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Solid oxide fuel cells for aviation: A comparative evaluation against alternative propulsion technologies

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A B S T R A C T

Conventional aircraft emit high greenhouse gases, hindering aviation decarbonization. Among sustainable solutions, battery-electric planes face range limitations, while renewable fuels can cut emissions without sacrificing endurance. Fuel cells enable full electrification, powering propulsion and auxiliary systems. Although they have lower power density than combustion engines, their promising efficiency can potentially reduce overall weight.

This study compares fuel cell and conventional propulsion systems, focusing on Solid Oxide Fuel Cells (SOFCs) and Proton-Exchange Membrane Fuel Cells (PEMFCs). The initial literature review emphasizes the potential of SOFCs for aviation and discusses ongoing projects, forming the basis for the subsequent technical analysis. A break-even analysis examines flight durations in which fuel cell systems match the weight of conventional alternatives. Additionally, various fuels and storage methods, including jet fuel and hydrogen, are assessed. Results show that jet fuel SOFCs are currently the lightest fuel cell option, while PEMFCs with liquid hydrogen require higher power density and lighter storage to compete. Looking ahead, liquid hydrogen storage appears most viable, with PEMFCs better for short-range and SOFCs for long-range flights. An environmental analysis evaluates CO_2 emissions across European countries, identifying break-even grid carbon intensities for jet fuel and hydrogen SOFCs. These findings highlight fuel cells' potential to reduce aviation's environmental footprint.

1. Introduction

Significant measures are expected in the next 20–30 years to reduce GHG (Greenhouse Gases) emissions, especially in the heavy-duty transport sector. According to the European Union (EU) [1], if global aviation were a country, it would be ranked among the top ten emitter countries in the world. To achieve climate neutrality, the European Green Deal sets the need to reduce transport emissions by 90 % by 2050 (referred to 1990 level) [2]. Additionally, in July 2022 the European parliament decided through the REFuelEU aviation plan that all the EU airports should use a minimum share of Sustainable Aviation Fuels (SAF): 2 % by 2025, 38 % by 2040 and 63 % by 2050 [3] and electricity from renewable sources and hydrogen should be part of this transition [4]. As shown in Fig. 1, within the SAF requirement, a sub-obligation is envisaged for synthetic aviation fuels.

Indeed, many efforts have been made to design aircraft propulsion systems aimed at reducing local emissions during flights. Certain layouts, completely powered by high-performance lithium-ion batteries, have been designed. However, their limited endurance and high weight suggest that they are not suitable for long-range transport applications. This can be noticed in the case study of the NASA X-57 Mx, where the maximum range of a 4-seats aircraft powered by batteries could not exceed 75 km [5]. For this reason, many turbo-electric designs have been analyzed to increase the flight duration, but the conversion efficiency of such systems is still low because of the energy conversion first from chemical to thermal energy (through combustion), and then into electrical energy. These limitations have led to an interest in investigating fuel cells for the aviation sector, thanks to their direct and high energy conversion efficiency and, when using Solid Oxide Fuel Cells (SOFCs), their fuel flexibility and the possibility of internal reforming [6]. In 2021, Barton et al. [7] conducted an extensive study on the feasibility of decarbonizing freight and passenger transport in India, suggesting that very long-distance vehicles would be better served by fuel cells.

There are mainly two types of fuel cells, operating at high (SOFCs) and low (Proton Exchange Membrane Fuel Cells - PEMFCs) temperatures. Low-temperature fuel cells for aviation have already received considerable attention in the literature in recent years [8,9]. Massaro

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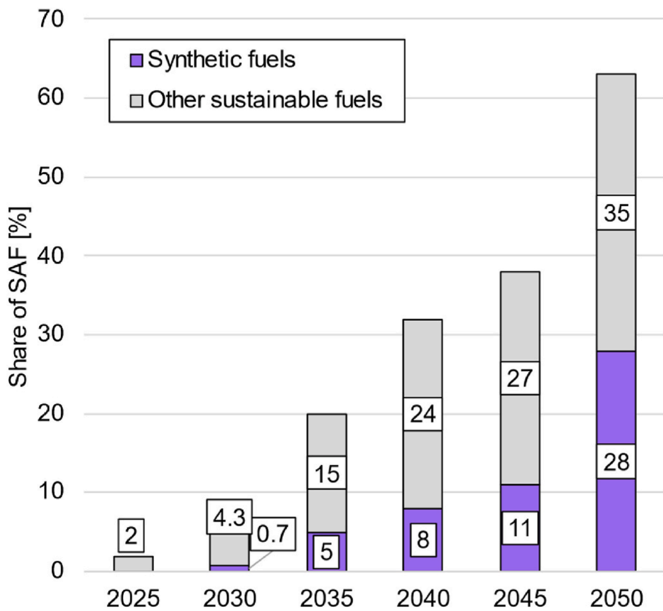

Fig. 1. Minimum share of synthetic and sustainable aviation fuels to be supplied according to the ReFuelEU in % of all fuel (from 2025 to 2050).

et al. [10] carried out a study on the potential requirements and challenges of on-board hydrogen storage coupled with a PEMFC power generation system, concluding that an all-electric aircraft equipped with this technology is not currently feasible. However, the authors stated that, with advancements in the gravimetric density of fuel cells and hydrogen storage technologies, envisioning an emissions-free future by the middle of this century is not unrealistic. Baroutaji et al. [11] identified various aerospace and aviation applications for fuel cells, imputing the PEMFC as the most suitable due to its higher power density. On the other hand, their work underlined many limits in the current scenario for the PEMFC operation, such as the need for high hydrogen purity, the lack of hydrogen refuelling infrastructure, the challenges of on-board liquid hydrogen storage, and the low power density of this kind of Energy Storage and Power Generation (ESPG) system [9].

Moving to SOFCs, they have some qualities that make them very interesting for aviation [12]. Their higher efficiency enables a significant reduction in fuel consumption. Moreover, the possibility of internal reforming allows SOFCs to work with a broader range of potential fuels, while PEMFCs need a very high hydrogen purity to avoid accelerated ageing [13,14]. As a matter of fact, many research groups and private companies have conducted compatibility analyses of the SOFC for propulsion purposes. Okai et al. [15] investigated the effects of fuel type on aircraft electric propulsion using a SOFC/Gas Turbine (GT) layout, whereas Lindahl et al. [16] developed a physically-based model for the design and optimization of a SOFC-powered electric propulsion system for an unmanned aerial vehicle. High temperatures on the aircraft typically do not pose significant issues, as many non-moving components are comparable to other high-temperature components already certified for flight. The primary risk arises from potential air leakage inside the system, which can lead to fuel auto-ignition, caused by the elevated temperatures. According to Ref. [17], this problem can be mitigated through enhanced redundancy and existing active and passive safety components, such as firewalls, instrumentation, and fuel shut-off valves.

As can be seen from Table 1, SOFCs can be easily scaled and shaped for many design applications. Indeed, the power output of the reported projects ranges from hundreds of watts (for commercial cases) to megawatts (for future projects), with the capability to use different fuels including propane, diesel, hydrogen, methanol, and many others. For this reason, each fuel requires different ESPG systems that must fit with the space and volume requirements of the aircraft.

Overall, no report has been found regarding the assessment of SOFCs as the optimal alternative in terms of weight for propulsion purposes. Whyatt et al. [28] analyzed the break-even weight of SOFC systems, but solely for on-board auxiliary power and not for propulsion purposes. In fact, SOFCs have a higher fixed weight and thus lower power density (in kW/kg) compared to PEMFCs [29], which would make the latter more suitable for propulsion purposes. However, the whole mass of the SOFC-based ESPG could potentially be lower for long flight times due to the SOFC higher operating efficiency [30]. The technical feasibility of SOFC for propulsion in the aviation sector thus necessitates deeper investigation.

This study aims to assess the feasibility of fuel cell-based propulsion systems for aviation, identifying conditions where they can provide a competitive alternative to conventional jet fuel engines. The analysis highlights the potential of SOFCs in reducing fuel consumption and emissions, contributing to the decarbonization of air transport. For comparison, PEMFC technology is also investigated. To provide a comprehensive assessment, different fuels and storage methods are examined, including jet fuel and hydrogen, with the latter stored in both liquid and solid forms. The analysis is conducted through a break-even point approach applied to the mass of the ESPG: the goal is to determine the flight duration at which the weight of the fuel cell-based layouts becomes lighter than that of the traditional case. Indeed, weight-and-balance is one of the most crucial characteristics for airliners [31], as any additional weight results in a reduction in the number of available seats if the take-off weight is kept unchanged. This would imply lower incomes or higher ticket prices per seat, necessitating consideration of the price elasticity of passengers in the analysis [32]. Furthermore, there are regulations limiting the maximum take-off weight due to structural limitations. Finally, aside from financial and regulative reasons, it is important to note that the fuel consumption of

Table 1
Main projects that use or plan to use SOFCs for propulsion in the aviation sector.

