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Challenges and Benefits offered by Liquid Hydrogen Fuels in Commercial Aviation

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Abstract

This paper aims to highlight the opportunities and challenges associated with the adoption of hydrogen fuels in aviation. An overview of the environmental and economic benefits and technological challenges is performed, including considerations in aircraft and airport design, operations and safety. A simplified model is subsequently introduced to quantify the benefits associated with the adoption of liquid hydrogen fuel in aviation. The model is used to evaluate the benefits of liquid hydrogen in aircraft of conventional configurations and encompasses the changes in volume, weights and environmental impacts. This paper concludes that hydrogen in cryogenic liquid form demonstrates great potential to become a highly sustainable commercial aviation fuel and to improve the safety of commercial air travel. However, with the implementation of this technology come many difficulties, which seemingly stretch beyond the current aviation capabilities. These include the identification of a sustainable production, storage and delivery systems that shall not dilute the nominal environmental benefits, and public and industry support to ensure financial feasibility.

Keywords: hydrogen, sustainable aviation, cryoplane, environmental gains.

1. Introduction

The highly dynamic context of the air transport sector is driving the aviation industry to attain ever rising economic, environmental and social standards. A major challenge is to establish and develop the future of aviation beyond 2050. This will involve the adoption of innovative air vehicle designs and systematic changes to the manufacture and operation of aircraft, including the type of fuel used, engine performance, weight metrics, air traffic management (ATM) strategies and advances in safety. The average annual growth rate of passenger and cargo traffic over the next two decades is estimated at 4.1%, and this is a major driving factor promoting change in aviation. The rapid increase of the overall market is mainly due to the estimated 3.2% annual increase in worldwide Gross Domestic Product (GDP) over the next 20 years (Current Market Outlook 2014-2033). Furthermore after the year 2042, it is expected that coal will be the only fossil fuel available (Singh & Singh, 2012), highlighting the importance of timely change and progress towards sustainable development. One highly anticipated and promising alternative relies on the use of hydrogen (H₂) as the main fuel source behind commercial aircraft engine propulsion due to its negligible environmental impacts. Combustion processes utilising H₂ only produce water (H₂O) and reduced amounts of nitrogen oxides (NOₓ) as its by-products (Contreras et al., 1997). However great challenges for aircraft and airport design and operation as well as safety considerations are associated with the introduction of hydrogen fuels.

1.1. Historical overview

Hydrogen (H₂) was featured during the 18th century in the voyage of notable gas balloons such as the Charlière Hydrogen Balloon in 1783 (Brewer, 1991). In the 19th century Ferdinand von Zeppelin utilised hydrogen for buoyancy of his rigid frame airships in conjunction with gasoline propulsion systems. The 20th century saw a substantial exploitation of H₂ propellants in space propulsion systems (Kocer, 1994). Russia experimented H₂ fuel for aviation in a customised TU-155 aircraft, running one engine on H₂ (Contreras et al., 1997). Russians subsequently united with Germans in 1991 in a joint program to develop a 200 passenger aircraft with a predicted range of 500 nautical miles (Leonorovitz, 1990; Pohl & Malychev, 1997). Both the Airbus 310 and the TU-204 airframes were evaluated as a reference platform. This cooperation led to a design placing the H₂ tanks on top of the aircraft fuselage and wings. Meanwhile, NASA was also developing its own cryoplane design, which adopted twin spherical tanks. This configuration limited the surface-to-volume ratio and allowed for 400 passengers travelling at Mach 0.85 for 5500 nautical miles (Contreras et al., 1997). The 21st century saw 35 aviation industry partners come together under the guidance of Airbus Deutschland to undertake a project known as ‘Cryoplane’. The project was funded by the European Commission and was aimed at initiating progress towards H₂-fuelled aircraft. Over 25 months of study were undertaken...
(Contreras et al., 1997), fostering political and industrial support for introducing H₂ in aviation. The study assessed the fundamental metrics associated with the introduction of H₂. Safety standards of H₂ were also evaluated and contrasted to that of jet fuels, highlighting need for special attention when handling H₂. However the overall safety standards, which could be achieved with H₂, were well on par with that of conventional jet fuels (Liquid Hydrogen Fuelled Aircraft - System Analysis, 2003).

2. Production of hydrogen

The energy usage and the pollutant emissions associated with the production must all be considered when evaluating a potential source of H₂, whilst the start-up, maintenance and operational costs must be considered as they will inevitably impact the customers and utilisers of H₂ fuel technology (Khandelwal et al., 2013). Many economically and environmentally sustainable H₂ production strategies have been proposed. The most probable and realistic source of H₂ involves fossil fuels, such as gas and coal, and renewable sources, such as water, biomass, wind, solar or hydropower. Various technologies and processes are proposed for H₂ production. These include photolytic, biological, electrolytic, thermo-chemical and chemical processes (Hydrogen production and storage - R&D priorities and gaps, 2006).

