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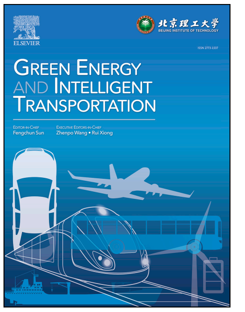

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A survey on hydrogen tanks for sustainable aviation

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The aviation industry is facing challenges related to its environmental impact and thus the pressing need to develop aircraft technologies aligned with the society climate goals. Hydrogen is emerging as a potential clean fuel for aviation, as it offers several advantages in terms of supply potential and weight specific energy. One of the key factors enabling the use of H_2 in aviation is the development of reliable and safe storage technologies to be integrated into aircraft design. This work provides an overview of the technologies currently being investigated or developed for the storage of hydrogen within the aircraft, which would enable the use of hydrogen as a sustainable fuel for aviation, with emphasis on tanks material and structural aspects. The requirements dictated by the need of integrating the fuel system within existing or ex-novo aircraft architectures are discussed. Both the storage of gaseous and liquid hydrogen are considered and the main challenges related to the presence of either high internal pressures or cryogenic conditions are explored, in the background of recent literature. The materials employed for the manufacturing of hydrogen tanks are overviewed. The need to improve the storage tanks efficiency is emphasized and issues such as thermal insulation and hydrogen embrittlement are covered as well as the reference to the main structural health monitoring strategies. Recent projects dealing with the development of onboard tanks for aviation are eventually listed and briefly reviewed. Finally, considerations on the tank layout deemed more realistic and achievable in the near future are discussed.

Keywords— Aviation Hydrogen, Aircraft Hydrogen Storage, High-pressure Vessels, Cryogenic Tanks, Sustainable Aviation

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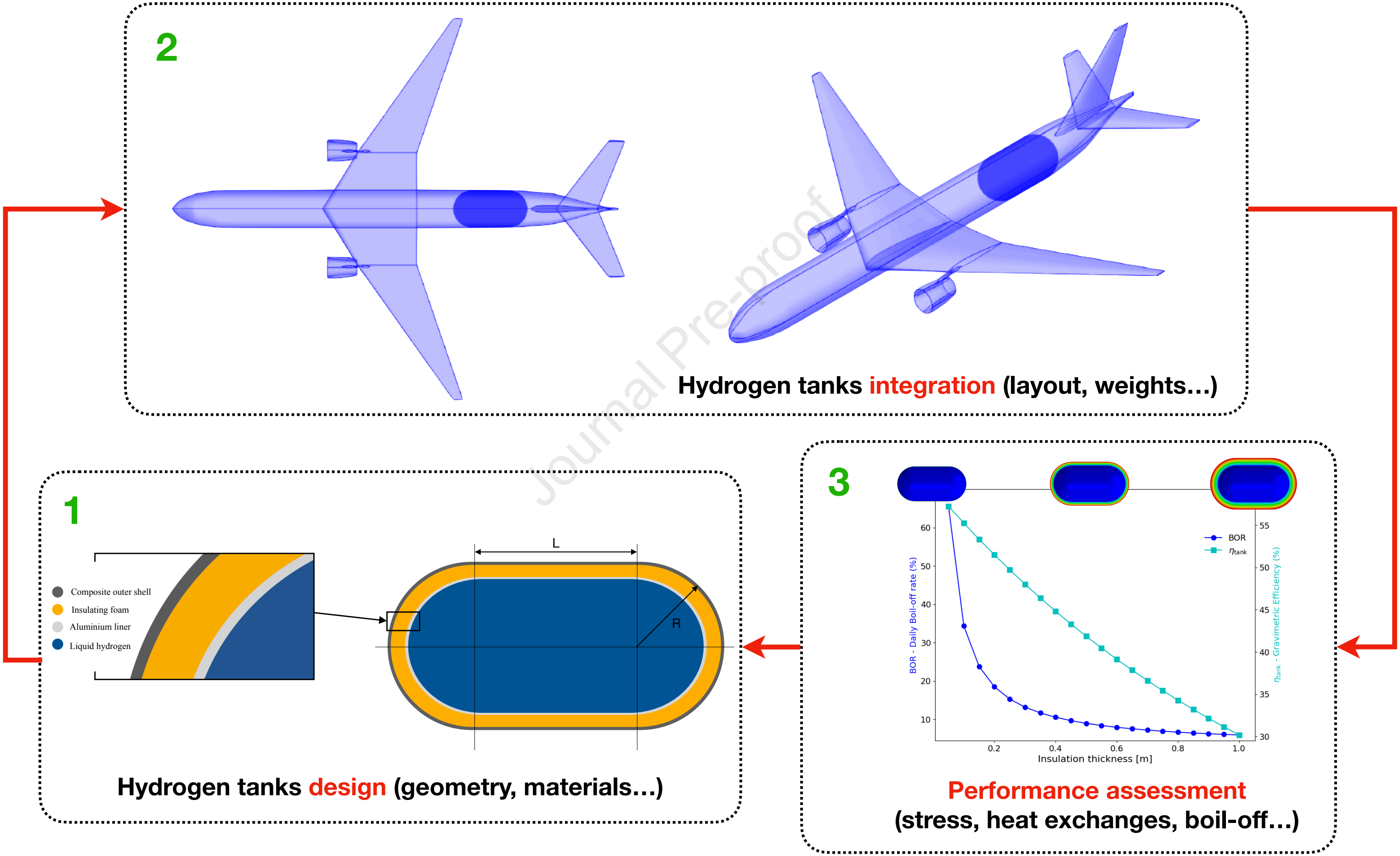

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I. Introduction

Sustainability and zero-emission propulsion have, in recent years, become of primary importance as global warming stands as one of the biggest threats to the development of our societies, endangering our economies, social conditions, and industries. The need for a systematic change in the means of transportation has seen countries and stakeholders investing in new and sustainable propulsion [1] and, while this innovation process will be long and complex, it is surely unavoidable [2]. The rising need for efficient, eco-friendly vehicles is driving industries and researchers to find solutions that minimize disruption to our lifestyles while preserving the planet. In this context the aviation industry has a crucial role. Aviation serves as the sole means of swiftly transporting people and commodities across the globe within a day. In 2016, aviation drove \$2.7 trillion in economic activity and supported 65.5 million jobs, which made up 3.6% of the global gross domestic product (GDP) [3]. However, aviation has destructive environmental consequences. Flying accounts for a relatively small portion of human-induced carbon emissions but is challenging to decarbonize [4] due to long aircraft development times. Despite its current 3-4% contribution to annual anthropogenic CO_2 emissions, this is expected to increase significantly with growing air travel demand [5]. The future potential growth of aviation emissions is a cause of concern, as it stems from a combination of CO_2 and non-CO_2 emissions [6]. These emissions have far-reaching consequences, affecting both local air quality and contributing to global climate change [7]. Apart from carbon dioxide, aviation also emits water vapor, nitrogen oxide (NOx), unburnt hydrocarbons, carbon monoxide (CO), particulate matter (PM), and sulphur dioxide (SO_2) [8]. Therefore, low and ideally non-pollutant means of propulsion in the aeronautical industry are being studied: biofuel, electric, hybrid and hydrogen propulsion are some of the most promising technologies for a greener future.

Biofuels like SAF (Sustainable Aviation Fuel) are made from renewable resources such as plant materials, waste oils, agricultural residues, or dedicated energy crops and have the potential to significantly reduce the carbon emissions of aviation, although their use is currently limited due to cost and availability [9]. Their energy content by weight is rather similar to that of kerosene and its use is already regulated by authorities under the form of blended fuel [10]. Cost represents one of the major drawback in SAFs use in aviation, being two to five times more expensive compared to kerosene [11] and, in order to represent a viable option, production capacity will need a significant scale-up process and require large investments in terms of safety, certification, and industrial plants [12]. Moreover, technical challenges have already emerged: current engine and propulsion systems are not entirely compatible with bio-jet fuels, thus requiring retrofitting and development of modified fuel systems [4].

Interest in fully electric and hybrid electric aviation is on the rise due to their potential for reduced emissions, noise, and operating costs, as well as improved reliability. While in fully electric airplanes the entirety of the energy used for the flight is provided by the batteries on board, hybrid electric configurations utilise more than one type of energy sources [13]. For example electro-chemical energy from batteries might be used in conjunction with chemical energy deriving from conventional fuel in order to achieve propulsion [14]. In most electric motors electricity is used to power a propeller, directly connected to the generally quiet, smooth and reliable electric unit [15]. If electric motors are generally compact and light, the same cannot be said for batteries. The potential success of electric aviation critically relies on improving batteries energy density [16], range, and endurance [17]. Advances in battery technology and energy storage are increasing the performances of electric aircraft, with several kinds of small electric aircraft, such as drones and gliders, already in operation [5].

Hydrogen represents a highly attractive option as aviation fuel as its supply potential are practically unlimited [18]. While being the most abundant element in the universe, hydrogen is not found in its gaseous form on planet Earth but it is found in combined stable forms with water and hydrocarbons and can be produced from these sources [19]. As a fuel, it is generally considered safe and environmentally friendly [20]. However, while hydrogen adoption has the potential to eliminate in-flight CO_2 emissions, H_2 burns with shorter residence times and higher flame temperatures, ultimately necessitating thorough mixing for leaner combustion when compared to traditional kerosene. Because of this, hot spots formation during combustion is a realistic possibility that may cause increased NOx release into the atmosphere. Overall pollutant emissions are strongly related to hydrogen production methods: these are classified using different colors, based on the carbon emissions during H_2 production. The main colors used are grey, blue, and green. Currently, the most affordable method for producing H_2 is methane steam reforming, but it releases CO_2, making it grey hydrogen. Blue hydrogen is also produced through this process, but the carbon dioxide is separated from the H_2 stream and stored using carbon capture storage technologies. The cleanest method, albeit the most expensive due to the energy-intensive water molecule splitting process, is water electrolysis [21]. It is referred to as green hydrogen when renewable sources provide the necessary carbon-free electricity [22]. Considering that these processes are energy-intensive, it has been estimated how the adoption of hydrogen as a fuel would demand significant electricity grid upgrades, of the order of 1.59 times the current value to be able to sustain the consumption of the new fuel [23]. Some studies suggest that fully decarbonizing the aviation sector using green hydrogen alone, before the entire electricity grid is transitioned to 100% renewable sources, could result in a net negative climate impact [24].

Significant modifications to airport facilities are necessary to sustain the use of hydrogen in commercial aviation. Degirmenci et Al. [18], assessed potential changes to the hydrogen supply network to achieve full aviation decarbonization, including modifications for hydrogen use at airports. Their study presents various concepts for production, liquefaction, transportation, storage, and distribution of hydrogen. It emerges how, while liquefaction could potentially occur within the airport facility, hydrogen production is primarily conceptualized as off-site for grey hydrogen via steam methane reforming. Green hydrogen production is envisioned on-site using renewable energy sources, though wind turbines cannot be located near airports due to collision risks, necessitating significant grid upgrade. Finally, airports would need to be equipped with hydrogen storage facilities to match the current kerosene reservoirs, which hold about three days worth of operations [25], as well as capillary distribution pipelines, fueling towers and specialized fueling trucks.

Hydrogen has a history in aviation [26], from its use in early lighter-than-air vehicles like hot-air balloons and rigid airships, to enabling the flight of massive airships like the Zeppelins in the early 20th century [27]. The United States Air Force achieved a significant milestone with the first flight powered by liquid hydrogen, using a modified B-57 bomber. Later, in the 1950s, the US developed the Lockheed CL-400 supersonic reconnaissance aircraft, while the Soviet Union invested in the TU-155 in the 1980s. The TU-155, based on the TU-154 airliner, featured a hydrogen-powered engine, showcasing their dedication to hydrogen aviation [28]. Test flights confirmed the feasibility and benefits of hydrogen propulsion but logistical challenges, like the need for liquid hydrogen availability at airports alongside kerosene, remained [29]. The new millennium saw the effort from the European Union to investigate the potentials of liquid hydrogen as a fuel for aviation and financed the Cryoplane Project [30], in which several configurations were studied and crucial conclusions were made. This project ultimately showed how liquid hydrogen powered aircraft is feasible, even though the fuel system for such airplanes requires tanks approximately four times larger when compared to conventional kerosene tanks [31, 32]. The efficiency of hydrogen production is heavily affected by the techniques employed. Steam reforming, while responsible for CO_2 emissions, is a mature technology characterized by high values of conversion efficiency, within the range 70% ÷ 85%. Sustainable H_2 production methods, such as electrolysis, can reach efficiencies up to 60% avoiding pollutants emission; however as the surrounding infrastructures scales-up, its efficiency is expected to increase further [33]. Novel production techniques are identified in Ref.[34]: while some processes are identified as more promising than others, a significant boost in process is needed to sustain future industry needs. From a global perspective, there is enough renewable energy and water for hydrogen aircraft. However, the practical implementation of hydrogen-powered aviation faces uncertainty due to regional disparities in resource availability and infrastructure. While some regions are rich in renewable energy sources (RES) and freshwater, others may lack in this respect, necessitating the import of hydrogen or renewable energy for specific airports. The efficiency of sustainable hydrogen production is heavily dependent on the local availability of RES, which varies significantly across different regions. Consequently, each region capacity for hydrogen production must be evaluated individually. In areas with low RES availability, options such as the transmission of renewable energy via grid infrastructure or the importation of hydrogen can be considered to meet the demand for aviation [35]. However, the high investment costs associated with lacking infrastructures and power transmission limits its feasibility to shorter distances [35]. In exploring the economic aspects of hydrogen fuelled aircraft, Hoelzen et Al. [36] delved into the relationship between the economy of H_2 aviation and the availability of cost-effective liquid hydrogen supply infrastructure. The study suggests that even under favourable hydrogen cost conditions, the total direct operating cost (DOC) might experience a slight reduction. However, the comprehensive DOC could potentially increase, primarily due to rising liquid hydrogen expenses. This increase is estimated to range between 10 to 70% for short-range flights and 15 to 102% for medium-range flights. However, once hydrogen production cost drops to the level of kerosene price, DOC's for conventional and H_2 fuelled aircraft may reach a crossover point at about the year 2040 [37]. Aspects related to maintenance have been investigated in Ref.[38], which shows how, even if this variable is strongly connected to the aircraft intended use, an increase of $22 - 32\%$ in maintenance cost is likely to be expected in the near term. However, once the technology is fully mature, it is expected that liquid hydrogen will be regarded as the most economic option of remotely produced renewable aviation fuel [39].