Project	Gravimetric power density[a] [kW/kg]	Volumetric power density[a] [W/L]	Power [kW]	Efficiency[a] [%]	Fuel
Mini-UAV DVF2000 EU Project [18,19]	0.112	280	0.335	56	Propane
X-57-F from NASA [20,21]	0.302–0.281[b]	120	120	62–55[b]	Diesel
Stalker XE UAS from Lockheed Martin [22]	0.294	n.a.	1	40 (using JP5)	Propane–JP5–JP8
SOFC's for FLIGHT from PCI [23]	>1	17.66	2 (prototype)	>70	Energy-dense carbon-neutral liquid fuel
SOFC-Combustor-GT concept from Tennessee Tech University [24,25]	2.25–3.6	n.a.	9000 (in cruising conditions)	65	Bio LNG, hydrogen, methane, propane, ammonia, ethanol, methanol
Hybrid SOFC/Turbogenerator for Aircraft from University of Maryland [26]	Only SOFC >1.6 SOFC + GT > 3.0	n.a.	1800	53	50 % reformed CH_4
HYLENA (HYdrogen eLectrical Engine Novel Architecture) [27]	>3-5	n.a.	n.a.	>65	Mainly Hydrogen, but SAF, Natural Gas or Ammonia are considered

[a] System-level values.
[b] Different values are referred to two different layouts called Design Analysis Cycle 1 and 2 (DAC 1 and DAC 2).

the aircraft is supposed to increase with weight. Weight is therefore the primary parameter for comparing innovative propulsion systems.

In this study, Section 2 explains the methodology and outlines the main assumptions necessary for the model, including input data for current and future scenarios. In Section 3, the results of both the technical (break-even point approach) and the environmental analysis are presented and discussed. Lastly, Section 4 provides concluding remarks of the findings of the work.

2. Methodology

This paragraph outlines the methodology utilized in the work. The metric used to compare different alternatives is the total weight of the Energy Storage and Power Generation (ESPG) system. A model is developed to estimate the mass of the different designs based on the flight duration and fixed-weight components.

2.1. ESPG weight contributions

The ESPG weight (W_{ESPG}, in t) can be estimated as the sum of a fixed and a variable weight contribution according to:

$$W_{ESPG} = W_{fixed} + W_{variable} \tag{1}$$

The fixed weight (W_{fixed}, in t) corresponds to the weight of the power generation system, which does not scale up with the distance travelled. The second term of the equation represents the variable weight ($W_{variable}$, in t), which depends on the distance covered and expresses the weight of the fuel and the energy storage system on-board. A similar methodology was used by Pagoni et al. [33] to calculate the weight of an aircraft, which was evaluated as the sum of a fixed and a variable contribution.

In the comparison of different ESPG configurations, the break-even point approach is employed: It is the flight duration at which the weight of the ESPG components in fuel cell-based configurations matches that of the reference case (jet fuel combustion engine).

2.2. Energy storage and power generation configurations

The study investigates two fuel cell typologies, namely SOFC and PEMFC, which are compared against a commercial aircraft (B737 MAX, here referred to as "reference case"). The main focus is on the usage of SOFCs for propulsion, while PEMFCs are considered a matter of comparison since they are the most widespread fuel cell technology for propulsion. For the sake of completeness of the analysis, two different scenarios have been addressed in terms of input data, one reflecting current conditions (Current scenario) and the other projecting future conditions (Future scenario).

2.2.1. Internal combustion engine configuration (reference case)

The selected aircraft (B737 MAX) is appointed by Boeing as one of their top aircraft and significant efforts have been made to showcase its reduced CO_2 emissions during flight [34]. Furthermore, the plane is on a scale of 150 passengers, so it can be compared in terms of distance, weight, and fuel consumption with the chosen fuel cell-based case study (which is presented in Section 2.2.2). Technical specifications for the reference case are shown in Table 2. The plane uses Jet A-1 as propulsive fuel stored in liquid form in tanks.

The total ESPG weight (W_{ESPG}) is evaluated using Eq. (1), summing the fixed weight term (engine weight [35,36], shown in in Table 2) and the variable term. The latter is evaluated by multiplying the specific fuel consumption by the distance travelled and dividing by the gravimetric storage density [37]. The gravimetric density (η_g, in wt%) of the liquid jet fuel storage is set equal to 75 wt% [38] for the current case, and 87.5 wt% for the future case, making the hypothesis of a reduction of half of the fuel storage system. In the future scenario, the fuel consumption has been reduced by 30 % (from 2.52 to 1.76 kg/km), as the Clean Sky2 project and EU predict for this specific model [39].

Table 2
Reference case specifications for both current and future scenarios.

Boeing 737 MAX	W_{fixed} [t]	η_g [wt%]	Specific fuel consumption [kg/km]
Current scenario	5.56	75	2.52
Future scenario	5.56	87.5	1.76

2.2.2. SOFC and PEMFC configurations

This section presents the layout of all the investigated fuel cell-based configurations, in terms of auxiliary components, weight calculation, system efficiency and storage gravimetric density.

2.2.2.1. SOFC system layout. SOFCs are considered the principal case study in this work, so a proper propulsion layout design is necessary to face the analysis. The SOFC-based layout is shown in Fig. 2a.

The SOFC configuration under study is composed of:

- Fuel storage: Each layout has its storage depending on the fuel typology.
- Compressor: The air is taken from the external environment and is compressed by a compressor before entering the SOFC. It is included following the results of Tennessee Tech. University's study for aviation shows an improving trend of the stack power density by increasing the stack pressure. Indeed a +35 % increase in power density has been detected when changing the pressure from 1 to 4 bar [24].
- Pre-combustor: The same research group experimented that a pre-combustor could be added too to elevate the air temperature to the required operating temperature of the SOFC and potentially better modulate the steep load changes. It has been demonstrated that by controlling the temperature at the cathode inlet, the full power can be reached in less than 30 min during the warm-up phase [24]. So, this component helps the stack to be more flexible in following the load required during the mission.
- Fuel cell stack: The case study layout uses a SOFC to run the aircraft. SOFCs for large-transport applications can work under pressure (2–15 bar), as many literature projects show [24,26].
- Turbine: Once the exhausts get out of the fuel cell, they are expanded in a turbine to take advantage of the high-temperature gases that would otherwise not be exploited. This permits to improve the efficiency of the system by producing more electrical energy.

2.2.2.2. PEMFC system layout. A scenario that sees the usage of PEM fuel cells is considered too (Fig. 2b). This is made to compare the performances of the two typologies of fuel cells and to prove the effectiveness of SOFCs for propulsion in terms of energy savings and so fuel economy. The PEMFC layout presents the same components of the SOFC case, except for.

- Compressor: A small compressor is normally used to increase the pressure since at altitude the ambient pressure would be low and so the fuel cell would underperform.
- Humidifier: Typically for low-temperature fuel cells, a humidifier for reactants at the PEMFC inlet is needed to prevent membrane dryness, which could cause a performance worsening of the cell.
- Fuel reformer: Eventually, if the PEMFC does not work with pure hydrogen as fuel, an external reformer is essential to avoid catalyst poisoning.
- Condenser and separator: The exhausts from the stack still have a share of unspent fuel that can be recirculated since a quantity higher than the stoichiometric one is sent to the anodic side. Same thing with the outlet water, which can be used for humidification with an economizer, saving space and weight.

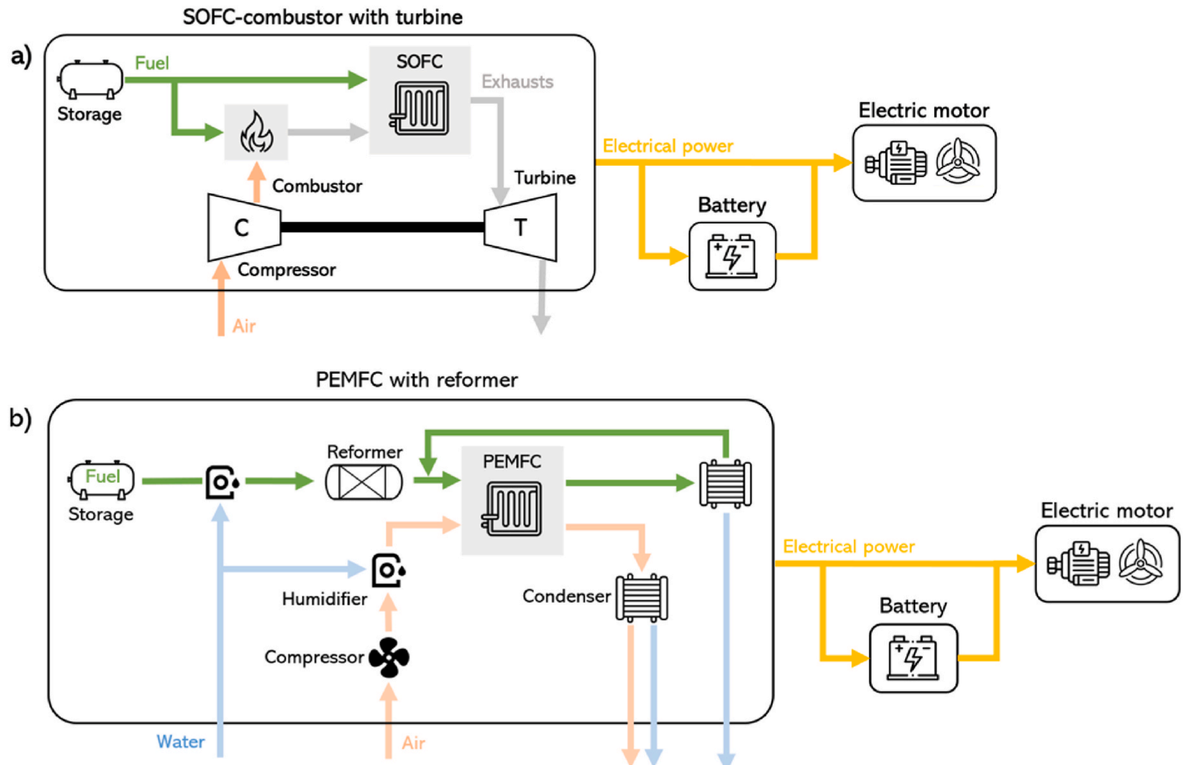

Fig. 2. (a) SOFC propulsion system layout (b) PEMFC propulsion system layout.