3. Aircraft design

Hydrogen fuels propose challenges for designers in terms of mass and volume requirements, as well as for fuel management and storage on-board aircraft. The high volume-to-energy characteristics of Liquid Hydrogen (LH₂) require hydrogen aircraft to carry a larger volume of fuel to that of conventional fuel aircraft. The design of a successful hydrogen aircraft is mainly centred on identifying the optimal tank configuration, in order to carry the required amounts of LH₂. Amongst industry, several design proposals have been identified. Tank configurations can be distinguished as either non-integral or integral. Non-integral tank configurations are external to the fuselage of the aircraft. They are usually mounted either on the airframe, above or under the wing. Non-integral tanks must be able to cope with the aerodynamic and inertial loads, in addition to the fuel containment loads (Khandelwal et al., 2013).

![Figure 1 – Proposed integral tank configurations for a regional aircraft (a) and for a long-range wide-body aircraft (b), including the proposed catwalk (c) (Liquid Hydrogen Fuelled Aircraft - System Analysis, 2003; Verstraete et al., 2010).](image)

Integral tanks, as depicted in Fig. 1, are located inside the fuselage, hence their shape and dimensions are interdependent with the fuselage design. Integral tanks are not required to withstand aerodynamic loads, and on the other hand may enhance the structural integrity of the fuselage by increasing the resistance to bending and shear forces. Integral tanks represent a more realistic and feasible aircraft design for wide body or long haul aircraft (Khandelwal et al., 2013). The Cryoplane project leaned towards an integral design for LH₂-fuelled aircraft, mainly due to cryogenic temperatures required for LH₂ containment (Verstraete, 2013) and the need to provide the required tank capacity for long-haul flights (Khandelwal et al., 2013). The length and width of the fuselage will both increase to accommodate the integral LH₂ tanks (Verstraete, 2013). The elimination of wing tanks detracts the associated shear stress and bending moment alleviation. In order to compensate, an approximate increase of 37% in the wing structure is required, leading to an overall weight increase of 6% (Verstraete, 2013) to support and affix the integral LH₂ tanks, but this will enhance
safety as the tanks are further protected by the supportive and rigid structure of the fuselage (Brewer, 1991). The increased drag and the boil-off issues also come into consideration as they impact range and operating costs. For this reason a significant part of the Cryoplane project involved evaluating the various possible tank configurations. Tanks over the fuselage and across the wing were also considered. Though these configurations improved the overall volume exploitation and attainable tank capacities, the LH$_2$ containment loads significantly impacted the structural weights. Thus a spherical or cylindrical design was preferred (Allideris & Janin, 2002). The spherical tank design minimises surface-to-volume ratio and hence the passive heat transfer across the tank wall, minimizing the boil off rate. For these reasons, spherical or quasi-spherical tanks have been frequently adopted in space launchers and vehicle. However, it involves a larger frontal area for the same volume in comparison to a cylindrical tank design (Mital et al., 2006). A cylindrical tank also provides greater volumetric efficiencies through maximising space usage within the fuselage (Brewer, 1991). However, fuel pressure loads are extremely inhomogeneous in a purely cylindrical tank. The ideal compromise is therefore a cylindrical tank with its bases shaped into a semi-spherical design, as such design adopts the best characteristics of both cylindrical and spherical shapes (Khandelwal et al., 2013). For a LH$_2$ regional airliner, several designs are possible. One layout incorporates a single tank at the rear of the fuselage, which offers the greatest benefits in terms of weight metrics. However, this design might frequently lead to weight and balance issues, which may in turn require increases to the tail planes weight and dimensions. In the second considered layout, LH$_2$ tanks may be positioned in both the aft and front of the fuselage. However this poses problems in terms of crew access to and from the cockpit, which may be rectified through implementation of a passageway within this design. Lastly, the LH$_2$ tanks may be configured along the top of the fuselage above passengers in conjunction with a tank in the aft of the fuselage, impacting upon luggage storage (Verstraete et al., 2010). Currently, aviation is undergoing a shift towards larger long-range aircraft in order to relieve congestion and improve efficiencies (Current Market Outlook 2014-2033). Long-range aircraft typically have a wide-body design, utilising multiple aisles in the passenger cabin. Possible designs for future long-range hydrogen aircraft may therefore further exploit the fuselage cross section increase, including a tri-story aircraft with LH$_2$ tanks located in the aft and front of the fuselage. For this design, the fuel tank at the front of the aircraft with contains approximately 40% of the total fuel in order to satisfy weight and balance requirements (Brewer, 1991; Verstraete et al., 2010). Furthermore, in comparison to a modern equivalent in a conventional fuel aircraft such as the Airbus 380 and Boeing 747, the size metrics vary considerably. For instance in the case of fuselage diameter, a tri-story LH$_2$ aircraft is likely to be up to 8.5 m wide in comparison to the smaller 7.14 m and 6.1 m airframe width as seen on the A380 and B747-8 respectively (Verstraete et al., 2010).