The present overview is structured as follows. Section II is the core of the present work and explores several aspects related to onboard H_2 storage, from key performance indicators to pressure vessels categories. Methods for storing hydrogen both in the gaseous (GH_2) and liquid (LH_2) physical state are reviewed, emphasising aspects related to materials, manufacturing processes, thermal insulation and analysis and design methodologies. A section on *Hydrogen embrittlement* provides a brief overview of the phenomenon relevance in tanks design and it is followed by a discussion on *Improving tanks efficiency*, which identifies and discusses innovative materials and approaches aimed at enhancing the component efficiency. In the *Recent endeavors: projects and companies* section, a compilation of past and ongoing projects related to hydrogen in aviation is presented, leading to the formulation of concluding remarks. Eventually, in section VI considerations on what is perceived as a realistic enabling technology in hydrogen tanks for short to middle-term adoption by the aviation industry are formulated.

II. Onboard hydrogen storage

Hydrogen exhibits a *gravimetric* energy density three times higher than conventional jet kerosene (120 MJ/kg vs 43.2 MJ/kg) and its combustion, despite being responsible for the emission of nitrogen oxide and water vapour, does not produce CO_2 [40], which makes it well suited to meet current environmental goals [41]. While the use of fuel cells could potentially reduce nitrogen oxide emissions to zero during operations, the hydrogen combustion process is still considered much more environmentally friendly when compared to conventional fossil fuel since, apart from a 100% reduction in carbon dioxide, sulphur oxide, and soot, emissions of NOx are reduced by 70% [42]. However, concern is attracted by the formation of contrails, originating from the water vapour contained in hot aircraft engine exhaust, which may saturate at specific ambient pressure and temperature. When ambient temperature and humidity reach liquid saturation, water vapour condenses and freezes, forming small ice crystals. Soot and other particles in the exhaust act as nucleation sites for the formation of such ice crystals [43]. Their detrimental effect on the environment is manly related to aircraft-induced cloudiness that alters the radiative forcing and ultimately results in increased warming effects, trapping long-wave thermal radiation emitted by the Earth [44]. The adoption of hydrogen turbofan engines is expected to eliminate particulate emissions, thus reducing nucleation sites for contrails formation. This should result in shorter residence times in the atmosphere and shallower contrail depths. However, since threshold temperature below which contrails form is expected to be higher for H_2-powered aircraft than for conventional jet aircraft, coupled with higher concentration of water vapour, they may form at generally lower altitudes, thereby increasing their presence in the atmosphere [45]. Hydrogen is flammable, has a very short ignition time in comparison to conventional jet fuel and provides a wider stability range. In addition to that, it has the highest thermal conductivity among all fuels, high heat capacity and low dynamic viscosity [46], which provide superior cooling properties for operation at high speeds and high combustor temperatures. It is the only energy carrier that can be produced on site, achieving true zero-emissions [47], using different thermochemical conversion processes, such as gasification, pyrolysis and steam gasification using biomass [48]. However, since liquid hydrogen features low *volumetric* energy density (10.1 MJ/L) when compared to conventional jet fuel (33 MJ/L), its storage requires larger volumes. In particular, as highlighted by the *Cryoplane Project* [30], the need of ensuring suitable thermal insulation for maintaining cryogenic conditions often results in bulky storage solutions, requiring approximately *four* times the volume required by conventional jet fuels for similar mission profiles and thus exacerbating the *spatial integration* challenge [49], which refers to the need of packing of all desired passengers, payload, structural elements, fuel, and equipment into a feasible aircraft layout [50]. Tab.(1) reports a comparison of the key properties between Jet A-1 and liquid hydrogen.

Table 1 Properties comparison between traditional aviation kerosene and liquid hydrogen.

Property/Feature	Unit	Jet A-1	Liquid hydrogen
Volumetric energy density	[MJ/L]	33	10.1
Gravimetric energy density	[MJ/kg]	43.2	120
Storage temperature	[K]	*Ambient*	20

A. Aircraft layout considerations

Due to the low volumetric energy density of H_2, hydrogen powered planes demand significant modifications over conventional ones [51] and one of the main differences resides in the need to accomodate peculiar fuel tanks and systems [52]. While engines can be converted to work on H_2 with relative ease [45], redesigned fuel pipes, pumps, seals and valves are also required in order to cope with the specific hydrogen properties [53]. However, the focus of this work is not on investigating propulsion systems, but rather on providing an overview of storage-related issues and potential methods to overcome or, at least, mitigate these challenges. Conventional powered aircraft store fuel inside the wing [54], this design has several benefits: it frees space inside the fuselage, it simplifies the fuel system and it creates a healthy bending moment at the root of the wing that counteracts lift, therefore reducing the need for a particularly heavy wingboxes. Hydrogen tanks do not fit well into the wing [49] and therefore alternative configurations must be explored, Fig.(1). It is therefore understandable how tanks are perceived as the enabling technology that must guarantee thermal insulation and pressurization during operations, in order to preserve the storage state of the energy carrier [55]. Liquid hydrogen storage demands vessels that, at least, resemble a sphere or a cylinder with spherical end caps, in order to limit boil-off and evenly distribute stresses. In fact, lower surface to volume ratios geometries have been found to perform better both from a structural point of view [56] and from a thermal perspective, having a lower surface to volume ratio. This type of geometry may not be ideal to fit into conventional wing design, and therefore the only feasible option (at least for tube-and-wing configurations) is to place the tanks inside the fuselage [57]. This certainly limits passengers or cargo capacity but, in the near term at least, it simply appears to be no other option.

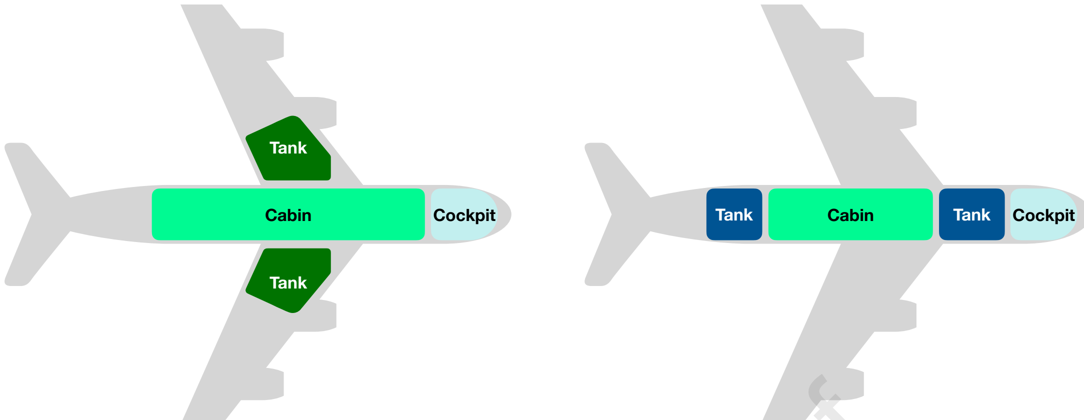

Fig. 1 Changes in layout for hydrogen fuelled aircraft: (left) conventional powered aircraft having fuel stored within the wings; (right) hydrogen fuelled aircraft with tanks placed inside the fuselage, to minimise the surface to volume ratio for limiting thermal exchange and stress concentrations.

Interesting perspectives are related to the development of the blended wing body (BWB) and hybrid wing body (HWB) [58] design, where the internal volume is maximised and interesting advantages, such as aerodynamic and structural efficiency, look promising [59, 60]. BWBs, however, will likely be the last step of a multi-decade industry revolution since their commercial operation will require a complete change of paradigm in regulations, design approaches and infrastructures.

When placing these components inside the fuselage care must be taken in complying with authorities requirements. For example, the european certification specifications for large commercial airplanes [61] requires that the crew has free access to the passenger cabin, therefore, in the case of a forward H_2 tank located behind the cockpit, a catwalk has to be included. Some other parts of existing regulations may be applicable to hydrogen pressure vessel design for aircraft implementation. An example of this is EASA CS§25.963 for hydrostatic pressure increment computation under acceleration. Parello et Al. (Ref.[62]) investigated current regulations by civil aviation authorities and ultimately proposed a methodology for LH_2 pressure vessel structural sizing compliant to current relevant requirements. However, even if the existing regulation can be partially applied to hydrogen aviation, several aspects specific to onboard H_2 storage, would need to be assessed in detail before commercial hydrogen-powered aircraft could become a viable option. In this sense, concerning tank integration within the aircraft cabin, special attention should be devoted to explosion and fire hazard, pressurization and leak detection, crashworthiness and impact resistance.

From a structural standpoint, one of the main considerations regarding hydrogen vessels is whether the tanks should be integral or not. Integral tanks are a structurally-integrated part of the airframe and must be capable of withstanding loads to which the supporting structure is exposed, given that tank's structure and the airframe are seamless. Generally, because of the more efficient use of available volume, their efficiency is higher. For example Brewer, in Ref.[63] calculates a fuel volumetric efficiency of 92.7% for integral tanks versus 85.5% for non-integral ones. In contrast, non-integral tank structures are only loaded by fuel, internal pressure and dynamic loads inside the tank [56] and they do not necessarily need to conform to the shape of the fuselage, Fig.(2).

Integral tanks may be chosen over non-integral ones since the structure of the integral tank itself blends with the structure of the fuselage and therefore makes inspections easier and, once the structural loads are well defined, the resulting design tends to be lighter

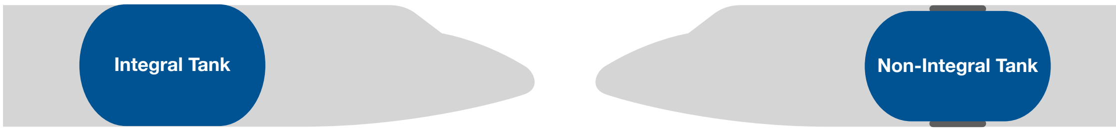

Fig. 2 Integral VS non-integral tanks: (left) integral tanks where the fuselage structure is used as part of the tank structure to store fuel; (right) non-integral tanks, where the tank structure is separated from the aircraft and anchored to it with other systems.

and simpler [63]. On the other hand, non-integral pressure vessels may enable the use of modular designs, enabling new concepts for refueling and maintenance.

B. Storage efficiency

Storage of hydrogen can be achieved through more conventional physical storage techniques or material-based methods [64]. More conventional physical-based methods involve storing the fuel in its gaseous (GH_2), subcooled (sLH_2) or liquid form (LH_2) while material-based methods include porous materials like metal organic frameworks (MOFs), hollow glass microspheres (HGM), carbon nanotubes (CNTs) or graphene. The use of hydrogen H_2 as a fuel poses some crucial complications over traditional kerosene. Hydrogen storage is quite challenging in the sense that while traditional Jet A or A-1 can be stored at ambient temperature and pressure, liquid or gaseous hydrogen demand particular conditions in order to achieve the required energy density. Hydrogen tanks, designed to store and deliver this highly flammable fuel safely, play a critical role in enabling the use of this energy carrier as a fuel in aircraft. These vessels used in aviation must be designed with geometrical, mechanical and thermal aspects in mind as well as specific considerations regarding the aircraft's mission profile [65].

The *gravimetric efficiency*, denoted as η_{tank}, stands as a crucial metric for comparing the efficiency of hydrogen tanks. It establishes a relationship between the stored fuel mass and the total tank mass, encompassing both the structural and fuel masses:

$$\eta_{\text{tank}} = \frac{W_{H_2}}{W_{H_2} + W_{\text{tank}}}. \tag{1}$$

Often it might be useful to quantify the entire fuel system efficiency through the *storage system gravimetric efficiency* which considers also the mass penalty given by the necessary subsystems, given by:

$$\eta_{\text{system}} = \frac{W_{H_2}}{W_{H_2} + W_{\text{tank}} + W_{\text{subsystem}}}, \tag{2}$$

where W_{H_2} represents the weight of hydrogen the tank can hold, W_{tank} quantifies the structural weight of the tank itself and $W_{\text{subsystem}}$ gives an information on the mass of the subsystems connected to the tank. It is clearly understandable how higher η_{tank} are desirable since it means that the weight penalty associated to the hydrogen storage system is less penalizing. This parameter represents a key figure since it quantifies how close the industry is to developing tanks comparable to conventional kerosene tanks, characterized by values of η_{tank} that push 100% [66]. Poor gravimetric efficiencies lead to rapid increases in operating empty weight and sharp decreases in performances, leading to substantial energy consumption increases [67].