2.2.2.3. ESPG weight assessment. The technical specifications for the SOFC and PEMFC configuration are shown in Table 3. Typically, PEMFCs have higher power densities than SOFCs if just the stack is considered, but the gap is reduced if the whole balance of plant (BoP) is considered [40]. Additionally, SOFCs have higher stack efficiencies compared with PEMFC, and this difference increases if an external reformer is used in the PEMFC configuration (where a high hydrogen purity is required [41]).

The total fixed weight (W_{fixed}, in t) of fuel cell configurations – expressed in Eq. (2) – can be computed as the sum of the fuel cell system weight ($W_{FC,syst}$, in t), batteries weight ($W_{battery}$, in t) and electric motors weight (W_{motor}, in t).

Table 3
Specifics of the Energy Storage and Power Generation System (ESPG) depending on fuel cell type and fuel used.

FC type	Storage type	Stack power density [kW/kg]	System power density [kW/kg]	FC system efficiency (η_{PG}) [%]	Gravimetric storage density η_g [wt%]
	CURRENT SCENARIO				
SOFC	Jet fuel	1.0	0.60	60	75
	LH_2	1.0	0.60	60	7.5–15
	NH_3	1.0	0.60	56	15.5
	$LiBH_4$	1.0	0.60	60	8–9.9
PEMFC	LH_2	1.6	0.75	39	7.5–15
	Jet fuel	1.6	0.55	34	75
	FUTURE SCENARIO				
SOFC	Jet fuel	2.5	1.46	65	87.5
	LH_2	2.5	1.46	65	25–50
	NH_3	2.5	1.46	61	17.8
	NH_4BH_4	2.5	1.46	65	13.9
PEMFC	LH_2	5.8	2.00	46	25–50
	Jet fuel	5.8	1.38	39	87.5

Table 4
Scenario "SOFC fed by synthetic jet fuel": input and output values for e-fuel production [53].

INPUT PARAMETERS		
Inputs		Values [l_{DE}/kg][a]
CO_2		2.54
H_2O		3.99
O_2		0.34
OUTPUT PARAMETERS		
Outputs	Share [%mass]	Energy density [kWh/kg]
Kerosene (jet fuel)	38.9	12.0
Diesel	61.1	11.6

[a] l_{DE}: liters of diesel equivalent = 35.9 MJ/kg.

$$W_{fixed} = W_{FC,syst} + W_{battery} + W_{motor} \tag{2}$$

The input data regarding Eq. (2) are shown in Appendix A (Table A1). The electric motor weight is retrieved from the University of Louisiana at Lafayette's study [24] and is kept constant for all the innovative fuel cell-based configurations (3.3 t). Regarding the batteries, the current scenario has a high-performance battery system (425 Wh/kg [24], assuming 90 % efficiency). In future scenarios, the battery system is assumed to slightly improve its gravimetric index (460 Wh/kg), while the efficiency does not change. Based on these energy densities and on the battery size presented in Section 2.3 (about 1700 kWh), the battery weight in the current and future scenarios is determined (results are available in Table A1). A similar approach is employed for the fuel cell system, whose weight is evaluated based on the fuel cell system size (7 MW, as shown in Section 2.3) and the energy density for the different configurations, shown in Table 3.

The variable weight contribution ($W_{variable}$, in t) in Eq. (1) is evaluated as:

$$W_{variable} = \frac{1}{E_{fuel} \bullet \eta_g} \bullet \int_{t_i}^{t_f} \frac{P_{load}(t)}{\eta_{PG}} \, dt \tag{3}$$

where.

- P_{load} (in MWe) is the electrical power required, derived from the mission profile presented in Section 2.3.
- t_i and t_f (in s) are the starting and ending points of the mission.
- η_{PG} is the system-level efficiency (including all the auxiliary components) of the power generation unit.
- E_{fuel} (in MWh/t) is the specific energy density of the fuel. This value is equal to 33.3 kWh/kg for the hydrogen-fed configurations, and 12 kWh/kg for the jet fuel-fed configurations.
- η_g (in wt%) is the gravimetric storage density, which accounts for the additional mass needed to store a specific amount of fuel. This parameter varies across each layout under analysis. It is defined as the mass of fuel (i.e. jet fuel, hydrogen) divided by the total mass of the storage system, encompassing the mass of fuel and related carrier (if any), the tank weight and the required BoP. The gravimetric storage density is crucial for the achievement of the competitiveness of a fuel for aviation, as it can heavily impact the on-board mass. For instance, a highly efficient propulsion system would allow a smaller amount of fuel to be brought on board, but at the same time the latter might have a low gravimetric storage density (η_g), so necessitating a higher weight to store it.

The assessment of the variable weight contribution ($W_{variable}$) is associated with the propulsion system efficiency (η_{PG}) and the gravimetric density of the storage (η_g), presented in Table 3 for the different system configurations.

The first investigated fuel type for fuel cell layouts is liquid hydrogen (LH_2). It is worth noting that the future LH_2 PEMFC scenario sees an increase of 7 % in the system efficiency (η_{PG}), from 39 % to 46 % [39, 42], and a system power density in line with the Clean Sky2 project and EU predictions (current: 0.75 kW/kg, future: 2 kW/kg) [39]. Currently, some commercial SOFC stacks exhibit a power density of 1 kW/kg [43], resulting in a system power density of about 0.6 kW/kg. Future SOFC stacks are expected to achieve power densities ranging from 2 to 3 kW/kg (e.g., High Power Density NASA's Solid Oxide Fuel Cell [44]). For this reason, a value equal to 2.5 kW/kg is chosen for the SOFC stack. This leads to a system power density for the SOFC future scenario of 1.46 kW/kg, according to Seitz et al. [40]. The system efficiency (η_{PG}) of the SOFC system increases from 60 % in the current scenario [28] to 65 % in the future scenario. The latter is assumed to be at the cutting edge of current technology due to limited information available in literature [45]. The assumed gravimetric storage density range for liquid hydrogen (current scenario) spans from a reasonable value of 7.5 wt% [10] to 15 wt% as a very optimistic value [46]. Regarding a possible future improvement of this parameter, it is set between 25 wt% [46] to 50 wt% [10]. Indeed, to use this kind of technology for long-range aircraft, at least a gravimetric index of 38 wt% is needed [39]. When a range of η_g is considered in Table 3, an average value has been taken into account for Eq. (3).

Regarding the jet fuel case, η_g is equal to 75 wt% [38] in the current scenario and 87.5 wt% in the future one (same assumption as in the reference case). System power density and efficiencies for jet fuel SOFC in both current and future scenarios are assumed to be the same as in the liquid hydrogen configuration (Table 3). For the PEMFC configuration, the values are lower compared to the liquid hydrogen case because of the necessity of a reformer to convert the inlet jet fuel.

A series of innovative energy storage solutions for mobility have been included for the fuel cell scenarios, besides the use of liquid hydrogen and jet fuel configurations. They include.

- Ammonia (NH_3): This type of energy storage is considered only for the SOFC configuration. In fact, it is not well suited for PEMFCs because it would need a heat source (reformer) to extract the hydrogen from the NH_3, which would lower the efficiency and the overall efficiency [10]. Moreover, impurities would damage the cell, necessitating the use of separators, which would further increase the overall weight [46]. The SOFC stack and system power densities are assumed to be the same as for the previous SOFC configurations. This case sees an increase in the gravimetric density (15.5 wt%) compared to typical literature values thanks to the SOFC's internal reforming feature that allows for direct NH_3 feeding. The value of 15.5 wt% was found by starting from the physical maximum value (17.8 wt%, found as the weight contribution of hydrogen in ammonia) and adding the mass of the tank and minor BoP. For the future scenario, optimal integration of the fuel storage with the aircraft is assumed, resulting in a η_g equal to the mass fraction of hydrogen contained in the liquid (17.8 wt%). The system efficiency for SOFC-fed ammonia is reduced by 4 % compared to the jet fuel case, and it is equal to 56 % in the current scenario. The reduction in the system efficiency due to the ammonia feeding is kept constant for both current and future cases [47,48].
There is still no clear and straight regulation related to the use of NH_3 in the aviation field, but the naval sector may offer hints. The use of fuels is regulated by the International Maritime Organization (IMO) through the International Convention for the Safety of Life at Sea (SOLAS). In particular, in the past the use of fuels with a flashpoint below 60 °C has generally been prohibited to prevent tank explosions and fires. However, in 2015, the SOLAS (Safety of Life at Sea) convention allowed the use of low flashpoint fuels for ships complying with the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF code), such as ammonia. NH_3 has a way lower flashpoint temperature (11 °C) compared with the threshold (60 °C). The avoidance of accidents may be permitted by the concepts of segregation, system integrity, double barriers, and leakage detection and isolation [49]. Leakage detection and isolation are essential not only to prevent inhalation, but it is important because the SOFC operating temperatures are usually above the autoignition point of NH_3 (651 °C).
- Solid storage: For the current scenario, the lithium tetrahydridoborate ($LiBH_4$) is used. Its η_g value goes from 8 wt% to 9.9 wt% [10]. This value is evaluated starting from 13.8 wt% (H_2 percentage weight in $LiBH_4$) and considering an increase in weight of about 40 % due to the necessity to have thermal BoP [10]. The analysis is focused only on SOFC since it enables optimal integration with the thermal needs of the solid storage solution. The low gravimetric parameters of solid storage are expected to grow in the future, while at the current state of the art it is not expected to be suitable for mobility applications [50]. The ammonium borohydride (NH_4BH_4) is one of the best-performing solid storages and it is thus selected for the future scenario. It permits to store hydrogen with a theoretical value of 26 wt% (H_2 percentage weight in NH_4BH_4) and with an actual value of about 18 wt% [51]. As for the case of lithium tetrahydridoborate, the thermal BoP mass is considered, thus finding a gravimetric density (η_g) equal to 13.9 wt%. The NH_4BH_4 is chosen to be only a future solution since it exhibits stability issues and decomposes if exposed to high temperatures at the current state of the art [51].