### 3.1. Tank structure and materials

A major aspect for the attainment of safety standard by LH$_2$ tank designs is the insulation, which upholds the safety standards of kerosene based conventional aircraft. Major development in new materials is aimed at alleviating the boil-off of hydrogen. This occurs when cryogenic conditions are compromised due to the inward heat transfer (Khandelwal et al., 2013). An effective insulation in LH$_2$ tanks will reduce the boil-off rate of LH$_2$ increasing operational efficiencies and improving safety. Three types of insulation have been highlighted (Khandelwal et al., 2013) which include:

- **Multilayer insulation (MLI):** this layout consists of up to 100 layers of insulating material such as polyester of glass fiber alternated with metal layers for fuel containment and radiative shielding, arranged perpendicularly to the heat transfer direction. The outside of the inner layer consists of a reflective foil to minimize radiative transfer. The effectiveness of this type of insulation is dependant on factors including the composition and pressure of the fuel gas phase. MLI does not operate effectively when experiencing pressures of more than 0.001 mbar (Allideris & Janin, 2002). It is also quite susceptible to manufacturing faults during production and is a heavy form of insulation (Khandelwal et al., 2013).

- **Vacuum Insulation:** this layout involves a pumping system to maintain the vacuum within the tank walls. Such a system must ensure that air does not interact with the vacuum walls as its freezing would cause a seizure of the tanks vital systems (Colozza, 2002). The vacuum insulation is also vulnerable to the external ambient pressure, as the walls may not withstand pressure spikes and fail. Therefore further strength must be introduced through stiffeners, which increase the mass of the tank (Millis et al., 2009). The vacuum insulation offers a promising alternative to the multilayer design, having the highest potential in terms of minimising lost mass during boil off. However it involves heavier structures and costs (Wilkins, 2002).
- **Foam Insulation**: this layout involves insulating foam introduced between the inner and the outer tank walls. The outer wall can consist of a thin metal sheet, which protects the foam and assists the structure in maintaining structural integrity. The insulating foam contains good characteristics in terms of low thermal conductivity whilst maintaining a low density (Cumaloglu, 2005). The feasibility of foam insulation is dependent on certain factors. This insulation provides acceptable boil off rates, tank weight and size characteristics. Foam insulation also represents a much cheaper option to that of multi-layer or vacuum insulation. In comparison to a vacuum system, the rate of failure of a foam system is also much smaller (Khandelwal et al., 2013).

### 3.2. Blended Wing Body

Given the predicted timeframes for the widespread adoption of LH₂ fuels and innovative propulsion systems in aviation, NASA and other governmental, academic and industrial R&D entities have also extended the study to encompass more innovative and futuristic aircraft configurations. A particularly attractive configuration is the Blended Wing Body (BWB), offering higher aerodynamic and payload efficiencies, greater airframe volumes, higher propulsive configuration flexibility and reduced noise footprints. BWB will notably enhance the technological feasibility of hydrogen propulsion systems, thanks to improved volumetric efficiencies and operational capabilities in terms of passenger and freight movements, offering considerable environmental benefits in comparison to conventional aircraft (Guynn et al., 2004); NASA’s model for a clean commercial aircraft of the future is based upon the ‘Quiet Green Transport’ concept. Therefore, their project for an environmentally friendly blended wing bodied aircraft involves a carbon-free fuel system that eliminates hydrocarbon and carbon/sulphur oxides (COₓ/SOₓ) emissions. This is achieved through the electrochemical release of hydrogen instead of gas turbine combustion. The hydrogen used is contained in insulated integral tanks located inside the airframe. Concerning NOₓ emissions, they are notably associated with high temperatures and pressures experienced in combustion chambers of conventional engines. With hydrogen fuel cells, they are entirely eliminated, in addition to a significant portion of noise emissions. Electric motors are powered by fuel cells, which turn a ducted fan generating thrust. The fuel-cell based electric propulsion typically involves a relatively higher number of smaller engines to generate the desired amount of thrust, leading to higher frequency noise with smaller amplitudes (Guynn et al., 2004). The BWB airframe features top mounted ducted fans, improving noise shielding as well as aerodynamic efficiency. The airframe also shows advancements in terms of noise mitigation through the management of gaps and edges amongst the airframes flaps. This is achieved through the continuous mold-line technology, which is incorporated into the flap system (Guynn et al., 2004). Research into the BWB design by NASA also incorporated considerations for operational improvements. An important contribution for the reduction of noise footprint is by increasing the final approach slope angle by 9° (from 3° to 12°). This increases the altitude at which arrival traffic overflies the ground on approach. In order to reduce degradation to the natural environment through contrail formation, NASA has further suggested a reduction in cruise altitude for its BWB aircraft. Conventional cruise altitudes in the upper troposphere provide ideal conditions for contrail formation from the H₂O exhausts (Guynn et al., 2004).