C. Gaseous hydrogen storage

As previously stated, hydrogen's low energy density on volume demands suitable modifications in order to obtain the required fuel density for aircraft use. In particular, one way to obtain respectable energy densities is to compress hydrogen to pressures of the order of 350 to 700 bar [68]. As the storage pressure increases, the density of the hydrogen gas will also increase, making it increasingly more feasible as an energy carrier.

Gaseous tanks benefit from reduced complexity compared to liquid hydrogen tanks. For gaseous hydrogen, managing thermal conditions is not a critical concern since GH_2 tanks operate at ambient temperature, therefore reducing complexity of the tank component itself and the connected subsystems. However, the extremely high pressures necessary to store GH_2 require adequately robust pressure vessels whose gravimetric efficiency, as today in the aeronautic industry, does not exceed 15% [45]. Poor gravimetric efficiency negatively impacts the range of H_2-powered aircraft compared to conventionally fueled counterparts. Thus, gaseous hydrogen is typically suitable for smaller aircraft where range is not a limiting factor. While the higher the pressure the higher the energy density, accurate trade-offs must be performed in order to identify the optimum pressure-to-tank-mass ratio [69]. Adler et Al. [45] shows how the fuel density to weight trade-off is highly dependable on storage pressure: very high pressure enable very high densities but this comes at the expenses of good gravimetric efficiency, which significantly decrease as pressure grows.

The severe storage conditions of gaseous hydrogen, and the extreme pressure in particular, often demand tanks whose geometry does not differ from spherical or cylindrical with end caps: this configurations are in fact the most structural efficient since they tend to evenly distribute pressure loads, enabling greater efficiencies [70]. The trade-off with utilizing high density/high pressure storage is the increase in tank mass necessary to withstand the higher stresses. With the higher gas pressure, the required thickness of the tank's walls will increase due to the increasing forces exerted circumferentially by the fuel. However, the reduction in volume is not linear with the increase in pressure because of hydrogen's compressibility [71]. Composite materials are commonly used within the hydrogen industry such as carbon or glass fiber-reinforced plastic (CFRP or GRP), where both weight and corrosion resistance are influential factors. Composite pressure vessels are generally lightweight, being one-fifth the weight of stainless steel and half the weight of aluminum, however they require a polymer or metal liner to prevent the hydrogen gas from leaking through the vessel's walls [68]. Designing a composite vessel that combines high reliability with practicality is a challenging task right from the start of the process. From a micromechanics perspective, composite failure involves complexities such as matrix cracking, fiber/matrix debonding, delamination, fiber rupture, and interactions among these modes. Optimization can enhance composite vessels by making them lighter, stronger, and more reliable through the careful design of fiber orientations and ply thicknesses in the winding process [72]. Moreover, cycle loading behaviour needs to be properly assessed so good knowledge of embrittlement, fatigue, aging and creep phenomena are necessary. Gaseous hydrogen tanks are classified according to their gravimetric efficiency and material of construction in five classes, as shown in Fig.(3): it starts with simple and relatively cheap *Type I* - all metal tanks with η_{tank} of about 2% through state-of-the-art, expensive, *Type V* liner-less composite tanks with η_{tank} of 6% [45]. Table 2 schematically reports different features of possible hydrogen storage tank types, including the values of the gravimetric energy density when the overall weight of the storage tank plus the fuel is considered, which is consistent with the reported values of tank gravimetric efficiency [72].

The spatial integration problem also represents a significant challenge: Breljie et Al. ([49]) utilized multidisciplinary design optimization techniques in order to look into the possibility of storing the gaseous tanks inside the wing structure considering the

Table 2 Materials and features of different types of hydrogen storage tanks.

Tank Type	Material	Energy Density [MJ/kg]	Operating Pressure [bar]	Gravimetric Efficiency
Type I	All-metal	4 – 5	250 – 700	~2%
Type II	Metal liner & Composite hoop wrap	4 – 5	700 – 875	~2%
Type III	Metal liner & Composite full wrap	4 – 5	875 – 1100	~4%
Type IV	Plastic liner & Composite full wrap	4 – 5	700 – 875	~5%
Type V	No liner & All composite	5 – 8	875 – 1100	~6%

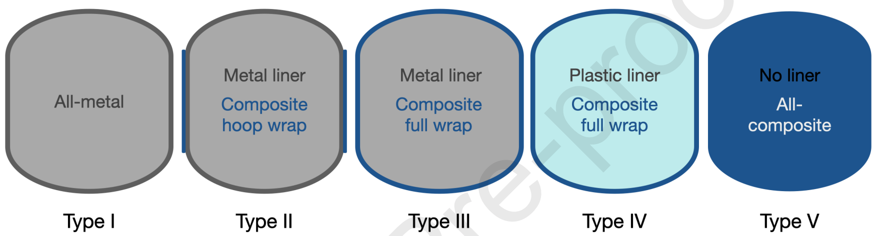

Fig. 3 Graphical representation of gaseous hydrogen pressure vessels classification.

mutual influence of the wing's and the pressure vessels geometries. They found that while compressed hydrogen may be feasible for regional-length missions, the considerable weight of GH_2 tanks, is a significant drawback and therefore, the weight penalty given by the use of compressed hydrogen probably forecloses the possibility of using it for transcontinental routes [45, 73], for whose cryogenic storage may be more suited. Moreover, the added complexity of the insulation and heat management system may be worthwhile only for long-range airplanes. As today, some hydrogen fuelled demonstrators have utlized GH_2 tanks like it is the case for Cransfield's University converted Britten-Norman [74] and its 700 bar gaseous tanks and ZeroAvia's Dornier 228 [75, 76]. According to NASA [24], for aircraft carrying more than 100 passengers, liquid hydrogen is a more appropriate option due to its higher energy density and better performance over longer distances. To this day, however, the passenger capacity of the vast majority of technology demonstrators that took off fuelled by GH_2 is considerably smaller, in the order of 15 to 50 seats [76, 77]. To conclude, GH_2 may represent a viable solution for applications where the tank's mass is not a critical considerations and the design is such to not be compatible with insulation and cryogenic temperature.

1. Materials

The material used to build high-pressure hydrogen vessels might be either a composite or a metal like steel, titanium, or aluminium [78]. A composite tank of *Type II-IV* will need a liner to stop the hydrogen from penetrating the tank wall because the majority of composites are permeable to hydrogen. Typically, liners are made of a particular polymer or a metal like aluminium. Additionally, coatings are being looked into as a possible way to stop hydrogen from penetrating the shell.

Type I cylinder vessels have been manufactured using high-strength steel for compressed natural gas storage applications on the road. Composite materials were introduced into the manufacturing process shortly thereafter because the alloys used had problems related to fatigue and corrosion damage [79]. *Type II* pressure vessels are made with a thick metal liner that has been wrapped with composite material. In this type of vessel, only in the cylindrical part composite materials are present, leaving the domes unwrapped. Liners were initially designed and manufactured through the rolling and welding of metal sheets [80]. Other techniques, such as the tube forming process, were then developed to reduce the manufacturing steps for making seamless tanks [81]. Usually, the fibre used in the composite material is glass, aramid or carbon and they are wrapped in the hoop direction [82]. *Type III* tanks use the same concept as *Type II* with the main difference that the composite material is present not only on the cylindrical part, but the overwrap includes the domes too. Therefore, both the metallic liner and the composite overwrap have structural purposes. This configuration allows the tanks to withstand higher pressure and improve the gravimetric efficiency of the fuel system.

Driven by a growing interest in composite materials due to their high strength-to-weight ratio and improvements in the manufacturing process, engineers have successfully pioneered the development of *Type IV* hydrogen pressure vessels. These vessels structure are made entirely of composite material, typically carbon fibre or hybrid carbon/glass fibres. However, a plastic liner is present to prevent possible gas leakage, which usually serves in the filament winding (FW) process as a mandrel [83]. In contrast to *Type IV* tanks, *Type V* are a complete linerless vessel made only by composite material [84]. Due to the absence of a liner, engineers need to take particular attention in both the design and test phase to ensure that vessels not only can carry loads given by the internal pressure, but also they are able to prevent leakages that tends to form microcracks and leak paths at high strain levels [85]. Due to these challenges, *Type V* hydrogen pressure vessels are in the design phase yet, and researchers are turning their attention to this topic. Moreover, the use of thermoplastic matrices in the composite materials can give hydrogen fuel tanks recycling advantages [86–88].

Colozza proposed an interesting comparison, shown in Fig.(4), of different materials and vessel shapes, where the reduction in terms of tank mass can be achieved when using composite materials instead of conventional metals [71]. For aeronautic and aerospace applications, where weight plays an important role, the use of composite materials is crucial.

In summary, the transition towards composite materials for high-pressure hydrogen vessels is a substantial advancement in aircraft industry, emphasizing their superiority in weight reduction, structural integrity, and innovation potential. This shift represents a step forward in the selection of materials for hydrogen storage technology, promising safer and more efficient solutions.

2. Manufacturing

Internally pressurized tanks for GH_2 storage have historically utilised spherical shapes due to the fact that spheres experience the lowest membrane stress on their walls. Nowadays, the most common fuel storage and transportation tanks have a cylindrical shape. The construction of cylindrical tanks involves simpler and more straightforward fabrication processes, resulting in lower production costs, compared to spherical vessels [68]. Manufacturing processes of high-pressure vessels for aircraft applications include the fabrication of the polymeric or metallic liner, filament winding of composite shell, safety test regarding pressurization and possible leakage and finally the assembly of the various components that lead to a complete fuel storage system [89]. Filament winding technique is one of the most common manufacturing processes in the production of *Type II – V* high-pressure composite cylindrical vessels [82, 90]. The FW process involves winding a tape of fibres around a cylindrical mandrel, having the ability to decide the fibre lamination direction to create the desired lamination sequence . Thanks to the high process automation, with the FW technique different process parameters can be optimised to achieve the properties required for the tank application. In the manufacturing of

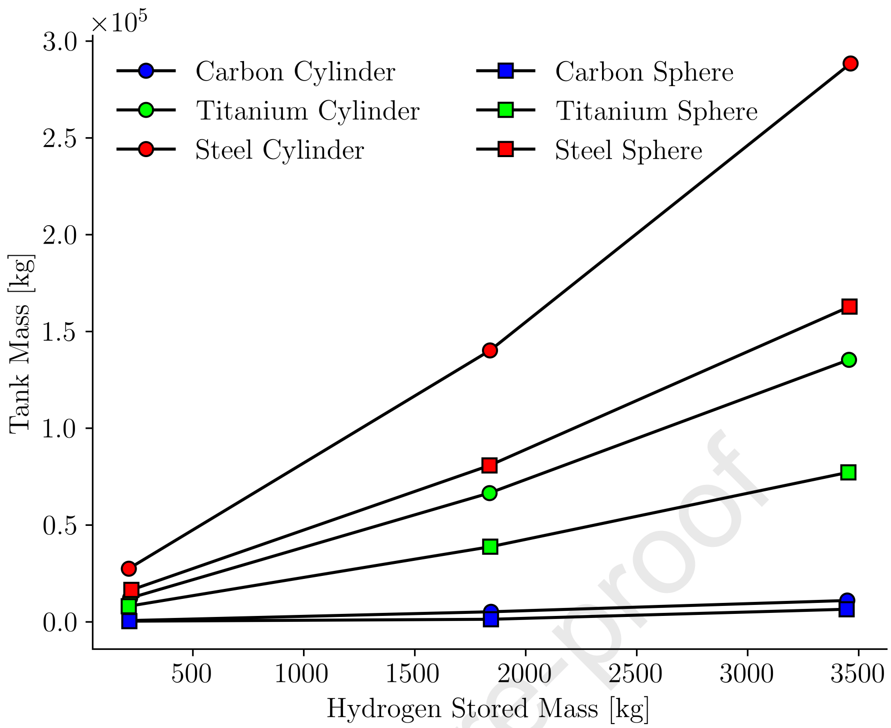

Fig. 4 Storage tank mass *versus* stored GH_2 fuel for different kinds of pressure vessels.

filament wound composites, it is essential to regulate fibre direction, fibre tension, and winding velocity in addition to material engineering parameters [91–94]. Cohen et Al., e.g., extensively studied the effect of the relation between fibre volume fraction and failure pressure [95, 96]. However, even if the FW technique is mature, the use of a more advanced manufacturing process can provide higher accuracy and quality as well as lower material waste. Automated Fibre Placement (AFP) has been seen as an evolution of FW [97]. The manufacturing process is very similar to the FW technique, but has the main advantage that more complicated shapes can be manufactured, thanks to the use of robot arms with more degrees of freedom [98]. Improvements in the manufacturing process give the designer the chance of developing new structures for advanced application of high pressurized hydrogen tanks [99].

3. Design and analysis methods

Design of pressure vessels is a critical task. Engineer must consider as their first concern the safety of the designed structure to ensure its operational functionality without the risk of catastrophic incidents. Additionally, tanks have to be lightweight structures to be seamlessly integrated into aircraft, where weight plays a fundamental role.

Different studies have been done in order to optimize the shape of the pressure vessels. Carbonari et Al. [100] explored the shape enhancement of axisymmetric pressure tanks through an integrated methodology that combines the complete pressure vessel model with a multi-objective function designed to minimize von-Mises mechanical stress.