2.3. Mission profile

The mission profile employed in this analysis is shown in Fig. 3 and it is taken from the assessment of the modified version of the NASA/Boeing VOLT Sugar from University of Louisiana at Lafayette, Nexceris and Idaho National Laboratory [52]. This concept plane uses a metal-supported SOFC-combustor-battery ESPG that permits very high fuel-to-electricity conversion efficiencies for an all-electric propulsion

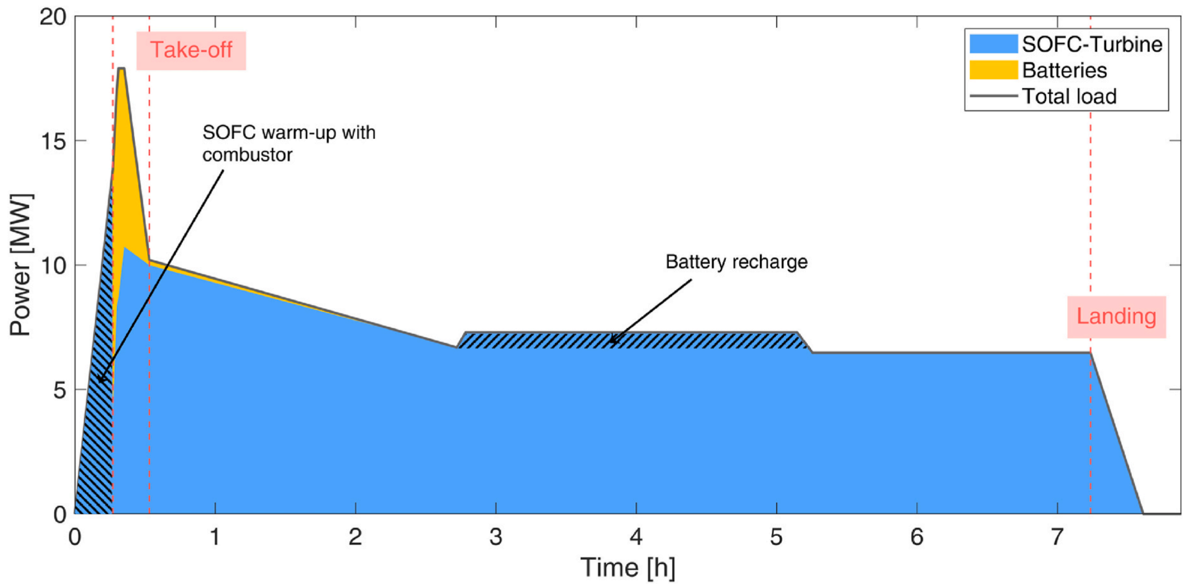

Fig. 3. Mission profile employed in this analysis. The energy contributions are shown in different colours.

system. The fuel utilized is a reformed carbon-neutral synfuel, with the properties of the Jet A-1 (12.0 kWh/kg, 9.68 kWh/L). Its reference mission profile is then applied to all the other scenarios as a benchmark.

Regarding the evolution of the load during the flight, the plane is kept still for 16 min before the take-off to reach the SOFC nominal operating temperature, which is in line with the goals of the American project ARPA-e (<20 min, e.g., a project from Tennessee Technological University [24]). This time frame thus involves SOFC warm up with the combustor to be ready for the flight (dashed area in Fig. 3). Then, the take-off phase starts (highlighted by red dashed lines in Fig. 3), and the contribution of the ~1700 kWh battery system is large (from 50 % to 90 %, depending on the power). Here, the battery stack performs a peak-shaving to reduce the steep load change of the 7 SOFCs modules (1 MW each) and to make up for the lower power density of the fuel cell. The battery size is taken from the NASA/Boeing VOLT Sugar project [52]. Once the take-off and the climbing phase are completed, the battery stack is not used anymore, and the cruise phase is completely carried on by the SOFC system. This phase is the longest one in terms of time and takes more than 6.5 h over the almost 8 h flight. In this time frame, the battery is recharged by the SOFC (dashed area in Fig. 3), which works in its optimal conditions, so for a long number of hours at constant power output. Then, the descendent phase happens (landing area in Fig. 3), and the flight is over. As explained in the previous section, the power (P_{load}) is integrated between the starting and ending point of the mission (t_i and t_f) in order to find the variable mass term as shown in Eq. (3).

2.4. Environmental analysis

An environmental analysis is also accomplished to understand the direct and indirect CO_2 emissions associated with the adoption of the innovative SOFC-based propulsion.

Two distinct innovative scenarios have been considered for comparison with the reference case (highlighted in Fig. 4).

1. Reference case (combustion engine fed by fossil jet fuel). In this scenario, only the emissions of the flight are considered (direct emissions), while the amount emitted by the fuel supply chain is not included. This choice is made to make the analysis as conservative as possible.
2. SOFC fed by synthetic jet fuel. This scenario considers the production of synthetic jet fuel employing a Power-to-Liquid (PtL) process. A syngas stream is first produced by the co-electrolysis process in a high-temperature SOEC (Solid Oxide Electrolyzer Cell) system, fed by steam and carbon dioxide. The production of the syngas is then followed by a thermo-chemical reactor able to convert the H_2-CO stream into jet fuel. In this case, the choice consists of a Fischer-Tropsch plant, whose specific energy and mass inputs/outputs are

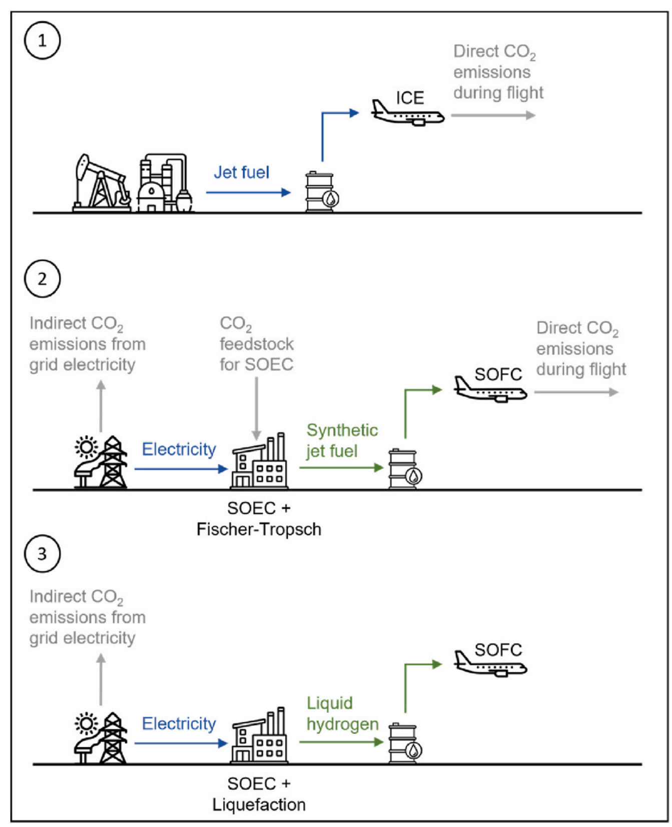

Fig. 4. Environmental assessment scenarios: 1. Reference case (internal combustion engine fed by jet fuel), 2. SOFC fed by synthetic jet fuel, 3. SOFC is fed by liquid hydrogen.

known and reported in Table 4. It shows the number of input parameters per litre of diesel equivalent energy as output [53].

The PtL process product is determined by summing the masses of diesel and kerosene, both of which can be used for the aircraft. The usage of products is regulated by the ASTM d7566 norm [54], which states that the common Jet A-1 fuel can be blended up to 50 % with synthetically produced kerosene. However, the present work will assume that the 100 % blending percentage can be reached.