### 3.3. Systems impacts

In order to accommodate LH₂ the present propulsion technologies will need to be partially redesigned. This will particularly affect sub-systems including the fuel lines and combustion chamber. LH₂-fuelled Auxiliary Power Unit (APU) will also be proposed. This would eliminate CO₂ emissions on the ground when external power sources cannot be gained. Air Traffic Management (ATM) and operational procedures will also have to evolve to allow the attainment of fuel, time, environmental and monetary benefits. This will imply a redesign of procedures, en-route and terminal airspace (IPCC - Aviation and the Global Atmosphere). During the aircraft start up, ambient air contamination within the fuel lines poses the risk of flash back, which may be prevented through flushing with an inert gas such as nitrogen. The flushing the lines should also occur upon shut down for analogous reasons (Dahl & Suttrop, 1998; Khandelwal et al., 2013). A pre-heating of LH₂ prior to entering the combustion chamber is desirable, and can be performed in a heat exchanger that could capture the heat from warm parts of the engine (i.e. turbine, exhaust and combustion chamber), improving the thermal efficiencies and longevity of the engine. An electrical heater may be used to heat the fuel when the engines are still cold. Furthermore, a tailored metering system will also be required to provide LH₂ to the engine in line with the throttle set by the flight crew (Dahl & Suttrop, 1998; Khandelwal et al., 2013). Combustion of hydrogen in aircraft engines raises complications beyond that of simple fuel to air mixing (Juste, 2006). The use of LH₂ in commercial aircraft requires redesigning the conventional
combustors in order to attain optimal efficiency (Dahl & Suttrop, 1998). Use of hydrogen in the conventional kerosene combustors would lead to excessive NO\textsubscript{X} emissions due to unnecessary increases in temperature during the combustion process (Dahl & Suttrop). Studies to reduce such effects on board LH\textsubscript{2} aircraft have been undertaken, with emphasis on improving combustion efficiency, noise and flame stability. Current efforts of industry have highlighted potential combustors as being the Lean Direct Injection (LDI) and Micro-Mix concepts. These two concepts are similar in methodology and both have been proven as viable. Both aim to reduce the presence of large flames in order to minimise NO\textsubscript{X} emissions, whilst reducing flashback. This is achieved through altering and increasing the mix intensity since NO\textsubscript{X} is dependent on residence time and temperature (Khandelwal et al., 2013).

- **Lean Direct Injection (LDI):**

Marek et al. (2005) conducted several experiments aimed at evaluating NO\textsubscript{X} emissions and combustion performance. The LDI system used featured quick mixing and multiple injection points. In order to combat flashback, velocities were high and induced mixing times were reduced. Results from these experiments demonstrated the capabilities of hydrogen to attain the same NO\textsubscript{X} levels of modern advanced kerosene LDI combustors (Marek et al., 2005).

- **Micro-mix combustion:**

If managed correctly, the micro mix or miniaturised diffusive combustion process of hydrogen can produce less NO\textsubscript{X} emission than that of conventional kerosene combustion (Heywood & Mikus, 1973). In this layout the number of local mixing zones between the fuel and air is increased in comparison to conventional kerosene burner designs, improving the mixing intensity whilst reducing its scale. Therefore the micro-mix combustion process involves thousands of miniature diffusion flames reducing the likelihood of flashback (Dahl & Suttrop, 1998). Dahl and Suttrop (1998) examined the effects of micro mix combustion on a modified KHD T215 gas turbine engine on an Airbus 320. Their study highlighted the ability of hydrogen to be metered safely whilst maintaining engine control during conditions similarly to that of kerosene fueled aircraft engine. Their configuration also demonstrated hydrogen’s ability under a micro mix system to produce less nitrogen oxides than kerosene combustion, all whilst adhering to a diffusive burning process that demonstrates a reduced risk of flashback and engine failure. Safe start up and engine ignition procedures were also demonstrated, with reduced risk of excess and dangerous pressure and heat transfer. Furthermore the technology evaluated also proposes potential in terms of its adoption in APU (Dahl & Suttrop, 1998).

