



JON HUETE

TECHNO-ECONOMIC, ENVIRONMENTAL AND RISK ANALYSIS
OF A HYDROGEN AIRLINER FAMILY MARKET ENTRY

SCHOOL OF AEROSPACE, TRANSPORT and MANUFACTURING

PhD

Academic Year: 2020 - 2022

Supervisor: Prof Pericles Pilidis

Associate Supervisor: Dr Richard Adams

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ABSTRACT

Civil aviation is in a profound transition motivated by the need to reduce its environmental impact. Most civil aviation institutions and stakeholders are now committed to reach net zero by 2050, though there is no feasible path drafted to achieve this goal. Projected energy efficiency improvements, and the use of sustainable aviation fuels could provide a significant reduction in CO₂ emissions, but to reach net zero all emissions should be eliminated or compensated, and none of these solutions achieve the target.

Hydrogen as fuel has zero emissions of CO₂ and can address aviation non-CO₂ emissions in an effective manner, to become a true zero emission alternative. Optimising a hydrogen aircraft to match the capabilities and flexibility of the existing narrowbody or the widebody point to point ultra-long-range capacity will take decades. An speculative alternative to expedite the introduction of hydrogen aircraft using existing technology is the focus of this research. A second and third generation of hydrogen aircraft could bring additional benefits in terms of capability and fuel consumption. But the first generation is focused on a swift change. An evaluation of the capabilities achievable with today's technology and tube and wing configuration is performed.

A redesigned double deck aircraft using the A380 as a baseline, with modified wings and engines, and with a variety of tank configurations is investigated as an initial airliner family. It can provide passenger capacities of 388 to 232 with a range of 3,300 nm to 5,600 nm, respectively. Such airliner family could start decarbonising the long-range sector in 15 years. It offers potential to go one-stop to anywhere in the world. A high-capacity version can travel 1,800 nm with 720 passenger is also studied as a solution for high demand city pair traffic. These findings were presented in ISABE 2022 and ICAS 2022 and published in the ISABE special issue of the Aeronautical Journal. The paper 'Propulsion System Integration for a First-Generation Hydrogen Airliner' was awarded a Bronze Prize by the RAeS in 2022 and was the 5th most downloaded paper in 2022 in the Aeronautical Journal with 1599 downloads.

Cryogenic storage is one of the most critical technologies to be addressed. Lightly insulated tanks can extend the range of the aircraft for a given tank volume, but they are unlikely to be used in a first generation due to the need to manage the vented vapour at the airport. Tank architecture and configurations are explored to understand the current and future implications, finding that diameter and dormancy time requirements are the key design parameters that drive the weight of the tank. This work significantly contributed to win three work packages for ATI managed FlyZero project – Tank Design, Fuel System and Combustion consultancy and Advanced Propulsion – where the methods developed in the thesis were adopted. Particularly relevant was the tank weight finally assumed by FlyZero due to the outcomes of this work, which was half the value assumed in most recent studies.

A final exploration looks at the emissions that this swift change route could lead to. Complete decarbonization is not achieved until 2080, despite the early introduction in 2035 of the hydrogen airliners. Nevertheless, it provides a decarbonizing solution superior in the long term to other the solutions being explored based on biofuels.

Keywords:

Decarbonization, net-zero, long-range, zero-emissions

ACKNOWLEDGEMENTS

This thesis must acknowledge in first instance the vision of those pioneers that looked beyond – Prof. Riti Singh, Prof. Pericles Pilidis and Dr Ken Ramsden (r.i.p.) among others in the Centre for Propulsion and Thermal Power Engineering at Cranfield at the times where hydrogen for aviation was a rare proposal.

Biggest and warmest thanks are owed to my supervisor, Prof. Pericles Pilidis. He had the intuition that a modified conventional aircraft could accelerate decarbonization by providing a phased approach to the migration to hydrogen as a fuel. He suspected that a two-deck aircraft would pose less challenges if one entire deck was used for fuel storage and that it could achieve quite a long range. He was right in all his guesses.

He invited Dr Richard Adams, second supervisor, from the School of Management, to try to show some light on the product design, from an innovation diffusion market dynamics point of view. Thanks to him for providing insight in the introduction of innovations.

Special thanks to Dr Andrew Rolt, who was leading a different line of research in maximum synergy hydrogen aircraft, aiming at long term introduction. He provided a generous and extremely useful point of contrast on all assumptions, developments, and conclusions, definitively contributing to the solidity of everything that is exposed here. He was assisted by Dr Pavlos Rompokos, and supported by Dr Devaiah Nalianda and Prof. Bobby Sethi, to whom this research owns gratitude. Prof. Riti Singh and Prof. John Fielding contributed to the debate, sharpening our ideas.

In the middle of the research, the pandemic brought the Hydrogen to the centre of the scene, and I participated with other colleagues from the Centre in a few joint research programmes in Hydrogen that contributed to the development of new knowledge that helped me to understand better the fuel efficiency of the hydrogen aircraft: Prof. Vassilios Pachidis, Dr Ioannis Roumeliotis, Dr Christos Mourouzidis, Dr Chana Saias, and the PhD students Raf Anish Ghelani and

Sarath Sasi. Dr Theoklis Nikolaidis provided the required support with gas turbine simulations.

A final thankyou to Jean Francois Brouckaert from Clean Sky, who has been following with sincere interest this research from the beginning, cheering, and challenging our work.

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FOREWORD

“Today’s IPCC Working Group 1 report is a code red for humanity. The alarm bells are deafening, and the evidence is irrefutable: greenhouse-gas emissions from fossil-fuel burning and deforestation are choking our planet and putting billions of people at immediate risk”

UN Secretary-General António Guterres, 9th August 2021.

When this research started in 2020, hydrogen as an alternative fuel for aviation was a minority view. It had already been studied on several occasions along history, but always ruled out due to an unfavourable balance between the challenge it presents and the benefits it brings. It was mostly at Cranfield University where Hydrogen research never stopped, with a wealth of publications in the last decade (Abdallah et al., 2018; Agarwal et al., 2019; Babazzi et al., 2019; Benson et al., 2019; Goldberg, 2018; Goldberg C, Nalianda D, Singh R, 2017; Gomez and Smith, 2019; Haglind, Hasselrot and Singh, 2006; Karakurt et al., 2012a, 2012b; Khandelwal et al., 2011, 2012, 2013; McClure et al., 2019; Murthy et al., 2011; SEFAIN, 2000; The Guardian, 2019; The Times, 2018; Verstraete, 2009; Verstraete et al., 2010a; Wenqing, Zhuoyi and Smith, 2018) and more recently, with ENABLEH2 project.

This vision of those pioneers must be recognised – Singh, Pilidis, Ramsden followed by Sethi, Rolt and Nalianda among others in the Centre for Propulsion and Thermal Power Engineering at Cranfield.

Still in 2020, ICAO measures to reduce the environmental impact of aviation consisted of efficiency improvements and offsetting of emissions through actions that reduce the emissions in other sectors, the so-called market-based measures, to keep carbon emission at 2020 level and managing a carbon neutral growth since then (ICAO, 2019a).

In the years 2020-2021, many things changed, and environmental pressures continued rising (FORBES, 2020). With only 11% of the population travelling by air, and with 1% of the world population being responsible for more than half of the warming (Gössling and Humpe, 2020), air travel was target of some criticism, challenging the status quo of the sector and its sustained growth. Although aviation represents only around 3% of global emissions today, it may become the largest emitter in few decades, once all other sectors become decarbonised.

In June 2020, amid the pandemic, the France Government announced a rescue plan of €15bn for Airbus and Air France in which Airbus should use the money to invest in the development of a hydrogen aircraft (The Guardian, 2020). In September 2020, Airbus announced the zero-e Aircraft powered by Hydrogen to enter market by 2035 (AIRBUS, 2020a). The concepts revealed by Airbus included a 100 pax 1,000 nm and a 200 pax 2,000 nm aircraft.

Since then, the debate as to how to decarbonise aviation has intensified with political and business stakeholders exerting more influence on the decarbonising scenario than any other technical consideration. Preferred solutions are those that do not increase the operational costs, and hence the extra costs that the passengers will finally have to bear; do not drag a discontinuity, severe disruptions, or risk in the business of aircraft and engine manufacturers, airlines, and airports; and do not entail risk for ground support, operators, or passengers. The sector is nowadays at a crossroad, with no single solution nor a silver bullet, pulling for a widespread range of solutions.

In October 2021, civil aviation institutions (ATAG, 2021a; IATA, 2021; ICAO, 2022a) adopted the target to achieve net-zero carbon emissions by 2050. To date, following the Paris Agreement 70 countries, including China, USA and EU has set targets for net zero (UN, 2022), but out of the biggest emitters, only EU, UK, Japan, Canada and Russian Federation have binding commitments (Energy & Climate Intelligence Unit, 2022).

1 INTRODUCTION

The Paris agreement stipulated in 2016 the need to limit global warming by 2100 to below 2°C, with efforts to limit it to 1.5°C even though it would still have a significant climate impact (IPCC, 2018). The plan promotes a progressive reduction in emissions that would lead to a 1.5°C peak temperature, which would be reached before 2030, with ambition to reach net zero CO₂ emissions in 2050 (United Nations, 2022a, 2022b)

Under this agreement, any CO₂ emissions can be balanced with a CO₂ withdrawal from the atmosphere. This can be achieved by growing vegetable species that take the CO₂ from the atmosphere to form the complex carbon-based molecules they are made of, or by using techniques to capture the CO₂ by any other means and store it in way that it is permanent. It is generally accepted that the required actions to guarantee net zero should be accomplished through the 'polluter pays' principle, meaning that it is each industry sector which should find their ways to balance any emissions.

Decarbonisation of aviation is imperative to avoid the economic and social damage that would follow restraining aircraft operations. In October 2021, IATA (IATA, 2021), ATAG (ATAG, 2021a) and many other civil aviation institutions and organizations (ICAO, 2022a) adopted the target to achieve net-zero carbon emissions by 2050.

Solutions to abate CO₂ to emissions from Civil Aviation are resulting rather more complex than in any other sector. The uniqueness of the aircraft, which requires high power, and must carry a large amount of energy airborne makes the heavy battery powered electric aircraft only feasible for very short ranges.

Biofuels would be the easiest alternative, with minimum risk since there is no or little need to change aircraft or infrastructure. However, their potential emission savings does not lead the industry to net zero, but somewhere between 30% and 70% CO₂ savings depending on the feedstock (Doliente et al., 2020) with a few exceptions (ICAO, 2018). The minimum viable cost is between 2 and 8 times that of the jet fuel (Pavlenko, Searle and Christensen, 2019). Furthermore, a scale-up

in biofuels production to meet the overall demand of aviation will require a massive amount of land, investment may prove unfeasible, prices higher than initially estimated and may bring local tension with the food supply chain.

Complementary, or alternatively, purely synthetic fuels, for example produced by Fischer Tropsch Synthesis (FT), also need a source of carbon, though it is more flexible to the variety of feedstocks it can use. Most existing and projected plants use coal or natural gas or industrial CO₂ emissions to produce the fuel which makes the fuel synthetic, but not sustainable. With the most adequate feedstocks, FT synthesis can reduce the CO₂ emissions by more than 90% but the production cost will be 4-fold to 6-fold the conventional fuel (Doliente et al., 2020). As with biofuels, scaling up to full aviation demand will be challenging. Synthetic fuel derived from CO₂ captured from the atmosphere depends on the successful development of the Direct Air Captured technology (DAC), and ultimately, will be far more energy intensive than combining DAC with conventional fuel.

Hydrogen has the potential to decarbonise aviation and to leave the non-CO₂ emissions at an extremely low level.

Contrary to the popular opinion, hydrogen combustion temperatures can be lower than those of Kerosene, since it burns in excess of air, with much wider flammability limits. It also burns faster, likely allowing a shorter combustion chamber. Lower temperatures and lower residence time in the primary combustion zone makes it an ideal fuel for ultra-low NO_x emissions (Haglund, Hasselrot and Singh, 2006). Low NO_x emission hydrogen combustion has been extensively researched at Cranfield (Abdallah et al., 2018; Agarwal et al., 2019; Babazzi et al., 2019; Karakurt et al., 2012a, 2012b; Khandelwal et al., 2011; McClure et al., 2019; Murthy et al., 2011) where currently experimental research is still ongoing.

Contrails remain unknown, although some studies suggest a steep reduction of contrails and cirrus induced cloudiness when unburnt hydrocarbons, soot and particles are absent in the hot stream (Voigt et al., 2021). Should higher water vapour in the exhaust of hydrogen combustion produce higher contrails, this will need to be by avoiding ice supersaturated zones through altitude variation.

Several studies estimate an overall increase in fuel consumption of no more than 6% (Teoh et al., 2020). In case if hydrogen, there is no drawback in terms of additional CO₂ emissions, and this solution will be effective.

Several scenarios have been set by many different institutions, although all of them share the basic characteristics (Figure 1.1).

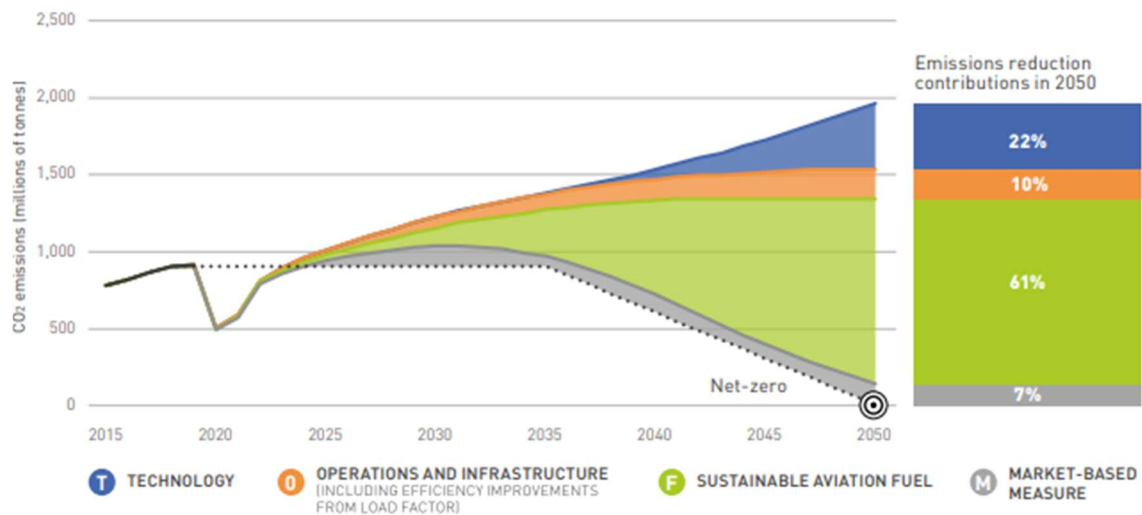


Figure 1.1: Scenario 1: pushing technology and operations. Source ATAG Waypoint 2050 Report (ATAG, 2021b)

A technology improvement though better aerodynamics, more composite material content and more efficient engines will account for 10-20% of the reduction and up to 35% if hydrogen aircraft is successful. Operational measures, including increasing load factors, which sum around 10% of the emission reduction. The rest – 60-80% must come from sustainable aviation fuels and offsets to close the gap to net-zero.

Regarding the aircraft segments and timescales, the consensus view of the sector can be seen in Figure 1.2 where it should be noted that any Hydrogen solution is always coupled with an 'and/or Sustainable Aviation Fuels (SAF), to mitigate the risk of a Hydrogen airliner introduction.

	2020	2025	2030	2035	2040	2045	2050
Commuter » 9-19 seats » < 60 minute flights » <1% of industry CO ₂	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Regional » 50-100 seats » 30-90 minute flights » ~3% of industry CO ₂	SAF	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Short haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO ₂	SAF	SAF	SAF	SAF potentially some Hydrogen	Hydrogen and/or SAF	Hydrogen and/or SAF	Hydrogen and/or SAF
Medium haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO ₂	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen	SAF potentially some Hydrogen	SAF potentially some Hydrogen
Long haul » 250+ seats » 150 minute + flights » ~30% of industry CO ₂	SAF	SAF	SAF	SAF	SAF	SAF	SAF

Figure 1.2: An indicative overview of where low- and zero-carbon energy could be deployed in commercial aviation. *Source: ATAG Waypoint 2050 Report (ATAG, 2021b)*

Relying on CO₂ withdrawals, aviation may struggle if biofuels fail to scale, if DAC finally does not deliver sustainable and affordable CO₂ removals or if climate change progression eventually requires both, zero emissions and CO₂ removals. However, the role of biofuels and synthetic fuels during the transition is crucial, since it is expected that conventional aircraft will need to be in the air at least for a few decades.

The present research investigates the progressive introduction of hydrogen as a fuel for civil aviation in successive innovation waves and focus on the first wave – an early entry into service of hydrogen airliner based on existing technology. It aims to reduce the environmental impact with a long-term perspective and in a sustainable manner, not only with the view on 2050 commitments.

Figure 1.3 shows three innovation waves. First wave will focus on certification and will incorporate only the minimum changes and technology developments to safely operate with liquid hydrogen storage and hydrogen powered gas turbines. These developments include the integration of the hydrogen tanks in a tube and wing aircraft, cryogenic storage technology and hydrogen combustion. For short ranges, tanks may be placed in the back and tail of the aircraft. For long range, and in the absence of lightweight and small-size-aircraft-conforming storage technology, the tanks will need to be longitudinally arranged along the fuselage, or in a double deck. The second generation will focus on improving the energy efficiency, by bringing in all other technologies that bring efficiency improvements but are not essential to safety. A third generation will benefit from non-conventional aircraft configurations and will capture all the potential of hydrogen as a fuel taking advantage of the heat sink implicit in the storage system.

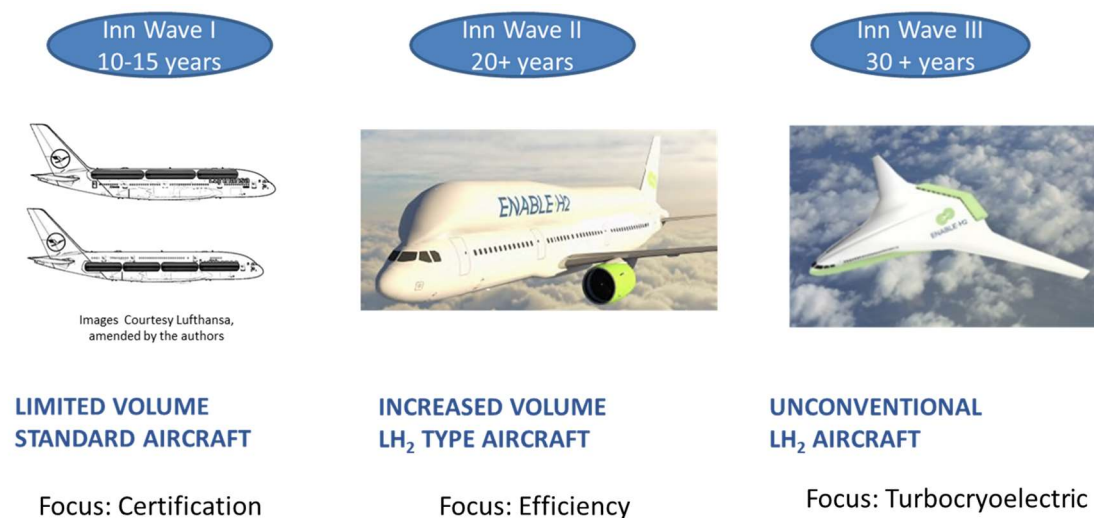


Figure 1.3: Innovation waves

Chapter 3 - Huete, J, Pilidis, P. (2022). *Hydrogen aircraft – a critical review of previous related work and a design space exploration. Unpublished* - analyses most previous relevant studies on hydrogen aircraft and explores the design space in which the first generation should be inscribed.

Chapter 4 - Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, P. (2021). *Early Entry Hydrogen Civil Aircraft Family Propulsion Integration Proposal (I): Intercontinental. Unpublished* - and **Chapter 5** - Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, P. 'Early Entry Hydrogen Civil Aircraft Family Propulsion Integration Proposal (II): Holistic Composition', *Unpublished*- describe an aircraft family within the design space explored in Chapter 3 that covers up to 75% of current civil aviation emissions and the methodology described in **Annexe I**.

Chapter 6 - Huete, J., Nalianda, D., Pilidis, P. (2021). *Propulsion system integration for a first-generation hydrogen civil airliner? The Aeronautical Journal, 125(1291), The 25th ISABE Conference special issue – Part I ,1654-1665. doi:10.1017/aer.2021.36* - focus on the long-range aircraft with a guessed gravimetric efficiency of the cryogenic hydrogen tanks of 0.45.

The sensitivity of the tank gravimetric efficiency of the long-range aircraft is studied in **Chapter 7** - Huete, J., Nalianda, D., & Pilidis, P. (2022). *Impact of tank gravimetric efficiency on propulsion system integration for a first-generation hydrogen civil airliner. The Aeronautical Journal, 126(1302), The 25th ISABE Conference special issue – Part II, 1324-1332. doi:10.1017/aer.2022.60*

Chapter 7 highlights the criticality of the tank weight and the impact on the first generation of aircraft performance, and **Chapter 8** - Huete, J., Pilidis, P. (2021). *Parametric study on tank integration for hydrogen civil aviation propulsion. International Journal of Hydrogen Energy, ISSN: 0360-3199, Vol: 46, Issue: 74, Page: 37049-37062* – shows the expected values of tank gravimetric efficiency depending on tank architecture choices and dimensions.

In the **Chapter 9**, emission scenarios are analysed and an entry into market of Hydrogen aviation is examined. The benefits of this approach are evaluated and compared to other alternatives being studied and potential impact is placed in context.

2 RESEARCH QUESTIONS, AIM AND OBJECTIVES

2.1 Research Questions

The thesis addresses several research questions not covered in any previous public study:

- Is it possible to fly on Hydrogen with today's technology?
- What minimum technology developments are necessary?
- What segments can be effectively decarbonised with today's technology?
- What the implication a first generation of hydrogen airliner are on customers, operators, and airports? Particularly with regards to configurations with rear tanks only and with the requirement of no venting at the airport. This introduces a new concept to tank design: the dormancy time
- Large variation of tank gravimetric efficiency estimations in literature – what can be expected for the first generation?
- What are the changes required to tanks if a dormancy time requirement is added?

2.2 Aim

The primary aim of this research is to demonstrate the viability of a first generation of hydrogen powered airliners, so that decarbonization of civil aviation can be accelerated.