3. SOFC fed by liquid hydrogen. In this scenario, it is assumed that the hydrogen is produced in a SOEC system. When liquid hydrogen is employed, the energy intensity of the liquefaction of hydrogen has to be considered (12.5 kWh/kg [55]) and summed to the energy intensity of the hydrogen production process (45 kWh/kg [55]). The on-board energy required to keep the hydrogen liquid is not accounted for. The scenario predicts a supply of 100 % renewable electricity to the SOEC, so that the net emissions of the flight would be zero. In addition, an assessment is conducted to determine the indirect quantity of CO_2 emitted when considering the average Italian electricity emission factor in 2023 (0.31 $kgCO_2$/kWh [56]). Finally, a sensitivity analysis of the electricity carbon intensity is carried out to encompass typical values found across various European countries.

The net CO_2 emissions ($M_{CO_2,net}$, in t) generated by the flight and the fuel processing are calculated as:

$$M_{CO_2,net} = M_{direct} + M_{indirect} - M_{SOEC} \tag{4}$$

The term M_{direct} (in t) represents the direct emissions caused by the flight, i.e. the quantity directly emitted during the mission. This contribution is equal to zero if hydrogen fuel is used. Based on the variable weight contribution (see Eq. (3)) [10], it can be evaluated, for the fossil jet fuel scenarios, as:

$$M_{direct} = W_{variable} \bullet \eta_g \bullet 3.16 \tag{5}$$

where the product between the total variable weight ($W_{variable}$) and the gravimetric storage density (η_g) is the total mass of consumed fuel. This quantity is then multiplied by the factor 3.16, which is the amount of emitted CO_2 (in kg) per kg of jet fuel, as reported by the International Civil Aviation Organization [57].

The term $M_{indirect}$ (in t) represents the emissions caused by the grid electricity, i.e. the indirect emission quantity associated with the carbon intensity of the grid electricity. Grid electricity is required to produce hydrogen or synthetic jet fuel in fuel cell-based scenarios, including both electrolysis and liquefaction processes. This quantity is equal to zero in scenarios where 100 % renewable electricity is utilized and exceeds zero when fossil resources contribute to electricity generation. The term CI_{grid} (i.e., the carbon intensity of grid electricity, in t_{CO2}/MWh) is multiplied by the total amount of electrical energy spent to run the hydrogen production processes (E_{el}, in MWh), as follows:

$$M_{indirect} = E_{el} \bullet CI_{grid} \tag{6}$$

Finally, the term M_{SOEC} (in t) expresses the mass of carbon dioxide required by the co-electrolysis process and is obtained from the input data in Tables 4 and ie., the required amount of CO_2 to supply the SOEC system. In the mass balance of Eq. (4), it turns out to be a negative contribution, as it is a quantity that is removed from the environment or absorbed from the exhausts of industrial processes (by means of carbon capture techniques).

3. Results

In this chapter, the results of both the technical (break-even point approach) and the environmental analysis are shown for the current scenario (Sections 3.1). The environmental analysis evaluates the sustainability of the new propulsion system under different decarbonization scenarios in Europe, considering the carbon intensity of the electricity grid. (Section 3.1.2). Furthermore, Section 3.2 explores future scenarios regarding the performance of the different ESPG systems. Finally, Section 3.3 presents a sensitivity analysis on the efficiency of the fuel cell-based propulsion system.

3.1. Current scenario

In the jet fuel SOFC scenario, the total mass of fuel used during the flight is 7.6 tonnes. This means that, compared to the amount of fuel used by a Boeing 737 MAX on a ~ 5800 km flight, it saves approximately 60 % of the fuel. This outcome is in line with the REEACH - University of Louisiana at Lafayette project, which predicts a fuel saving higher than 60 % [52]. Table 5 shows the resulting specific fuel consumption values for the current jet fuel SOFC case of this study and the one from Ref. [52].

3.1.1. Break-even point results

The W_{ESPG} mass indicator has been evaluated as a function of the total duration of the flight. Different flight durations have been explored, from around 1.5 to 8 h. The total duration of the flight has been increased by stretching the cruise phase of the plane, while keeping constant all the other phases. The break-even point is defined as the moment in time when the W_{ESPG} of the fuel cell-based configuration equals that of the reference case, occurring where the two lines intersect. The results are categorized into subplots based on the type of storage system and fuel used, as shown in Fig. 5. The graphs include SOFC and PEMFC layouts for the reformed jet fuel scenario (Fig. 5a), SOFC and PEMFC layouts for the liquid hydrogen scenario (Fig. 5b), and two additional scenarios to investigate alternative storage solutions (solid storage and ammonia) only for the SOFC case (Fig. 5c). A range of gravimetric densities has been explored for liquid hydrogen and solid storage and is depicted by the coloured areas around the lines. In order to identify a distinct break-even point, the average values within the investigated ranges have been used.

Looking at Fig. 5, for a given configuration the y-axis intercept represents the fixed weight of the system, while the slope of the line depends on the power generation efficiency (η_{PG}) and the gravimetric storage density (η_g). As displayed in the figure, SOFC configurations typically show a lower slope, which is associated with high fuel-to-electricity efficiency. Considering the jet fuel case (Fig. 5a), the high efficiency of the SOFC system does not offset its higher fixed weight, and longer flights should be considered to find a break-even point with the reference case. The same can be seen for the PEMFC system, which exhibits a lower power generation efficiency (higher slope of the line compared to the SOFC one) and a higher fixed weight. This is due to the lower efficiency of the PEMFC stack compared to the SOFC stack and the use of an external reformer, which increases the BoP mass and further reduces the η_{PG} (without benefiting from the higher PEMFC stack power density). The weight contribution of the different components and fuels is shown in Appendix B (Figure B1).

The resulting break-even point for the jet fuel SOFC case is reported in Table 6 (current and future scenarios).

As regards the liquid hydrogen case (Fig. 5b), no break-even point can be found even considering a large range of η_g. To make the LH_2 cases competitive, it is thus crucial to further increase the gravimetric storage

Table 5
SOFC with jet fuel case - specific fuel consumption for the current scenario.

Project	Jet fuel SOFC – present study	REEACH [52] - University of Louisiana at Lafayette
Specific fuel consumption [kg/km]	1.17	1.10

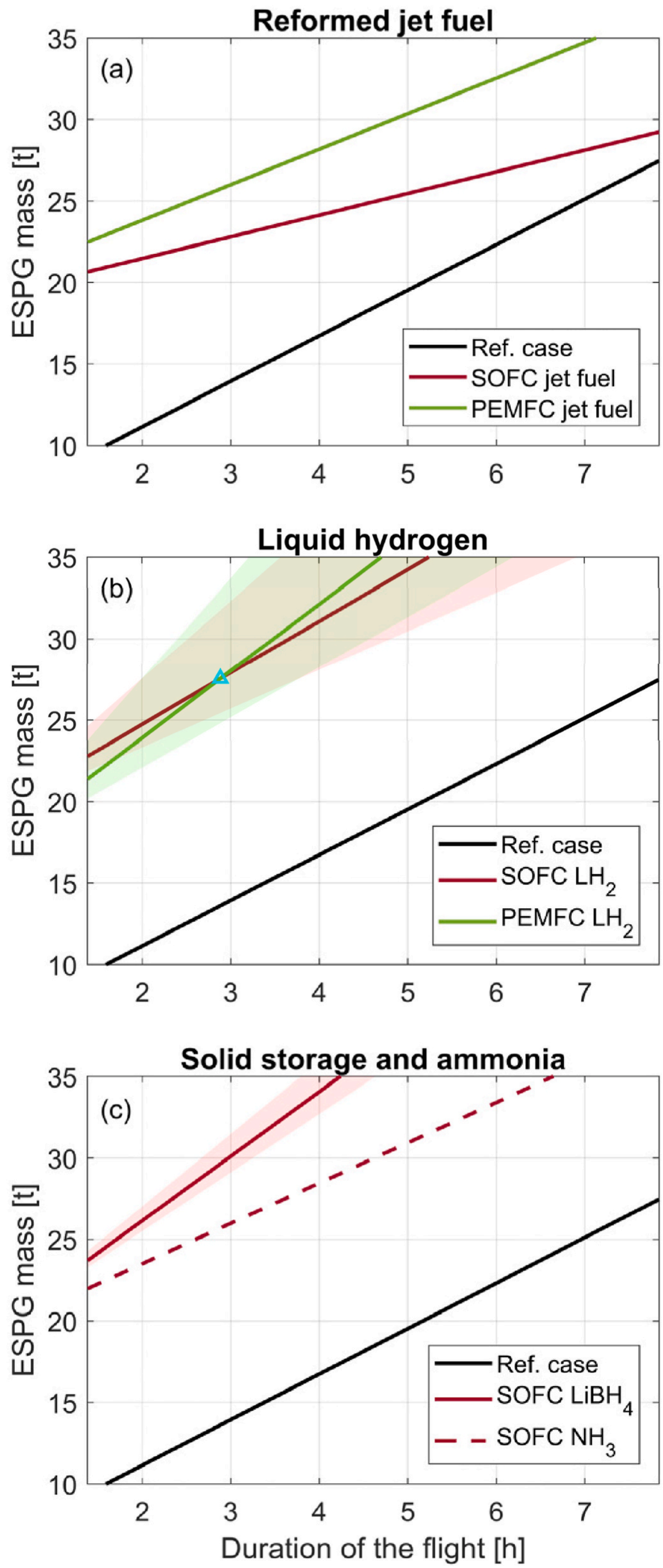

Fig. 5. ESPG mass comparison for different technologies and storage solutions in the current scenario. The black-coloured line refers to the Reference case (Boeing 737 MAX fed by jet fuel). Coloured areas refer to different values of gravimetric energy density of the storage solutions, in particular $\eta_g = 7.5$–15 % for LH_2 case and $\eta_g = 8$–9.9 % for $LiBH_4$ case. The cyan triangle stands for the break-even point between the two LH_2 cases.