4. **Hydrogen aircraft operations**

LH\textsubscript{2}-fuelled aircraft poses exciting prospects for the aviation industry by not only eliminating CO\textsubscript{2} emissions from operations but also by the potential improvements on the operational costs for airlines (Contreras et al., 1997). However in order to accurately evaluate the potential and effects of LH\textsubscript{2} aircraft, an in-depth analysis of all factors is required, going beyond the scope of current knowledge. This includes but is not limited to the traditional aircraft performance metrics such as payload and range capabilities. All direct and indirect operating costs associated with such aircraft have to be considered, including logistics and maintenance implications. The past five years have demonstrated a rising trend in aviation fuel prices (Current Market Outlook 2014-2033). Recent spikes in the jet fuel prices have made it become the greatest direct operating cost for most aircraft operators. Trends have witnessed the fluctuation of fuel prices for airlines entail over 30% of operating expenses (Fact sheet: fuel, 2014). In order to deal with such trends, aircraft operators and particularly the airlines are left with limited options. The most sustainable solution to combat fuel expenses is alleviation from fossil based conventional fuels. Historic knowledge shows that unless action is mediated in terms of subsidising, an alternative fuel will one day reach the same price point as the fuel it is directly competing with (Price, 1991). The adoption of a fuel such as LH\textsubscript{2} in aviation may hold the key to reducing fuel related operating costs. For instance, a kerosene price of $5 USD per gallon will allow LH\textsubscript{2} to be $0.7 USD more expensive to produce the same direct operating costs as conventional jet fuel allowing for a 50% increase in acquisition and maintenance costs in the early introduction stages (Verstraete, 2013). Benefits of the adoption of LH\textsubscript{2} based fuels are also associated to its excellent Energy Specific Fuel Consumption (ESFC) in comparison to conventional aircraft fuels. The high ESFC of LH\textsubscript{2} may allow for lighter engines which may lead to a 3% indirect savings in energy consumption. Similar results have been highlighted by Verstraete (2013) and in several other papers, providing support for the energy efficiencies of LH\textsubscript{2} engines. The adoption of LH\textsubscript{2} fuel may lead to up
to a 30% reduction in gross weight brought on by the lower mass of LH₂ in comparison to kerosene. Though the operating empty weight (OEW) of both aircraft would be similar, a long-range LH₂ fuelled aircraft would likely be about 7m longer. Coupled with a double deck fuselage and smaller wing size, a comparable LH₂ aircraft will see a reduction of approximately 15% in its cruise average lift to drag ratio. However this increase in drag will be counteracted by an 11% improvement in terms of energy usage (Verstraete, 2013), slightly reducing direct operating costs. Savings in direct operating costs are also expected to be diluted in the early stages due to the predicted increases in aircraft purchase price, maintenance and servicing in comparison to conventional aircraft (Verstraete, 2013). Airfreight has a rising importance for the profitability of airline routes. In order to benefit from it, there must be a dedicated cargo capacity in addition to passenger luggage requirements. In a comparison between conventional kerosene fuelled aircraft and a LH₂ aircraft of conventional configuration, it becomes apparent that conventional aircraft have more volumetric capacity for payload. This potentially economic disadvantage may be outweighed by a LH₂ aircrafts extended range capabilities. The weight and energy advantages of LH₂ allow these aircraft to fly at greater distances to that of conventional kerosene aircraft, as represented in Fig. 2 (Verstraete, 2013).

![Figure 2 - Payload vs. range curve of LH₂ and kerosene-fuelled aircraft (Verstraete, 2013).](image)

5. Airport design and operations

It is evident that airports will need to evolve to host regular hydrogen powered aircraft operations, ensuring the required maintenance and support for hydrogen aircraft. The integration of LH₂ fuel systems will require airports to adopt new technologies and systems. This may involve an integrated logistics and supply chain, which can meet the LH₂ demands of aircraft operators, an onsite hydrogen production facility, or the adoption of infrastructure which secures and safely houses the airports reserve of LH₂. For LH₂ fuel systems to be introduced, there needs to be a reasonable demand by the aircraft operators. Multiple airports will need to be equipped to supply LH₂ in order for the fuel to be commercially viable. During the implementation stage of hydrogen fuel systems at airports, airports shall seamlessly accommodate hydrogen fuel infrastructure in conjunction with conventional kerosene fuel delivery systems. For these reasons it is expected that the larger airports will be the first to adopt such infrastructure, as the first LH₂ aircraft are likely long-range transport category type aircraft (Janic, 2010). Modern international route structures are mainly based on the hub and spoke model, where feeder flights are flown into a central location or hub, where passengers can benefit from a significant number of flight connections. This network structure is particularly well suited for long range LH₂ aircraft viability, allowing hubs to be major supply and maintenance centres for LH₂ aircraft. Such practices may alleviate demand for all airports to contain LH₂ refuelling and maintenance capabilities, instead concentrating the efforts on a steady and reliable supply where the fuel is mostly needed. Future network planning will need to consider the regions that are supported by strong hydrogen production capacities. The regions producing the most LH₂ currently include North America, Japan and Europe. Within these regions, the largest airports are likely to be the first integrators of LH₂ technologies. Based on departure movements and location in correspondence to liquefiers, certain cities stand out as plausible LH₂ adopters. This includes Chicago, Los Angeles and Ontario in the United States, Tokyo and Osaka in Japan, and Amsterdam in Europe (Stiller & Schmidt, 2010). The
optimal fuel delivery systems for LH$_2$ aircraft of the future would likely involve onsite production. Careful consideration should be taken when locating the storage tanks (Janic, 2010; Schmidtchen et al., 1997). The piping will need adequate insulation in order to the liquid hydrogen at -253$^\circ$C and may consist of three pipes, satisfying the requirements to transfer the LH$_2$, collect the boiled off H$_2$, and a allow for redundancy (Janic, 2010; Korycinski, 1978). Airports themselves also contribute approximately 30 million tons or 5% of the total air pollution of the aviation industry (Cherry, 2008). Contributing factors include aircraft, passengers, freight and airside/landside vehicle movements (Janic, 2010). The widespread adoption of hydrogen fuels also for ground vehicles will provide great environmental benefits to airport, not only restricted to the complete elimination of carbon emissions. Currently, fuel delivery systems for kerosene aircraft are usually large and in some instances can be quite complex, and typically involve a tank area or fuel farm within reasonable distance from the apron. These tanks usually provide a fuel supply for 1-3 days and their fuel is supplied to the airport via trucks or a system of underground pipes. Typically larger airport utilise underground piping to ease congestion, however smaller or regional airports may utilise fuel tankers for simplicity (Janic, 2010; Korycinski, 1978). It is important to note a fuel distribution based on fossil fuelled trucks emits emissions throughout the whole process. Proposition as to the installation of distribution lines should include entrenched yet open plans, which allows for the vent of potentially dangerous hydrogen gases (Schmidtchen et al., 1997). Further improvements or reductions in airport related aircraft emissions may come about through the adoption of LH$_2$ powered APU, which could also contribute to aircraft weight reduction through eliminating the need for generators within the engine assembly (Stiller & Schmidt, 2010)