- Assess payload / range capabilities of existing technology – minimum change aircraft
- Identify minimum technology developments / limitations
- Assess utility and operational / business model challenges. Identify changes required to passengers / operators / airports
- Identify a favourable entry into market and the economic implications for stakeholders

2.3 Objectives

To demonstrate this, four objectives had to be realised:

- A. Hydrogen Airliner - An airliner family based on existing technology but with the significant change of using hydrogen fuel
 - Conceive a process to evaluate capability of existing technology
 - Define an airliner family oriented to quickest possible decarbonization
 - Identify limitations of the first generation that will be solved in subsequent generations
- B. Hydrogen Storage - Integration of the tank into the aircraft taking into consideration the properties of hydrogen
 - Conduct a sensitivity analysis on aircraft performance to the most relevant storage parameters
 - Develop a tank design method that incorporates the dormancy time as a main design parameter
 - Evaluate feasible tank technology for the first generation
- C. Hydrogen Carbon Footprint - Evaluation of the green credentials of hydrogen fuel compared to other alternatives
 - Compare the CO₂ emissions of the proposed alternative compared to other alternatives
- D. Hydrogen Airliner Market entry - Conception of a market entry scenario
 - Draft a market entry scenario
 - Compare the CO₂ emissions of the scenario compared to other alternatives

Four papers were produced addressing the objective A: Chapter 3 - *Huete, J, Pilidis, P. (2022). Hydrogen aircraft – a critical review of previous related work and a design space exploration. Unpublished* - identifies the design space suitable for a first generation of hydrogen aircraft. Chapter 6 - *Huete, J., Nalianda, D., Pilidis, P. (2021). Propulsion system integration for a first-generation hydrogen civil airliner? The Aeronautical Journal, 125(1291), The 25th ISABE Conference special issue – Part I ,1654-1665. doi:10.1017/aer.2021.36* – describes a double deck long range aircraft capability taking the Airbus 380 as a

baseline but resizing the wings and engines for the new weights. Chapter 4 - Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, P. (2021). *Early Entry Hydrogen Civil Aircraft Family Propulsion Integration Proposal (I): Intercontinental. Unpublished* - and Chapter 5 - Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, P. 'Early Entry Hydrogen Civil Aircraft Family Propulsion Integration Proposal (II): Holistic Composition', *Unpublished*- describe the whole aircraft family and the decarbonization potential.

Objective B and tanks are explored in Chapter 7 - Huete, J., Nalianda, D., & Pilidis, P. (2022). *Impact of tank gravimetric efficiency on propulsion system integration for a first-generation hydrogen civil airliner. The Aeronautical Journal*, 126(1302), *The 25th ISABE Conference special issue – Part II*, 1324-1332. doi:10.1017/aer.2022.60 through a sensitivity analysis on the double deck aircraft and in Chapter 8 - Huete, J., Pilidis, P. (2021). *Parametric study on tank integration for hydrogen civil aviation propulsion. International Journal of Hydrogen Energy*, ISSN: 0360-3199, Vol: 46, Issue: 74, Page: 37049-37062 – where the impact on insulation technology and size of the tanks are investigated.

Objectives C and D are dealt with in the Chapter 9. Innovation waves and Objective D is also addressed in the Appendix A - J. Huete, D. Nalianda, B. Zaghari and P. Pilidis, "A Strategy to Decarbonize Civil Aviation: A phased innovation approach to hydrogen technologies," in *IEEE Electrification Magazine*, vol. 10, no. 2, pp. 27-33, June 2022.

3 HYDROGEN AIRCRAFT – A CRITICAL REVIEW OF PREVIOUS STUDIES AND AN EARLY ENTRY DESIGN SPACE EXPLORATION

Huete, J, Pilidis, P. (2022). Hydrogen aircraft – a critical review of previous studies and an early entry design space exploration. Unpublished

3.1 Abstract

Hydrogen aircraft is not new to scientific community. It has been widely studied in a variety of circumstances and geographical areas. The studies show a wide variation in aircraft designs, performance, and configurations. A comprehensive review of most important previous studies is reviewed here, with an emphasis on understanding the assumptions and the implications derived from them.

Tank integration plays a key role in hydrogen aircraft design, configuration, and performance. A review of the technologies and available studies is presented.

Technology factors, that account for future technology developments have conditioned the designs and the capability of the hydrogen aircraft in previous studies. A design space exploration is completed, showing the capability of the first generation and second generation of hydrogen aircraft. Changing the fuel to hydrogen is a vast technical and logistical change, in parallel the need to decarbonise is very urgent. To succeed in this challenge the concept of innovation waves is proposed. So, a first generation would focus primarily on changes related to the huge change arising from a hydrogen fuel system, minimising the introduction of other technologies, except those that affect safety/certification. This would take place in parallel with the significant modifications needed of the certification rules. A second generation incorporates the technologies foreseen in the following 10-15 years, focused on improving aircraft efficiency.

Several proposals are presented to substitute the narrowbody as well as the long-range aircraft. The different possibilities are discussed with a focus on airline operation. A novel proposal using dual fuel is presented, that could be another alternative to accelerate the transition to green propulsion.

Nomenclature

BWB	Blended Wing Body
GHG	Greenhouse Gas
L/D	Lift to Drag Ratio
LH ₂	Liquid Hydrogen
LNG	Liquified Natural Gas
LW	Landing Weight
MLI	Multilayer Insulation
MTOW	Maximum Take-Off Weight
MZFW	Maximum Zero Fuel Weight
NO _x	Nitrogen Oxides
OEW	Operating Empty Weight (tons)
SFC	Specific Fuel consumption (kg/s/MN)
TO	Take Off
TOW	Take-off Weight
UAV	Unmanned Air Vehicle
ZFW	Zero Fuel Weight

3.3 Introduction

Hydrogen has a long history in aviation. It was analysed as a potential high-performance fuel in the 50s and 60s, particularly for military and hypersonic applications, and it was first demonstrated that no major changes in the gas turbines were required except for those associated with the fuel system and combustion chamber (Contreras et al., 1997; Sloop, 1978). NASA sponsored a series of studies at Lockheed-California in the 70s in the midst of the oil crisis (Brewer, 1974, 1976; Brewer et al., 1975, 1978; Brewer and Morris, 1976). In the 80s, a Russian Tupolev Tu155 modified for hydrogen combustion was tested (Pohl and Malychev, 1997; Price, 1991) (Figure 3.1).

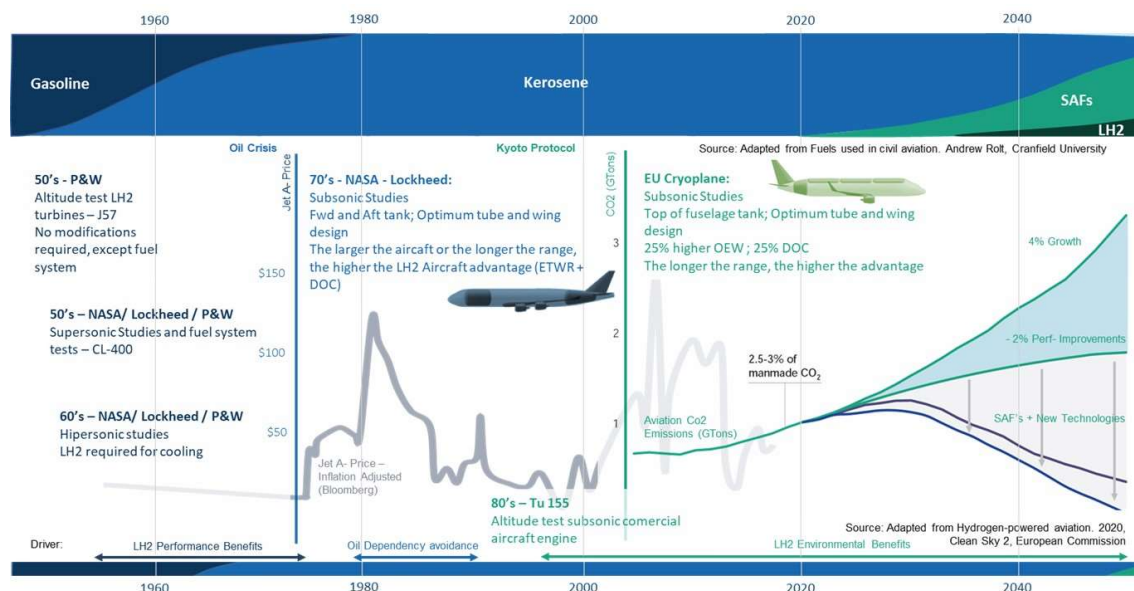


Figure 3.1: Hydrogen studies in aviation history

Modern studies aiming to reduce the environmental impact started in 00's with the Cryoplane Project (Cryoplane EU Consortium, 2003; Krijnen and Astaburuaga, 2002; Westenberger, 2003a, 2003b). Cranfield University continued the research on Hydrogen since then (Goldberg, 2018; Goldberg C, Nalianda D, Singh R, 2017; Haglind, Hasselrot and Singh, 2006; Karakurt et al., 2012a, 2012b; Khandelwal et al., 2011, 2012, 2013; Murthy et al., 2011; SEFAIN, 2000; Verstraete, 2009; Verstraete et al., 2010a) and more recently led a 20's EU

project - ENABLEH2 (ENABLEH2, 2020) – that took again the hydrogen as most likely fuel to abate sector's emissions. It is only after AIRBUS announcement that a Hydrogen Aircraft will be developed (AIRBUS, 2020a) that hydrogen aviation has become the centre of many engineering studies.

Previous studies, however, show specific designs, either with fuel in the aft fuselage, both in aft and forward fuselage, on top of the passenger cabin, or in the cargo area, single and double deck designs, with a wide range of passenger capacity-range pairs that gives the impression that there is no optimum solution. Most studies focus on advanced designs, sometimes with technology factors that is aimed to forward the design several decades into the future, at the risk of being unreasonably optimistic.

The present report shows an analysis of most of previous studies understanding where possible its assumptions and limitations and attempting to show some light on how a first generation of hydrogen aircraft would look like and what technologies can be incorporated in future generations.

Based on these comparisons, estimation is made of the potential capacity of a single aisle aircraft, a single deck designs when using existing technology and powered by hydrogen.

Perhaps the usage of single deck designs is behind the current common belief that hydrogen can only sustain short and medium range flights (ATAG, 2021b). Double decked and double bubble fuselages have been recently analysed at Cranfield (ENABLEH2, 2020; Huete, J; Nalianda, D, Pilidis, 2021) showing that hydrogen has enormous potential for long and very long ranges.

3.4 Hydrogen storage

Hydrogen storage onboard the aircraft has received the great attention because it has an exceptionally significant impact in aircraft configuration, weight, and performance. Hydrogen has a high heating value, 120 MJ/kg, around 2.8 times kerosene, but the extremely low density makes the cryogenic storage the only viable option. If stored at 700 bars, as the automobile sector is proposing, with a density of 40.2 kg/m³, the volumetric energy density is 4.8 GJ/m³, compared to

35.5 GJ/m³ of kerosene. Even in liquid state at 20 K and 1 bar, with a density of 70.8 kg/m³, the volumetric energy density is 8.5 GJ/m³, requiring over 4 times the volume to store the same amount of energy as kerosene. These and other storage methods are analysed in (Colozza, 2002; Züttel, 2003), liquid storage being the most suitable and widely accepted method for civil aviation.

The large volume and shape requirement indicates that hydrogen cannot be installed in the wings and has been in most studies placed in the fuselage. Storing part of the hydrogen in the wings is also challenging, since the surface to volume ratio of a wing conforming shape tank is larger than a cylindrical tank and the heat losses will be higher.

Any heat leakage into the tank makes some liquid to vaporise and increases the pressure of the tank. The vapour phase usually experiences a higher temperature increase and develops a temperature gradient growing vertically. Several studies, including experimental results focus on pressurization and temperature stratification in the tank (van Dresar, Lin and Hasan, 1992; Hasan, Lin and van Dresar, 1991; Lin, 1991; Petitpas, 2018; Schmidt et al., 1960; Stewart and Moder, 2016). How to insulate the tank to keep the hydrogen liquid has been subject to numerous investigations, mostly for long term storage spacecraft applications (Fesmire et al., 2012; Mital et al., 2006; Nast, Frank and Feller, 2014; Stark, Leonhard and Bennett, 1974). When the pressure in tank reached the design limit, some vapour must be vented overboard.

Long term storage designs for space applications favour insulation by means of a vacuum jacket usually layered with reflecting material to reduce radiation (multi-layer insulation). However, conditions in space differ from those in the atmosphere for civil aviation. Firstly, vacuum in space is easy to maintain. Loss of vacuum in the insulation degrades the thermal conductivity of the insulation by two orders of magnitude (Sun et al., 2009). Secondly, it is the overall weight of tank and vented vapour, and not the weight of the tank that is minimised for space applications. Long term missions favour heavy insulation since it avoids hydrogen to be vented. Even for long endurance applications (UAVs) in the atmosphere, vacuum insulation performs better (Sullivan et al., 2006). Thirdly, power

requirements in space are typically lower than those of an aircraft. Hydrogen removal from the tank tends to reduce the pressure and eventually balances out the heat ingress in civil aviation applications, reducing the insulation requirements at cruise.

Space applications may afford to incorporate more complex venting systems (Lin, 1991) or refrigeration power, aiming for zero-boil-off (Notardonato et al., 2017; Plachta, 1999).

Foam insulation is preferred for short-term storage of the main cryogenic tanks of space launch vehicles, like the space shuttle (Fesmire et al., 2012),.

Foam insulation has been studied in (Brewer, 1991; Colozza, 2002; Sharifzadeh, Verstraete and Hendrick, 2015; Sullivan et al., 2006; Weiser et al., 2000) and its properties are shown in Figure 3.2. It has been the preferred choice in several previous studies in Hydrogen Aircraft (Beddoes et al., 2022a; Brewer, 1991; Verstraete, 2009). Aerogels can provide similar performance to some foams and are analysed in (Coffman et al., 2010; Sharifzadeh, Verstraete and Hendrick, 2015; Sullivan et al., 2006).

Tank inner wall material must prevent hydrogen permeation and not be subject of hydrogen embrittlement at cryogenic temperatures. The most comprehensive public study susceptibility of metallic materials to hydrogen embrittlement of material was carried out for the space shuttle (Lee, 2016). Aluminium is typically used for space applications since it provides the maximum specific strength with no hydrogen embrittlement. Composite tanks have been studied but they present the need of a liner to prevent hydrogen permeation and it should be designed to avoid microcracking when subject to thermal cycling (Islam et al., 2016; Sippel et al., 2015; Sullivan et al., 2006).

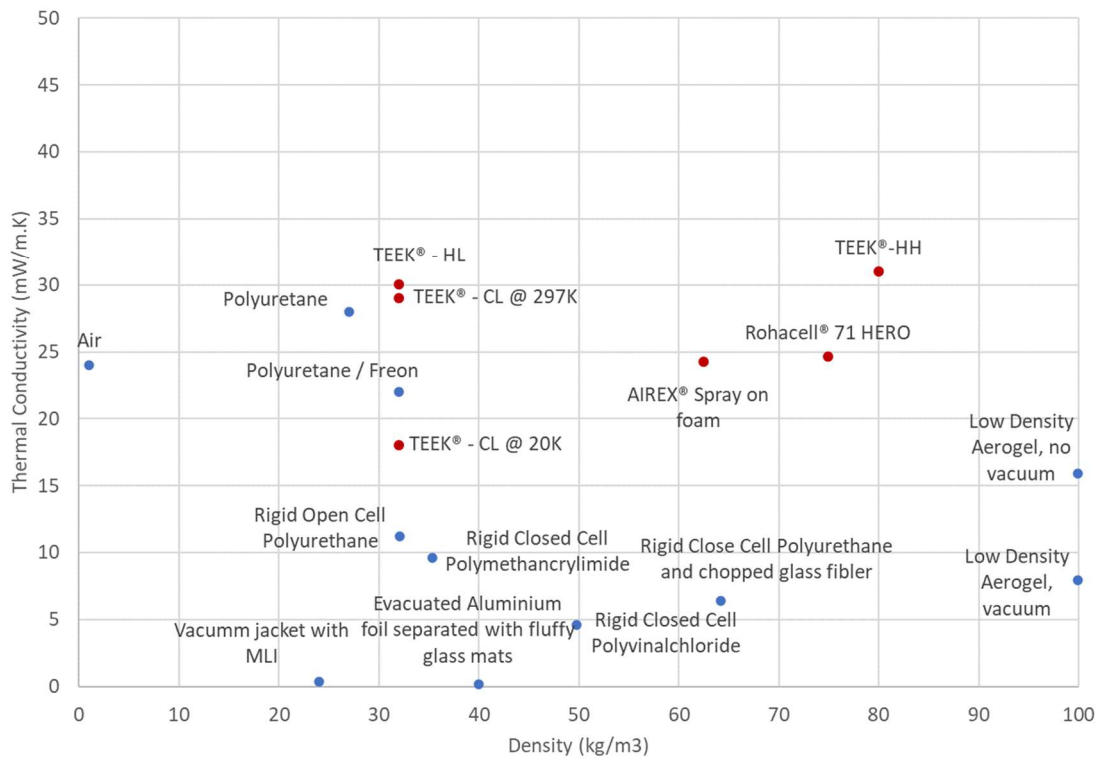


Figure 3.2: Insulation properties of selected materials. Red dots indicate commercial materials obtained from (Evonik Industries, 2022; Sullivan et al., 2006; Weiser et al., 2000). Blue dots generic materials from (Brewer, 1991; Colozza, 2002; Sullivan et al., 2006)

Vacuum insulated tanks can have an outer wall made of metallic or composite material, but (Sullivan et al., 2006) shows little advantage of the composite over the metallic under the buckling/crippling failure mode.

Foam or aerogel insulated tanks may have an outer composite wall that provides protection and avoids contamination and risk of detachment of the foam.

(Winnefeld et al., 2018) studied the performance of ellipsoidal tanks of a range of aspect ratios showing the deterioration of thermal performance as the surface to volume ratio of the tanks increase.

A parametric study showing the impact of the size of the tanks and the technology, architecture and insulation choices has been performed by (Huete and Pilidis, 2021)

3.5 Previous Aircraft Studies

NASA – Lockheed (70s)

Brewer conducted a work sponsored by NASA-Ames Research Centre at Lockheed-California during 1974-1976 (Brewer, 1974, 1976; Brewer et al., 1975; Brewer and Morris, 1976). It is the most comprehensive work publicly available to date partially assembled in the book he wrote in the 90s: Hydrogen Aircraft technology (Brewer, 1991). A wide range of different configurations, propulsion powerplants, fuel systems and tank architectures were studied and down selected. Its medium range aircraft holds 200 passengers for 3,000 nm in 8 abreast. It is a conventional tube and wing configuration with tanks in the forward and aft fuselage to keep the centre of gravity within range. The long-range aircraft is designed for 400 passengers and 5,500 nm. It requires a double deck fuselage with cylindrical tanks aft and forward of the passenger compartment.

Short and medium range aircraft showed little or no advantage against kerosene fuelled aircraft from a performance or operational cost point of view as the advantage of higher energy density of fuel are offset by weight of tanks, fuel system and increased drag due to larger volume required for the LH₂ fuel tanks. However, his long-range mission aircraft showed important advantages over the Jet A1 equivalent – it was lighter, with smaller wings but a larger fuselage, used smaller engines could operate from smaller runways and used 25% less of energy per seat mile (Brewer et al., 1975). And concluded that the advantage of using LH₂ as fuel in transport aircraft increases with the amount of energy required to perform the mission and recommended an aggressive program of technology development on the long-range aircraft.

For the short-range mission, he designed an aircraft with a 4.2 diameter, 42.5m length fuselage and a wing area of 85 m², nearly identical to today's 737MAX and

A321neo longest stretched versions but with a wing area some 30% lower. It had two integral tanks in front and back of the fuselage, providing separated cabins for pilot and passengers. Tanks were aircraft shaped but with dimensions that resemble a spherical form.

Medium range version exhibited a 6.3m diameter 53 m length fuselage with a 149 m² wing, quite like today's 777 or A350, slightly shorter and with a wing area of half or less. Tank configuration was identical to short range described above.

On the contrary, long-range aircraft was a double deck fuselage 8.8m height and 77 m long with a wing area of 466 m², again, similar to today's A380, slightly shorter, with a wing about half the area. Tanks were fitted into the fuselage, at the front and back of the bulkheads, in a similar fashion to short and medium range aircrafts, with more cylindrical tanks, as required amount of fuel was larger.

Compared to today's "similar" dimension aircraft, Brewer et al underestimated Operating Empty Weight by around 50%. This was probably due to two facts: (1) - They were requested to incorporate advanced technologies which were then under development, and which showed promise of improving the performance of transport aircraft 15 years or more ahead, which probably led them to underestimate weight of LH₂ aircraft and overestimate performance benefits. They considered a control-configured aircraft not constrained to meet conventional requirements of static stability which allowed them to use of control surfaces of minimum size and weight. Additionally. component efficiencies and capabilities of gas turbines were based on extrapolation of observed development trends. And (2) – As a consequence of (1) they considered quite small wing areas and empennage while meeting take-off and landing performance in existing airports.

Take-off weight was additionally underestimated due to an optimistic evaluation of tank weight, which they designed at a gravimetric efficiency in the order of 0.8. As a result, energy to work ratio or energy used per passenger mile was substantially lower in the long-range aircraft and only slightly higher in the short-range design.

Following these encouraging trends, NASA, and later the US Air Force, sponsored a series of additional studies which permitted exploration of more of the details of the technologies required for hydrogen systems for aircraft (Brewer et al., 1978). Fuel systems, including detail design of valves, pumps, lines and all required components along with turbine engines, tanks, and aircraft systems were studied in detail under NASA contracts by Airesearch (Garrett Corporation), Rocketdyne Division of Rockwell International and some others. The arisen long-range aircraft had a similar arrangement than the initial one, double deck with 66m length and a wing area of 297 m². OEW was 103 tons down from 148 tons, and MTOW 169 tons, down from 266 tons. Fuselage size was of the A380 type, 7 m shorter, and wings smaller than 787 or A350, closer to 767 aircraft. Both OEW and MTOW were like 767 extended range version, however, OEW is 60% lower than the A380.

Highly likely, Brewer et al were setting the technological limits of a hydrogen powered aircraft, should the aerospace sector had focused their efforts on such projects for the following 20 years, but today, their estimations should be considered either for a very long term or perhaps too optimistic. In any case, their influence in the design criteria and methods over all posterior works on hydrogen powered aircraft have been, and probably will be, strong and decisive.