In contrast to most commons cylindrical and spherical tanks, researchers are exploring other shapes. Toroidal composite pressure vessels have emerged as a space-efficient alternative that can potentially mitigate issues related to classical vessels, resulting in reduced weight and enhanced storage efficiency [101]. Daghighi et Al. [102, 103] studies introduced super ellipsoids of revolution as a design solution to prevent bending in curved composite shells under uniform internal pressure. These super ellipsoids offer advantages like enhanced efficiency, smoother stress distribution, reduced stress concentration, and cost savings in assembly. The researches present a new set of equations for analytically achieving bend-free states and utilizes stiffness tailoring using the variable angle tow composite concept.

Besides developing new analytical models to study more reliable shapes for hydrogen vessel applications, numerical models are commonly used by designers to predict the structural response of the designed tank [104], including a constitutive damage model for predicting the operational limit of the configuration analyzed [105].

The finite element (FE) method stands as the most widely employed approach in the development and testing of damage models for hydrogen tanks, due to its maturity and robustness. Indeed, it constitutes the numerical method integrated into leading commercial software for structural analysis, such as `ABAQUS`®, `MSC NASTRAN`® and `ANSYS`®. These software packages possess the capability to implement user-defined progressive damage routines, seamlessly integrated with the FE code [106, 107]. This feature enables researchers to examine different damage models that properly characterize the material behavior.

Modelling damage with composite material is more difficult compared with classical material, due to its anisotropy and heterogeneity. The failure is a progressive and complex process, therefore different damage models have been proposed to proper describe the mechanism in composite materials such as continuum damage mechanics (CDM) or phase field (PF) approaches [108, 109]. In this context, multiple studies have been performed to analyze pressurized vessels. These investigations have laid the foundation for a more comprehensive understanding of the damage phenomena within internally pressurized tanks. Whithin CDM framework where micro-cracks and void are modelled as loss of stiffness, different works have been proposed in the context of hydrogen pressure vessels. Liu and co-workers [110] proposed a multi-scale damage model to predict the failure properties and ultimate burst pressure of composite pressure vessels. The multi-scale progressive failure analysis of the composite vessel is implemented by associating the FE codes `ANSYS`-APDL with `ABAQUS`-UMAT. Wang et Al. [111, 112] have formulated a numerical algorithm to capture complex failure modes and the progressive post-failure behaviors exhibited by composite laminates. This algorithm incorporates a material property degradation method to simulate intralaminar failure and employs cohesive elements to address delamination at the interface. The model is then employed to predict the ultimate strength and complex failure behaviors of an aluminum–carbon/epoxy composite vessel. The proposed model is validated by correlation with experimental results and traditional FE analysis providing theoretical guidance for the safety and economical design as well as practical application of composite vessels.

Advanced numerical models can incorporate the multi-physics aspects of the problem, ensuring a comprehensive representation of various mechanisms contributing to the degradation of properties in designed pressurized vessels. A fully coupled mechanical–chemical–thermal PF computational framework for failure analysis of multilayered composite pressure vessels was developed to reproduce the different damage patterns of composite structures under the action of multi-physical fields in extreme environments, considering material degradation, thermal conduction, and long-term concentration diffusion [113]. This study allows for the reproduction of various damage patterns observed in composite structures subjected to multiple physical fields in extreme environments, providing a predictive computational methodology to mitigate the risk of catastrophic failures.

Tab.(3) reports an overview of recent developments in numerical modeling for progressive damage analysis in hydrogen pressure vessels. These works are grouped by the software employed, while also providing information on the damage model used and a brief description of each study.

Table 3 Overview of recent numerical models developed for progressive damage analysis in composite pressure vessels.

Software	Damage Model	Description
ANSYS-APDL	Istantaneous Degradation	3D parametric FE model of cylindrical composite vessel to explore the non-linear stress–strain relationship and the final failure pressure. [114]
	CDM	Adaptive genetic algorithm in conjuction with FE analysis to perform the optimal design of composite hydrogen storage vessel for reaching the minimum weight under the burst pressure constraint. [115]
		FE-CDM burst simulation analysis of hydrogen pressure vessels manufactured by filament winding. [116]
ABAQUS	CDM	FE analysis to predict the failure properties and burst strengths of aluminum–carbon fiber/epoxy composite cylindrical laminate structures. [117]
		FE-CDM progressive damage analysis model to predict the ultimate strength and complex failure behaviors of the composite vessel structure. [111]
		Micromechanics-based progressive damage analysis strategy to predict the coupled thermal-mechanical responses and complex failure behaviors of the composite vessel structure. [112]
		3D damage analyses of a cryogenically compressed H2 storage vessel model subjected to thermomechanical loadings to investigate effects of the helical layer fiber orientation and loading scenario on damage development, vessel integrity and burst pressure. [118]
	First-ply-failure	Estimation of the burst pressure of filament wound composite pressure vessel considering imperfection associated with production process. [119]
	Stiffness degradation model	Numerical modelling of micro-macro progressive damage based on Puck criterion to predict the burst pressure of the composite pressure vessels. [120]
ABAQUS & ANSYS-APDL	CDM	Multiscale damage model to predict the failure properties and ultimate burst pressure of composite pressure vessel. [110]
LMS Samtech		FE damage analysis for the prediction of the behavior of wound composite, from the evolution of the different damage mechanisms to their influence on the global behavior of wound structures. [121]
In-house FE code	PF	Fully coupled mechanical–chemical–thermal phase field computational framework for failure analysis of multi-layer composite pressure vessels, material degradation, thermal conduction, and long-term concentration diffusion. [113]

D. Liquid hydrogen storage

Storing hydrogen at cryogenic temperatures greatly increases its volumetric energy density (from 2.9 MJ/L at 350 bar and ambient temperature for GH_2 to 8.5 MJ/L at 2 bar and 20 K for LH_2 [122]) and allows the use of lower storage pressures, therefore reducing the vessels structural mass and enabling tank gravimetric efficiencies up to 50% and beyond [45]. While other technologies can achieve maximum gravimetric storage densities up to 30 wt%, the highest gravimetric storage density can currently be achieved utilizing liquid hydrogen [123]. So, storing hydrogen as a liquid not only offers a reduction in tank weight, but also allows higher volumetric efficiency [124]. High gravimetric efficiencies enable greater ranges and, for very high values of η_{tank}, some studies suggest how range for hydrogen aircraft can be greater than conventional kerosene-fuelled counterparts [53, 125].

Liquid hydrogen requires extremely low storage temperatures to remain in its state, typically around 20 K [126]. The substantial temperature difference between the cryogenic fuel of the cryogenic tank and the ambient temperature, which can exceed 318 K during certain phases of operation, underscores the significant thermal challenges that must be addressed when designing and engineering liquid hydrogen storage systems. Proper insulation, structural integrity, and safety measures are crucial in managing these extreme temperature differentials in hydrogen tanks, especially during ground operations and various operational phases. Compared to GH_2 storage, cryogenic pressure vessels are generally more complex because of the necessity to cope with extreme temperatures. Heat exchangers, safety valves, level probes, filling ports, gas extraction lines and sloshing bulkhead are all necessary components whose mass, while not accounted for when computing η_{tank}, needs to be taken into consideration when evaluating the gravimetric efficiency of the whole system.

Given the limited available volume inside the aircraft's fuselage it is particularly important to ensure that pipes, electronics, structures and generally subsystems around the cryogenic tanks are capable of dealing with the low temperature of the tank proximity. Therefore the importance of proper thermal insulation and adequate monitoring is vital for the tank component itself but also for the aircraft systems as well. Hydrogen density can be further increased if infrastructures and systems permit so: this can be achieved using *slush hydrogen* [127, 128], or *subcooled Liquid Hydrogen* sLH_2 [129], mixtures of solid and liquid hydrogen which enable densities in the order of $80\,\text{kg/m}^3$.

In LH_2 storage, the necessity of avoiding excessive *boil-off* rates is recognized as the limiting factor. This term refers to the evaporated vapor resulting from the heat leak into the tank. Thanks to various studies, it has become possible to accurately investigate and model this behavior [130]. The main ways heat fluxes through pressure vessels and their content are convection and radiation with the surroundings of the tank and conduction between the tanks structure and insulation. Due to the heat flux from the external environment directed towards the tank, a pressure increase occurs, making mandatory the use of a venting valve. This valve prevents the internal pressure from exceeding the maximum allowable pressure determined by the tank's mechanical properties. and generally, tank pressure must be slightly higher than the ambient pressure at any point in time to prevent ambient air from flowing into the tank [131]. The venting of fuel is an essential requirement, albeit one that results in the wastage of hydrogen and subsequent degradation of aircraft performance. Therefore, the wise use of thermal insulation can significantly minimize this fuel wastage [55]. Moreover, the use of liquid hydrogen requires a dedicated fuel delivery and heat management system to convert the LH_2 into GH_2 to be injected into the combustion chamber at an adequate temperature. While compressed hydrogen tanks enable higher flexibility on account of their generally oversized geometry, liquid hydrogen tanks tend to be more efficient especially when larger quantities of hydrogen are needed for flight and fewer tanks are used, minimizing the surface area heat can leak in [123]. Otherwise, using multiple smaller vessels, the percentage of insulation versus the total tank mass increases significantly [48], thus reducing the overall tank efficiency.

When considering cryogenic tanks the designers must take into account that hydrogen possesses a tremendous amount of energy, but it is also an excellent heat sink for component cooling. Hydrogen has a cooling capacity, in fact, about 4.9 times the cooling capacity of Jet-A, thanks to its high specific heat capacity and thermal conductivity [63] . Therefore, an accurate system integration of the tank with the aircraft systems can solve the problem of presenting the fuel at the adequate temperature to the combustor while being used to cool other components that would otherwise need a dedicated cooling system [132]. The design of a lightweight and highly insulated tank for storing cryogenic liquid hydrogen is of paramount importance in facilitating the widespread use of liquid hydrogen in aviation [133].

1. Materials

Ideally, hydrogen cryogenic tanks are constructed using lightweight and durable materials, with an emphasis on safety features. These safety features often include pressure relief systems and leak detection mechanisms to ensure the safe handling of hydrogen. Materials chosen for tank wall construction should possess a combination of high strength, high fracture toughness, high stiffness, low density, and low permeability to LH_2. This selection criteria aims to optimize both the structural integrity and the containment of cryogenic hydrogen, ensuring the overall safety and efficiency of the tank system [134]. The selection of tank wall materials is intricately linked to their performance characteristics in cryogenic environments. Specifically, for the detection of cracks measuring 5 mm or smaller, composite materials may prove to be suitable options. Conversely, monolithic metallic alloys are considered practical choices for tolerating cracks of up to 5 mm in size [135].

Aluminium is a major candidate as a tank material since its susceptibility to embrittlement is limited [136, 137], however composites, thanks to their low density and high strenght offer an interesting and generally feasible opportunity [138]. Millis et Al. [139] showed that CFRPs are the most mass efficient materials. In general, composites can offer a potential weight saving of 25% on the tank wall structure thanks to their properties [133]. Considering that future operating costs for airlines are likely to be increasingly sensitive to energy consumption, a hybrid CFRP tank wall material, employing metallic liners to seal the inner volume and high-strength, low-density composites as the outer structural layer, may represent the best short term option. This conclusion is further supported by the European Union funded project CHATT (Cryogenic Hypersonic Advanced Tank Technologies) which had the objective to investigate CFRP cryogenic hydrogen tanks and claimed at least 30% mass saving compared to aluminum [140]. The design and engineering of hydrogen tanks for aviation require careful consideration of various factors, including structural integrity, weight distribution, and compatibility with aircraft systems. These tanks must be able to withstand the extreme conditions experienced during flight, which encompass changes in altitude, temperature, and pressure. Achieving a balance between strength, weight, and safety is a complex challenge, necessitating the use of advanced technologies and materials to develop hydrogen tanks that meet the stringent requirements of aviation applications [141]. Some of the main materials candidates for tank wall construction are listed in Table 4, as well as possible use cases, densities, LH_2 permeation susceptibility, main advantages and disadvantages.

2. Insulation

Key parameters for thermal insulation in aerospace applications are low thermal conductivity and low emissivity at low mass density. Moreover, the material ability to maintain low thermal diffusivity, a modest thermal expansion coefficient, and to withstand thermal distortions resulting from significant thermal gradients is also important [134]. Fuel system design must take into account that heat from the environment can passively enter the tank and cause *boil-off*. This can be extremely dangerous since the gasified hydrogen exerts pressure on the tank walls that can exceed structural limits in a process called *autogenous pressurization* [139]: therefore the need for a venting system translates in added weight, complexity and fuel wasting.

In order to contain boil-off rates, hydrogen tanks need to be heavily insulated and have the lowest possible surface to volume ratio. This explains how bigger tanks are generally more efficient than smaller tanks [142]: for example, NASA used a pair of LH_2

Table 4 Material candidates for tank walls construction.

