a FC in parallel with a lithium-ion battery. Three different configurations were analyzed (D, D bis, and D future), representing respectively the current state of the art with LT-PEMFC (D), a system with an oversized battery to use the FC only during cruise (D bis), and a future scenario in which HT-PEMFC and more performant batteries are used (D future).

In the first case, to size the battery, its usage time was calculated by multiplying it by the power required in the segment where it is used, thus obtaining the necessary energy that the battery must deliver for the considered flight mission. The battery does not need an additional fuel tank to contain fuel because it is charged before the flight mission, allowing for the installation of less bulky tanks. However, the power-to-weight ratio and volumetric density of the battery limit its application. In fact, in configuration cases D and D future, the use of the battery is exclusively dedicated to flight phases where the FC cannot provide all the required power, namely during takeoff and climb. The FC is sized to meet all the power demand during cruise (2.5 MW), and the remaining part is covered by the battery.

Table 5: Architecture D weight evaluation

		200 NM		400 NM		600 NM	
		LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]
CONF. D	N. pax	29	20	15	2	1	0
		200 NM		400 NM		600 NM	
		LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]	LIQUID	COMPRESSED [700 bar]
CONF. D Future	N. pax	45	37	32	20	18	2

The results obtained for the current application are shown in Table 5, where for distances higher than 400 NM, it is no longer possible to have passengers' presence. In this propulsion architecture as well, the possibility of using the FC exclusively during cruise was analyzed (Conf. D-bis) to allow for a larger temperature difference between the FC and the ambient temperature, thus obtaining a lighter radiator. Consequently, the remaining flight phases (taxi, takeoff, climb, and landing) are covered by the battery. However, as mentioned earlier, the limitations of the battery make this application unfeasible, with the absence of payload starting even in the 200 NM scenario. As previously done for architecture B and C, a future scenario was analyzed too foreseeing the integration of HT-PEMFC and the use of enhanced

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batteries, having a specific energy value of 370 Wh/kg. Looking at the reduction of payload while increasing flight mission distance, a similar trend can be observed between the future configurations D and B (Fig.4 and Fig.6), thus demonstrating the relevance of HT-PEM technology to enable the possibility to use hydrogen on-board of aircraft even larger distance.

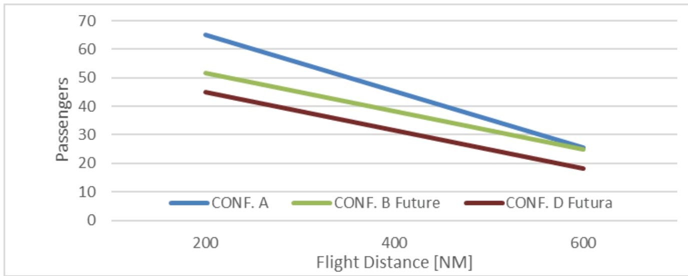

Fig. 6 Passengers number against flight journey distance for different configurations

4 EVALUATION OF THE HYDROGEN NEED TO COVER THE OVERALL EU REGIONAL AVIATION SECTOR

The final analysis is related to the assessment of the hydrogen needed to fuel regional flights around EU, considering statistics from 2019 [EUROSTAT, 2019], as the last year without any influence of the COVID-19 pandemic, considering transitioning to hydrogen flights operating within the three analysed flight distances (200, 400, and 600 NM) and equipped with configuration A and future configuration B. The first one can be indeed seen as the best among the currently feasible scenarios, while the second one, having higher efficiency, could require less fuel for the flights.

Table 6: Figures about how to transition to hydrogen EU Regional transport.

Flight Distance	Analysed Configuration	Hydrogen needed [kg]	Electricity Needed [MWh]	PV surface needed [km^2]	% of EU regional aviation
Within 200 NM	Conf. A	1.46×10^8	8.01×10^6	36.40	4 %
	Conf. B future	1.27×10^8	6.96×10^6	31.63	4 %
Within 400 NM	Conf. A	1.03×10^9	5.65×10^7	256.82	14 %
	Conf. B future	8.39×10^8	4.62×10^7	209.84	14 %
Within 600 NM	Conf. A	5.94×10^9	3.27×10^8	1485.02	37 %
	Conf. B future	4.26×10^9	2.34×10^8	1064.33	37 %

First, the number of passengers who flew within 200, 400, and 600 NM in 2019 was determined. Then, this value was divided by the number of passengers that can be transported by each hydrogen aircraft for the corresponding flight mission as calculated in §3.1 and §3.2 for conf.A and conf.B-future. Once the number of hydrogen flights required to cover the entire passenger demand was obtained, this value was multiplied by the calculated amount of fuel required for 200, 400, and 600 NM, thus obtaining the overall amount of hydrogen required. At the end, the potential electricity needed to generate such amount of hydrogen via electrolysis is calculated (considering producing 1 kg of H_2 via 55 kWh_{el}), also evaluating the potential PV surface needed to produce it (considering an average EU solar irradiation of 1100 kWh/m^2). Results are reported in Table 6.

5 CONCLUSIONS

The use of hydrogen as an alternative fuel for regional air transport presents several technological challenges currently being analyzed by many companies and research centers. The objective of this study was to conduct a pre-evaluation regarding the weights that four architectures for the propulsion

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of an ATR-72 aircraft powered by hydrogen could present, not changing any specific propulsion capacity of the aircraft, but being open to reduce the payload and the number of passengers on board.
From the results obtained in this analysis, it can be demonstrated that for short distances such as 200, 300, or 400 NM, the possibility of using hydrogen in turbine driven propulsion systems, similar to those currently powered by kerosene, appears to be the best technological solution with a foreseen additional weight relative only to hydrogen storage. As the distance increases, up to 600 NM, at the current state of art of technology, the most suitable technological scenario is still linked to the use of a hydrogen-fuelled gas turbine, as for electric technologies, the low power-to-weight ratios have made their applications challenging now. However, soon, the potential development of HT-PEMFCs and batteries with higher specific energy values makes such propulsion types particularly interesting, allowing for the study of different hybridizations to maintain the payload as unchanged as possible even in longer distance flight missions.
The above considerations have been verified not only for the case of the ATR-72 aircraft but also for a smaller aircraft (ATR-42) also used for regional air transport: in this case, many configurations previously analyzed were found to be unfeasible even for shorter distances.
The goal of this paper is therefore to further stimulate the research on HT-PEMFC and Hydrogen fuelled aeroderivate GTs as enabling technologies for EU regional aviation sector decarbonization, being aware that a significant effort should be needed also to produce the hydrogen potentially needed for such flights.

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