Project Cryoplane (00s)

During 80s and 90s a Russian programme performed flight tests of a hydrogen powered aircraft Tu155, a testbed for alternative fuels in which no aircraft modifications were considered, only one of the turbines had been modified to burn LH₂ or LNG and therefore was aimed to test the powerplants rather than to develop its integration into a commercial airliner.

In 2000, because of the Russian tests and DASA (Airbus) interest on the project, a European R&D program was set under the name of “Cryoplane” with a limited budget of 4.5M€. 35 partners from industry, research and academia looked at the different aspects of an aircraft powered by hydrogen, including aircraft conceptual design, turbines and systems (Corchero and Montañés, 2005; Cryoplane EU Consortium, 2003; Krijnen and Astaburuaga, 2002; Westenberger, 2003b). Both

conventional and unconventional configurations were considered. The medium range aircraft had a tank at the rear of the fuselage and top tanks all along the fuselage. It was designed for 185 pax and 4,000 nm. The long-range aircraft had a similar configuration to Brewer's and hold 380 pax for 8,500 nm. An even larger version was designed, but it is not shown here since it is not comparable to any other work.

Small regional aircraft was a top mounted wing, 26 m length aircraft with tanks at the rear fuselage section. However, they found an excessive centre of gravity travel, probably requiring a combination of fly-by-wire and a very large horizontal tail, or operational restrictions to the centre of gravity. (Westenberger, 2003a)

Standard regional aircraft was design with tanks of top of fuselage as the fuselage diameter was too small to enable a catwalk parallel to and beside the forward tank, to serve as the cockpit-cabin connection. A special bay to contain a potential turbine disc burst reduced the attractiveness of the configuration.

Medium range aircraft had fuel tanks in both locations - back and top of fuselage and long-range aircraft was a double deck design which hold two tanks, front and rear of fuselage (Figure 3.3).

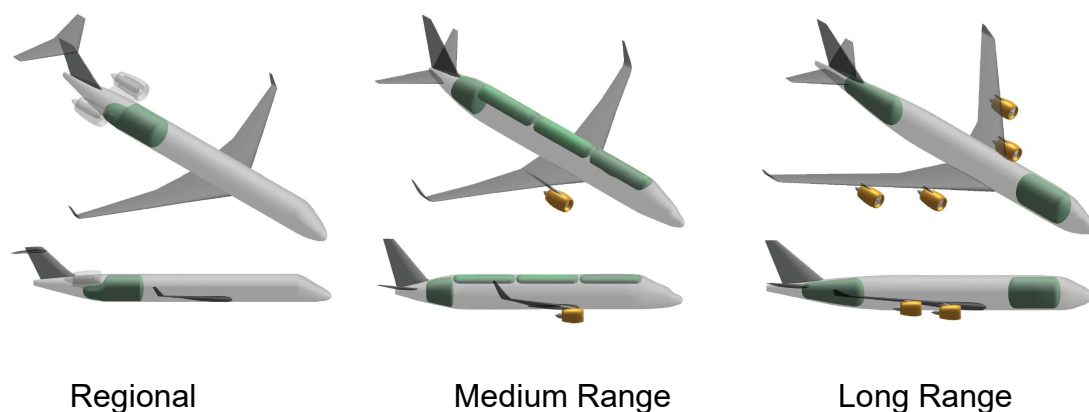


Figure 3.3: Tank configurations for medium and long-range aircraft of Cryoplane studies (Schutte et al., 2015) Originally from Oelkers and Prenzel

Long range aircraft was a 7.65m diameter 68.3m length fuselage with wing area (not published) probably around 300-350 m², like a A380 body (slightly shorter) with 787 wings or slightly smaller.

Cryoplane project concluded that OEW of LH₂ powered aircraft would be 25% heavier with lower MTOW in all cases due to lightness of fuel. Energy to work ratio was higher in all cases about 10-15% compared to an equivalent kerosene fuelled aircraft.

As part of the Cryoplane project, several non-conventional configurations were analysed at Cranfield University. A team of researchers and experts from Delft University, Sweden Defence Research Agency, DASA, Dornier and Cranfield University evaluated more than 20 unconventional concepts and concluded that Twin Tail-Boom and Tail-Tank concepts were most appropriate configurations (SEFAIN, 2000) (Figure 3.4).

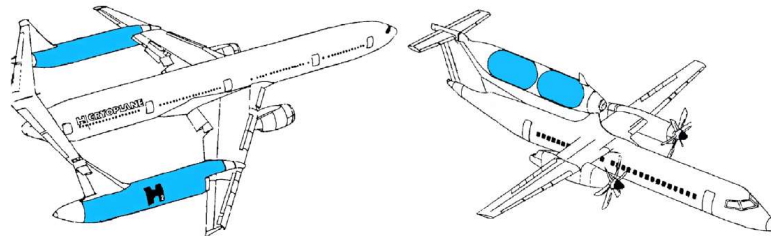


Figure 3.4: Non-conventional configurations down selected by Cryoplane project
(SEFAIN, 2000)

Selected data from the different public domain studies are shown in Tables 3.1 and 3.2 for medium and long range, respectively. Only public domain data is shown. Data *in italics* has been estimated from publicly data available.

	Brewer (1976)	Cryoplane (2003)	Verstraete SR (2015)	ENABLEH2 (2020)	Clean Sky (2021)	FlyZero (2022)	A320neo	A321neo	737-MAX 8
Passenger Capacity (pax)	200	185	150	200	250	171	165	206	178
Range (nm)	3,000	4,000	2,160	3,000	3,780	2,400	3,500	4,000	3,550
OEW (tonnes)	52.0	<i>88.9</i>	58.2			48.0	44.9	46.5	45.1
TOW (tonnes)	81.4	<i>127.4</i>	78			70.7	79.0	89.0	82.6
LW (tonnes)	<i>72.0</i>	<i>105.5</i>	71.7			62.2	64.9	<i>72.0</i>	<i>66.0</i>
LH ₂ (tonnes)	7.7	21.9	4.7		17.0	3.3			
Tank Weight (tonnes)			3.2		29	2.7			
Gravimetric Efficiency Tanks			0.59		0.37	0.55			
Energy Efficiency (MJ/pax.nm)	1.54	3.56	1.74		2.16	0.96			
N abreast	8	6	7			7	6	6	6
Fuselage Diameter (m)	6.27	4.14				5.00	4.14	4.14	3.76
Fuselage Length (m)	53		54.5			44.8	37.6	44.5	39.5
Fuselage Fitness Ratio	8.45					9.0	9.1	10.8	10.5
Wingspan (m)	37.6					39.3	35.8	35.8	35.9
Wing Area (m ²)	149		154.9			119	128	122	127
Wing Loading Landing (kg/m ²)	484		463			523	507	588	519
Wing Loading TO (kg/m ²)	547		504			594	617	727	650
Installed Thrust (kN)	267					206		294	261

Table 3.1: Medium Range (show estimated data in *italics*)

	Brewer (1976)	Cryoplane (2003)	Verstraete LR (2015)	Verstraete MR (2015)	ENABLEH2 (2020)	Clean Sky (2021)	FlyZero (2022)	787-9	A350-900
Passenger Capacity (pax)	400	380	400	300	414	325	222	290	315
Range (nm)	5,500	8,500	7,559	4,860	7,500	5,400	5,750	7,635	8,100
OEW (tonnes)	103.3	218.4	161.6	122.9			106.3	128.9	145.0
TOW (tonnes)	168.8	316.5	250.1	175.7			152.4	254.0	280.0
LW (tonnes)	139.3	252.6	199.5	149.9			135.6	192.8	207.0
LH ₂ (tonnes)	25.6	63.9	44.5	21.1		31.9	16.7		
Tank Weight (tonnes)	9.4		13.9	11.2		52	12.16		
Gravimetric Efficiency Tanks	0.73		0.76	0.65		0.38	0.58		
Energy Efficiency (MJ/pax.nm)	1.40	2.37	1.77	1.74		2.18	1.57		
N abreast	16			11			9	9	9
Fuselage Diameter (m)	6.63	8.00					6.00	5.77	5.96
Fuselage Length (m)	65.7	68.3	69.7	70.9			59.6	62.8	66.8
Fuselage Fitness Ratio	9.90	8.54					9.93	10.89	11.21
Wingspan (m)	51.7	58.0					52.0	60.1	64.8
Wing Area (m ²)	297		307.7	261.1			249.9	377	443
Wing Loading Landing (kg/m ²)	469		648	574			543	511	467
Wing Loading TO (kg/m ²)	569		813	673			610	674	632
Installed Thrust (kN)	540						476	680	749

Table 3.2: Long Range (show estimated data in *italics*)

Cranfield Studies (00-10s)

Since then, most efforts made in Hydrogen powered Aircraft have been made by academics until recently. An extensive study done between Swedish Defence Research Centre and Cranfield University in 2006 concluded that when comparing two equally performing medium-range aircraft – one powered by kerosene and one powered by LH₂ – the energy consumption is inevitably higher (in this case by about 10%) for the cryoplane although contribution to global warming (GWP) is considerably lower from the cryoplane, particularly, if

cryoplanes were allowed to fly 2-3km below current altitudes. (Haglind, Hasselrot and Singh, 2006)

Verstraete revisited Cryoplane designs and conducted several parametric optimisations to the Long-Range aircraft including an in-depth fuel tanks analysis (Verstraete, 2009; Verstraete et al., 2010a). He concluded that energy to work ratio of long-range aircraft could improve up to 12% whilst for short and medium range energy efficiency will be lower (Verstraete, 2015). His latest aircraft designs consider for medium range a 55m length fuselage with a 155 m² wing and a OEW of 58 tons, such as the shortest 767 versions but with wings slightly larger than the narrowbody aircraft. For long range he considered a 70m length fuselage with 300 m² wings with an OEW of 162 tons, a sort of A380 with wings smaller than A330. Wing loading for this one is 813 kg/m² probably leading to approach he speeds and landing field lengths longer than previous designs. In his work, used NASA Flops to optimise the aircraft dimensions and the weight estimations and concluded a 7 abreast aircraft capable of transporting 150 passengers over 2,160 nm and a double deck design for 400 passengers and 7,560 nm.

Extensive work was performed by Chana Goldberg at Cranfield (Goldberg, 2018) on BWB designs powered by hydrogen. Certainly, all potential of Hydrogen as a fuel will reach reality with an aircraft which is also superior in many instances to conventional aircrafts but also more friendly to hydrogen tank installation. However, state of technology development and urgency to avoid further aircraft emissions require an early introduction which will probably need to be realised either on an existing aircraft or on a relatively new aircraft derived from current technology.

ENABLEH2 (10s)

ENABLEH2 is an EU H2020 project involving more than 30 key civil aviation stakeholders, including partners and a large international advisory board. It targets maturing technologies for LH₂ which will contribute to decarbonising civil aviation, including an ultra-low NO_x hydrogen micromix combustion chamber, a fuel system heat management system which exploits the LH₂ formidable heat

sink potential and technoeconomic assessments of several configurations (ENABLEH2, 2020).

A total of 31 potential airframe architectures and 21 propulsion arrangements were analysed. The short list of 9 designs were ranked against 34 criteria (Rompokos et al., 2021). Final selected configurations showed a 6 abreast tube and wing arrangement with mid wings enlarged to fit elliptical tanks inside them (Figure 3.5). Power is provided by a partial hybrid-electric distributed propulsion in which a single tail mounted turbofan produces excess power to drive distributed fans under the wing.

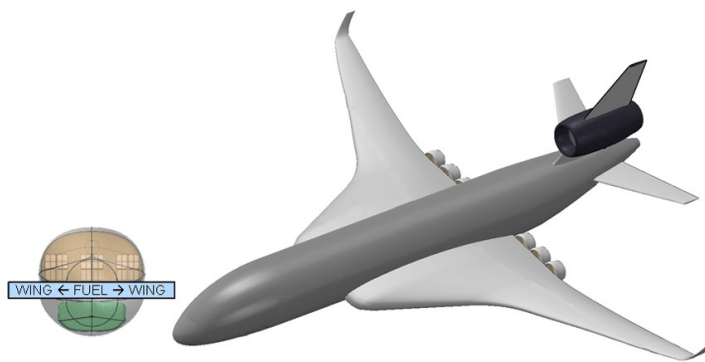


Figure 3.5: Cobalt blue 2 SMR concept selected in ENABLEH2 project

For long range, the max synergy aircraft is a BWB, stretch of the NASA N3-X to increase the passenger capacity and provide space for the tanks underneath the passenger floor (Figure 3.6).



Figure 3.6: BWB concept selected for long range in ENABLEH2 project

Additionally, to these maximum synergy configurations, the project considered two more conventional designs, with top tanks. Dimensions remain confidential.

Study for Clean Sky (20s)

An influential study has been done at DLR for CleanSky (Clean Sky 2 and European Commission, 2020). Most data remain confidential and only public domain data has been included in Tables 3.1 and 3.2.

The tank gravimetric efficiency assumption is 35% for the short-range aircraft increasing only to 38% for the largest long-range version. Likely, the tank architecture choice was vacuum insulated tanks. Still the figures seem especially low and do not fit with the correlations developed in (Huete and Pilidis, 2021), indicating that either a high safety coefficient was used, or a detail assessment of the tank weight was not performed. Also, this does not fit with Brewer and FlyZero. Consequently, the amount of hydrogen burnt during the mission is 17 tonnes for the medium range aircraft and 31 tonnes for the long range, values that are 2 to 3-fold those of other studies. With these values it is not surprising

that the energy efficiency worsened with the range and that the hydrogen aircraft presented an excess energy consumption of 20 to 40% more than a kerosene aircraft.

FlyZero (20s)

FlyZero was a project financed by ATI to investigate the possibilities of zero carbon emission commercial flight. It was run by a large team of experts seconded from companies like Rolls-Royce, GKN, GE, Mott MacDonald, Reaction Engines, Airbus, EasyJet, Eaton and Capgemini among others. The team managed many work packages that focused on specific technologies or issues, conducted by well-respected organizations from industry and academia. Cranfield University contributed substantially to the research, particularly in areas of combustion, propulsion, tanks and fuel system.

It is the widest and deepest work done on hydrogen aircraft since Brewer's time, and it mostly confirmed his work, although there were some distinctive design approaches in many cases. The work is confidential, except for several reports publicly available in website. This data included here only accounts for the public data.

Although initially opened to other fuels, like ammonia, it quickly concluded that hydrogen had the highest potential and the project focused on hydrogen aircraft only.

The project aimed to define technologies needed for an entry into service in 2035. Three traditional segments were considered: regional narrowbody and midsize, inspired by the ATR72-600, A320neo and 767-200ER, respectively. The reference aircraft were 'upgraded' with the technology levels expected by 2035 and then changed to be able to fly on hydrogen.

The narrowbody was 180 seats, 2,400 nm. The reference aircraft was enlarged from 4 to 5 m diameter-7 abreast, to place two tanks at the tail of the aircraft although the fuselage did not have a constant diameter. The length was also increased 7 m. The wings were reduced from 128 m² (A320neo) to 119 m². The operational empty weight only increased 3 tons from the reference aircraft. From

these data it can be deduced that they used technology factors to forecast weight and powerplant efficiencies in 2035. For example, from (Beddoes et al., 2022a) it can be estimated an sfc improvement of 14.2% when upgrading the reference aircraft to 2035 standards. Similarly, a 7.6% in weight reduction can be observed. Although initially inspired in an A320neo, their final design resembles more a short version of a 676 with 5m diameter in 7 abreast and 45m long.

The aircraft was provided with canards to provide the aircraft with enough longitudinal control capability. The energy efficiency bettered that of the kerosene aircraft by nearly 25% (Figure 3.7).



Figure 3.7: Medium range concept selected by Fly Zero

The long-range aircraft although inspired initially on a Boeing 676, ended up being a 9 abreast, 6 m diameter, 60 m long aircraft, more like an A350 or a Boeing 787-9 but with wings half the size, as it happened in other studies.

Two tanks were placed one at the back and another slim non-cylindrical tank at the belly to keep the centre of gravity within known limits.

The energy efficiency is better than the kerosene equivalent aircraft, but the gain is in this case shorter than the narrowbody aircraft.

3.6 Analysis of Previous Hydrogen Aircraft Studies

Tank Placement and Cabin layout

Previous section of hydrogen storage as well as the work published in (Huete and Pilidis, 2021) justifies that the reason of most studies to place the tanks inscribed in the fuselage is to gain gravimetric efficiency and reduce the weight of the aircraft. Such arrangement compromises the passenger capacity, which needs to be accommodated in a wider and longer passenger cabin.

It can be concluded from the available studies that a 200 pax hydrogen powered aircraft with a range in the 2,000 – 3,000 nm is not a single aisle anymore. Only Cryoplane kept the 6 abreast but placed top tanks, moving away from a conventional cylindrical tube and wing configuration. All studies placed tanks at the rear and some of them also at the front. The medium range aircraft seem to be a double aisle aircraft and will have to bear the extra weight of an additional aisle and the associated increased fuselage diameter. The question that arises is what the maximum capacity in terms of passenger and range for a single aisle aircraft would be and what the maximum amount of fuel that can be stored in a tank in the rear cone without compromising the longitudinal stability.

For long range, all studies go to double deck designs with tanks both at the front and rear of the passenger cabin or to unconventional designs with longitudinal tanks on top of the fuselage. The former is feasible but pose several additional challenges. The latter brings additional penalties to the hydrogen aircraft. Subsequent sections analyse what the maximum passenger capacity and range would be that could be offered with a single deck, conventional tube and wing aircraft.

Separate doors and facilities for cockpit crew and cabin crew/passengers are needed if a forward tank is contemplated. Emergency evacuation for crewmembers in the cockpit should be provisioned through, for example, a new top hatch as specified in (European Aviation Safety Agency, 2008). Having no walkway between cockpit and cabin, requires the following elements to be considered, as acknowledged during early discussions on pilot-cabin communication (Rudolf, 1972) and analysed in (SKYbrary Aviation Safety, 2020a, 2020b): (i) need to accommodate separate doors for cockpit and cabin, (ii) need to place toilets at cockpit area, (iii) it improves cockpit security but could require additional crew at cockpit, (iv) need to incorporate separate emergency exit for cockpit crew as discussed in previous paragraph, (v) no possibility to visual inspect engines/control surfaces ... by cockpit crew unless emergency passage is considered, (vi) No possibility to help in cabin crew in emergency situation, (vii) Reduced situation awareness by cockpit crew, (viii) Current regulations seem to force independent access two ways in case of emergency. Emergency means to enable crewmembers to enter pilot compartment and vice versa could be done in a variety of ways in case regulations are clarified requiring such access. Emergency passages could be designed either on one side of the fwd. hydrogen tank or through a special designed passage through the cargo deck at a lower level.

Top tanks or longitudinal tanks on top of the fuselage need to be low diameter tanks and this will increase the weight of the tanks compared to the weight of stored hydrogen. The increased cross section fuselage adds more weight and drag than fuselage longitudinal extensions. There are no major aerodynamic challenges, as demonstrated with Airbus Beluga and other similar aircraft, but this configuration will penalise the weight and range of the aircraft. Energy efficiency will diminish and will probably be inferior to a cylindrical tube and wing solution.

Hydrogen tank Architectures and Aircraft Weight

Studies on medium range aircraft fall onto two categories. One that utilises vacuum insulated tanks – Cryoplane and Clean Sky - and another one that

installs foam insulated tanks – Brewer, Verstraete, FlyZero, ENABLEH2. The former requires heavy tanks in the order of 30 tonnes to carry around 20 tonnes of liquid hydrogen to perform an equivalent mission to the existing narrow body aircraft. Such a large amount of fuel makes it impossible to be installed in rear tanks, since the variation in centre of gravity position between a full aircraft with empty tanks and an empty aircraft with full tanks is too large to be managed with conventional control surfaces, and they employ either tanks at rear and front or top tanks. The latter employs less than a third of hydrogen (6.6t) in tanks which weigh just a few tonnes. This can be done with rear tanks. The aircraft in this category are substantially lighter and will require smaller wings and engines. The OEW of the aircraft within this category ranges from 48 tonnes (FlyZero) to 58 tonnes (Verstraete). The difference being caused by the hypothesis employed in each study. This hypothesis become clearer when looking at the long-range aircraft studies.

The variations observed on the long-range aircraft are far greater, due to a higher impact of a much larger amount of fuel and a larger passenger capacity. So, in Cryoplane and Clean Sky studies the amount of liquid hydrogen approximately doubles that of the other studies for a similar mission. The resulting aircraft is larger and heavier. But the large variation of OEW estimations of the different studies cannot be fully explained by the tank weight, but also by the hypothesis and constraints used in them.

Brewer was using technologies forecast to be available in 1985, so aircraft initial operational capability would be feasible in 1990-1995. He incorporated several advance technologies still under development with a forecasted performance based on initial experimental results or by extrapolating trends observed in past component generations. The conceptualised aircraft used an active control system not constrained to meet conventional requirements of static stability, using minimum size control surfaces; using of composite materials making a state-of-art forecast 15 years ahead, advanced aerodynamics, engine component efficiencies and capabilities extrapolated from past trends. These assumptions explain the optimistic estimations of aircraft weight, which is larger

than today's very long-range aircraft, and still 30 to 50 tons lighter despite of 10 tons of added cryogenic tanks.

Verstraete estimations used NASA FLOPS correlations to calculate the weight and it does not seem that he used technology improvements, but state of the art technology. Still, in his estimations he considered unusual values of wing loading at landing which could lead either to unusual approach speeds and landing lengths or to the need of advanced high lift devices and increased noise.

The work led by FlyZero used technology factors to reduce the estimated weight of the different aircraft and engine components in the order of 5-7% and for the estimation of aerodynamic efficiency of the aircraft and efficiency of the engine.

The impact of the weight estimation in the rest of the analysis is enormous. It affects in a first instance the wing area, to achieve the required approach speed and landing field length. It follows a snowball effect that also affects installed power and has an exponential effect on range and in energy efficiency.

Energy Efficiency

All studies, except for Clean Sky's and FlyZero's concluded that the energy efficiency of the hydrogen aircraft improves with the design range of the aircraft. The differences among the studies, however, is important, sometimes two-fold.