6. Safety

Aircraft fuelled by hydrogen have a reputation for being a dangerous endeavor. This was largely brought on by the Hindenburg disaster. The flammable cloth of the containment bag back then is vastly different from the highly insulated and structurally sound ergonomic tanks proposed for modern LH$_2$ applications (Brewer, 1983). Most recent in-depth studies highlight hydrogen as a safer alternative to conventional kerosene fuels (Khandelwal et al., 2013). In the event of an aircraft crash, liquid hydrogen is more likely to result in a safer outcome than that of a kerosene fuelled aircraft crash, due to the rigidity of LH$_2$ tanks, less likely to rupture, to the buoyancy of the gas, dissipating quickly, and to the smaller heat and intensity of a hydrogen-fuelled fire (Brewer, 1983). Unlike kerosene, hydrogen cannot contaminate the natural environment such as water or soil. Hydrogen in its liquid form is much safer than its gaseous state due to the lower pressures in storage tanks, which reduce the likelihood of fatigue induced structural failures (Schmidtchen et al., 1997). However hydrogen's ability as a gas to seep through containment lines or tanks unlike air or other gases causes challenges in identifying leaks. Hydrogen can even engrain its self in solid materials such as polymers through permeation, demanding careful consideration when selecting hydrogen containment materials (Schmidtchen et al., 1997; Schmidtchen et al., 1994). Like almost all fuels, hydrogen represents a flammability hazard. In its gaseous state, hydrogen has more potential to mix with air or kerosene fumes and form a dangerous detonating mixture. However the heat from a hydrogen flame represents about a tenth of that of a hydrocarbon fuelled flame. This not only reduces the extent of possible damage caused during a major accident, but it also allows authorities to get closer to the heat source. In the event of a leak, hydrogen in reasonable quantity may asphyxiate the air, starving organisms of oxygen. Though hydrogen is still not corrosive or poisonous, its cryogenic temperatures would injure a person upon touch (Schmidtchen et al., 1997). A liquefier incorporated into an airport requires careful design considerations. Components such as pumps, connections and accessories for LH$_2$ require accurate engineering due to the cryogenic conditions they experience (Brewer, 1976; Jones et al., 1983). Personnel in contact with such systems require specialist training, as contact with any cryogenically cooled metals will likely result in injury. Airports must implement technologies, procedures and policies for a safe and economical handling LH$_2$. Consideration should encompass the impact of disasters or emergencies. Current design requirement prescribe that accidents remain at the lowest possible level and internal to the confines of the affected structure. Considerations should nonetheless extend beyond that of internal emergencies. Such events may cause fire or flying debris to reach areas of LH$_2$ production and/or containment. Mitigation of this should be in the form of suitable location of ground LH$_2$ resources, by enforcing certain distances of safety or protection. Likewise on aircraft, tank shape is an important aspect in terms of upholding the interests of safety. Though there is not much difference in terms of operation of either a cylindrical or spherical tank, there is a greater associated risk in manufacturing faults of spherical tanks due to its complexity. Cylindrical tanks also offer more efficient use of capital resources through vertical installation.
Likewise with any LH\textsubscript{2} structure, the fuel tanks require protection from external elements. This may come about in the form of partial submersion underground, with the top elements of the tank being exposed to the qualified operators, however still protected via fortification. Further recognition should also be devoted to security measures, implementing strict scrutiny and restriction in the access to LH\textsubscript{2} reserves (Schmidtchen et al., 1997).