Table 6
Break-even points results for current and future scenarios. Comparison with reference case.

	Jet fuel SOFC	LH_2 PEMFC	LH_2 SOFC
CURRENT SCENARIO			
Break-even point [hh:min]	>8	–	–
FUTURE SCENARIO			
Break-even point [hh:min]	7:42	6:37	6:44

density of liquid hydrogen, which heavily penalizes these two ESPG layouts. However, a break-even point between the two LH_2 cases can be found (cyan-coloured triangle in Fig. 5b). It shows how the higher efficiency of SOFCs can make this last case more convenient than the LH_2 PEMFC case. Finally, Fig. 5c shows the results for the solid storage and ammonia cases. The solid storage emerges as one of the least favourable options in terms of weight, characterized by an additional mass that renders it unsuitable for transport purposes. The ammonia case does not allow a break-even point to be identified, but a future reduction in storage weight could make this case as competitive as other liquid fuels.

It is also important to highlight that the large weight required for the PEMFC's balance of plant contributes to making it uncompetitive with SOFCs. Indeed, SOFCs operate at high temperatures, while PEMFCs are limited to around 80 °C due to constant humidification needs. This limitation increases the heat exchanger area required for the PEMFC-based layout. In addition, the lower efficiency of PEMFCs poses challenges in dissipating low-temperature heat, leading to larger volumes and increased on-board mass. This causes the weight of the PEMFC cooling system to contribute more significantly than in SOFCs [58].

3.1.2. Environmental analysis

Flight emissions (expressed in t_{CO2}/1000 km) have been evaluated according to Eq. (4) for the three scenarios presented in Fig. 4. The analysis involves a case with 100 % renewable electricity (Fig. 6a) and a case with the current value of the Italian electricity carbon intensity (Fig. 6b).

The bar plots in Fig. 6 show the comparison – in terms of CO_2 emissions per 1000 km of flight – between the two SOFC layouts (fed by synthetic jet fuel and liquid hydrogen) and the reference case (jet fuel engine). The emissions from both fuel cell-based layouts are always lower (and even reduced to zero in the case with $CI_{grid} = 0$ g_{CO2}/kWh) compared to the commercial case of the Boeing 737 MAX. The amount of CO_2 that is converted into syngas by the electrolyzer can be considered as removed from the environment, thereby subtracted from the emission balance (depicted as the dashed area, representing the difference between gross and net emissions). It is worth noting that the reference case is conservative since it does not take into account the emissions related to the fuel supply chain, but only those from the burned fuel. Therefore, the actual emissions of the reference case would be even higher.

A sensitivity analysis has been then performed to analyze the maximum value of electricity carbon intensity that would allow the SOFC-based scenarios to emit less CO_2 than the internal combustion case. To achieve this, the CI_{grid} parameter has been varied between two extreme values observed in the European area: from 2.00 gCO_2/kWh (Sweden in 2023) to 720 gCO_2/kWh (Poland in 2023) [56,59]. Fig. 7a shows how CO_2 emissions vary with the CI_{grid} for the three different scenarios: reference case (solid line), SOFC with synthetic jet fuel (dashed line) and SOFC with liquid hydrogen (dotted line). It should be noted that only the two SOFC cases experience an increase in emissions with the growth of CI_{grid}, as electricity is used to synthesize the fuels in these scenarios. Conversely, emissions remain constant in the reference scenario since no electrical energy is drawn from the grid. Two break-even points are discernible from Fig. 7a: 338 and 380 gCO_2/kWh. Below 338 gCO_2/kWh, both the jet-fuel and LH_2 SOFC cases are environmentally favourable, while within the range between 338 and 380 gCO_2/kWh, only the usage LH_2 would lead to a reduction in emissions

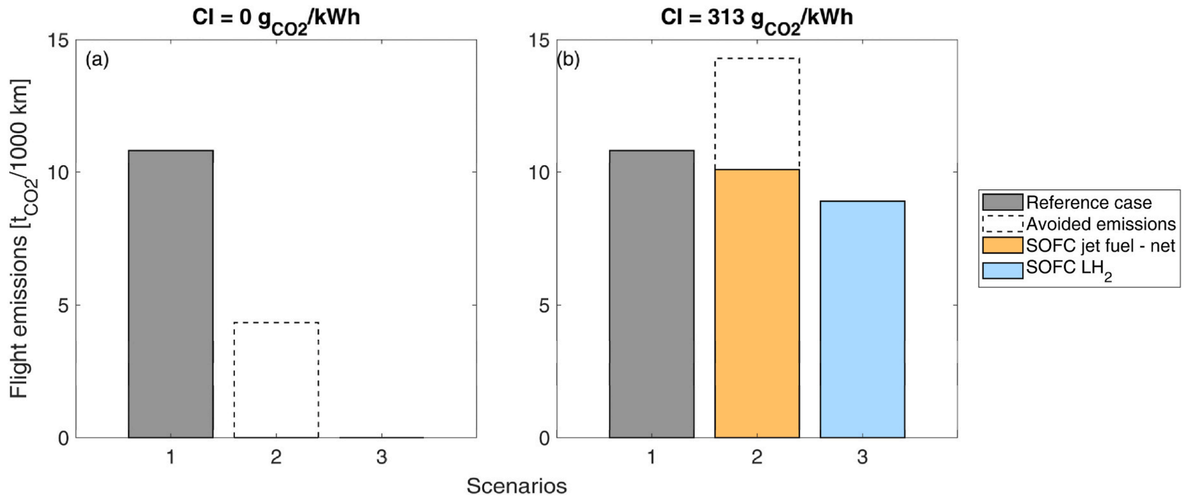

Fig. 6. Environmental results. (a) 100 % renewable electricity scenario and (b) Italian carbon intensity scenario. The avoided emissions represent the fraction of CO_2 that is used to synthetize the synthetic fuel, so subtracted from the balance.

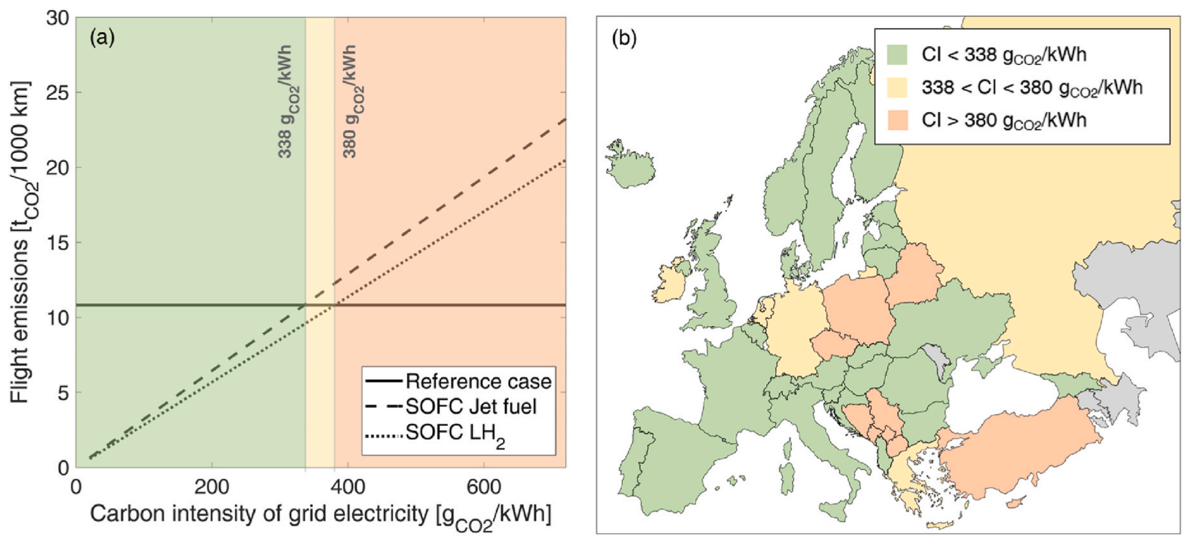

Fig. 7. (a) Sensitivity analysis on the electricity carbon intensity; (b) Clustering of the countries based on the results of the sensitivity analysis (considering the electricity carbon intensity values in 2023).

compared to the reference case. Finally, beyond 380 gCO_2/kWh, traditional jet fuel emerges as the environmentally preferable option compared to the SOFC cases. This is attributed to the high CO_2 emissions associated with the fuel production process, resulting from the high carbon intensity of grid electricity.