That the energy efficiency improves with range is, at first sight, a logical conclusion from the thrust required at cruise. If we consider two identical missions, performed by a kerosene and a hydrogen powered aircraft, a lighter fuel weight of the hydrogen aircraft at take-off will require less lift and hence less drag or thrust for a segment of the mission. At some point along the way, the weight of the tanks of the hydrogen aircraft counterbalances the lighter fuel weight and it would weigh the same as the equivalent kerosene aircraft. For the last part of the flight, the kerosene aircraft will consume less. For a very short mission, the weight of the tanks makes the hydrogen aircraft heavier for most of the flight. In a very long-range mission, the advantage of a lighter fuel is dominant for most of the flight. Therefore, a short-range mission the cross-over point in which the

kerosene aircraft is more efficient occurs early in the flight, while for a very long-range mission, late in the flight.

The difference among studies also becomes a logical conclusion since for heavier tanks, like the ones used in Clean Sky study, and the central tank incorporated in the FlyZero study, the advantage of a lighter fuel becomes shorter.

It should be noted, however, the high impact that the so called 'technology factors' for weight estimation have in energy efficiency, although not so in aircraft performance. Such hypothesis may flip over the energy efficiency of the hydrogen aircraft compared to the kerosene one. Brewer, for example, estimated a long-range hydrogen aircraft that is lighter than an equivalent kerosene one, if same technology factors are employed for both, even though the hydrogen aircraft was double deck and longer. This was not the case in his studies on short and medium range. The reason for this is the so-called snowball effect that a lighter aircraft activates in wing size, engines, and fuel. Other hypothesis may also have a significant effect. So, although the estimation of OEW in Verstraete's of the long-range aircraft was 60% larger than Brewer's, wings were unusually small, with 20% less area than current very long aircraft of the same landing weight. Should he had considered a conventional approach speed for wing sizing he would have probably reached to the opposite conclusion.

The advantage in energy efficiency of the hydrogen aircraft is very dependent on the possibility of designing an aircraft that is not heavily penalised in weight due to the hydrogen tanks and the required fuselage arrangements.

The disparity of weight estimations also show that weight does not restrict the range. The capability of hydrogen for medium and for long range transport has been recently validated in numerous studies at Cranfield. Nevertheless, long range aircraft on hydrogen seems to call for a double deck or top tanks designs, which introduces additional challenges. In the following sections, the limits of single deck designs are also explored.

3.7 Design Space for and early entry into market

The design space of the hydrogen aircraft is mostly driven by the need to accommodate large cryogenic tanks. Optimum and maximum synergy configurations have been extensively explored in (Rompokos et al., 2021; SEFAIN, 2000). The strongest limitation of the hydrogen aircraft is probably the volume required by the hydrogen tanks. Here only tube and wing configurations, more suitable for a first and second innovation wave of hydrogen aircraft are studied, where tanks are placed inside the fuselage. Other configurations, such as blended wing bodies may open new possibilities but encompass a broad number of innovative technologies and a larger amount of development effort. It is unlikely that the hydrogen aircraft will be initially developed in a novel configuration, since the R&D effort will be colossal.

In a tube and wing configuration, tanks can be placed at one or two of the extremes of the passenger cabin or longitudinally laid out, either on top of the cabin or in the cargo area. The benefits of large diameter tanks have been published in (Huetel and Pilidis, 2021). Inscribed tanks at the back of the rear bulkhead will be lighter than top tanks but have a limit in volume that does not compromise the stability of the aircraft. When this limit is reached, either tanks are placed at the front, or tanks are arranged longitudinally along the fuselage.

Storage technology can also play a significant role in the design space. The impracticality to vent at the airport, in take-off delays or overnight stays, introduces a massive weight increase in the tanks, which need to be heavily insulated to withstand extended periods of time without venting. Recovering safely the vented vapour at the airport would require additional ground technologies to be developed, such as reliquefying or gaseous storage trucks.

Availability of non-venting lightweight tanks would have a strong effect on aircraft performance as pointed out in previous section 'Analysis of Previous Hydrogen Aircraft Studies'. It would extend the range that can be performed with single deck designs and back tanks only, without stability concerns. The development of small lightweight tank technology will also open the possibility to have longer range flights without energy efficiency penalties either by placing tanks on top of

the fuselage or by having a forward and a back tank. Ultimately, it could enable to place tanks inside the wing, which would otherwise be very heavy.

Other technologies may have some effect in the design space. Specific to hydrogen are for example improve aerodynamics, advanced high lift devices, folding wing tips and several propulsion advances. The removal of the fuel from the wings frees space in the wing to place the fairings that move the flaps or install a hybrid laminar flow control and benefit from a reduced drag. Advanced high lift devices could reduce the size of the wing since in the hydrogen aircraft is mostly sized to meet a given approach speed and noise. Folding wing tips allow a good aspect ratio in the larger wing required for the hydrogen aircraft if any given aircraft size group is to be met (wingspan constrained).

The storage of the fuel at cryogenic temperatures allows the hydrogen aircraft to benefit from several technology innovations that are not possible in a kerosene aircraft. The cooling air could be further cooled by the cryogenic flow before being directed to the hot section of the engine, allowing an increase in gas temperature or a reduction in cooling flow, and hence a smaller and lighter engine. Ultimately, it permits the cryocooling of the superconducting system required for a turboelectric distributed propulsion which would itself bring many other benefits. (ENABLEH2, 2020; Goldberg, 2018). These are envisaged for a 3rd innovation wave.

Several developments will benefit both, kerosene and hydrogen powered aircraft, but the payback for the hydrogen aircraft will be much higher if it means that a front tank or a second deck is avoided. Among them there are a higher content of composite material in the airframe which will reduce the weight of the aircraft and will extend the range for a given size of hydrogen tanks, or a more electric aircraft with the elimination of the pneumatic system and the engine bleed.

This panorama suggests that Hydrogen aircraft may be developed in innovation waves, phasing out technological challenges and reducing the risk to acceptable levels. Figure 3.8 shows three innovation waves. First wave will focus on certification and will incorporate only the minimum changes and technology developments to safely operate with liquid hydrogen storage and hydrogen

powered gas turbines. These developments include the integration of the hydrogen tanks in a tube and wing aircraft, cryogenic storage technology and hydrogen combustion. For short ranges, tanks may be placed at the back of the passenger cabin. For long range, and in the absence of lightweight wing conforming storage technology, the tanks will need to be longitudinally arranged along the fuselage, or in double deck. The second generation will focus on improving the energy efficiency, by bringing in all other technologies pointed out in this section that are not essential to safety. A third generation will benefit from non-conventional aircraft configurations and will capture all the potential of hydrogen as a fuel taking advantage of the heat sink implicit in the storage system.

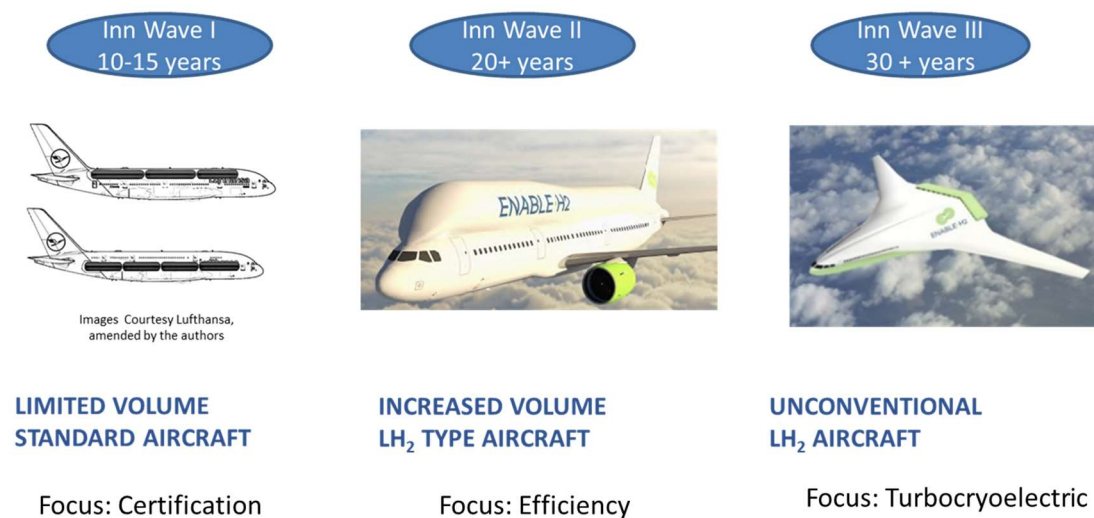


Figure 3.8: Innovation waves proposed to phase out development effort, reduce risk and accelerate decarbonization

For the first generation, fuselage volume is split into passengers and tanks. Small fuselage extensions are possible within limits, imposed by aircraft stability and a reasonable fuselage fitness ratio. Existing kerosene aircraft have fitness ratio values in the range of 8-13. Too short a value, i.e., a short and thick fuselage,

results in large empennage structures, which should operate with noticeably short lever arms to provide stability to the aircraft and will result in a higher drag and weight. On the contrary, too large a value of the aspect ratio will make the aircraft heavier and with a larger drag due to an increasing fuselage surface per passenger volume and it will be limited by rotation at take-off. Multiple designs and optimisations through aviation history has ended up with fuselage ratio of 10 to 12, indicating an optimum practical value.

Figure 3.9 shows the passenger capacity of a hydrogen aircraft compared to a kerosene equivalent aircraft when cylindrical tanks of a favourable aspect ratio are installed at the back of the cabin. In all designs, a fuselage aspect ratio of 11 has been kept and the width of the aircraft has been varied from 3 abreast to 10 abreast. The figure shows the passenger capacity when an overall tank length of 2 and 4 times the fuselage diameter is installed. X axis has been removed. Passenger capacity should be read from the intersection of number of abreast and tank length, as any other plot did not make it clearer. For the cabin design, the calculation considers usual values obtained from (Torenbeek, 1982): a cone and cockpit length of 3 times the diameter of the fuselage, a seat pitch of 30" and width of 0.5m, aisle width of 0.508 m, cabin wall thickness of 150 mm and a length occupied by the galleys and services of 25% the available length. The model has been validated through existing aircraft, A320, B767, A330, A350 and B777. It shows that a single aisle (6 abreast) will reduce its capacity to below 150 pax. To perform useful missions with 200 passengers, the aircraft will need to be 7 or 8 abreast and have a double aisle. This justifies that a hydrogen aircraft will be somewhat 'fatter' or wider than a kerosene equivalent aircraft.



Figure 3.9: Passenger capacity of single deck hydrogen aircraft for changing tank lengths

To have an approximate value of the range that can be achieved with the different aircraft and tank sizes in the plot, a model has been set. For the weight estimation, existing aircraft are used as reference, A320, B767, A330, A350 and B777 for 6 to 10 abreast, respectively. To account for a lighter take-off weight, hydrogen aircraft wing is resized by approach speed, scaled to match ICAO airport approach category C, since it is expected that range will not be long enough to justify another category. Range is then estimated using Breguet range equation with a cruise speed of 0.85 Mach at 35,000 ft. Maximum landing weight is estimated assuming 120 kg/pax and a cargo load of 15,000 kg. Two scenarios are considered: one for the first generation, with MLI vacuum insulated tanks, state of art aerodynamics with a L/D of 18, and current sfc level of 5.94 g/kN.s at cruise. Another for the second generation, with foam or aerogel insulated tanks, improved aerodynamics (8%) with a L/D ratio of 19.44 and a 20% improvement in engine performance resulting in a sfc of 4.7 g/kN.s. Tank gravimetric efficiency is for the first generation 0.45 and for the second generation it has been calculated with method published in (Huete and Pilidis, 2021) according to the cabin diameter – 0.66 for the 6-abreast growing to 0.72 for the 10-abreast. Engine

efficiency is mid cruise with a similar core as today's engines and a BPR of 11 and 12.5 in the first and second generation respectively running on hydrogen. A stability limit has been illustrated calculated as a centre of gravity shift from MZFW to zero payload/max fuel of 40% MAC. MAC has been estimated using a correlation with wing area of existing wings.

The following charts 3.10 and 3.11 show the estimated payload range capability. The chart shows little sensitivity to wing size escalation which makes the estimation appropriate to set approximate limits. As expected, the second generation shows a payload-range line that shows a smaller reduction in passengers for an increase in range, i.e., less steep lines, although for very short ranges the capacity is similar. The stability limit increases in the second generation due to a lower amount of fuel needed to perform the mission, and despite a lower OEW of the aircraft.

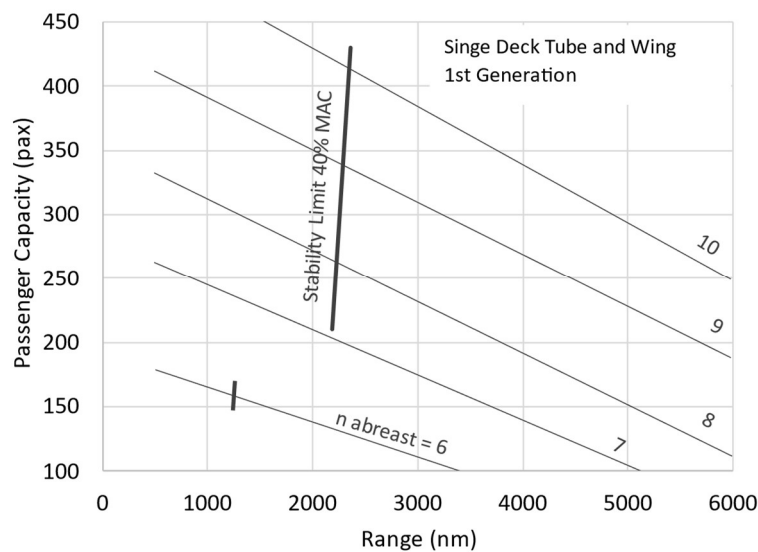


Figure 3.10: Estimation of the payload-range capability of the first-generation hydrogen aircraft. Gravimetric efficiency 0.45; $L/D=18$; $sfc=5.94$ g/kN.s

For the first generation, the narrowbody aircraft shows either a significant reduction of passenger capacity or a drastic reduction in range achieving 3,500 nm for 100 passengers or 1,500 nm for 150 passengers. The second generation shows some improvement, delivering 2,000 nm for 150 passengers, or 3,500 nm

for 125 pax but still falls short for today's narrowbody operations. The main problem, though, comes from the centre of gravity shift. If a limit is set to 40% MAC, then the narrow body could not travel more than 1,200 nm in the first generation and 1,500 nm in the second generation, unless a third control surface is in place, such as a canard or equivalent solution.

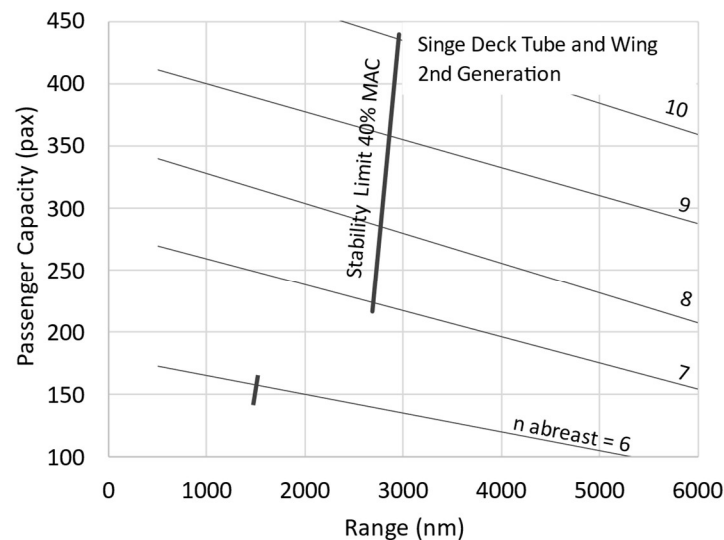


Figure 3.11: Estimation of the payload-range capability of the second-generation hydrogen aircraft. Gravimetric efficiency 0.66-.72; L/D=19.44; sfc=4.7 g/kN.s; Weight technology factor 0.9.

The location of tanks at the back of the aircraft limits the achievable range for any widebody aircraft size at around 2,200 nm for the first generation and 2,800 nm for the second generation., although more than 95% of the operations performed with the narrowbody are shorter than that.

3.8 Discussion

Substitute of the Narrowbody Aircraft

A 7-abreast aircraft with 200 passenger capacity could perform 2,100 nm and 2,600 nm in the first and second generation of hydrogen aircraft and this could be a good substitute for the narrow body aircraft. It would have tanks at the back of the passenger cabin, minimising the changes in airport operations and

infrastructure. However, wingspan would be significantly higher than the existing narrowbody aircraft and the substitute would need to use airport gates code D, limiting the operations in many airports. The operational empty weight would double that of the narrowbody, resulting in a much higher energy consumption. These trends remain equal in the second generation.

Alternatively, a smaller 3,500 nm hydrogen powered narrowbody, with tanks fwd. and aft. the passenger compartment with around 96 and 125 passengers in first and second generation respectively would take the baton. This aircraft would keep the maximum span of currently used gates C (Ref ICAO) and would have a comparable OEW to the existing narrowbody aircraft. However, the energy consumption per passenger would increase because of a reduced capacity.

If the hydrogen used in the aircraft is green hydrogen, the energy intensity should not be of major concern, but the GHG emissions become the focus. It would impact the operating costs of the flight, which could possibly double. If the contrails produced by the hydrogen aircraft are similar or higher than those produced by the kerosene aircraft, this may impose further pressures to increase the energy efficiency, though this is unlikely to be the case (Voigt et al., 2021).

The energy efficiency improves rapidly with passenger capacity and therefore it is possible to foresee a single deck, 8 or 9-abrest with capacity for 250 passengers in the first generation growing to 300+ in the second generation.

The energy efficiency will not match that of the existing aircraft, probably in any of the proposed aircraft due to reduced passenger capacity or increased weight due to an additional isle and the hydrogen tanks.

Long range aircraft

Longer ranges could only be accomplished with tanks both, at the front and back of the passenger compartment. This a necessary complication that can be solved as explained in previous section 'Tank Placement and Cabin Lay-out', but it will also require minor airport operations adaptation, since the crew will need a separate access ramp.

The need to split the available volume between passengers and fuel imposes limitations to the capacity of the aircraft, and 5,500 nm could only be done with a 9-abreast for 200 passengers and a 10-abreast for 275 passengers in the first generation. This capacity seems low for a long-range aircraft and a sharp increase in the energy efficiency penalty is expected. For the second generation, the capacity increases to 300 and 370 passengers, which could possibly be more affordable.

For the first generation, a double deck design could maintain the airlines' capacities with a reduced energy usage due to higher capacity. Such concepts have been studied in (Huete, J; Nalianda, D, Pilidis, 2021).

Dual Fuel Aircraft

Another solution may come from a dual fuel aircraft, which uses hydrogen for the typical mission and supplements the trip with kerosene for longer missions. If the fuels are used sequentially, i.e., first the heavy kerosene, and later the hydrogen, the energy efficiency of the flight results lower than both, if only hydrogen and only kerosene were used.

The minimum average weight is achieved when a mix of both fuels are envisioned, since the utilization of kerosene for the early phases of flight reduces the weight of the hydrogen tanks and the usage of hydrogen at the late phases reduces the weight of the dead fuel carried along the flight. The finding is being further explored at Cranfield and could bring important proprietary technology that can change the course of the transition.

With this concept, a first-generation dual fuel narrowbody aircraft could do 1,200 nm with 156 passengers on hydrogen covering around 75% of the flights. For longer flights, it could supplement with kerosene in the wings another 2,300 nm with a lower energy intensity than the existing narrowbody aircraft.

The challenge remains to design a low NO_x combustion chamber that could burn both, hydrogen, and kerosene, but this development does not affect the airport infrastructure and is seen as a solution to be considered.

A further benefit of the concept is the reduced risk of an early entry into market of the hydrogen aircraft, which could initially absolve technical problems with the fuel system, hydrogen tanks, or logistic problems with the liquid hydrogen the airport.

3.9 Conclusions

Previous studies show a wide variation in aircraft operating empty weight of the hydrogen aircraft, due to technology factors embedded in the designs. The weight of the aircraft has an exponential effect of the performance of the aircraft through wing, empennage and engine sizing and the studies should be analysed in the context they were produced and in the timeframes that were considered for the introduction of the hydrogen aircraft.

Tank architecture has one of the biggest effects in the hydrogen aircraft performance. Some studies, based on vacuum insulated tanks show significantly lower performance and higher energy consumption than those that used foam insulated tanks.

The design space exploration of the hydrogen aircraft shows that hydrogen aircraft will be limited in capacity due to need to split the fuselage volume between passengers and fuel and that the longitudinal stability of the aircraft poses a limit on the amount fuel that can be loaded on tail tanks.

A narrowbody aircraft powered by hydrogen will have around half the capacity for the same range than the kerosene narrowbody aircraft. Alternatively, it will be limited in capacity to around 150 passengers and 1,500 nm, with poor energy efficiency.

The substitute of the narrowbody aircraft could be a 7-abreast or even wider body aircraft, but it will also be limited to 2,800 nm due to centre of gravity position.

Long ranges will need to be performed with double deck designs if passenger capacity and energy efficiency is to be maintained.

A dual fuel aircraft, which burns first the kerosene and later the hydrogen is an interesting option for early entry into service, which reduces the risk and lowers the energy consumption.

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4 PROPULSION INTEGRATION PROPOSAL FOR AN EARLY ENTRY HYDROGEN CIVIL AIRCRAFT FAMILY. PART I INTERCONTINENTAL

Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, P. (2021). Early Entry Hydrogen Civil Aircraft Family Propulsion Integration Proposal (I): Intercontinental. Unpublished

4.1 Abstract

‘Greening’ civil aviation is imperative, avoiding the potential economic and social damage that would follow constraining aircraft operations. Radical propulsion technologies are needed; very likely to succeed in this challenge is Green Hydrogen. Among the problems accompanying such a fundamental change in aviation are the integration of Hydrogen tanks into an aircraft and the conversion of airport terminals. To circumvent these, several innovation waves are advocated, the first maximizing use of existing technology and infrastructure: later waves delivering the whole underlying advantages of Hydrogen. This research investigates the degree to which existing airframes can be redesigned for Hydrogen. A first generation of Hydrogen airliners is proposed in which aircraft is limited to current dimensions, features, and materials. Part I of the paper develops the method to preliminary assess the viability of aircraft conversion. A twin deck fuselage with resized wings and engines adapted from a 300t long-range airliner could transport up to 380 passengers over ranges up to 4,800 nm.