7. Environmental gains modeling

In line with all the factors described previously, we introduce a quantitative analysis of the potential environmental and economic benefits associated with the adoption of liquid hydrogen (LH\textsubscript{2}) fuels for aviation. As a practical reference, we assume conventional aircraft currently adopted in both regional, medium-range and long-range commercial airline flights, evaluating their hypothetical retrofit for conversion to LH\textsubscript{2} fuel. For this analysis, we start from the Breguet range equation in its traditional form:

$$R = \left( \eta \frac{L}{D} \right) \frac{h_c}{g} \ln \frac{m_i}{m_f}$$

where:
- $R$ is the range;
- $\eta$ is the overall propulsive efficiency;
- $\frac{L}{D}$ is the nominal lift-to-drag ratio;
- $h_c$ is the lower combustion heat;
- $m_i$ is the initial mass;
- $m_f$ is the final mass;
- $g$ is the gravity;

We also define $K = \left( \eta \frac{L}{D} \right)$. The comparison is based on the following assumptions:

- Aircraft are listed by their International Civil Aviation Organization (ICAO) code, which are:
  - E190: Embraer E-190;
  - A320: Airbus A320-200;
  - B738: Boeing 737-800;
  - A333: Airbus A330-300;
  - B788: Boeing 787-800;
  - B77W: Boeing 777-300ER;
  - A388: Airbus A380-800;
- The assumed characteristics for each aircraft are meant to represent an average of the advertised or published ones;
- Aircraft are configured for maximum range, therefore loaded with maximum fuel and a partial payload;
- $K_{\text{Jet-A1}}$ is deduced from the advertised aircraft performance by means of the rearranged Breguet range equation;
- $K_{\text{LH}_2}$ is calculated as 85% of $K_{\text{Jet-A1}}$, to represent the increased drag associated with the additional LH\textsubscript{2} tank volumes, in line with the findings documented in section 3;
- The Operational Empty Weight (OEW) of the hydrogen aircraft is increased by 6% to represent the additional structural mass required for the LH\textsubscript{2} tank, in line with the findings documented in section 3;
- The chemical composition of Jet-A1 is approximated as 99.7% in mass of $C_{11}H_{22}$, with a sulfur content of 0.15% in mass, corresponding to half of the maximum regulatory threshold (0.3% in mass);
- The chemical composition of Jet-A1 emissions is calculated by assuming that 1% of the carbon content is processed into CO and 0.5% originates unburned HydroCarbons (HC);
- In order to economically represent their noxious effect, emissions charges are hypothetically set to: 20 $/t$ for CO\textsubscript{2}; 200 $/t$ for CO and SO\textsubscript{2}; 2000 $/t$ for HC; 10 $/t$ for H\textsubscript{2}O. The carbon dioxide charge is very closely related to the average value from a number of nations presently adopting
carbon taxation schemes. The remaining figures are meant to represent an educated guess correlated to the noxious potential of the various substances to the environment and the living beings.

Table 1 summarized the assumed aircraft characteristics, the estimated Jet-A1 gaseous emissions and the corresponding hypothetical charges. Table 2 presents the results of the analysis based on the assumptions in terms of changes of weight, volume, and economic savings.

### Table 1. Assumed aircraft characteristics and calculated emissions for Jet-A1 fuel.

<table>
<thead>
<tr>
<th>Aircraft Model</th>
<th>E190</th>
<th>A320</th>
<th>B738</th>
<th>A333</th>
<th>B788</th>
<th>B77W</th>
<th>A388</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range [nmi]</td>
<td>2400</td>
<td>2950</td>
<td>3060</td>
<td>5550</td>
<td>7850</td>
<td>7930</td>
<td>8500</td>
</tr>
<tr>
<td>Total length [m]</td>
<td>36.2</td>
<td>37.5</td>
<td>39.5</td>
<td>63.7</td>
<td>56.7</td>
<td>73.9</td>
<td>72.7</td>
</tr>
<tr>
<td>Hydraulic diameter of fuselage [m]</td>
<td>3.15</td>
<td>4.04</td>
<td>3.76</td>
<td>5.64</td>
<td>5.87</td>
<td>6.2</td>
<td>7.75</td>
</tr>
<tr>
<td>Approximate $K_{jet-A1}$</td>
<td>3.6</td>
<td>4.4</td>
<td>4.3</td>
<td>5.7</td>
<td>6.9</td>
<td>6.2</td>
<td>6.0</td>
</tr>
<tr>
<td>OEW [t]</td>
<td>28.1</td>
<td>42.6</td>
<td>41.4</td>
<td>124.5</td>
<td>118.0</td>
<td>167.8</td>
<td>276.8</td>
</tr>
<tr>
<td>Payload [t]</td>
<td>11</td>
<td>16.2</td>
<td>17</td>
<td>30</td>
<td>23</td>
<td>37</td>
<td>40</td>
</tr>
<tr>
<td>MTOW [t]</td>
<td>51.8</td>
<td>78</td>
<td>79</td>
<td>233</td>
<td>228</td>
<td>351.5</td>
<td>575</td>
</tr>
<tr>
<td>Generated CO₂ [t]</td>
<td>39.4</td>
<td>59.5</td>
<td>63.9</td>
<td>243.4</td>
<td>269.7</td>
<td>454.8</td>
<td>800.4</td>
</tr>
<tr>
<td>Generated CO [t]</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.8</td>
<td>0.9</td>
<td>1.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Generated SOₓ [t]</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Generated HC [t]</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Generated H₂O [t]</td>
<td>16.3</td>
<td>24.6</td>
<td>26.4</td>
<td>100.5</td>
<td>111.4</td>
<td>187.8</td>
<td>330.5</td>
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<tr>
<td>Total charge [USD]</td>
<td>$1,110</td>
<td>$1,678</td>
<td>$1,800</td>
<td>$6,861</td>
<td>$7,604</td>
<td>$12,822</td>
<td>$22,567</td>
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</table>