Based on these findings, three clusters of countries can be delineated. Countries falling in the green-shaded area exhibit an energy mix with a high penetration of low-emission energy sources such as renewable energy (e.g., northern part of Europe) and nuclear power plants (e.g., France). In these countries, the usage of high-temperature fuel cells – whether powered by synthetic jet fuel or liquid hydrogen – is always the best option from an environmental perspective. On the other hand, yellow-coloured countries are those undergoing an energy transition phase (e.g., Germany) or employing a combination of low-carbon emitting energy sources and fossil energy resources, with a predominance of the latter contribution (e.g., Russia). Ultimately, countries in red (e.g., Poland) would not experience environmental benefits from adopting the two innovative SOFC propulsion systems, as they still heavily rely on coal and other fossil fuels for electricity production. Starting from the graph in Fig. 7a, relevant countries in the industrial panorama may be included in the analysis. Under this perspective, some important industrialized countries and potential H_2 producers are listed below, along with their CI data and the respective cluster they belong to: Cina (red, CI = 582 gCO_2/kWh [60]), United States (orange, CI = 369 gCO_2/kWh [60]), India (red, CI = 658 gCO_2/kWh), Morocco (red, CI = 630 gCO_2/kWh), Brazil (green, CI = 98 gCO_2/kWh [60]), Australia (red, CI = 549 gCO_2/kWh [60]). It is important to highlight that these nations may not currently be environmentally suitable for hydrogen production powered by grid electricity. However, they could benefit from large-scale deployment of renewable energy resources (e.g., north African countries), which would favour low-carbon hydrogen production and enhance its sustainability for end-use applications.

3.2. Future scenario

This section presents the results for the future scenario in terms of W_{ESPG} comparison between the layouts previously presented in Table 3. As can be seen in Fig. 8, the initial values of the ESPG mass and the slopes of the lines confirm an improvement both in power density and fuel-to-electricity efficiency. As a matter of fact, the break-even points can be found within the 8-h flight range, as also indicated in Table 6 for the future scenario. However, the trend remains consistent with the

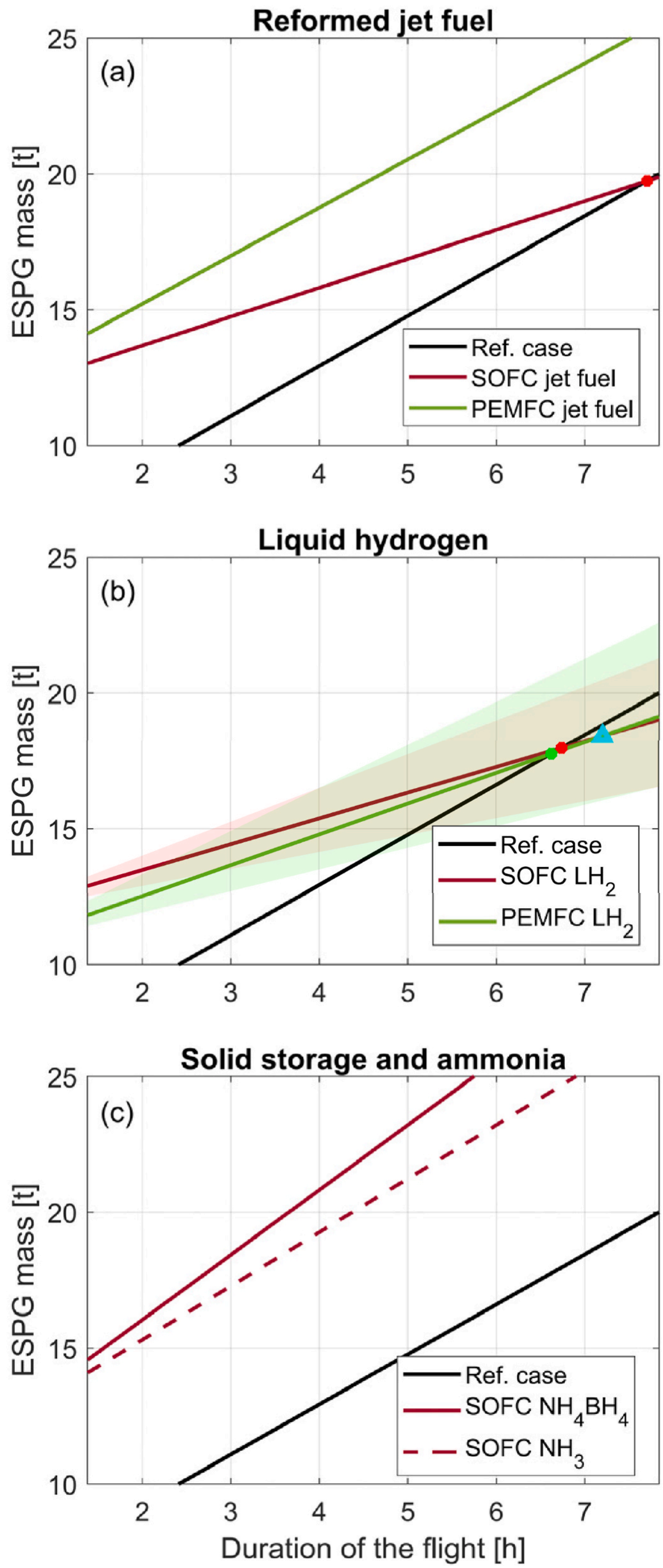

Fig. 8. ESPG mass comparison for different technologies and storage solutions in the future scenario. The black-coloured line refers to the Reference case (737 MAX fed by jet fuel). Coloured areas refer to different values of gravimetric energy density of the storage solutions, in particular $\eta_g = 25–50$ % for LH_2 case.

current scenario, where the reference case exhibits lower fixed weights but becomes less favourable as the flight duration increases. As Fig. 8a shows, even in future scenarios, PEMFC powered by reformed jet fuel will not be able to intercept the reference case. Conversely, Fig. 8b shows that the LH_2 PEMFC case can reach a break-even point (6:37 h) with the reference case shortly before the LH_2 SOFC case (6:44 h). However, the higher SOFC efficiency enables the detection of a break-even point with the LH_2 PEMFC case as well, which is highlighted by the cyan-coloured triangle (7:12 h). This implies that for flight durations below this value, the usage of PEMFCs allows for a reduction in total weight compared to adopting SOFCs. The results from Fig. 8c even suggest that solid storage will not be competitive with liquid storage options (jet fuel and LH_2). Additionally, the ammonia case – even with the best possible η_g equal to the physical limit – appears to be out of reach in comparison to other ESPGs.

As summarized in Table 6 for the future scenario, the SOFC-based propulsion layouts now exhibit two break-even points, but the one that uses LH_2 proves to be the best option in terms of total mass. These break-even points offer valuable insights into the operational efficiency and sustainability of each technology. Propulsion systems with shorter break-even times typically hold greater potential for widespread adoption in the aviation industry.

3.3. *Sensitivity analysis on the fuel cell stack efficiency*

An additional study has been done by assessing the break-even point as a function of the efficiency of the fuel cell stack for both PEMFC and SOFC cases.

The efficiency has varied to find the minimum threshold where fuel cell configurations are more advantageous by mass than the reference case (jet fuel combustion engine), while also examining the evolution of the break-even point.

In the current scenario, the sensitivity analysis does not reveal any break-even point concerning variations in efficiency, emphasizing that improved gravimetric storage density is crucial for competitiveness. For the future scenario (Fig. 9), the results indicate a significant improvement in the case of liquid hydrogen with respect to the current scenario. It is worth noting that the LH_2 PEMFC design enables the detection of the break-even point at lower efficiencies compared to SOFCs ($\geq$ 50 % for

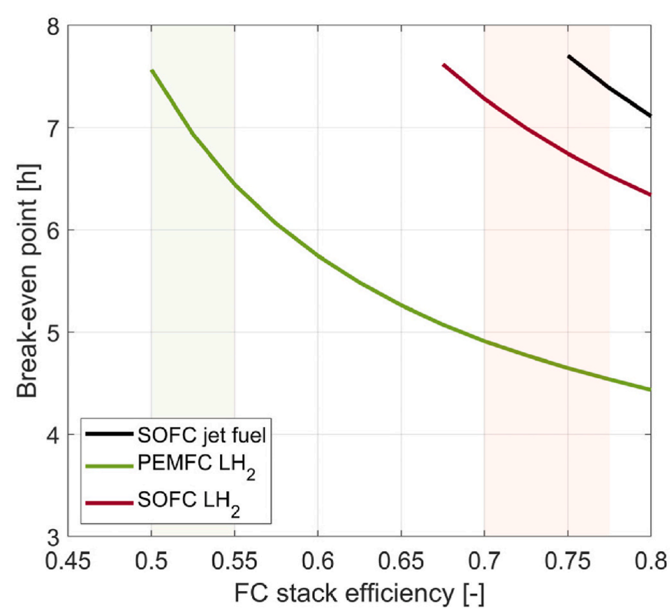

Fig. 9. Future scenario: Break-even point with reference case as a function of the fuel cell stack efficiency. Coloured areas indicate the most typical stack efficiency ranges for SOFC (red) and PEMFC (green).

PEMFC, $\geq$ 67.5% for LH_2 SOFC, $\geq$ 75 % for jet fuel SOFC), thanks to the higher power density of the cell. However, only the range of likely efficiencies must be considered (shaded areas in Fig. 9), and as observed in Figs. 8 and 9, the break-even point between LH_2 SOFC and LH_2 PEMFC can still be identified. As seen in Section 3.2, the behaviours of the LH_2 SOFC and jet fuel SOFC are similar but their break-even points occur at different times. Both SOFC-based cases exhibit break-even points above 6:30 h flight, which are within their likely stack efficiency ranges, with the LH_2 SOFC case being a better option in terms of total weight. In conclusion, the need for improvements in gravimetric storage density is essential to make these configurations competitive. Enhancements in this area are crucial for the advancement and viability of various energy systems, as other works confirm [61].