Nomenclature

ESFC	Energy Specific Fuel Consumption (MJ/s/MN)
ETWR	Energy to Work Ratio (MJ/pass.km)
GT	Gas Turbine
HVLLR	Hydrogen Very Large Aircraft Long Range
HVLMR	Hydrogen Very Large Aircraft Medium Range
ISA	International Standard Atmosphere
L/D	Lift to Drag Ratio
LH ₂	Liquid Hydrogen
MAC	Mean Aerodynamic Cord (m)
MTOW	Maximum Take-Off Weight
NO _x	Nitrogen Oxides
OEW	Operating Empty Weight (tons)
SFC	Specific Fuel consumption (kg/s/MN)
SLS	Sea Level Static
TET	Turbine Entry Temperature
TOW	Take-off Weight
TRL	Technology Readiness Level
ZFW	Zero Fuel Weight

4.2 Introduction

Extreme decarbonization is promised for 2050, but emerging is a strong consensus that this is too late. The use of green hydrogen as a civil aviation fuel is an alternative to decarbonize aviation. Switching jet engine fuel to hydrogen promises to decarbonize civil aviation if hydrogen production is carbon-free and aircraft engines deliver very low NO_x. Hydrogen also removes other harmful emissions such as unburnt hydrocarbons, aromatic compounds, sulphur oxides, soot, and smoke (ENABLEH2, 2020; Troeltsch et al., 2020; Verstraete, 2009; Westenberger, 2003a). Contrail cirrus, if proved to create a significant greenhouse effect, should be treated, the easiest means by rerouting a minor fraction of flights (Noppel and Singh, 2007; Teoh et al., 2020). Nonetheless, it will require colossal changes in aircraft, infrastructure, management, safety, and regulation. Such a change will be very expensive. However, the authors firmly believe that, socially and economically, it is a far superior alternative to the vast economic damage that will result from reducing air traffic. Hydrogen is a technology solution to provide combined sustainability in environmental, economic, and social terms (Khandelwal et al., 2012). With the appropriate investments an introduction in approximately 15 years is conceivable.

Many tests and evaluations of hydrogen-fuelled aircraft have been carried out. From Von Ohain's hydrogen fuelled demonstrator in the late 30s (Giffard, 2016), the flight test of a B57-Canberra in the late 50s (Kaufman, 1957), the TU-155 in the late 80s (Tupolev, 2012). More recently, significant tests at engine conditions to deliver hydrogen combustion with low NO_x are being carried out in the European project ENABLEH2 (ENABLEH2, 2020).

It is widely acknowledged that market forces alone will not bring the changes needed. It will be necessary to adopt direct international financial support or economic-taxation measures to enable the transition to zero-carbon aviation. Techniques for evaluating the impact of different policy scenarios are available (Nalianda, 2012). Considering the significant challenge will arise from the systems needed to store, move, and use hydrogen on board, the development of certification requirements, delivery of low NO_x systems, and public support to

decarbonize a sector, this will need to be of a similar magnitude to the support received for Renewable Energy Systems in the electricity generation industry.

Figure 4.1 shows air traffic characteristics (Schäfer et al., 2019) where cumulative aircraft movements (departures), NO_x, Revenue Passenger Kilometres (RPK) and fuel used are shown on a basis of aircraft range. Whole aircraft families will need to bring into service to address large scale. A 'portfolio approach' through a large aircraft family is proposed here.

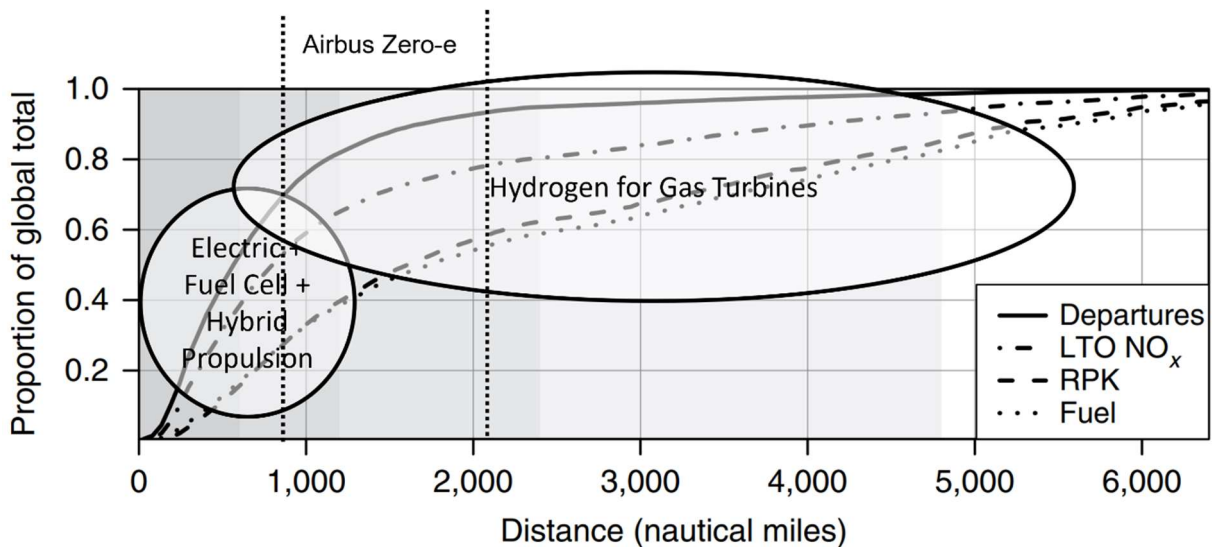


Figure 4.1: Commercial Aircraft Traffic Characteristics. Source: Schafer, AW et al. [9] annotated by the authors

For a swift change, several innovation waves are needed. For early service (2035? - assuming TRL6 can be reached by 2027 and additional 8 years to reach TLR 9), the first wave must maximize the use of existing design and technology. Later innovation waves will deliver the full potential of hydrogen in the aircraft. For a holistic decarbonization effort, whole aircraft families will need to bring into service to address a wide range of traffic requirements. Figure 4.1 shows how such a first wave of innovation could be shared between electric (including all electric, fuel cell electric and hybrid) and hydrogen propulsion systems. This may give rise to an increase in popularity of hub and spoke systems (where inter-hub traffic is served by hydrogen fuelled transports with gas turbine engines and the

spokes by all-electric, fuel-cell electric and hybrid electric aircraft) (Oliveira et al., 2021).

The maximum estimated range of the 'Hydrogen for Gas Turbines' bubble in Fig. 1 is shown at 5500 nm based on an aircraft designed to go from any place on the planet to any other with only one stop (Huete, J; Nalianda, D, Pilidis, 2021). In the longer term, second, third and fourth generation aircraft could be designed to exploit the synergies between electrical and hydrogen systems (Goldberg, 2018; Goldberg et al., 2018; Nalianda and Singh, 2014; Silberhorn et al., 2020) to deliver improved engine and aircraft performance.

The initial and original idea of this research line was to modify existing aircraft designs to integrate hydrogen powered turbines rather than designing optimized new hydrogen powered aircraft that resemble payload and range capabilities of existing kerosene powered aircraft (Brewer et al., 1975; Brewer and Morris, 1976; Clean Sky 2 and European Commission, 2020; Troeltsch et al., 2020; Verstraete, 2015; Westenberger, 2003b). It was, therefore, accepted that, because hydrogen would need to be placed inside the fuselage, a derived aircraft will deliver a lower range and a reduced payload. The aspiration was to be able to adapt a large capacity long range aircraft to a lower capacity and range that still offers significant benefits in terms of decarbonization i.e., that tackles a segment with high CO₂ emissions. It was soon apparent that medium and large aircraft could be modified and still fly with reasonable efficiency. But the largest aircraft examined had wings that were too large, bigger than what would be required for hydrogen propulsion, since aircraft take-off weight is substantially reduced, and hydrogen is better stored in rounded tanks inside the fuselage rather than in slim tanks inside the wings. This difficulty greatly influenced the current approach of the research. Some aircraft designs cannot be modified effectively to hydrogen propulsion. So, to accelerate product development, it may be beneficial to use existing engine and wing designs, adapted into the fuselage of a different aircraft design. While the adjustment will require significant effort, it gives a lower risk alternative to designing a new wing and a new engine to best fit the aircraft. With such a larger design space, it was possible to cover most of the popular segments

in current civil aviation (Clean Sky 2 and European Commission, 2020; Schäfer et al., 2019).

This derivative design approach will enable a reduction of development costs, concentrate scarce research resources in the key hydrogen focused components. Such initial aircraft designs may not be optimal; but will greatly reduce development time and risk. This could, hopefully, bring entry into service forward by 15 years or more. The savings in terms of lower CO₂ emissions achieved would be colossal. Subsequent generations of designs, capitalizing on the experience of this first 'innovation wave' would move to more optimal arrangements and layouts, for example a Blended Wing Body aircraft. The authors ask: why not fully decarbonize civil aviation in 50 years? Figure 4.2 shows a scenario, where five technology options are compared, all with the hypothesis of a continuous growth in air traffic of 4% per annum. Baseline shows CO₂ emissions with the continued use of current state of the art equipment. '25% Tech +' and '50% Tech +' show the benefits of immediate introductions of technology improvements that would yield, in 100 years these respective improvements. '50% Tech Gradual' shows a gradual move to 50% and 'H2+Electric ?' shows a fully decarbonized scenario. The authors believe that the zero-carbon option in 50 years is feasible if decisive and wide-ranging international action is taken.

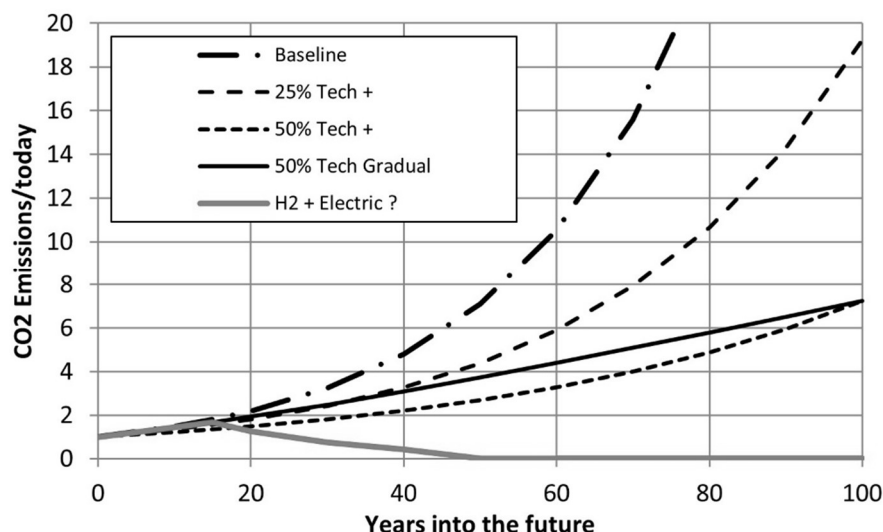


Figure 4.2: Comparison of five technology options in CO₂ emissions

This study examines and suggests possible aircraft designs to implement the first hydrogen fuelled innovation wave to offer aircraft decarbonization scenarios long before 2050. It maximizes the use of current state of the art using designs derived from advanced existing aircraft concepts. Part 1 describes the evaluation method and the case of a long-range aircraft. Part 2 introduces the whole family to bring about swift and holistic decarbonization based on designs derived from existing advanced concepts.

4.3 Adapting existing aircraft designs

Minimum changes to existing aircraft designs are discussed herein, knowing that optimum solutions will appear later in subsequent innovation waves. To enable these derivative designs, the fundamentals for the adaptations proposed here revolve around the need to locate the fuel tanks inside the fuselage and the use of gas turbines based on existing state of the art machines modified for hydrogen combustion.

It is assumed that hydrogen is stored in cryogenic conditions at 20-30K in liquid – vapor equilibrium inside the fuselage in insulated tanks. The tanks have been placed inside fuselage rather than in the wings, to achieve a better heat leakage performance of tanks with a rounder section. The passenger cabin and cockpit must be isolated from the hydrogen tanks. Precise methods for isolation and safety issues require further consideration but it is not covered here. However, it is widely accepted that the overall safety level of hydrogen is at least as high as kerosene, providing enough investment and attention to details is performed (Benson et al., 2019; Haglind, Hasselrot and Singh, 2006; Khandelwal et al., 2012, 2013). In this study, passenger compartment sections are used for fuel storage. An analytical evaluation indicated that the added weight (tanks, fuel system and fuel) is lower or similar to the weight removed (passenger, seats and furniture removed) for tank gravimetric efficiencies in the order of 0.4, and therefore, there is no increased structural requirement in the fuselage section (Gravimetric efficiency is the ratio of weight of hydrogen to weight of full tank, including the tank plus hydrogen plus accessories). Tanks may be placed in the

forward, aft passenger compartment, in the cargo section or in a separate deck in double deck aircraft. Location of tanks have an impact on both, centre of gravity location and shift with fuel consumption.

Figure 4.3 shows schematically a sample of tank location and main components of the fuel storage system. Most of these technologies are in TRL 2 to 4 requiring extensive research and development activities.

The OEW of the modified aircraft increases due to the tanks. Since Hydrogen is three times lighter than Kerosene for an equal energy content, TOW is importantly reduced. ZFW reduces, since in this approach, tanks are substituting passengers, and so it does the landing weight. Note that compared to a kerosene aircraft of same passenger capacity, and hence shorter fuselage and no hydrogen tanks, ZFW and landing weight would be larger. But when considering a derived aircraft, with a fixed fuselage size, ZFW and landing weight reduces.

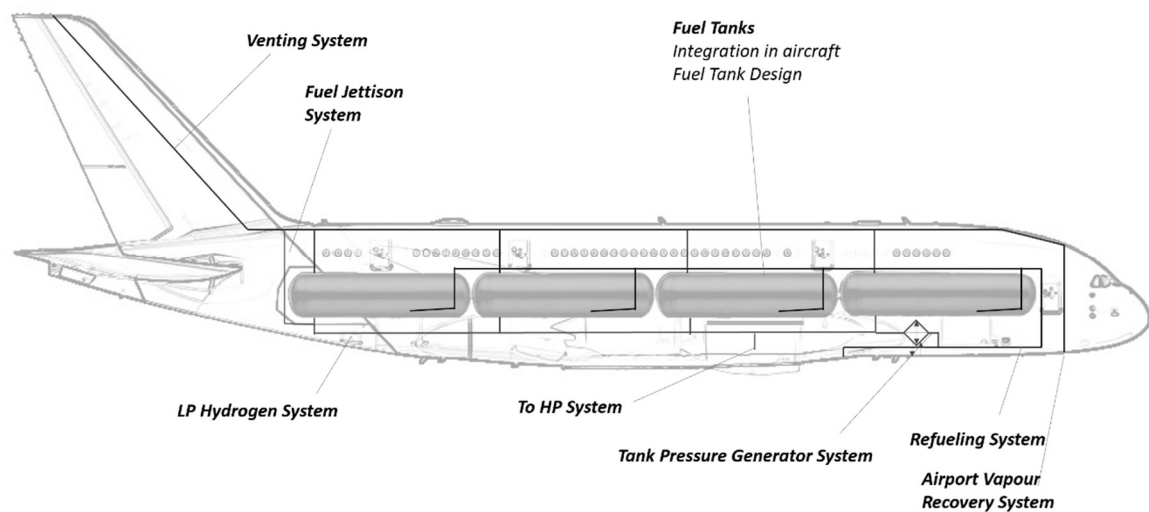


Figure 4.3: Schematic of main components of fuel system of a hydrogen powered gas turbine aircraft

For long range aircraft, with a large number of passenger rows replaced, reduction in landing weight is significant. Such large wings are no longer required for landing, nor are they required for take-off. Keeping the same wings would

bring no benefit on any flight segment, and impose a lower cruise lift coefficient, leading additionally to a dead weight to the whole mission, increasing energy consumption and reducing range drastically. In this cases, smaller wings have been evaluated, adapted from smaller aircraft, according to the methodology explained in section 3.

Attaching an existing wing to a different fuselage will require a significant design and development effort. For example, the loss of bending relief due to the absence of fuel in the wings calls for further structural consideration. The additional weight of a sturdier structure will be partially, or wholly, compensated by the absence of any fuel tanks and ancillary equipment within the wing. Nonetheless if appropriate existing wings, existing designs, and dimensions are used, this enables the continuing support of existing suppliers, machinery, technology, manufacturing methods and engine attachments. Undoubtedly this will shorten and reduce the risk of development of hydrogen aircraft. The same reasoning applies to the empennage.

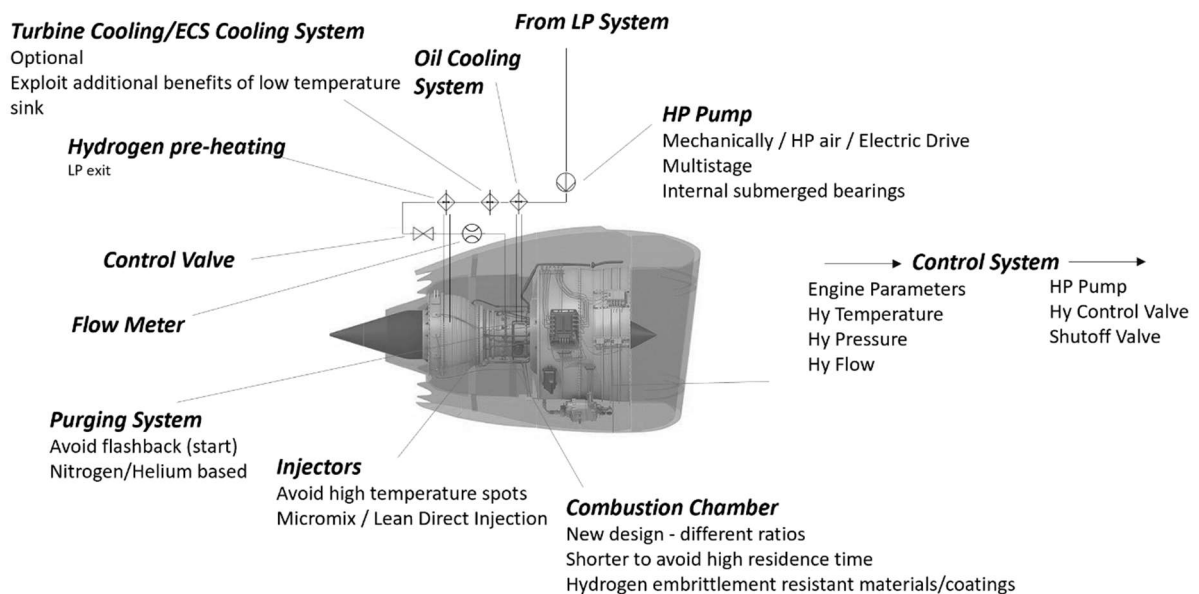


Figure 4.4: Main modifications to be performed to existing gas turbines to burn hydrogen. Image courtesy of 3dhorse modified by the authors

The required thrust is also lower, due to a lower TOW. Usually, engine families offer a range of thrust for different applications. The engines considered here are de-rated engines adapted for hydrogen, if possible, from the same engine family as the original aircraft, except when a different wing is considered. In such cases a different but appropriate engine family is chosen.

For the first innovation wave a minimum number of hardware changes are proposed. In addition to re-designing the combustion chamber, the minimum change that needs to be adopted with the engine cycle is the implementation of facilities to evaporate the hydrogen prior to its entry into the combustion chamber (Haglind, Hasselrot and Singh, 2006). Figure 4.4 illustrates the main changes needed to adapt existing gas turbine designs to burn hydrogen.

	Take-off			Cruise		
	<i>Jet A-1</i>	<i>H₂</i>	<i>H₂</i>	<i>Jet A-1</i>	<i>H₂</i>	<i>H₂</i>
		<i>Same TET</i>	<i>SameThru st</i>		<i>Same TET</i>	<i>SameThru st</i>
Mass Flow (kg/s)	1391.0	1418.3	1378.6			
Fuel Flow (kg/s)	3.5827	1.4043	1.2709	1.3700	0.5272	0.4896
TET (K)	1,969	1,969	1,908	1,809	1,809	1,767
Nett Thrust (kN)	436.0	465.2	436.1	89.1	94.6	89.1
SFC (g/kN/s)	8.22	3.02	2.91	15.38	5.57	5.49
ESFC (J/N/s)	353.2	358.6	346.2	661.2	661.8	652.6
Core Flow (kg/s)	153.2	156.1	148.3			

Table 4.1: Comparison of performance of a gas turbine burning kerosene – Jet A-1 – and hydrogen

Engine performance is not substantially changed when adapted for hydrogen fuel, as shown in Table 4.1. For comparison purposes, SFC is also expressed as

ESFC, similar to the concept of Heat Rate, extensively used in land-based gas turbines. This is necessary, due to the very large difference in FCV, lower fuel calorific values, 120 and 43 MJ/kg for hydrogen and kerosene respectively [10]. However, small differences in engine performance figures compared to (Huete, J; Nalianda, D, Pilidis, 2021) are due to a cycle optimization in the current models following (Mourouzidis, 2016).

An assessment of engine performance at various flight conditions has also been carried out as shown in Figure 4.5. Trends are identical to kerosene, although the absolute values differ, particularly the specific fuel consumption.

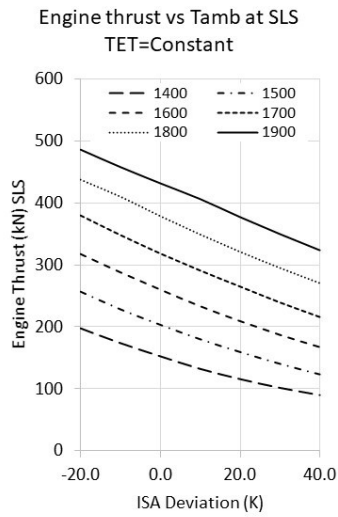


Fig. 4.5a Thrust vs SLS ISA Temp. Deviation

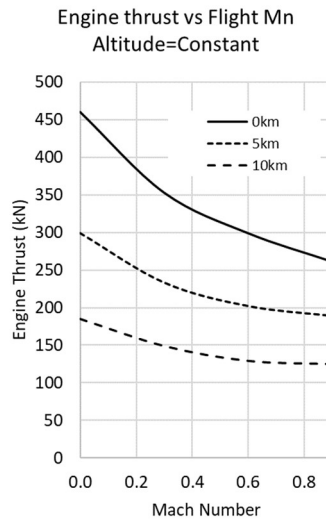


Fig. 4.5b Thrust vs Flight Mach Number

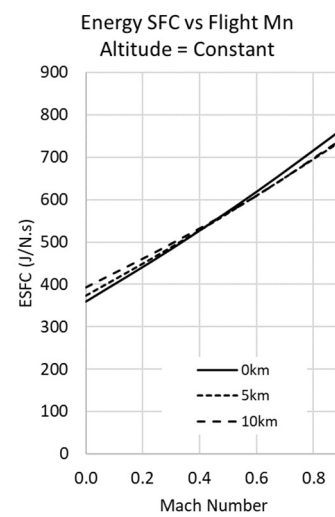


Fig. 4.5c ESFC vs Flight Mach Number

4.4 Evaluation method

While previous studies have explored a wider design space in terms of aircraft configuration (Goldberg, 2018; SEFAIN, 2000) or optimum tube and wing aircraft (Brewer et al., 1975; Brewer and Morris, 1976; Clean Sky 2 and European Commission, 2020; Verstraete, 2015; Westenberger, 2003a) over the conventional flying segments, this study is limited to adapted existing aircraft. The design space has been constrained by a take-off runway lower than 3,000 m, an approach speed of 80 m/s, a landing length lower than 2,000 m, provisions specified in CS-25 for take-off, climb, approach and landing, and a configuration of a tube and wing aircraft with fuselage, wing and empennage dimensions,

features and materials identical to any existing aircraft, to be powered by an existing engine modified for hydrogen usage. The objective function has been range, to be maximized. For any given existing fuselage size, there are three main variables: tank volume, wing area and engine power. Empennage has been selected or checked against tail volume design rule.