### Table 2. Results of the analysis.

<table>
<thead>
<tr>
<th>Aircraft Model</th>
<th>E190</th>
<th>A320</th>
<th>B738</th>
<th>A333</th>
<th>B788</th>
<th>B77W</th>
<th>A388</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed $K_{LiH₂}$</td>
<td>3.1</td>
<td>3.7</td>
<td>3.6</td>
<td>4.8</td>
<td>5.8</td>
<td>5.3</td>
<td>5.1</td>
</tr>
<tr>
<td>TOW of corresponding hypothetical LH₂-powered aircraft [t]</td>
<td>45.9</td>
<td>69.1</td>
<td>69.2</td>
<td>192.7</td>
<td>181.5</td>
<td>270.0</td>
<td>429.0</td>
</tr>
<tr>
<td>Total LH₂ mass [t]</td>
<td>6.8</td>
<td>10.3</td>
<td>10.8</td>
<td>38.2</td>
<td>40.5</td>
<td>65.2</td>
<td>112.2</td>
</tr>
<tr>
<td>Total LH₂ volume [m³]</td>
<td>96.3</td>
<td>145.7</td>
<td>151.9</td>
<td>538.2</td>
<td>569.9</td>
<td>918.8</td>
<td>1580.8</td>
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<tr>
<td>Equivalent fuselage length [m]</td>
<td>12.4</td>
<td>11.4</td>
<td>13.7</td>
<td>21.5</td>
<td>21.1</td>
<td>30.4</td>
<td>33.5</td>
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<tr>
<td>Fraction of the total length</td>
<td>34.1%</td>
<td>30.3%</td>
<td>34.6%</td>
<td>33.8%</td>
<td>37.1%</td>
<td>41.2%</td>
<td>46.1%</td>
</tr>
<tr>
<td>Weight savings</td>
<td>11%</td>
<td>11%</td>
<td>12%</td>
<td>17%</td>
<td>20%</td>
<td>23%</td>
<td>25%</td>
</tr>
<tr>
<td>Generated H₂O [t]</td>
<td>61.0</td>
<td>92.3</td>
<td>96.2</td>
<td>340.9</td>
<td>360.9</td>
<td>581.9</td>
<td>1001.1</td>
</tr>
<tr>
<td>Total environmental charge [USD]</td>
<td>$610</td>
<td>$923</td>
<td>$962</td>
<td>$3,409</td>
<td>$3,609</td>
<td>$5,819</td>
<td>$10,011</td>
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<tr>
<td>Total savings per flight [USD]</td>
<td>$500</td>
<td>$755</td>
<td>$838</td>
<td>$3,452</td>
<td>$3,995</td>
<td>$7,003</td>
<td>$12,556</td>
</tr>
</tbody>
</table>

### 8. Conclusions

This paper overviewed the main benefits and challenges associated with the introduction of hydrogen fuels in aviation. The paper introduced a simplified model for the estimation of the environmental gains in realistic operational conditions. The results highlight the remarkable economic and environmental benefits associated with hydrogen fuels, even considering the lower aerodynamic efficiency and higher structural mass. The worsened volumetric efficiency and the challenges associated with the production and supply are nonetheless substantial and will require significant technological and political support. Future research will extend and integrate the models in the novel avionics and air traffic management systems being developed (Gardi et al., 2013; Gardi, Sabatini, Ramasamy, et al., 2014; Ramasamy et al., 2014; Ramasamy et al., 2013), to estimate the
environmental gains associated with enhanced flight trajectories and operations. Future research activities will also consider the actual pollutant concentrations around airports obtained with the researched systems (Gardi, Sabatini & Ramasamy, 2014; Gardi, Sabatini & Wild, 2014; Sabatini & Richardson, 2008, 2010, 2013; Sabatini et al., 2012). Particular consideration will be given to identifying the combined benefits and the additional challenges associated with the adoption of hydrogen fuels in advanced aircraft configurations (Marino & Sabatini, 2014) and in more electric aircraft configurations (Seresinhe et al., 2013).

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