Material	Use case	Density [kg/m^3]	Permeation susceptibility	Advantages	Disadvantages
Al 2219-T8	Inner liner & tank wall	2840	Very low	Low cost, established	High mass, high conductivity
Al 8090-T8	Inner liner & tank wall	2540	Low	Low cost, established	High mass, high conductivity
Al 2090-T8	Inner liner & tank wall	2590	Very low	Low cost, established	High mass, high conductivity
CFRP	Outer structural layer	1600	High	Low mass, high mechanical properties	Higher cost, prone to microcracking and permeation

tanks, each containing more than 3 million liters of fuel with a diametre of over 21 m. Boil-off rates for this specific units has been estimated to be of about 0.0625% of the total volume every 24 hours [143]. However, such low rates of boil-off are only achievable if a considerable quantity of insulation is applied to the pressure vessel, for example during long duration ground storage where the total mass of the component is not an influential factor. For vehicle applications a compromise on thermal performance is necessary in order to contain mass. For instance, NASA used cryogenic sandwich pressure vessels during spacecraft operations, however, because of the relatively low storage times, high levels of boil-off rates have been allowed. As a matter of fact, the external tank (ET) of the Space Shuttle accepted a loss rate of 38.4% of fuel mass loss every day while being characterized by unusually high values of gravimetric efficiency, in the order of 80% [134]. [131].

In the study performed by Millis et Al. [139], significant relevance was given to the trade analysis whose output was the optimum ratio between insulation thickness and system *total* mass, namely the sum of the mass of the tank, the insulation and the hydrogen. More insulating material around the vessel reduces heat leak and consequently reduces hydrogen boil-off, but at the expense of additional insulation mass and costs. In contrast, less insulation results in lower insulation mass, but the gain is offset by additional hydrogen propellant and tank mass required to balance boiled-off fuel. Moreover, oversized insulation comes with penalties in terms of weight but also negatively impacts autogeneus pressurization. The study focused on a specific application, namely an high-altitude long-endurance unmanned aircraft, and concluded that the combination of a vacuum-jacketed tank with a modest (approximately 3.81 cm) thickness of multilayer insulation inside a vacuum gap of 4.32 cm between the hydrogen tank and its vacuum jacket is the most efficient insulation layout. A similar conclusion is presented by Rompokos et Al. [144] where optimum insulation thickness is achieved through a parametric study and utilizing the definition of η_{tank}. The reduction in tank insulation thickness leads to increased ambient heat infiltrating the liquid, causing a higher mass of liquid to exist at temperatures above the standard 20 K. In this work, the specific requirements underscore the need to integrate the tank into a commercial airliner. The results show that a double-wall, aluminum, and foam-insulated cylindrical pressure vessel with hemispherical endcaps would need 12.4 cm of insulation to achieve optimal performance. Ambient conditions and heat flux influence the tank's outer surface temperature, which in turn affects the heat in-leak and subsequently, the tank pressure. Optimization for insulation thickness should consider also other parameters such as increase in insulation mass with higher insulation thickness and condensation or ice-formation over the tank insulation for lower insulation thickness, higher tank insulation thickness is required to minimize the liquid stratified mass and ullage pressure rise [145].

A further classification in insulation methods distinguishes internal or external methods, meaning the insulating material can be in direct contact with the fuel or not. Because of the reduction in volume and the corrosive nature of hydrogen, external insulation is often preferred. Insulation of the cryogenic tanks is designed based on temperature, pressure and insulation thickness. Currently, the most common methods used for tank insulation are multilayer, vacuum and foam insulation and future perspective may include aerogels.

The *Multilayer insulation* system, known as MLI, Fig.(5), uses a number of thermal radiation shields perpendicular to the direction heat flow [146]. It consists of a reflective foil whose task is to minimize radiation heat, alternated with metal radiation shields, usually aluminized or goldized mylarand, and insulating materials like fibre glass, silk tissue or polyester. Generally, from 60 to 100 layers are used to achieve good insulation, although an increase in tank mass is to be expected [31]. In particular, the MLI mass depends on the tank geometry: for a classical cylindrical tank with hemispherical end caps, the insulation mass M_{ins} exhibits a generic cubic dependency on the number of layers N, i.e. $M_{\text{ins}} = aN + bN^2 + cN^3$, where the coefficients a, b, and c depend on the internal radius of the tank, on the height of the cylindrical region, on the thickness of each insulation layer as well as on the mass density of the insulating material. However, when the tank dimensions, i.e. the internal radius and the length of the cylindrical portion, are much larger than the MLI thickness, as it is usually the case, the dependency can be approximated as $M_{\text{ins}} \approx aN$, see also Ref.[147]. A vacuum jacket, Fig.(6) can be installed between the warm and cold boundaries [148] enhancing the insulation efficiency but further adding mass and complexity to the component. MLI used in association with vacuum insulation is characterized by values of density in the range $10 \div 100\,\text{kg/m}^3$ and allows thermal conductivity in the range $3 \times 10^{-4} \div 3 \times 10^{-5}\,\text{W/mK}$. The main drawback is the added mass and complexity originating from the presence of the vacuum system. An evolution of this system is represented by variable density multi layer insulation (VDMLI), which may enable heat fluxes reduced by a factor of 58% compared to conventional MLI [149].

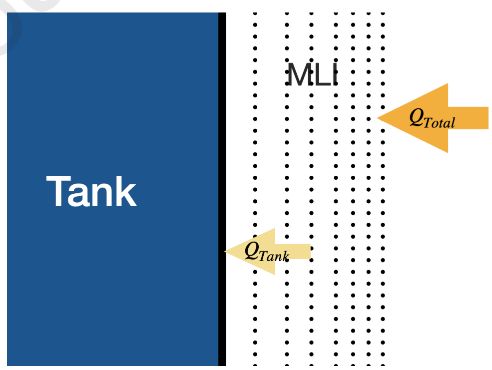

Fig. 5 Schematic of Multilayer insulation. It employs multiple perpendicular thermal radiation shields like reflective foil, metal radiation shields, and insulating materials like fiberglass, silk tissue, or polyester.

While the use of vacuum jackets is found to be effective, it requires venting subsystems in order to seal the vacuumed region [150]. An additional issue is the ability of the insulation system to handle dimensional variations due to the imposed thermal cycles as a result of filling and emptying the tank with cryogenic hydrogen [134]. Consequently, the thermal coefficients mismatches between the components of the tank system are key factors [139]. When designing a tank system, it is crucial to thoroughly evaluate and account for issues related to thermal expansion coefficient mismatches between the various tank wall components. Failure to do so can lead to structural problems, leakage, or other operational issues in the tank system. Proper consideration of thermal expansion coefficients ensures that the tank can withstand temperature variations without compromising its integrity or performance. Moreover, the tank wall thickness must be sufficient in order to withstand the mechanical loads during operation. This method of insulation is highly effective even though additional stiffeners are required between the vacuum jacket shell outer wall and the inner wall which increases the weight and complexity of the tank. Huete et Al. [66] confirmed how, when compared to foam insulation, the overall performance of vacuum insulated systems may not offer a better solution because of their higher weight and complexity. The same study also outlined how this configurations may be beneficial only for very small tanks or long endurance applications, such as those employed in the automotive sector.

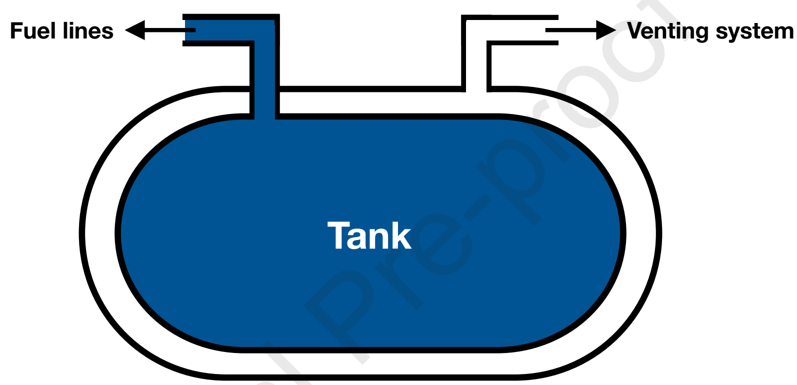

Fig. 6 Vacuum insulation system schematic representation, where a vacuum jacket connected to a venting system insulates the cryogenic tank.

As mentioned, ideal insulation has very low conductivity, diffusivity and density, therefore, *foams* are often selected as insulation materials as evidenced by the Space Shuttle's ET. The insulation thickness of the tank depends upon the insulation material properties, tank size, allowable boil-off and overall allowable tank weight. Polyurethane foams offer a versatile material for *passive* insulation, with the possibility of selecting tailored density ranging from 32 to 96 $\mathrm{kg/m^3}$ for specific applications. The variant PUR64, for example, with density 64 $\mathrm{kg/m^3}$ and thermal conductivity 5.91×10^{-3} W/mK is a suitable material for the manufacturing of storage tanks insulation layers. Foam insulation is relatively low cost, easy to implement and generally light weight. This method of insulation, however, is not free of risk: insulating spray-on foams (SOFI), Fig.(7) are known for a variety of risks such as environmental impact, fire hazard and structural considerations as testified by the events involving the Columbia Space Shuttle [151]. Hence, since foam can not be used as stand-alone solution for H_2 storage, careful integration with other materials is necessary. It is for example required that both sides of the foam layer are protected: on the inside from the corrosive fuel and on the outside from the external environment. However, one of the most challenging aspect resides in the solidification of the air adjacent the tank. Here the cooled air solidifies and creates a vacuum condition that fuels itself creating a great quantity of solidified air, especially in architectures where an open-cell foam layer sits on a closed-cell one to allow for thermal expansion. In order to mitigate this phenomenon, known as *cryopumping*, it is possible to further insulate the outer surface of the foam with some kind of barrier, solid or gaseous, even though this add cost and complexity [152]. Moreover, because of the higher thermal conductivity of foams, compared to MLI, their use results in a generally thicker insulation [135], but not necessarily an heavier one. However, despite these considerations, foams remain highly effective insulation passive materials. Unlike vacuum insulating systems, which typically requires a double tank wall to support the vacuum coupled with multiple subsystems, foams can provide efficient insulation without additional hardware.

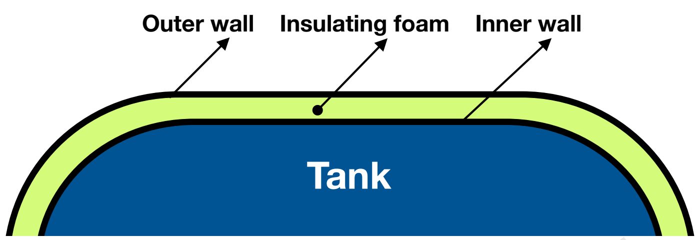

Fig. 7 Foam insulated tank schematic representation, where insulation of cryogenic tank is made thanks to i) an outer wall; ii) an insulating foam ; iii) an inner wall.

Future perspectives in cryogenic LH_2 insulation may include the employment of *aerogel*, a lightweight and highly porous material featuring density $80\,kg/m^3$ and thermal conductivity $0.014\,W/mK$, which makes it a suitable candidate for light hydrogen tank insulation. Moreover, their compression resistance may offer a significant advantage, as it may contribute to the structural integrity of the tank, making it a valuable choice for maintaining the safety and performance of cryogenic LH_2 storage and transportation systems [153]. Some studies further suggest how the implementation of aerogel technology would yield several benefits, encompassing reduced weight, simplified design, enhanced safety, cost savings, and improved sustainability [154]. However, the specific design and requirements of the hydrogen tank would need to be considered when using aerogel as insulation, given its peculiar characteristics. Safety considerations, compatibility with other tank materials, and any regulatory requirements should be thoroughly evaluated to ensure the suitability and effectiveness of aerogel insulation in hydrogen vessel applications [155].

Research in this field is ongoing and the ultimate goal is to identify the industry standard that will enable competitve gravimetric efficiencies, safety and low cost. In this sense, some previous studies, like Mital et Al. [134] reviewed advantage and disadvantages of various insulation methods and identified trends in material development, however, given the fundamental importance of proper thermal insulation in liquid hydrogen tanks and its mutual influence with material's mechanics, future development in this field is expected.

III. Hydrogen embrittlement

A crucial consideration for storage is hydrogen embrittlement, which occurs when materials under tensile stress, as it is often the case with tanks, are exposed to the small hydrogen molecules, causing drastic decreases in yield stress and ductility [134, 138, 156].

Due to their small size, hydrogen molecules are highly prone to permeating through the tank wall and diffusing into many metals and compounds, which can lead to hydrogen permeation and mechanical properties degradation. Hydrogen embrittlement (HE) is a process resulting in a decrease in the fracture toughness or ductility of a material due to the presence of atomic hydrogen [157]. This phenomenon occurs since hydrogen atoms infiltrate the structure of the material itself, leading to its mechanical degradation and increased susceptibility to fracture.

The presence of hydrogen alters the material internal structure, causing H_2 atoms to accumulate in certain regions, like grain boundaries or dislocations. As a result, the material strength, ductility, and toughness are significantly reduced, making it more prone to sudden failure or catastrophic fractures under applied stress. The reduction of fracture loads can occur at levels well below the yield strength of the material. Cracks due to embrittlement can grow rapidly with little macroscopic evidence of mechanical deformation in materials that are normally quite ductile. Hydrogen embrittlement usually manifests in terms of singular sharp cracks, in contrast to the extensive branching observed for stress corrosion cracking [156].