The starting point of the evaluation for any of the aircraft family members is the utilization of an existing fuselage design. For any given fuselage, a first iteration is performed with its corresponding wings, empennage, and engines. An iterative sub-process to accommodate a reasonable number of passengers while providing enough space for hydrogen tanks to reach a useful range, shifting tank locations and size. This sub-process has led to several iterations and various successful potential members of the aircraft family in some cases. Existing aircraft dimensions have been obtained from public sources, mainly Janes (Janes, 2020) and Aircraft Characteristics documents published by Airbus (AIRBUS, n.d.) and Boeing (BOEING, n.d.). A weight model has been produced from Torenbeek correlations (Torenbeek, 1982) that estimates weight of aircraft components: fuselage, wings, empennage, landing gear, engines and systems. It has been validated through several existing aircraft in the range of the studied aircraft at an OEW level. While correlations are based on historical data and non-dimensionless parameters, the corrections and validation against most modern aircraft, yield a weight component estimation within 5% at an aggregate level.

Fuel tank and system weight has been added, calculated from the volume employed to store hydrogen, through the gravimetric efficiency of the tanks. Several tank designs and technologies have been reported by Brewer (Brewer, 1991; Brewer et al., 1975), Colozza (Colozza, 2002), Mital (Mital et al., 2006), Verstraete (Sharifzadeh, Verstraete and Hendrick, 2015; Verstraete, 2009, 2013; Verstraete et al., 2010) and Goldberg (Goldberg, 2018), among others, leading to gravimetric efficiencies in the range of 0.7-0.8. Experimental work on HALE revealed that foam insulated LH₂ tanks can be successfully tested with zero boil-off for the first 20 hours of mission with a gravimetric efficiency of 0.6. [36]. However, a recent EU funded study from a Joint Undertaking between Fuel Cell

and Hydrogen and Clean Sky2, shows the concern of hydrogen technology companies to develop a high gravimetric efficiency tank and reports that “the latest concepts for commuter aircraft have a gravimetric index as low as 20 percent” (Clean Sky 2 and European Commission, 2020). Very likely, discrepancies between mission requirements, and fuelling strategies, between NASA work and EU work along with a reference framework on automobile applications developed by the latter explain the differences in gravimetric efficiencies. A value of 0.45 has been considered for this work.

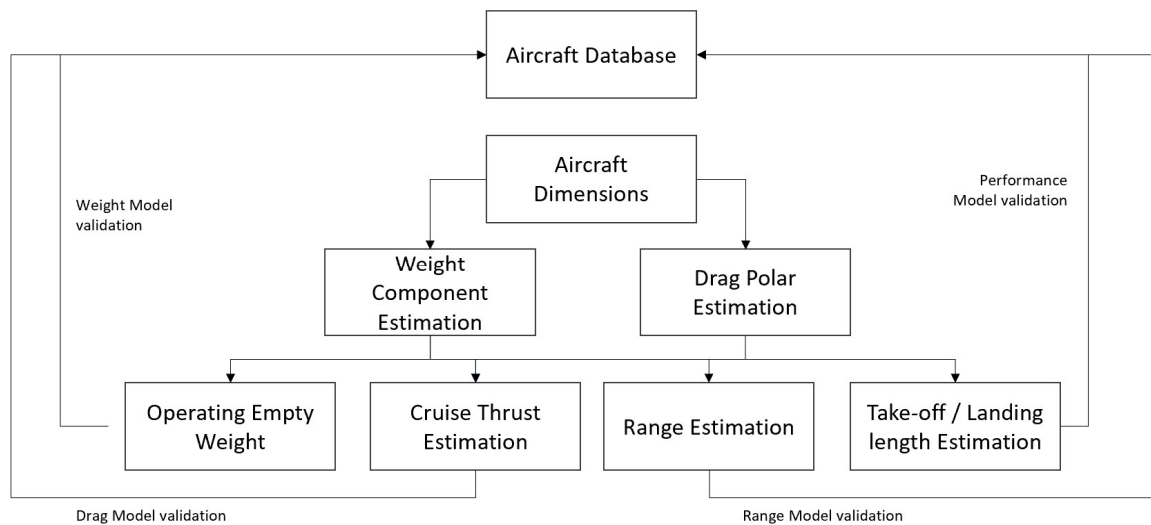


Figure 4.6: Aircraft Performance Evaluation method diagram

Engine thrust is, at this point, guessed in order to complete the weight estimation. A drag polar model has been set using method and correlations developed by Raymer (Raymer, 1992) except for the drag divergence Mach number calculation, in which Korn equation has been used (MASON, 1990) for convenience. Validation of the model has been done through both, installed thrust and range with an estimated error < 5% for most existing aircraft.

Performance is then evaluated over all flight segments following the standard procedure explained in common textbooks (Fielding, 2017; Loftin, 1980; Raymer, 1992; Torenbeek, 1982) and checked against constraints. Thrust is iterated until there is no extra power installed and it is within the engine family thrust range. If

the aircraft meets all the constraints while having the right wing, which is checked by an approach speed higher than 65 m/s, then range is estimated by the Breguet range equation. If range is not within the most popular aviation segments, another iteration is tried for a higher fuel and lower passenger capacity split. If the loop is successful, the aircraft is considered a potential candidate for the family. In case the aircraft has low approach speed, indicative of a larger than required wing, then a smaller wing from another existing but smaller aircraft is selected and the process is repeated until a better match is achieved. The compound aircraft will require redesign of certain areas to ensure acceptable aerodynamic and mechanical performance.

4.5 Very large aircraft basic options – HVLMR AND HVLLR

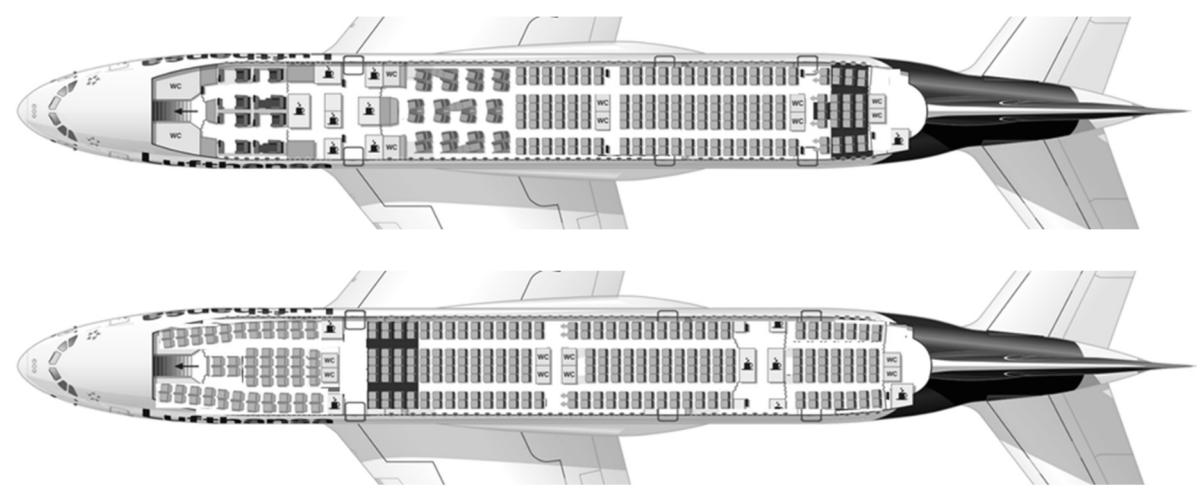
Within the scope of this study a very large aircraft based on the size of an A380, has been evaluated as an option to utilize hydrogen.

With dimensional data from (AIRBUS, n.d.), a first iteration with 845 m² wings (A380) is performed. Two basic lay-out options for fuel tank placement were generated by dedicating one deck to passenger accommodation and the other deck for hydrogen tanks. Other options, combined with fuel in cargo compartments, wings or additional tanks in aft fuselage sections have been generated during the optimization process, and these will be dealt with in part II of the paper.

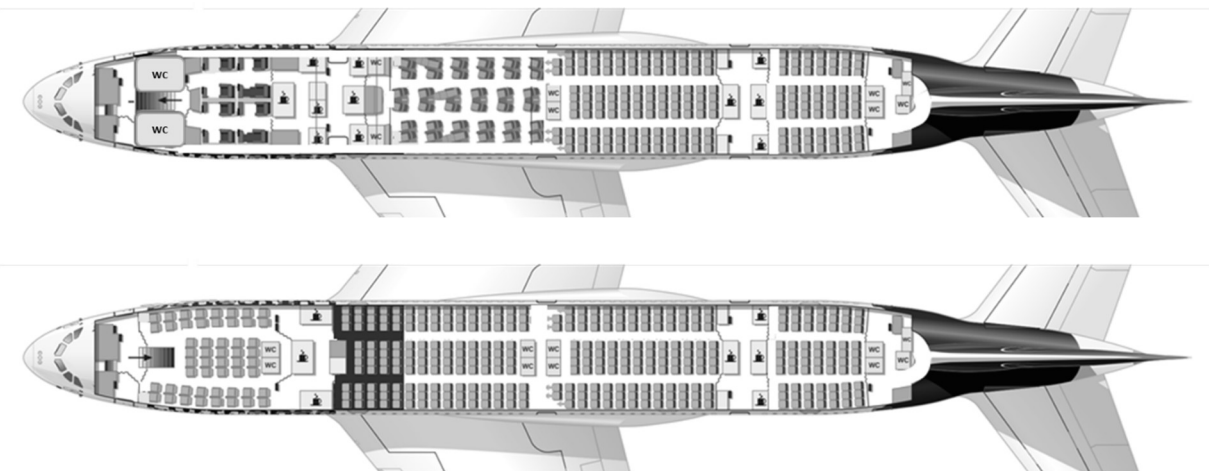
	Main Deck	Upper Deck
Available volume (m ³)	775	530
Available volume Utilization	0.80	0.75
LH ₂ Usable Volume (m ³)	551	353
LH ₂ Usable Capacity (t)	38.24	24.52
Tank Weight (t)	46.74	29.97

Table 4.2: Tank capacity and Weight of Hydrogen Powered Very Large Aircraft Basic Options

Table 4.2 shows tank capacities in both decks of an aircraft of the A380 kind. “Available volume utilization” in the table accounts for the non-utilized deck volume due to roundness of tanks as derived from drawings produced by the authors. Usable capacity has been calculated for a maximum operating pressure of 140 kPa., and a minimum ullage volume fraction of 3.5%. Weights have been estimated with a gravimetric efficiency of 0.45.



(a)



(b)

Figure 4.7: Hypothetical cabin lay-out of double deck very large aircraft: (a) Upper Deck and (b) Main Deck. Image courtesy of Lufthansa modified by the authors

Passenger capacity in each deck is depicted in the Figures 4.7(a)(b). Upper Deck 308 passengers in 2 –class arrangement (52 Premium Economy + 264 Economy (332 Passengers) or 44 Business Class + 264 Economy (308 Passengers) or 8 First Class + 24 Business Class + 192 Economy (224 Passengers). Similarly, Main Deck can accommodate 372 passengers in 2-class arrangement (52 Premium Economy + 336 Economy (388 Passengers) or 36 Business Class + 336 Economy (372 Passengers) or 8 First Class + 36 Business Class + 194 Economy (238 Passengers).

Designs showed approach speeds in the order of 60 m/s, landing lengths below 1,500 m and take-off length below 2,000 m. Indeed, such large wings with bulky kerosene tanks built-in was not required and had no positive effect on any flight segment. Lift coefficient at initial cruise was in the order of 0.35 with a lift to drag ratio around 16, compared to 18 from the same aircraft running on kerosene. Range was 2,700 nm and 4,200 nm for the aircraft with passengers in the main and upper deck, respectively.

New iterations with wings of 465 m² (A350), 443 m² (A330 neo), and 363 m² (A340) were carried out as per Table 4.3 and lay-out option evaluated in Figure 4.8. with tanks in (a) upper deck and (b) main deck.

	Wing Iteration			
	1	2	3	4
Wing:				
Area (m ²)	845.00	465.00	443.00	363.10
Span (m)	79.80	64.00	64.75	60.30

Table 4.3: Characteristics of Wings of evaluated for the Hydrogen Powered Very Large Aircraft

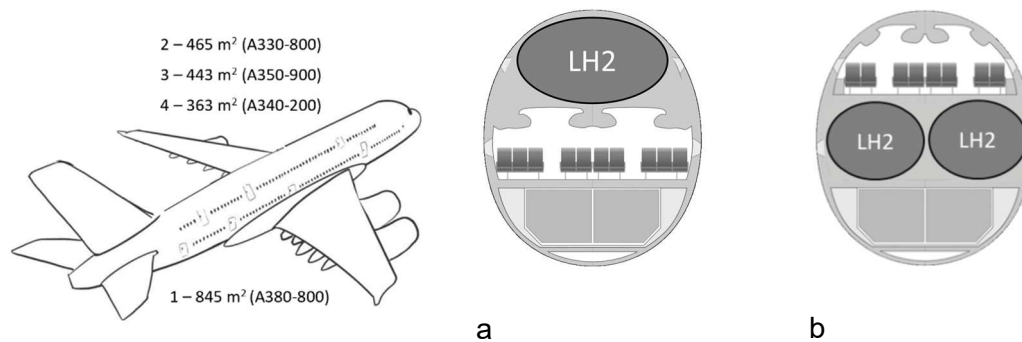


Figure 4.8: Wing size iterations and basic lay-out options evaluated

Figure 9 shows the thrust to weight ratio vs wing loading (aircraft matching chart) and the relative position against peers of the iterations for both lay-out options using the nomenclature defined in Fig. 4.8. First impression is that all evaluated aircraft have a higher thrust to weight ratio than similar kerosene aircraft. In case of iteration 1 it is due to a low wing loading at cruise that makes the aircraft to operate a low lift to drag ratio. Lay-out option b has a higher take-off weight, which improves the wing loading and demands a lower thrust to weight ratio. In the case of iterations 2 to 4, although wing loading improves significantly, to the level of existing kerosene aircraft, aerodynamic efficiency of the aircraft with smaller wings – wetted area per unit wing area – worsens, and the cruise thrust required increases, leading to a higher thrust to weight ratio. It should be noted that for iteration 4, wing loading is too high (showed in the graph at take-off), as for a hydrogen aircraft, wing loading variation during flight is much lower than for a kerosene aircraft. Approach speeds for iteration 4 are 79 and 83 m/s for options a and b, respectively. It was decided that iteration 3 is the minimum allowable wing with an approach speed in the order of 75 m/s. Take-off or climb requirements did not pose any constraint.

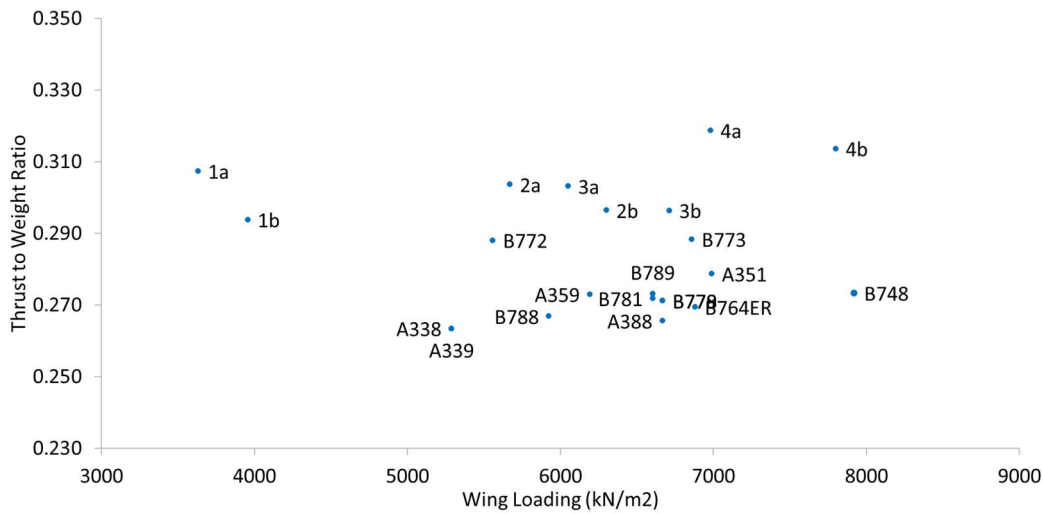


Figure 4.9: Aircraft matching chart of evaluated options

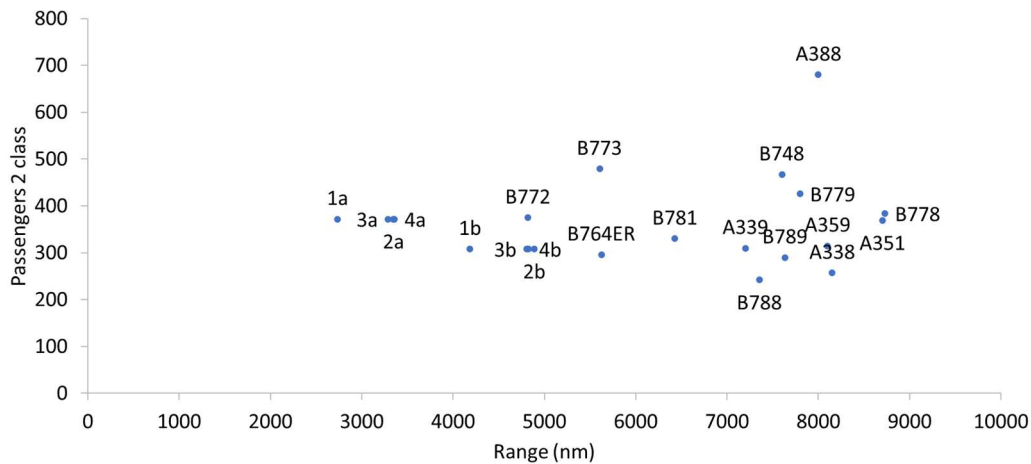


Figure 4.10: Passenger/Range diagram of evaluated options

The range of iterations and lay-out options is compared in Figure 4.10. As expected, the range of all evaluated hydrogen fuelled aircraft is much lower than comparable conventional aircraft. Volume limitations makes the energy stored on board much lower in a hydrogen aircraft. The range increases with lower wing area mainly as a consequence of reducing the OEW of the aircraft. By changing to a smaller wing, on an A380 fuselage, the range was increased by around 600 nm to 3,300 and 4,800 nm for lay-out options a and b, respectively, and installed thrust reduced by about 15%. Still highly popular aviation segments include up to

5,500 nm and Part II includes additional lay-out options for longer ranges. A 5,500 nm aircraft range is very attractive because it allows flights to anywhere with only one stop.

Aircraft 3a and 3b are selected for the aircraft family, named as HVLMR and HVLLR, respectively. Table 4.4 shows main characteristics and results for these aircraft in comparison to similar existing aircraft.

	787-8	A350-1000	777-9	HVLMR	HVLLR
<i>Main aircraft dimensions</i>					
Wing Area (m ²)	377.00	443.00	516.70	443.00	
Wingspan (m)	60.12	64.75	71.80	64.75	
MAC (m)	7.07	7.95	8.06	7.95	
Wing Aspect Ratio	9.59	9.46	9.98	9.46	
Length Overall (m)	56.72	73.79	76.70	73.00	
Cabin Height (m)	5.94	6.09	6.20	8.41	
<i>Passenger capacity</i>					
Max Density Pax	359	480	426	388	332
2 class Pax	242	369	349	372	308
<i>Engines</i>					
Number of Engines	2	2	2	2	
Thrust ISA SLS (kN)	298	431.5	467	406	441
<i>Weight</i>					
MTOW (ton)	227,930	316,000	351,534	273,557	303,426
Max. landing (ton)	172,365	236,000	266,258	251,318	274,890
Max Zero-fuel (ton)	161,025	223,000	254,918	250,383	273,432
Max. payload (ton)	44,000	64,000	73,500	49,920	44,880
OEW (ton)	119,950	159,000	181,400	200,463	228,552
<i>Fuel Capacity</i>					
Max Fuel Capacity (l)	126,206	158,791	207,876	385,220	600,490
<i>Cruise</i>					
Cruise altitude (m)	10667	10667	10667	10667	

Cruise Mach Number	0.85	0.85	0.85	0.80	
<i>Take-off and landing</i>					
Take-off Field Length (m)	2600	2900	2900	2,346	2,556
Landing Field Length (m)	1600	2100	1900	1937	2012
Approach Speed (m/s)				74	77
<i>Range</i>					
Max Payload (nm)	5500	5500	5685	2,618	3,260
Design Payload (nm)	7800	8300	7,552	3,289	4,807
<i>Energy efficiency</i>					
ETWR (MJ/pass.km)	1.12	0.89	0.88	1.32	1.69

Table 4.4: Main aircraft characteristics of evaluated options in comparison to similar existing aircraft.