3.4. Additional considerations

Despite the promising outcomes in terms of weight, there may be challenges regarding the compatibility of SOFCs with mobility. One of the most impacting issues is the thermal load cycling of the solid oxide cell. If the cell is frequently switched on and off, its aging can progress more rapidly [62].

To avoid this, the SOFC stack could be kept at high temperatures in hot standby mode, even when the aircraft is not in service. Even if only minimal degradation is observed in hot standby mode [63], maintaining the stack at elevated temperatures for many hours consumes energy.

Another option consists of keeping the fuel cell working, with the electricity generated by the SOFC utilized to power either the grid or the airport itself. This option could be feasible since the electricity would be produced at high efficiency, but the match with the airport's electrical demand introduces an additional variable to consider.

Alternatively, the possibility of utilizing reversible cells for the propulsion could be explored. While the aircraft is parked, the SOFC would remain operational, working in co-electrolysis mode (SOEC) to be part of a PtL process. The SOEC, powered with electricity and supplied with steam and CO_2, would generate syngas mainly composed of H_2 and CO through co-electrolysis. The syngas could then be transformed into synthetic fuel for aircraft use. This is possible thanks to the reversible solid oxide cell (rSOC) operating mode. In addition, co-electrolysis offers some energetic advantages if compared to other syngas production routes. For example, it is possible to utilize the high exothermicity of the gas-to-liquid process to run the steam production phase that precedes the electrolyzer, thus increasing the PtL efficiency [53]. The reversibility of the solid oxide cell brings some benefits in terms of durability too. As a matter of fact, the degradation rate of the rSOC is decreased by the repeated change between SOFC and SOEC operating modes [64].

4. Conclusions

In this study, a break-even point analysis was conducted to determine the flight duration at which the weight of the SOFC-based propulsion system would equal that of the reference case, represented by a jet fuel internal combustion engine. To provide a comprehensive overview of the potential role of fuel cells in the aviation sector, PEMFC-based configurations were also assessed for comparison.

The findings reveal that, under current conditions, fuel cells are not competitive in terms of mass when compared to the reference solution, even for long-range flights. Among the various fuel cell configurations analyzed, the jet fuel SOFC option emerged as the most favourable. However, despite the minimal mass difference between this solution and the reference case as the 8-h flight duration is approached, no break-even point could be identified. Consequently, the transition to a more sustainable aviation sector currently relies on synthetic and biofuels, which offer superior gravimetric storage densities.

Looking to the future, if targeted improvements in the gravimetric storage density of liquid hydrogen (reaching 25–50 %) are achieved, both PEMFC and SOFC configurations using liquid hydrogen as the energy storage medium could become the optimal solutions for weight reduction. These designs are expected to outperform the reference case in terms of weight for flights lasting more than 6–7 h, even considering optimistic fuel consumption improvements for the conventional solution. SOFC, although characterized by lower power density, offers higher operating efficiency when compared to PEMFC. This feature suggests that short-range aircraft would likely adopt PEMFCs, while medium to long-range aircraft could benefit from SOFCs, taking advantage of their higher efficiency.

The results indicate that fuel cells have the potential to revolutionise transportation technology in the long run. Given the aviation sector's urgent need for low-emission alternatives, this work provides a foundation for assessing the practical implementation of fuel cells, highlighting key technological advancements and infrastructure requirements necessary for their adoption. Future research will further explore this potential through environmental analyses, including life cycle assessments, and economic evaluations of energy storage and propulsion systems, with an emphasis on their practical feasibility in the real world.

CRediT authorship contribution statement

Gabriele Peyrani: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Paolo Marocco:** Writing – review & editing, Supervision, Methodology, Conceptualization, Project administration, Funding acquisition. **Marta Gandiglio:** Writing – review & editing, Visualization, Supervision, Project administration. **Roberta Biga:** Writing – review & editing, Investigation, Conceptualization, Funding acquisition. **Massimo Santarelli:** Writing – review & editing, Conceptualization, Project administration, Funding acquisition.

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.

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Nomenclature

Acronyms		
BoP	Balance of Plant	
CI	Carbon Intensity	
DAC	Design Analysis Cycle	
ESPG	Energy Storage and Power Generation	
EU	European Union	
FC	Fuel Cell	
GHG	Greenhouse Gases	
GT	Gas Turbine	
ICE	Internal Combustion Engine	
LH_2	Liquid Hydrogen	
LNG	Liquified Natural Gas	
PEMFC	Proton Exchange Membrane Fuel Cell	
PG	Power Generation	
PtL	Power To Liquid	
rSOC	Reversible Solid Oxide Cell	
SAF	Sustainable Aviation Fuels	
SOEC	Solid Oxide Electrolysis Cell	
SOFC	Solid Oxide Fuel Cell	
Symbols		
CI_{grid}	Grid electricity carbon intensity	t_{CO2}/MWh
E_{el}	Electricity spent to run the hydrogen production processes	MWh
E_{fuel}	Specific energy density of the fuel	MWh/t
l_{DE}	Liters of diesel equivalent	l
$M_{CO_2,net}$	Net CO_2 emissions	t
M_{direct}	Direct flight emissions	t
$M_{indirect}$	Indirect flight emissions	t
M_{SOEC}	Carbon dioxide required by the co-electrolysis process	t
P_{load}	Gross power required during the flight	MW
$W_{battery}$	Weight of the battery system	t
W_{ESPG}	Entire weight of the ESPG system	t
$W_{FC,syst}$	Weight of the Fuel Cell system	t
W_{fixed}	Fixed weight of the ESPG system	t
W_{motor}	Weight of the motors	t
$W_{variable}$	Variable weight contribution	t
w_{fuel}	Specific fuel consumption	kg/km
η_{PG}	Power Generation Efficiency	%
η_g	Gravimetric storage density	wt%

Appendix A

Table A1
Weight breakdown of the layouts. The sum of the fuel cell system, battery and motor weights corresponds – for the fuel cell-based configurations – to the W_{fixed} term in Eq. (1).

FC type	Aircraft ESPG	FC stack [t]	FC system [t]	Battery [t]	Motors [t]
	CURRENT SCENARIO				
SOFC	Jet fuel LH_2 NH_3 $LiBH_4$	6.9	11.8	4.0	3.3
PEMFC	LH_2 Jet fuel	3.2	9.3 12.6	4.0	3.3
	FUTURE SCENARIO				
SOFC	Jet fuel LH_2 NH_4BH_4 NH_3	2.8	4.8	3.7	3.3
PEMFC	LH_2 Jet fuel	1.3	3.5 5.1	3.7	3.3

Appendix B

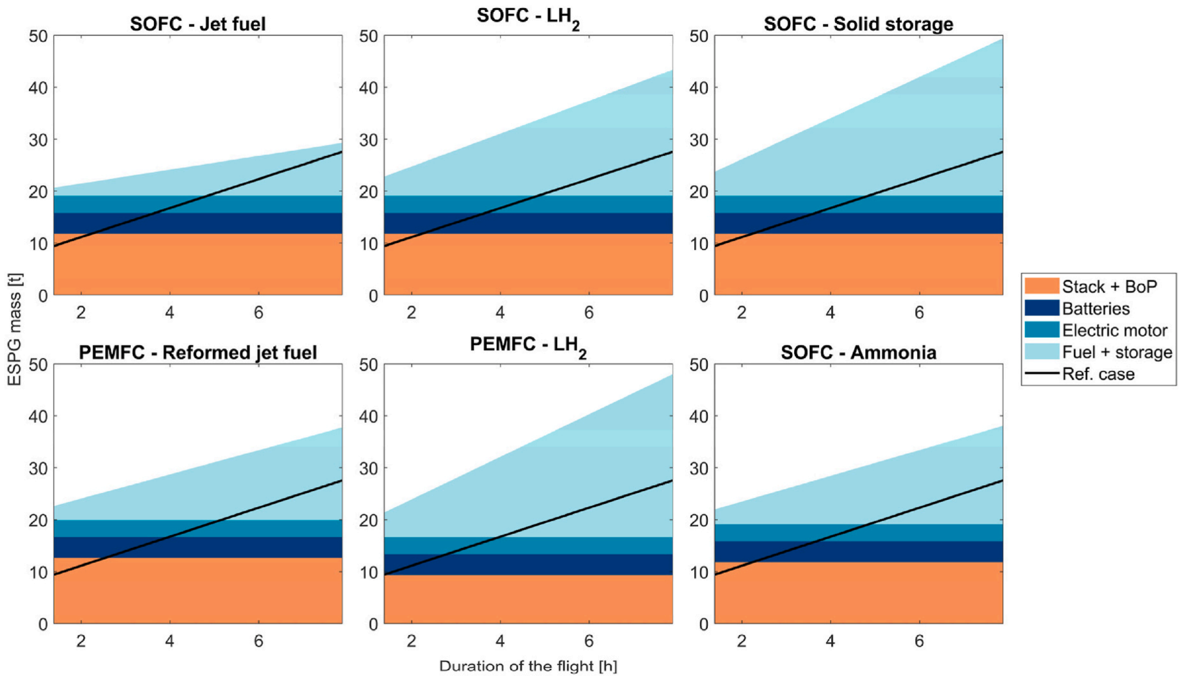

Fig. B1. ESPG weight contributions as a function of the flight duration for the six investigated fuel cell-based configurations in the current scenario. The black continuous line represents the Reference Case.

Data availability

No data was used for the research described in the article.

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