This process commonly affects metals, such as steel and titanium [158], and can occur during various stages of their operation, production, or maintenance. Other materials such as aluminium, copper and stainless steel have shown to be much less prone to hydrogen-induced embrittlement [159]. Actually, some aluminium alloys like 50-86 AlMg are considered for use with liquid hydrogen as the material remains ductile even if exposed to the combination of hydrogen and very low temperatures [160]. Metallic tanks were studied as a solution to this problem, since hydrogen permeates metals at a slower rate than through the nonmetallic materials [134]. For aircraft, however, all-metal tanks might be unfeasible due to their excessive mass, therefore, a solution combining a metal liner inside a composite tank may represent a viable option. In this scenario, the compatibility of coefficients of thermal expansion (CTE) is a crucial consideration that must be taken into account in order to avoid catastrophic failures like testified by the case of the X-33 demonstrator [161]. Here, the microcracking of the composite resulted from a combination of factors, including the CTE mismatch between the carbon fiber and the polymer matrix, as well as a significant difference between operational and fabrication temperatures, leading to the development of residual stresses. These microcracks served as pathways for pressurized hydrogen to permeate through the composite wall and enter the honeycomb core. Upon heating, the matrix cracks closed, causing the liquid to evaporate and trapping the resulting gases, which had no way to escape. This buildup in pressure eventually led to the delamination of the core from the inner composite skin [162].

Hydrogen embrittilement has been the cause of failure in several notable instances in the past. For example, during World War II, the U.S. Liberty Ship Building Program noted sudden fracture in several vessels, some of them even being split in half. While these failures where indeed caused by a combination of factors, HE resulting from poor welding was found to be a major contributor in mechanical failure [163]. Less evident but equally dangerous effects of embrittlement were later found in the Apollo XV service module, where H_2 generated during fuel cell operation caused embrittlement and cracking of the stainless steel components [164]. Civil structures are exposed HE phenomenon too as testified by the case of the Leadenhall Building, a 225 m skyscraper located in central London. Here, investigation on several broken bolts identified hydrogen embrittlement as a cause of fastener fracture [165].

Hydrogen embrittlement is surely a complex and challenging issue in engineering and requires careful consideration in the design and selection of materials, as well as in the implementation of preventive measures to mitigate its detrimental effects. While the correct mechanism responsible for HE in the material is still somewhat unclear [166], hydrogen embrittlement does not represent a bottleneck per se. HE prevention methods are known and effective like adding some alloys such as titanium and aluminium liners to the base material [157] or using plating techniques as zinc and nickel plating [167]. However, the current challenge is represented by the limited knowledge of the interaction of the liner-composite-insulation system under cryogenic temperatures.

IV. Improving tanks efficiency

Improving the gravimetric efficiency of hydrogen tanks is an endeavour that can be pursued through various approaches, or, more realistically, with a combination of several of technological solutions involving engineering, material science and chemistry.

Better values of η_{tank} can be obatined increasing the amount of hydrogen that can be stored per unit of tank weight or reducing the weight of the tanks needed to contain a certain amount of fuel. A more conventional approach utilizes composite materials for tank construction reducing weight while maintaining strength. As mentioned earlier, carbon fiber composites are frequently used in aerospace applications because of their high strength-to-weight ratio. Even though composite characterization under cryogenic temperature is not fully mature, optimizing the shape and structure of the tank can increase the packing density of hydrogen by maximizing the available volume while better distributing the stresses. Additionally, cleverly integrating the hydrogen storage system with other aircraft components, such as fuel cells or propulsion systems, can enhance overall efficiency by reducing redundancies and optimizing weight distribution. More novel approaches rely on the use of lightweight advanced materials with high hydrogen storage capacity. Research has focused on developing materials such as graphene, metal-organic frameworks (MOFs) [168], and porous materials [169] like carbon nanotubes or hollow glass microspheres, which are able to store hydrogen at high densities [170]. Nanostructuring hydrogen storage materials can enhance their surface area, improving hydrogen adsorption and desorption kinetics. This can lead to higher storage capacities and more efficient utilization of tank volume. In addition to all stated before, structural health monitoring coupled with reduced safety factors can enable higher values of η_{tank} and make hydrogen use more feasible.

A. Graphene

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, has attracted significant attention in various fields due to its peculiar properties [171]. Graphene itself is not typically used directly in hydrogen tanks, however, it can be employed in combination with other materials to enhance hydrogen tanks performances [172].

Graphene-like materials (GLMs), in particular, have been investigated for their potential use in hydrogen vessels on the basis of their high gravimetric and volumetric density [173]. By incorporating graphene or graphene derivatives, such as graphene oxide or functionalized graphene, into the structure of storage materials like metal hydrides, it is possible to improve their hydrogen adsorption and desorption properties therefore obtaining the effect of maximizing hydrogen storage properties. When 3D-printed it is possible to exploit the high porosity, high specific surface area, low thermal conductivity, high adsorption, high conductivity and low density of graphene in graphene aerogels [174]. Graphene may also enhance the kinetics and capacity of hydrogen storage, making it more efficient and practical [175]. GLMs can be incorporated into composite materials used in hydrogen tanks to improve their mechanical characteristics and resistance to gas permeation: thanks to their excellent impermeability to gases, the coating of the inner surface of the vessel with a layer of graphene, acting as a gas barrier, can minimize the hydrogen embrittlement, improving safety and efficiency. Similarly, by dispersing graphene within a polymer matrix, it is possible to improve the structural integrity of the tank and reduce the risk of hydrogen leakage [176].

However, while graphene shows potential in hydrogen storage applications, the technology is still evolving and the development of efficient, light and cost-effective storage systems using graphene-based nanomaterials is still needed in future hydrogen storage research [177]. These challenges include scalability of production, cost-effectiveness, and long-term durability [178]. Ongoing research and development efforts are focused on overcoming these obstacles and unlocking the full potential of graphene in hydrogen storage and related applications.

B. Carbon Nanotubes - CNTs

In recent years, due to the advantages of high hydrogen storage capacity, low production cost, and a long life cycle, activated carbon has become a research focus for hydrogen storage through adsorption phenomenon [179–181]. Carbon nanotubes are tubular carbon structures with dimensions on the order of 2 nanometers in size synthesized for the first time in 1991. Single-walled carbon nanotubes (SWCNT), among various nanomaterials, have garnered attention due to their potentials in large surface area, low weight, and pore structure enabling hydrogen adsorption at ambient temperature. Surface modification, introduced as one of the most effective methods, aims to enhance hydrogen absorption despite the limitations posed by the extremely weak Van der Waals interactions between hydrogen and pristine carbon nanotubes [182].

These structures are theoretically capable of storing hydrogen within the tube structure itself [183]: carbon nanotubes can potentially store anywhere from 0.46 wt% to 0.78 wt% in hydrogen [184]. This technology, while promising, is still within the development stage. Very little is known for example about the effect of hydrogen over-pressure on the stability of the adsorbed fuel. However, if CNTs can live up to their projected potential, this would represent an effective and appealing way to store hydrogen [185].

C. Metal-organic frameworks - MOFs

Metal-organic frameworks (MOFs) for hydrogen storage are a family of nano-porous materials composed of well-defined building blocks, including polar metal oxide centers (connectors) and nonpolar organic linkers [186]. Over the past decade, there has been a significant amount of interest generated by hydrogen adsorption in high surface metal-organic frameworks (MOFs) because of their high gravimetric storage density, rapid kinetics, and complete reversibility [187]. MOFs have shown promise as potential materials for hydrogen storage also due to their high specific surface area, high gravimetric maximum uptake, tunable structures, and porosity. For example, through adsorption-based storage, MOFs can adsorb hydrogen molecules within their porous structures, effectively storing hydrogen through physical adsorption [170]. Researchers have developed MOFs with tailored structures and pore sizes to maximize the amount of hydrogen that can be stored within the material [188]: this increased capacity is crucial for applications like aircraft, where space is limited, and maximizing the amount of stored fuel is essential [189]. MOFs can also help manage temperature and pressure during hydrogen storage. In fact, by selecting MOFs with suitable thermal stability and adsorption/desorption characteristics, the release of hydrogen can be optimized to occur within a specific temperature and pressure range [190] and the amount of heat generated by the adsorption process is marginal [191]. This theoretically allows for controlled and safe storage and release of hydrogen on airplanes and therefore represent an interesting potential asset. The main challenge is to develop MOFs with optimum pore size, without decreasing the specific surface area and at acceptable cost, finding the best available compromise [192].

D. Hollow Glass Microspheres - HGMs

Hollow glass microspheres are engineered spherical bubbles under the form of finely dispersed and free moving powder approximately 50 µm in size, with a really low density. The industry's interest is HGM is primarily focused on their use as additives for reducing the weight of hydrogen tanks. By incorporating glass microspheres into the tank material, the overall weight of the tank can be reduced enabling greater gravimetric efficiencies [193].

Commercially produced glass microspheres were first studied in the late 1970s for their application in storage of hydrogen. At high temperatures, glass exhibits an increased permeability to hydrogen molecules which permits the microspheres to be pressurized by immersion in high pressure fuel. Hydrogen diffuses through the microsphere membranes, equilibrating the internal and external pressures, thus filling the spheres. Once the spheres are filled, cooling them to room temperature reduces permeability, trapping the hydrogen within [194]. Hydrogen may be released from the microspheres by heating which increases permeability again. Glass microspheres can also provide reinforcement and increase rigidity of the tanks as well acting as insulating additives, reducing heat transfer between the tank and its surroundings. The crush strength of hollow spheres depends on their wall thickness. Typically, a higher density of spheres corresponds to a greater crush strength [195].

Although the storage capabilities of glass microspheres has potential for commercial use, there are a number of drawbacks to their use from a system standpoint: the main issue is that to get the hydrogen into and out of the spheres, they must be heated under specific conditions and therefore considerable energy and time must be spent to accomplish the task [71]. Moreover, their use demands a series of dedicated subsystems with subsequent plausible weight and cost penalty.

E. Structural Health Monitoring - SHM

The use of mandated safety factors in the range of 1.4 to 2.0 are usually augmented by conservative material strength estimates and make it very difficult to achieve lightweight hydrogen tank designs. This is particularly true when non-traditional advanced materials are used in the construction of such structures. This is necessary because new and advanced materials are not very well characterized, especially under cryogenic temperatures encountered during operations with liquid hydrogen, and manufacturing and fabrication processes introduce additional variability in the material properties. To achieve efficient tank structures, innovative designs calibrated with tests and incorporating integrated health-monitoring techniques will be necessary. This results from a considerable variation in material properties, necessitating a significant margin between average measured and allowable values, in turn affecting safety factors [134]. In past research, a safety factor of 2 has been considered a standard, being applied also by Brewer [63] in his study. This is a rather conservative approach but today, at least, is needed to cope with the insecurities related to hydrogen propulsion and storage.

One way to enable the use of smaller safety factors may be to implement structural health monitoring (SHM) systems in vessel design. The primary objective of advanced SHM is to conduct comprehensive tests, examining all structural elements and subsystems of a component to verify their safety and operational capability [196]. This systems are required to provide information regarding the local critical conditions and operational parameters of the component, possibly enabling a lower frequency of inspections during the component life-cycle, thus reducing operating costs. However, several challenges have been found to limit the use of SHM in long-term pressure vessels: cryogenic temperatures and thermal cycling are factors that may adversely influence the effectiveness of the sensor system [197]. Researchers have been assessing the performances of SHM and found Lead Zirconated Titanate (PZT) may be suitable compound for embedded sensors being able to withstand and survive cryogenic thermal cycles under cycling pressure loading while performing meaningful damage detection tasks [198, 199]. In this context the use of nondestructive inspection (NDI) and embedded sensors, while still costly, may represent the way forward. Optical fibres are also used because of their resistance to electromagnetic fields interference and ability to withstand harsh environments, some having also the ability to detect hydrogen leakage [200]. For reusable cryogenic tanks, the integrated health monitoring concept encompasses real-time in-flight monitoring and ground verification phases between flights [201]. This requires both novel smart onboard sensors and data processing units as well as advanced ground based NDI methods suitable for effective inspection of the whole assembled tank and its subsystems during maintenance. Key considerations in SHM design include: identification of critical components, conditions, and failure modes; selection of operating parameters; selection and trade-offs between sensors and system diagnostic and failure mode recognition. Furthermore, it is essential to carefully determine the optimal locations for sensors to achieve both maximum area coverage and optimal resolution in order to effectively identify and classify damage [202, 203]. Liang et Al. [204] addressed a deficiency in the existing research on the thermomechanical response of stiffened composite tanks providing an investigation of cryogenic and room temperature experimental assessment and monitoring technology.