Compared to an aircraft of similar passenger capacity, a hydrogen aircraft will have a larger and heavier fuselage due to the need to store cryogenic low-density hydrogen inside the fuselage. It will also require larger wings. For long range applications, large fuel tanks volume involves either a double deck or extended length fuselage. Therefore, it will have a larger OEW and will also be heavier at landing. As landing speed is limited by wing loading, wings have to be slightly larger for the same landing speed. Therefore, the aerodynamic efficiency will be lower and will achieve a lower L/D ratio. Wing loading at take-off will be also lower. A larger fuselage results in a higher Zero Lift Drag Coefficient. Maximum L/D will therefore be lower. Additionally, wing loading will be lower during the flight, if it is to be the same at landing due to reduced fuel weight, resulting in even lower L/D ratio. It is therefore a volume limited aircraft, with lower payload and range compared to kerosene aircraft. If measured against a similar fuselage size aircraft, wings will be considerably smaller, so it will always look like a large body/small wing assembly. Range diagrams for the optimum derivative aircraft designs evaluated here are shown in Figure 4.11.

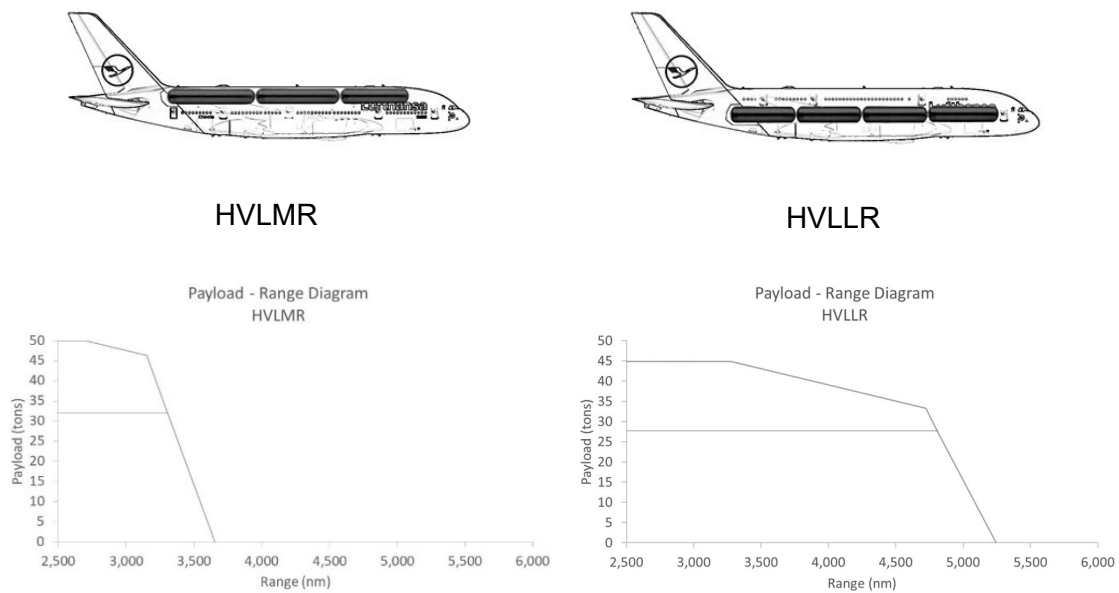


Figure 4.11: Range diagrams of Hydrogen Powered Very Large Aircraft Basic Options.
Image courtesy of Lufthansa modified by the authors.

4.6 Conclusions

A reliable method for evaluating suitability of derived designs from existing aircraft to use liquid hydrogen as a fuel has been developed. Adaptation of state of art aircraft or engine platforms to burn hydrogen fuel instead of kerosene will shorten the path towards clean aviation substantially.

A case study for a Very Large Aircraft shows that a fuselage of the A380 size is quite suitable for LH₂. Optimum wings for such an airframe would be in the order of 450 m², close to the A350 size. Thrust requirements broadly match actual thrust installed in A350. Two basic lay-out options have been analysed, with fuel tanks installed in the upper deck and lower deck. Aircraft can carry 372 passengers over 3,300 nm (London-New York) and 308 passengers over 4,800 nm (London – Pekin), respectively.

A faster than commonly thought introduction of sustainable aviation can be achieved in 15 years if existing design and technology is used and adequate investment is secured. Focus could in such case be derived to key hydrogen

specific systems. Resulting conventional, tube and wing aircraft may not bring all benefits of hydrogen powered aviation, but they could contribute significantly to emission abatement and smooth the transition to decarbonization.

There are some balancing uncertainties in the method. For example, correlations used are based on conventional aircraft, which use kerosene. When switching fuel to hydrogen that is lighter, it is expected that component weight will be lower for the same component dimensions, since the overall density of system will drop, and so will some sections of the structure. In the range calculations, climb and approach segments range have been disregarded. Careful overall fuel fractions for climbing, diversion and approach have been used, as well as a 6.5% of fuel fraction for reserves. Nonetheless most of these assumptions make the authors believe that the method is conservative. This makes it reliable and gives confidence that the designs proposed are a good starting point on which to base the development of airliners of the first innovation wave to decarbonize aviation.

4.7 Acknowledgement

The authors acknowledge the support of Lufthansa via the provision of artwork used in this paper and for their interest in this environment enhancing project.

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5 PROPULSION INTEGRATION PROPOSAL FOR AN EARLY ENTRY HYDROGEN CIVIL AIRCRAFT FAMILY. PART II HOLISTIC COMPOSITION

Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, P. 'Early Entry Hydrogen Civil Aircraft Family Propulsion Integration Proposal (II): Holistic Composition', Unpublished

5.1 Abstract

'Greening' civil aviation is imperative, avoiding the potential economic and social damage that would follow constraining aircraft operations. Radical propulsion technologies are needed; very likely to succeed in this challenge is Green Hydrogen. Among the problems accompanying such a fundamental change in aviation are the integration of Hydrogen tanks into an aircraft and the conversion of airport terminals. To circumvent these, several innovation waves are advocated, the first maximising use of existing technology and infrastructure: later waves delivering the whole underlying advantages of Hydrogen. This research investigates the degree to which existing aircraft can be redesigned for Hydrogen. A first generation of Hydrogen airliners is proposed in which aircraft is limited to current dimensions, features, and materials. Part II of the paper presents an airliner family that could cover up to 75% of current CO₂ emissions based on three aircraft. Regional and medium haul markets can be successfully served with modified versions of a conventional narrow body and a widebody aircraft, respectively. Long range missions are limited by current aircraft dimensions. A redesigned twin deck aircraft could transport up to 380 passengers over ranges up to 4,800 nm.

Nomenclature

ETWR	Energy to Work Ratio (MJ/pass.km)
GT	Gas Turbine
HVLER	Hydrogen Very Large Aircraft Extended Range
HVLLR	Hydrogen Very Large Aircraft Long Range
HVLMR	Hydrogen Very Large Aircraft Medium Range
HVLSR	Hydrogen Very Large Aircraft Short Range
ISA	International Standard Atmosphere
LH ₂	Liquid Hydrogen
MAC	Mean Aerodynamic Cord (m)
MTOW	Maximum Take-Off Weight
NO _x	Nitrogen Oxides
OEW	Operating Empty Weight (tons)
SFC	Specific Fuel consumption (kg/s/MN)
SLS	Sea Level Static
TET	Turbine Entry Temperature
TOW	Take-off Weight
TRL	Technology Readiness Level
ZFW	Zero Fuel Weight

5.2 Introduction

Current emissions of aviation, in 2020, are of nearly 1 Gtons of CO₂ emissions per year (ICTT, 2020), and it will reach 2-3 Gtons at the well consolidated yearly growth of 3- 4% by 2050. Holistic decarbonisation can be accomplished by the integration of a hydrogen propulsion system into existing aircraft the cover most flying segments. Hydrogen not only removes carbon, but it also eliminates smoke, sulphur, aromatics and has great potential for a very low NO_x signature. Up to 35% of emissions and fuel consumption are originated in flights with a range bellow 1,000 nm (Clean Sky 2 and European Commission, 2020; Schäfer et al., 2019). A number of technologies and architectures are very promising for commuter and regional segments (AIRBUS, 2020b; Eviation, 2021; Finger, Braun and Bil, 2020; LILIUM, 2020; ZEROAVIA, 2020; ZUNUM, 2021). A combination of electric, fuel cell and hybrid electric aircraft are likely to become short- and medium-term solutions for these segments. However, current limitations of gravimetric energy density of batteries and power density of fuel cells impede payload and range to be extended far beyond the 1,000 nm range (Clean Sky 2 and European Commission, 2020). Nearly 60% of CO₂ emissions are produced in flights ranging from 1,000 to 5,500 nm. For these longer ranges hydrogen powered turbine aircraft can offer a valid solution. (Clean Sky 2 and European Commission, 2020; ENABLEH2, 2020; Khandelwal et al., 2013; Troeltsch et al., 2020; Verstraete, 2009; Westenberger, 2003). But developing Hydrogen aviation is a colossal investment in aircraft, engine and airport infrastructure development that will take decades and poses large technological and market development risks. This paper investigates an approach based on successive waves of innovation for short to long haul segments and focus on a first wave in the integration of hydrogen gas turbines for civil aviation to bring forward the benefits of decarbonisation.

Part I of these article series (Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, 2021) describes a rigorous and validated method for the evaluation of hydrogen propulsion integration. For the very large aircraft, a complex integration of existing fuselage designs, wing and engines inspired by different aircraft combined in a new design was investigated. It shows a case study of a very large aircraft of 600-

ton MTOW adapted with wings and engines of a 300-ton MTOW airliner modified for hydrogen usage. The resulting aircraft capacity is between 300 and 370 passengers and the range varies between 3,300 and 4,800 nm.

Part II details a full aircraft airliner proposal that covers most popular segments of current civil aviation. Previous studies have mostly focused on specific aircraft concepts rather than a family of aircraft. Brewer (Brewer, 1976a; Brewer et al., 1975) conducted parametric design comparisons of liquid hydrogen aircraft and conventional aircraft in a range of passenger capacity and range, reaching the conclusion that “the more energy required to perform the mission, the greater the advantage to be gained by using a high energy fuel” (Brewer, 1976b). Cryoplane project (Westenberger, 2003) revisited the matter with an objective to “identify aircraft configurations, which meet the requirements of efficient and safe operation in all aircraft categories, from business jets to very large, long-range aircraft”. Verstraete focused only on long range aircraft (Verstraete, 2009). More recently, the EU Clean Sky / FC Joint Undertaking (Clean Sky 2 and European Commission, 2020) published a study in which five of the aircraft categories are studied and a preferred aircraft configuration and power is presented for each category. Part II of these article presents an aircraft family that covers current high emission segments conceived for short term development, although not optimal in performance.

Figure 5.1 shows air traffic characteristics (Schäfer et al., 2019) where cumulative aircraft movements (departures), NO_x, Revenue Passenger Kilometres (RPK) and fuel used are shown on a basis of aircraft range. For large scale decarbonisation to take place, the whole range of operations needs to be addressed. A ‘portfolio approach’ through a large aircraft family is proposed here. Figure 5.1 bottom extension, sharing the horizontal axis, shows the highest fuel consumption or CO₂ emission segments produced by the authors from data from (Airbus, 2019; Boeing, 2019; Clean Sky 2 and European Commission, 2020).

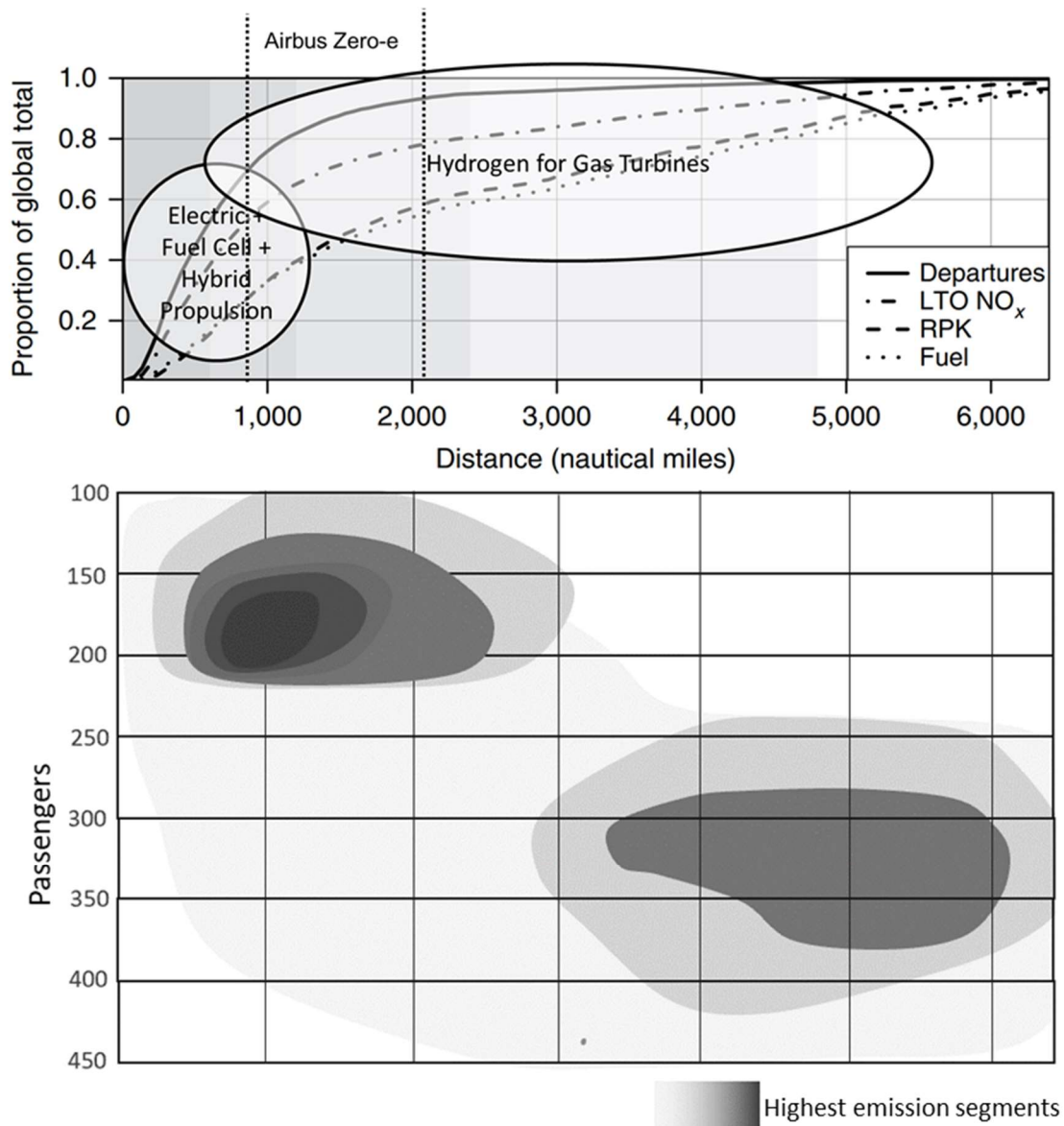


Figure 5.1: Commercial Aircraft Traffic extended downwards to show projected highest emission segments. Source: Schafer, AW et al. (Schäfer et al., 2019) annotated by the authors

The dark spot on the left/top of the lower diagram of Fig.5.1 (short range bubble), 500 to 1,500 nm and 150 to 220 passengers, represent an area operated on the highly popular single aisle aircraft, such as the A220 and A320 series and the 737MAX. It includes operations between nearby cities or to and from hubs as well as low-cost point to point flights between secondary cities. With a maximum range in the order of 3,000 nm, these aircraft are mostly flown for shorter ranges, as has also been previously reported (Rutherford and Zeinali, 2010). Flexibility in

terms of range required today by operators, more intensely by fast growing segment of low-cost operators, makes the narrow body aircraft the preferred option.

The second highly contaminating area is in the long haul, between 3,500 and 6,000 nm and 275 and 375 passengers. This area relates to medium and long-range flights operated on modern aircraft on A300, A340 and A350, B767 and 787. The top left part of the long-haul contaminant bubble relates to medium size wide body aircraft with a popular range on the 4,000-4,500 nm. The right bottom area corresponds to large wide body aircraft with most frequent ranges around 5,000-5,500 nm. Rapid growth of smaller wide body aircraft with very long-range capability operating non-stop long-haul flights has probably extended the bubble further up and right.

A number of different aircraft are evaluated and discussed in the following sections to assess the suitability for a quick decarbonisation.

Civil aviation transformation may also bring additional paradigmatic changes. Hydrogen aircraft naturally requires larger and longer fuselages, which would put pressure on airliner passenger capacity. Lower average aircraft capacity would congest the airports further, through an increased number of operations. Such situation may give rise to hub and spoke operations, in which high density routes are served through high capacity short and medium range aircraft fed from cities around the region through electric/hybrid aircraft. In such a scenario, hot spot of the short-range bubble would extend further down. New aircraft concepts for these potential new segments are also investigated.

5.3 Medium range aircraft – HLMR (220 pax; <3,500 nm)

A hydrogen aircraft equivalent to the kerosene narrow body aircraft, capable of confronting the short-range bubble in Fig.1 is investigated here. As explained in Part I (Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, 2021), it is expected, that due to large volume required by hydrogen within the fuselage, an existing kerosene aircraft results in a lower capacity and range when adjusted for hydrogen usage. Therefore a 250 ton, 250 to 300 pax airliner is used as a

baseline. Here, a 787 has been used, although an A330 would lead to similar results. Dimensional and limited performance data has been obtained from (BOEING, n.d.).

A 787-10 aircraft design has been conceptually adapted to hold 285 m³ of liquid hydrogen in several locations. To keep the passenger capacity above 200 pax, 100 m³ of tanks are installed in the forward cargo compartment as shown in Figure 5.2. Elliptical tanks inscribed in the deck as well as in cargo compartment optimise the available volume utilization. The remaining capacity is 234 passengers in high density (29" pitch) or 216 pax in two class (162@29"+ 54@36").

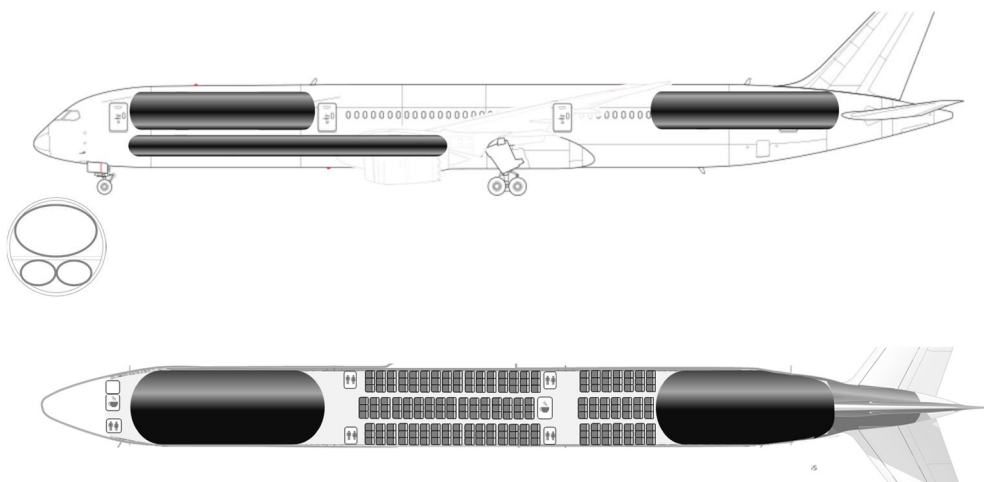


Figure 5.2: Hypothetical cabin lay-out of a medium range aircraft. Image courtesy of Norebbo (Norebbo, 2021a) modified by the authors

Separate doors and facilities for cockpit crew and cabin crew/passengers are contemplated. Emergency evacuation for crewmembers in the cockpit should be provisioned through, for example, a new top hatch as specified in (European Aviation Safety Agency, 2008).

Having no walkway between cockpit and cabin, requires the following elements to be considered, as acknowledged during early discussions on pilot-cabin

communication (Rudolf, 1972) and analysed in (SKYbrary Aviation Safety, 2020a, 2020b): (i) need to accommodate separate doors for cockpit and cabin, (ii) need to place toilets at cockpit area, (iii) it improves cockpit security but could require additional crew at cockpit, (iv) need to incorporate separate emergency exit for cockpit crew as discussed in previous paragraph, (v) no possibility to visually inspect engines/control surfaces by cockpit crew unless emergency passage is considered, (vi) No possibility to help in cabin crew in emergency situation, (vii) Reduced situation awareness by cockpit crew (viii) Current regulations seem to force independent access two ways in case of emergency. Emergency means to enable crewmembers to enter pilot compartment and vice versa could be done in a variety of ways in case regulations are clarified requiring such access. Emergency passages could be designed either on one side of the fwd. hydrogen tank or through a special designed passage through the cargo deck at a lower level.

A similar evaluation explained in Paper I (Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, 2021) has been carried out for this aircraft with dimensions and results of the iterations shown in table 5.1. In this case, wings, empennage, and engines could be kept as they are although they should be derated. Engine power will be covered in section 5.6.

	Typical Narrow Body (A321)	787-10	HLMR
<i>Main aircraft dimensions</i>			
Wing Area (m ²)	122.40	377.00	377.00
Wingspan (m)	35.80	60.12	60.12
MAC (m)	4.29	7.07	7.07
Wing Aspect Ratio	9.50	9.59	9.59
Length Overall (m)	44.51	68.28	68.28
Cabin Height (m)	4.14	5.94	5.94
<i>Passenger capacity</i>			
Max Density Pax	240	440	234
2 class Pax	206	330	216

	<i>Engines</i>		
Number of Engines	2	2	2
Thrust ISA SLS (kN)	147	338	281
	<i>Weight</i>		
Max. take-off (ton)	89,000	254,011	200,377
Max. landing (ton)	77,300	201,848	183,326
Max Zero-fuel (ton)	73,300	192,776	182,634
Max. payload (ton)	23,000	57,276	36,060
Max load of fuselage (ton)	39,700	83,676	50,100
Operational empty (ton)	46,500	135,500	146,574
	<i>Fuel Capacity</i>		
Max Fuel Capacity (l)	32,940	130,000	285,000
	<i>Cruise</i>		
Cruise altitude (m)	10,667	10,667	10,667
Cruise Mach Number	0.78	0.85	0.80
	<i>Take-off and landing</i>		
Take-off Field Length (m)	1,988	2,900	2,351
Landing Field Length (m)	1,577	1,900	
Approach Speed (m/s)			69
	<i>Range</i>		
Max Payload (nm)	2,300	4,200	2,977
Design Payload (nm)	2,800	6,950	3,551
	<i>Energy efficiency</i>		
ETWR (MJ/pass.km)	1.12	0.97	1.55

Table 5.1: Main aircraft characteristics of Hydrogen Powered Medium Range Aircraft

In relation to the aircraft taken as starting point, the 787-10, the resulting aircraft has a passenger capacity of 100 pax lower, an OEW increased from 135 ton to 147 tons due to tank weight and despite a reduction in engine thrust (and weight) from 338 kN to 281 kN. MTOW reduces to 200 ton from 254 tons due to the lighter fuel. Landing weight also reduces.