V. Recent endeavors: projects and companies

Given the importance of hydrogen in building a sustainable future in aviation, governments and stakeholders have manifested interest in the technology funding numerous projects. In this section a selection of some of these projects will be listed and schematically reported in Tab.(5):

- Airbus ZEROe [205]. Recognizing the urgent need to address environmental challenges, the european manufacturer is employing cutting-edge technology and innovation to create a new generation of aircraft that run on sustainable energy sources. The ZEROe program encompasses three concept aircraft: the turbofan, turboprop, and blended-wing body. These aircraft are being designed to incorporate hydrogen as the primary power source, with the aim of achieving zero carbon emissions during flight. Airbus's vision relies on liquid hydrogen as a fuel for combustion with oxygen and hydrogen fuel cells to create electrical power that complements the gas turbine, resulting in a highly efficient hybrid-electric propulsion system. Cryogenic tanks will be designed and manufactured in the Zero Emission Development Centres (ZEDCs) in Nantes, France, and Bremen, Germany: first software models will be produced in Toulouse, then the ZEDCs will review and explore the process for manufacture. Once a final design is finalized a prototype will be tested with nitrogen. Airbus aims to launch the world's first hydrogen-powered commercial aircraft by 2035.
- Universal Hydrogen [77]. The US-based company is working on the purpose of decarbonizing aviation and put the industry on a trajectory to meet the Paris Agreement obligations. Their vision relies on the retrofit of two established regional transport, namely the ATR-72 and the De Havilland Canada Dash-8, to be converted to hydrogen propulsion via a retrofit process. This consists of a fuel cell electric powertrain that will replace the conventional turboprop engines and fuel systems. As for hydrogen storage, the company plans to accomodate it in the rear of the fuselage in modular hydrogen capsules that are transported directly from green hydrogen production sites to the airport and loaded into the aircraft using the existing intermodal freight network and cargo handling equipment, thus mitigating the need to rely on specific infrastructures to sustain operations. A cryogenic hydrogen storage module is under development, characterized by aluminium, double-walled, vacuum insulated construction. Universal Hydrogen plans to introduce its hydrogen powertrain for passenger service in 2026, using retrofitted ATR 72 regional aircraft.
- H_2FLY [206]. This company aims to build, qualify, and deliver the first commercial hydrogen storage and fuel cell power system for aircraft by the end of this decade. The experience with hydrogen comes form the involvement of the company in

the Antares program of the German Aerospace Center (DLR) and culminated with the first flight of the HY4 demonstrator. Fuel cell technology is the primary focus; however great emphasis is given to surrounding infrastructures, crucial for the introduction of electric propulsion. On september 7th 2023 H_2FLY announced the completion of the first piloted flight of an electric aircraft powered by liquid hydrogen as part of its flight test campaign. The HY4 demonstrator aircraft was equipped with hydrogen-electric fuel cell propulsion system and powered by cryogenically stored liquid hydrogen. The company aims to deliver a operational and certified fuel cell system for aircraft applications by late 2020s. Scaled-up, certified, systems for commercial operations are planned to enter into service by early 2030s.

- ZeroAvia [207]. Like Universal Hydrogen, ZeroAvia has opted for the retro-fit approach and is currently in the process of converting a Dornier Do 228 twin-turboprop to hydrogen propulsion through the use of the their ZA600 engine providing a claimed continuous electric power of 500 to 750 kW. In their first prototype, they choose to substitute only one of the two engines in order to create a proof of concept for hydrogen aircraft. The project relies on gaseous hydrogen tanks, stored inside the fuselage, coupled with fuel cells that generate electricity to be used by the electric motor. ZeroAvia plans to introduce the first 300-mile range powertrain for 9-19 seat airplanes by 2025. By 2027, they aim to have a second powertrain operational, capable of delivering a 700-mile range for 40-80 seat aircraft.
- Thermoplastic Hydrogen tanks Optimised and Recyclable [208]. This project, co-funded by the European Union, aimed at developing a thermoplastic Type V or 4.5 composite pressure vessel for hydrogen storage in a cost-effective way in order to be used both for vehicle and for transportation applications. This project has focused on the use of thermoplastic material as an asset to improve hydrogen compatibility and market requirements, improving safety, enabling optimized tank geometries while reducing cost, mass and environmental impact. The process to manufacture high pressure monolithic structure vessels with tape relied on five main objectives, namely: materials selection and development of an improved consolidation process for high pressure H_2 tank; numerical tools; tank performance; increased safety and operational capacity; and mass production and market introduction. THOR Project also introduced the use of optical fibres for structural monitoring purposes and studied the behaviour of the thermoplastic tank exposed to fire conditions. The project has been concluded in late 2022.
- ENABLing cryogenic Hydrogen based CO_2 free air transport [209]. ENABLEH_2 Project is a Cranfield University coordinated effort to mature critical technologies for LH_2 based propulsion in order to achieve zero mission-level CO_2 and ultra-low NOx emissions, with long term safety and sustainability. The project has developed tools for the conceptual design and performance analysis of fuel system components while investigating the behaviour of the H_2 and air combustion mix. The project has been concluded in late 2022.
- HYdrogen DEmonstrator for Aviation [210]. In line with the European Green Deal and Clean Aviation Strategic Research and Innovation Agenda (SRIA), The HYDEA project aims to develop a robust and efficient technology maturation plan for a hydrogen propulsion system. Its primary focus is on gaining a clear understanding of how simplifications in the technology demonstrator may impact commercial operations in the near future. The project strives to obtain definitive data on hydrogen propulsion emissions, thereby paving the way for the certification of the technology and enabling its integration into Airbus' ZEROe framework [205]. This project is planned to be concluded by December 2026.
- Cryogenic Hypersonic Advanced Tank Technologies [211]. The main objective of the CHATT project was to investigate Carbon

Fiber Reinforced Plastic (CFRP) cryogenic pressure tanks considering possible future development in aircraft technology. Four different demonstrator tank structures were designed and manufactured: the largest tank used a cylindrical geometry approximately 3 m in length and 1 m in diameter, utilising a carbon fibre-reinforced polymer (CFRP) shell design wound on a polymer liner. Tanks relying on dry-winging technology and liner-less designs were also manufactured in addition to unconventional geometries. CHATT found how thin-ply laminates can largely reduce or even prevent microcracking in cryogenic environments making the use of liners not only unnecessary but counterproductive. At the same time the project relied on cryogels whose performance is superior to aerogels as insulation material, while simultaneously being considerably less costly. CHATT project ended in the summer of 2015.

- Project Fresson [74]. Cranfield Aerospace Solutions' ambition is to become an aircraft designer and manufacturer of zero emissions aircraft and is currently investigating the retrofit of a Britten-Norman Islander 9-seat aircraft from conventional fossil fuel to that of gaseous hydrogen propulsion. CAeS claims to deliver the world's first fully certified, truly green, passenger-carrying aircraft using hydrogen fuel cell technology delivered by 2026 and new, optimized aircraft designs to entry in service by 2035. First flight for the modified Britten-Noman BN-2 Islander is set to take place in 2025.
- HydrogEn Lightweight & Innovative tank for zerO-emisSion aircraft (H_2ELIOS) [212]. H_2ELIOS project focused on the development of an innovative hydrogen storage solution for aviation use. The project goal is to contribute to the reduction of emissions and minimize the environmental impact of the aviation industry by developing a lightweight and cost-effective solution for storing liquid hydrogen. The final aim of the project is to develop a hydrogen storage system that can be seamlessly integrated into aircraft's primary structure using sustainable, lightweight polymer-based materials for the tank structure and employing automated techniques for manufacturing process to ensure close tolerances and high-quality finishes. The end date for this project is set for 2025.

Table 5 Summary of past and ongoing projects regarding hydrogen in aviation.

Project	Status	Main goal
Airbus ZEROe	In development	1st hydrogen-powered commercial aircraft avalible on the market by 2035.
Universal Hydrogen	In development	Introduce hydrogen in aviation with minimal infrastructure changes.
H_2FLY	In development	Develop the 1st qualified hydrogen-electric powertrain for aviation.
ZeroAvia	In testing	Developing the world's 1st zero-emission engines for commercial aviation.
THOR	Concluded	Develop thermoplastic composite tank for hydrogen storage.
ENABLEH_2	Concluded	Demonstrate LH_2 offers long-term sustainability for civil aviation.
HYDEA	In development	Develop an H_2 propulsion system to enter service by 2035.
CHATT	Concluded	Development, manufacturing and testing of tank structures.
Project Fresson	In development	Develop an hydrogen power train to retro-fit to a BN-2 Islander.
H_2ELIOS	In development	Develop integrated liquid hydrogen storage system for aircraft.

VI. Tank design and performance evaluation

From the studies and projects surveyed in this work it emerges that a specific tank technology has the potential to enable hydrogen use in aviation with limited modifications to the current state of commercial aviation: *passively insulated cryogenic composite* *sandwich pressure vessels*.

The design of a typical tank of this kind is schematically sketched in Fig.(8): they generally consist of a core, which may be realized using different materials – e.g. either honeycomb [213] or foam [214] – and usually much thicker than the interior and exterior layers, sandwiched between either metallic or composite face sheets, made for example of aluminum, carbon fiber-reinforced polymers or glass fiber-reinforced polymers [215, 216]. The layered architecture eliminates the need of an external open-foam layer, since an external composite layer can be employed as outer layer, thus acting as a protection for the insulation and preventing the cryopumping phenomenon [63]. While the use of fiber-reinforced composites is considered challenging [217], due to the proximity to the cryogenic temperature [135], placing the composite layer in the exterior side of the insulation has the additional benefit of keeping the thermal expansion coefficients mismatch and the thermal induced stresses [134] on the outer shell at a minimum, being subjected to temperatures close to the ambient one. The middle insulating layer should possess low conductivity, low diffusivity and low density, such as those of either foams or aerogels. However, given the relatively poor characterization of aerogels, spray-on foams such as PU64 polyurethane [218] should be considered for this purpose. Given the corrosive nature of hydrogen and the necessity to protect the middle insulating layer, an inner aluminium liner, likely made by 2219 Al as suggested in Ref.[22], should be used considering the good resistance to embrittlement of aluminum, its low density, consolidated manufacturing know-how, and contained costs [219, 220].

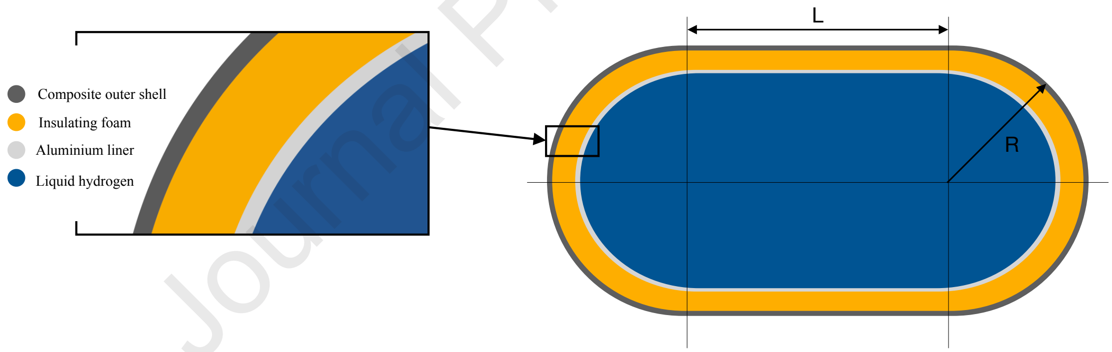

Fig. 8 Conceptual design of a passively insulated cryogenic composite sandwich pressure vessel.

Besides the layered architecture, also the overall geometry and tanks integration strategies play an active role in stress and thermal management of cryogenic pressure vessels. Spherical configurations offer optimal stress distribution and minimize heat exchanges [133]; however, they pose challenges related to their integration into existing aircraft architectures or viable new aircraft designs. Indeed, in addition to meeting the intended storage volumetric requirement, the tanks dimensions are constrained by aircraft design parameters such as the fuselage and cabin diameter and lengths. Therefore, a pragmatic compromise is needed. A feasible alternative to spherical tanks is provided by cylindrical vessels with hemispherical end caps [221], whose geometry can be defined by two parameters only, namely the radius of the hemispherical caps (R) and the length of the cylindrical part (L). The best performance would be obtained using a single, large component integrated into the airplane layout, minimizing the surface-to-volume ratio and thus the boil-off and fuel venting [222]. To account for the reduced cabin capacity and therefore higher direct operating costs, fuselage lengthening should be considered [67], especially since this practise has been extensively used in current commercial aircraft like the

A320 or B737 families [223]. In existing architectures, the rear part of the fuselage is a viable location for large hydrogen pressure vessels placement [224]. However, it is necessary to preserve space for essential components historically found in the tail cone of airplanes, such as the auxiliary power unit (APU) [225] and additional components for hydrogen operations, e.g. an inert system to fill the ullage of pressure vessels as the fuel is consumed [226]. Moreover, the substantial up-sweep angle of the fuselage in this area diminishes significantly the available tank volume. There is also the risk of compromising longitudinal stability if the vessel is placed too far back, necessitating complex redesigns. A suitable configuration for a large passenger aircraft could resemble the one sketched – using `OpenVSP` [227] – in Fig.(9).

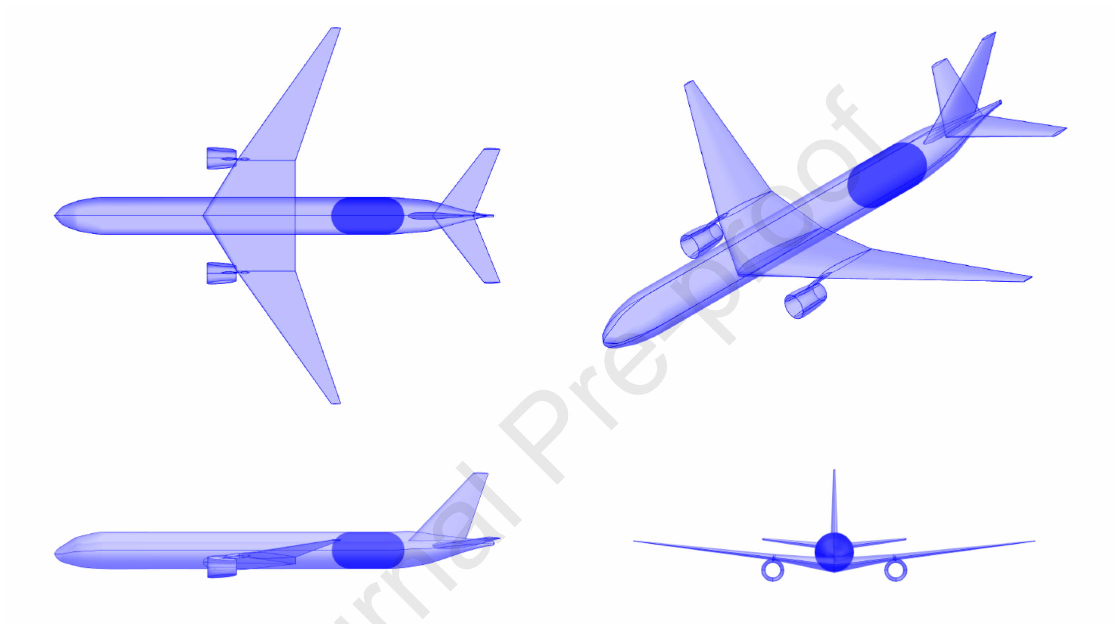

Fig. 9 Cryogenic hydrogen tank implemented in a conventional commercial transport.

As previously mentioned, integral tanks typically offer greater volumetric efficiency compared to non-integral ones. However, ensuring the safety and performance of an integral tank necessitates an implementation process tailored to aircraft designed and manufactured with hydrogen utilization in mind from the conceptual stage. Presently, the industry appears to favor non-integral units [74, 77, 206, 207, 211], prioritizing installation versatility and laying groundwork for future layout implementation.

The performance of a cryogenic pressure vessel can be evaluated considering both the gravimetric efficiency (η_{tank}), computed through Eq.(1), and the boil-off rate (BOR) [228], given by

$$\text{BOR} = \frac{Q}{\rho_{\text{LH}_2} V_{\text{tank}} H_{\text{LH}_2}}, \tag{3}$$

where Q represents the total heat flux from the exterior to the interior of the tank, ρ_{LH_2} is the density of the liquid fuel, V_{tank} is the tank storage volume and H_{LH_2} represents the latent heat of vaporization for liquid hydrogen. For a given storage volume and selected materials, the design variable that has the greatest influence on both η_{tank} and BOR is the thickness of the insulating middle layer, t_{foam}, which directly impacts the thermal resistance [229], the through-the-thickness heat transfer and the overall weight of the tank. As an example, considering a tank with an outer layer of CFRP, an insulating middle layer of polyurethane and an inner layer of aluminum, as schematized in Fig.(8), the thermal resistance is computed as

$$R_{\text{th}} = \sum_i \frac{t_i}{k_i} \qquad i \in \{\text{Al, foam, CFRP}\} \tag{4}$$

where t_i is the thickness of each layer while k_i quantifies the thermal conductivity of the material constituting that layer. Therefore, the heat transfer is given by

$$Q = \frac{\Delta T}{R_{\text{th}}} A_{\text{tot}} \tag{5}$$

where ΔT quantifies the temperature difference between the external ambient and the inner volume of the tank and A_{tot} is the total surface through which heat enters the tank.

A simple analytical model has been developed to assess the performance of cryogenic composite LH_2 sandwich tanks. A cylindrical pressure vessel with hemispherical caps with $R = 2.12$ m, $L = 4.24$ m and an internal volume $V_{\text{tank}} = 100\,\text{m}^3$ is considered. The value V_{tank} has been selected as a reference value: in the context of large transport aircraft, focusing solely on energy requirements, this quantity of LH_2 would be insufficient for satisfying the energy demands of intercontinental routes. In fact, it is approximately 4.7 times less than the energy content provided by kerosene for fully loaded conventional tanks. The analysis is performed keeping R, L, the thickness of the internal aluminum liner t_{Al} and the thickness of the external CFRP layer t_{CFRP} fixed [140, 230, 231], with $t_{\text{Al}} = t_{\text{CFRP}} = 0.01$ m, and varying the thickness of the low-density polyurethane insulating layer, for which $\rho_{\text{foam}} = 64\,\text{kg/m}^3$ (even smaller values of ρ_{foam} are available at the detriment of rigidity [232]). It is worth noting that varying the thickness of the insulating layer induces the variation of size and weight of the external CFRP layer, although its thickness is kept constant. This composite CFRP layer has the quasi-isotropic lamination sequence $[0/45/90/-45]_s$, so to uncouple extension and shear effects [142, 233], with a resulting individual ply thickness of 1.25 mm [56, 234].

Fig.(10) shows the variation of the daily BOR and η_{tank} versus t_{foam}. The gravimetric efficiency is computed considering that $m_{LH_2} = 7085$ kg. It is observed that the BOR decreases more rapidly than η_{tank} as t_{foam} increases. Considering the specific aircraft mission profile, this observation may be exploited to find a convenient trade-off in view of the observations made in Ref.[45], where it was highlighted that $\eta_{\text{tank}} > 55\%$ should be sought to make hydrogen aviation energetically and economically viable.

Similarly, Fig.(11) illustrates the variation of the two performance indices η_{tank} and BOR for different tank capacities. Variations in internal volume that range from 50 to 150 m^3 induce variations in both internal and external tank sizes. To ensure a consistent comparison, for each considered internal volume the ratio between the insulating layer thickness and the internal radius, i.e. t_{foam}/R, and the ratio between the external structural layer thickness and the internal radius, i.e. t_{CFRP}/R, are kept constant. More specifically, for the insulating layer, the thickness $t_{\text{foam}} = 0.5$ m is selected as a reference value when $V_{\text{tank}} = 100\,\text{m}^3$, which corresponds to the intermediate value in Fig.(10), associated with an internal radius $R = 2.12$ m; then, for the other considered internal volumes, the insulating layer is chosen so that

$$\left.\frac{t_{\text{foam}}}{R}\right|_V = \left.\frac{t_{\text{foam}}}{R}\right|_{V_{\text{ref}}}. \tag{6}$$

On the other hand, the thickness of external layer is assumed to vary proportionally to the internal radius, so to maintain constant values of longitudinal and hoop stresses in the structural walls. Under such assumptions, it is observed that as the pressure vessel capacity increases both performance indices improve. Specifically, as the dimensions of the tank increase, its surface area increases

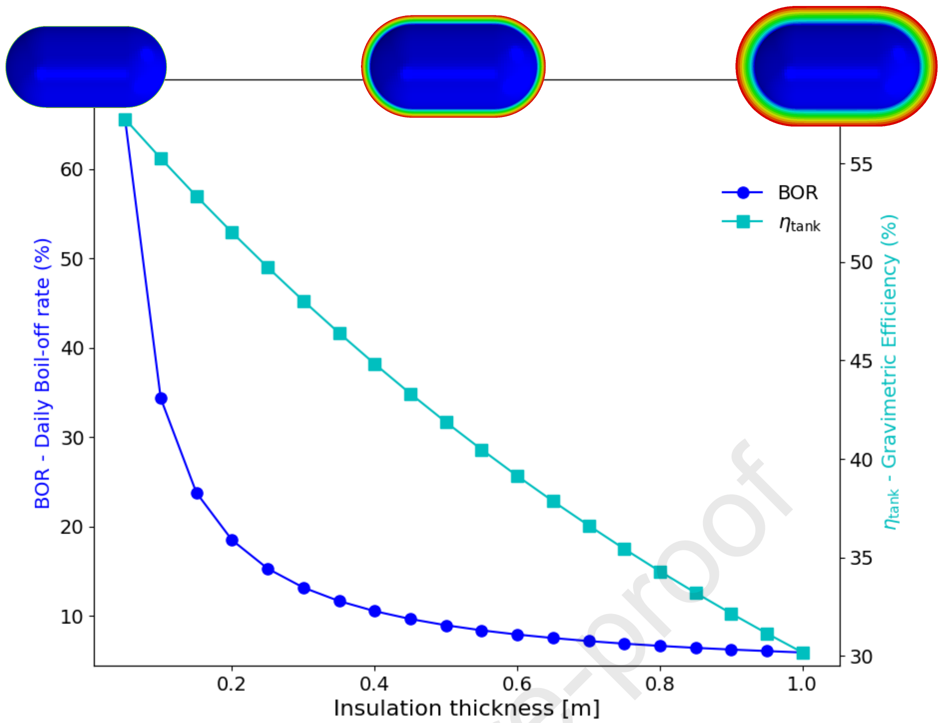

Fig. 10 Daily boil-off (blue) and gravimetric efficiency (green) behaviour varying the thickness of the insulation material. Three reference tank configuration with increasing insulation thickness are reported.

proportionally to the square of the characteristic size, while the volume increases proportionally to its cube, thus leading to lower surface to volume ratios and effectively reducing the total heat ingress per unit fuel weight. Analogously, the gravimetric efficiency improves thanks to the increased volume/surface ratio of larger containers.

In conclusion, passively insulated cryogenic composite sandwich pressure LH_2 tanks offer several advantages for aviation employment: *i*) they are technologically simple, as the number and weight of the subsystems necessary to their operation are lower with respect to other cryogenic pressure vessels configurations [235]; *ii*) They do not necessitate complex vacuum systems nor particularly heavy structures, being subjected to internal pressures lower than 2 bar; *iii*) Being passive components, the risk of subsystems fail is greatly reduced.

However, they still pose challenges, especially in terms maintainability, since the inner layers are generally not accessible from outside. For such a reason, their component service life should be comparable with that of the aircraft they would equip [57], and the possibility to implement structural health monitoring strategies should be considered.

VII. Concluding remarks

Hydrogen-powered aviation could become a viable solution for balancing economic and social growth with environmental constraints. The challenge of H_2 onboard storage, both in gaseous and liquid form, still remains one of the bottlenecks for large-scale integration of such technology in aviation. The reduction of weight of pressure vessels is crucial for enabling competitive designs, which may offer a better option with respect to conventional kerosene-powered aircraft. This goal might be achievable with a combination of expertise and innovative technologies, including new materials for insulation and storage, better understanding of

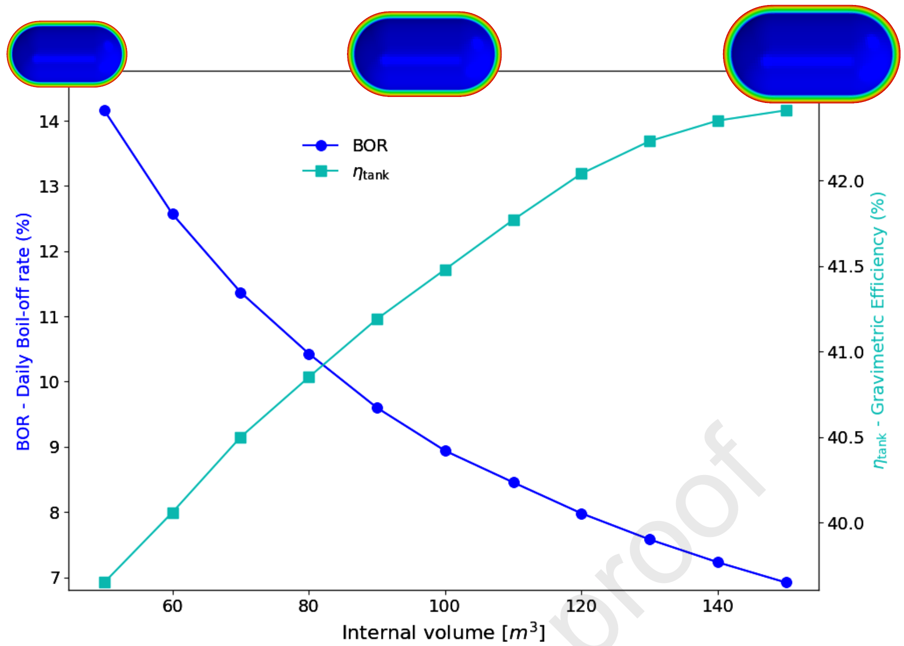

Fig. 11 Daily boil-off (blue) and gravimetric efficiency (green) behaviour for increasing pressure vessel capacities. Three reference tank configuration with increasing internal volume are reported.

hydrogen embrittlement and the use of structural health monitoring coupled with a reduction of safety factors. Several studies suggest that liquid hydrogen storage will be the key technology enabling its use in large scale commercial operations. A better understanding of the behaviour of composite materials under cryogenic conditions, a subject where literature is still lacking, would benefit the manufacturing and reliability of liquid hydrogen storage tanks. The potential of passively insulated cryogenic composite sandwich pressure vessel for near- to mid-term integration into existing tube-and-wing architectures should be considered, to shorten the road to greener aviation; however, a deeper shift in design paradigms and the advent of unconventional configurations may represent a necessity to exploit the full potential of hydrogen. The advancement in hydrogen storage systems is crucial to promote more sustainable and environmentally friendly aviation. A synergistic approach, and significant contributions from research bodies, governments, regulating authorities and manufacturers, is needed to drive hydrogen powered aircraft integration in commercial operations.

Acknowledgments

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Highlights for the manuscript

"*A survey on hydrogen tanks for sustainable aviation*"

- The challenges related to the use of hydrogen in aviation are discussed.
- Hydrogen storage is identified as an enabling technology for hydrogen aviation.
- Current technologies for onboard hydrogen storage are overviewed.
- Relevant recent/ongoing projects about hydrogen-based aviation are overviewed.
- Composite cryogenic vessels are identified as a promising technology in the field.

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Palermo, 8 May 2024

Dear Editors,

Regarding our paper titled "A survey on *hydrogen tanks for sustainable aviation*"

WE DECLARE THAT

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

Sincerely,
Ivano Benedetti

On behalf of the co-authors