In comparison to a similar application aircraft, for example an A321neo, the fuselage is more than 24m longer despite nearly 30m of hydrogen tanks installed in the main deck. Length increase is compensated by a wider aircraft that is 9 abreast, instead of 6. Wing size is remarkably larger, 377m² and 60m span instead of 122m² and 35.8m span, showing that a kerosene aircraft wing is not optimal for hydrogen usage. Indeed, 787 wings have provisioned space for 130m³ of fuel to be stored within. Such a large wing makes the OEW of the aircraft heavier, from 46 tons to 146 tons. This increase is not only due the wings themselves, but also to the associated empennage, landing gear and engine power. Due to the nature of this study explained in the introduction, the optimisation of tube and wing aircraft could be left for a second wave of innovation. MTOW is 200 tons, compared to 90 tons of a narrow body aircraft.

Range is 3,500 nm, enough to cover the whole short-range bubble shown in Figure 5.1. Even though the aircraft can be optimised, time to market would be remarkably shorter if using an aircraft as similar as possible to existing ones, and no wing design modifications were assessed.

5.4 Double deck aircraft for long range

Part I of the paper (Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, 2021) showed a case study of a double deck aircraft fuselage, inspired in that of the A380, modified to hold large hydrogen tanks and hydrogen powered turbines. It was there developed the optimisation method that led to the choice of wings, empennage, and engines of an aircraft such as the A350. Two options were analysed: HVLMR, with tanks in upper deck and passengers in the main deck and the opposite, HVLLR, as shown in Fig.5.3. HVLLR delivered 308 pax/4,800 nm, lying in the middle of the long-range bubble of Figure 5.1. It is therefore a suitable aircraft to decarbonise part of the long-range segment that typically performed on medium size wide body aircraft such as A330 or 767.

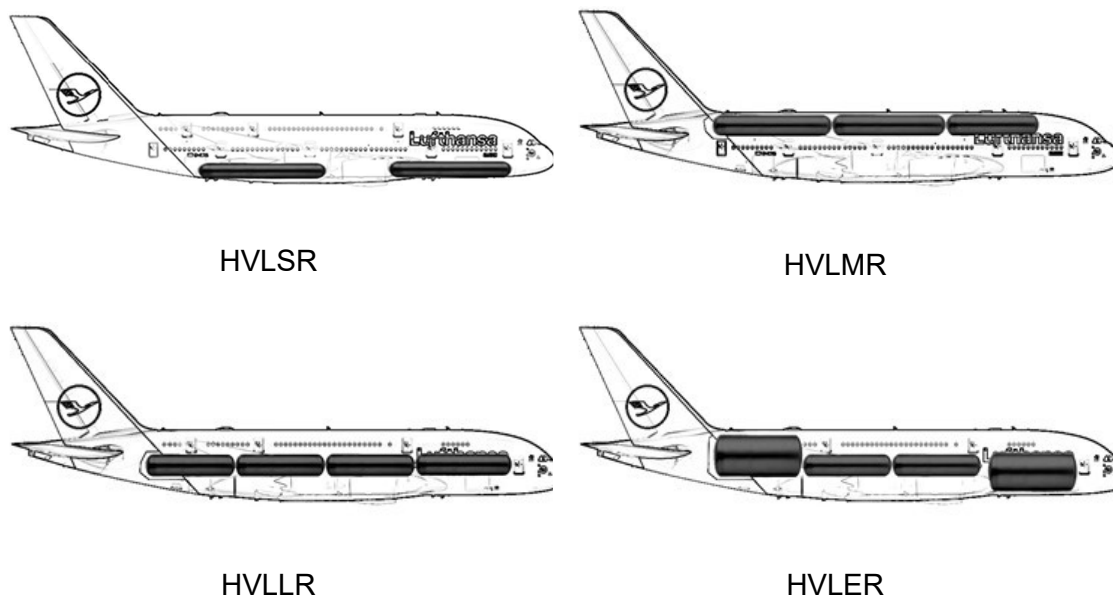


Figure 5.3: HVLSR, HVLMR, HVLLR and HVLER concepts. Image courtesy of Lufthansa modified by the authors

When compared to an aircraft of similar payload and range, the trends are equal to those observed in the medium range aircraft analysed in previous chapter. The differences in this case are not so strong since wing, empennage and engine of the original aircraft has been substituted for the most appropriate among the existing elements from other aircraft. Still, wings are from an existing kerosene aircraft with integral tanks built on them, which makes them thicker and heavier.

HVLMR was also analysed in Part I. It had a capacity of 372 pax/3,300 nm, the standard medium range capability but a larger capacity than usually run by carriers at those ranges. Therefore, sits in a segment that today is a medium to low contributor to CO₂ emissions. However, as explained in the introduction, highly congested airport may lead to flights with a higher passenger capacity, developing the so-called hub and spoke flight schemes.

Pels recently reviewed the hub and spoke networks (Pels, 2021). Higher fixed cost per take-off originated in carbon compensation schemes would push airlines to concentrate as many passengers as possible on each flight. He also identified a convergence of the traditional airlines and new low-cost airlines in terms of service characteristics, leading to a stronger competition for hub and spoke

model. Travel to hubs would be eventually done in early future electric and hybrid powered small or regional aircraft while hub to hub may benefit from large capacity aircraft in intracontinental routes and standard capacity aircraft for intercontinental routes. HVLMR is a candidate to enlarge the capacity of a medium range aircraft to the 400 pax category. Further enlargement of capacity is possible if both decks are kept with passengers and tanks are placed in the cargo compartments, which are large enough. This generated a larger capacity short range version, the HVLSR. Passenger capacity is 680 pax with both decks for passenger accommodation. With 283 m³ of liquid hydrogen tanks, it can take 61 tons of payload to 1,800 nm or maximum payload of 80 tons to 1,360 nm.

But a highly contaminating area in the large aircraft market, is that with flying lengths from 4,500 nm to 5,400 nm and passenger capacity 350+. While HLVLRL could cover the 4,500 nm routes, it would be desirable to develop an option with slightly higher range. 5,500 nm is also the very important trigger for one-stop to anywhere flights, as explained above. For these reasons, a 5,500 nm aircraft was also evaluated.

Several extended range versions have been considered: tanks in wings, additional tanks in cargo compartment and additional tanks in the aft upper deck fuselage and fwd. cargo compartment. Last option (HVLER) is shown here, leaving the aft cargo compartment for baggage. Tank volume is increased to 700 m³ considering independent tanks for upper and lower deck. Should the floor of the upper deck be modified, aft and fwd. tanks can be made occupying the full aircraft section, allowing for further increase in volume and offering a better performance tank, with lower surface to volume ratio while keeping a good centre of gravity control. Fig.5.3 shows this last option, while performance calculations have been made on the separate deck tank assumption. Passenger capacity of the HVLER aircraft is 208 passengers and range are 5,600 nm, making it possible to reach any part of the world from any other part in a two-leg flight. Longer flight routes are not within reach with derived hydrogen powered aircraft due to volumetric restrictions of existing airframes with accommodate enough liquid hydrogen.

In all cases, MTOW is around 300 tons, down from 600 tons of the A380, and more comparable to 787 or A350 kind. Consequently, take-off lengths are well below the 3,000 m making it suitable for most airport operations. OEW is larger than equivalent passenger capacity aircraft leading to higher approach speeds and landing lengths. Still, calculated approach speeds are in the order of 77-78 m/s, and landing lengths just above 2,500 m for the heavier variants. See table 5.2 for a complete set of characteristics and comparison to existing aircraft.

Power plant evaluation has been detailed in part I (Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, 2021). All aircraft variants of the hydrogen powered double deck aircraft require a thrust that lies within the offered performance of the engine family finally selected (ICAO, 2020). This aircraft subfamily covers a whole array of payloads and ranges with same structure but varying the fuel tank location and size.

		787-8	A350-1000	777-9	HVLSR	HVLMR	HVLLR	HVLER
<i>Main aircraft dimensions</i>								
Wing Area (m ²)		377.0	443.00	516.70		443.00		
Wingspan (m)		60.12	64.75	71.80		64.75		
MAC (m)		7.07	7.95	8.06		7.95		
Wing Aspect Ratio		9.59	9.46	9.98		9.46		
Length Overall (m)		56.72	73.79	76.70		73.00		
Cabin Height (m)		5.94	6.09	6.20		8.41		
<i>Passenger capacity</i>								
Max Density Pax		359	480	426	720	388	332	232
2 class Pax		242	369	349	680	372	308	208
<i>Engines</i>								
Number of Engines		2	2	2		2		
Thrust ISA SLS (kN)		298	431.5	467	421	406	441	448

<i>Weight</i>								
Max. (ton)	take-off	227,930	316,000	351,534	287,660	273,557	303,426	309,069
Max. (ton)	landing	172,365	236,000	266,258	274,636	251,318	274,890	276,074
Max (ton)	Zero-fuel	161,025	223,000	254,918	274,058	250,383	273,433	274,375
Max. (ton)	payload	44,000	64,000	73,500	79,800	49,920	44,880	35,880
Max load of fuselage (ton)		65,540	92,800	99,060	159,684	132,575	157,356	157,708
Operational empty (ton)		119,950	159,000	181,400	194,258	200,463	228,553	238,495
<i>Fuel Capacity</i>								
Max Capacity (l)	Fuel	126,206	158,791	207,876	238,000	385,220	600,490	700,097
<i>Cruise</i>								
Cruise (m)	altitude	10667	10667	10667		10,667		
Cruise Number	Mach	0.85	0.85	0.85		0.80		
<i>Take-off and landing</i>								
Take-off Length (m)	Field	2600	2900	2900	2,450	2,346	2,556	2,758
Landing Length (m)	Field	1600	2100	1900	2,011	1,937	2,012	2,015
Approach Speed (m/s)					77	74	77	78
<i>Range</i>								
Range								
Max (nm)	Payload	5500	5500	5685	1,359	2,682	3,260	3,775
Design (nm)	Payload	7800	8300	7,552	1,818	3,289	4,807	5,572
<i>Energy efficiency</i>								
ETWR (MJ/pass.km)		1.12	0.89	0.88	0.80	1.32	1.69	2.52

Table 5.2: Main aircraft characteristics of Hydrogen Powered Very Large Aircraft

5.5 Short range aircraft – HMSR (140 pax; <1,500 nm)

Following the methodology developed in Part I of the paper, a single aisle aircraft of the A320 or 737 MAX kind has also been assessed (AIRBUS, n.d.; BOEING, n.d.). In the chosen configuration, tanks are placed as shown in the Figure 5.4, outside pressure bulkheads.

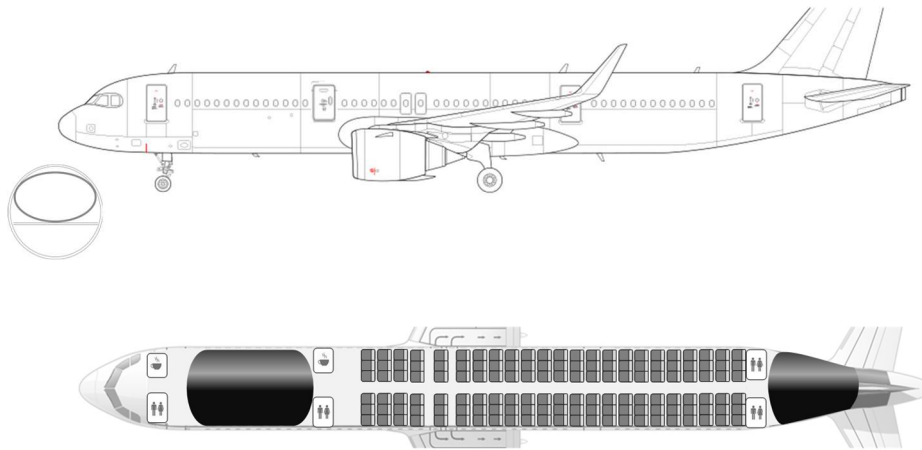


Figure 5.4: Hypothetical cabin lay-out of a single aisle aircraft. Image courtesy of Norebbo (Norebbo, 2021b) modified by the authors

Tanks are elliptical with ellipsoid ends. Fwd. tank is slightly larger than aft tank, with a negligible impact on centre of gravity. A total of 54 m³ of liquid hydrogen can be stored with a remaining passenger capacity of 138 pax (144 in maximum density). Table 5.3 shows a comparison of the original aircraft an HMSR.

MTOW reduces from 89 tons to 64 tons mostly due to a lower fuel weight. Semi-empirical correlations used for weight estimation, as explained in Part I, gives a OEW which is 3.5 tons lower for the hydrogen configuration This is due to a relatively high payload density. This is not the case for larger aircraft, with larger cross sections and more volume per passenger. Except for the medium aircraft, any larger aircraft shows a heavier OEW.

Thrust required reduces to 116 kN down from 147 kN. Both powerplant alternatives for A321, LEAP-1A or PW1100G offer variants with reduced thrust

from 107 kN , which makes conceivable to adapt the engines for hydrogen fuel (ICAO, 2020).

	A321-neo	HMSR
<i>Main aircraft dimensions</i>		
Wing Area (m ²)	122.40	122.40
Wing Span (m)	35.80	35.80
MAC (m)	4.29	4.29
Wing Aspect Ratio	9.50	9.50
Length Overall (m)	44.51	44.51
Cabin Height (m)	4.14	4.14
<i>Passenger capacity</i>		
Max Density Pax	240	144
2 class Pax	206	138
<i>Engines</i>		
Number of Engines	2	2
Thrust ISA SLS (kN)	147	116
<i>Weight</i>		
Max. take-off (ton)	89,000	64,127
Max. landing (ton)	77,300	61,160
Max Zero-fuel (ton)	73,300	61,029
Max. payload (ton)	25,300	17,960
Max load of fuselage (ton)	39,700	26,600
Operational empty (ton)	46,500	43,069
<i>Fuel Capacity</i>		
Max Fuel Capacity (l)	32,940	54,000
<i>Cruise</i>		
Cruise altitude (m)	10,667	10,667
Cruise Mach Number	0.78	0.80
<i>Take-off and landing</i>		
Take-off Field Length (m)	1,988	1,950

Landing Field Length (m)	1,577	
Approach Speed (m/s)		69
<i>Range</i>		
Max Payload (nm)	2,500	1,141
Design Payload (nm)	4,000	1,517
<i>Energy efficiency</i>		
ETWR (MJ/pass.km)	1.12	1.08

Table 5.3: Main aircraft characteristics of Hydrogen Powered Medium Size Short Range Aircraft

5.6 Powerplant performance: hydrogen powered derivative turbofans

A simulation of the engines required by each aircraft of the family, as per tables 5.1-3, has been performed with TURBOMACH (Nikolaidis, 2017) with data of the existing engines from (ICAO, 2020) and performance matched to existing public data (EASA, 2019; European Aviation Safety Agency (EASA), 2018; European Union Aviation Safety Agency, 2019; ICAO, 2020) with multipoint optimization method described in (Mourouzidis, 2016).

Engine performance when adapting a kerosene engine to hydrogen combustion has been discussed in (Corchero and Montañés, 2005; Haglind, Hasselrot and Singh, 2006; Khandelwal et al., 2013) and an example is shown in Part I.

Table 5.4 shows the main engine characteristics as well as the results of expected average variations when fuel is changed to hydrogen.

	Jet A-1			Change to Hydrogen	
	HMSR	HLMR	HVLSR/MR/LR/ER	Same TET	Same Thrust
Take-off Mass Flow (kg/s)	464	1,009	1,354-1,450	1	0.984
TET (K)	1739	1800	1,750-1,865	1	0.987

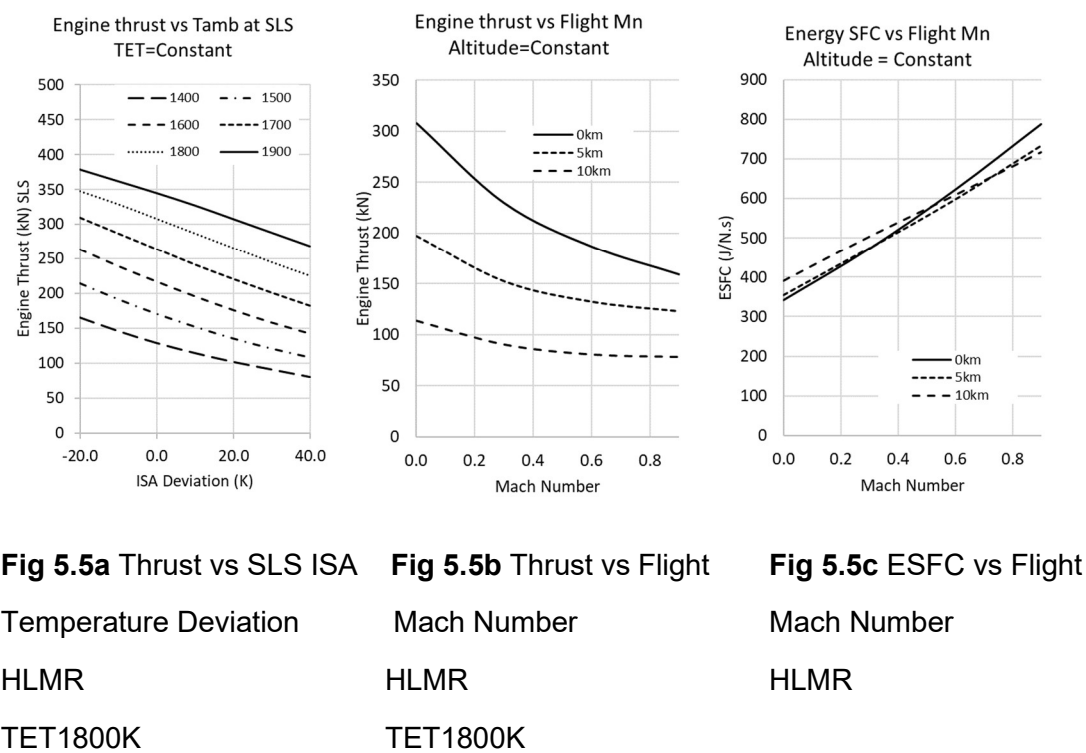
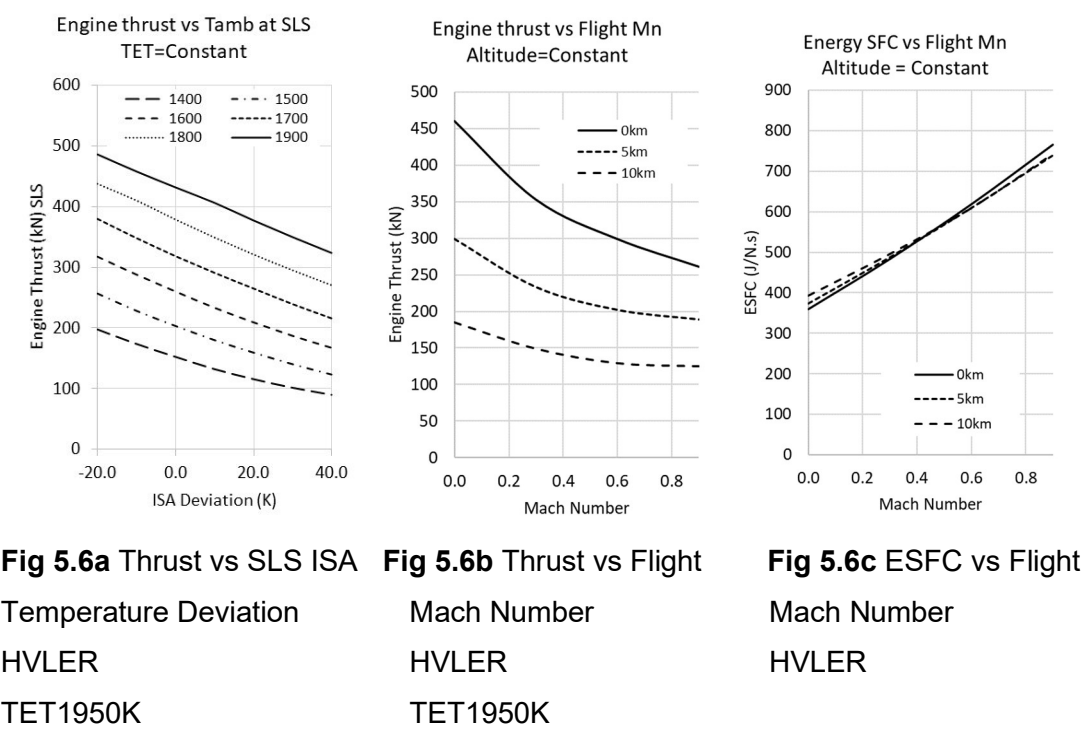
OPR	31.6	39.8	41.7-48.8	1	0.964
BPR	11.80	9.30	9.1-8.55	1	1.016
Take-off Thrust (kN)	115.6	286.1	406-448	1.035	1

Table 5.4: Main engine characteristics of Airliner Family and its effect of change of fuel to Hydrogen.

Several hypotheses can be done when switching fuel. First column shows “Same TET”, in which same mass flows and pressure ratio through the fan and core, and same TET have been kept and just the fuel has been changed. The result is an increase in thrust due to a higher energy content of the hydrogen powered cycle exhaust gases. If on this hydrogen cycle, TET is reduced till a point in which the thrust equals the kerosene one. Then, the result is a reduction on TET and OPR and a slight increase in BPR, as shown in “Same Thrust” column. In these cases, turbines and nozzle areas are to be reduced since the temperature of the exhaust gases at the exit of the turbines is slightly higher than the kerosene equivalent.

Variation of engine thrust with ISA temperature deviation and flight Mach number, and energy specific fuel consumption follow the same trends. Figure 5.5 shows the performance of a high bypass ratio three shaft turbofan to power the HLMR aircraft inspired in that of the original aircraft. Engine power required by the hydrogen aircraft reduces from original kerosene aircraft from 338 kN to 281 kN, so that the derated engine can run at lower TET level. Engine options powering the baseline aircraft offer derated versions of the engine covering 281 kN, and therefore the same engine family series can be used (ICAO, 2020). Figure 5.6 relates to the engine that powers the HVLER aircraft. This is the highest thrust requirement for all very large aircraft options analysed. As explained in Part I (Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, 2021), such engine is inspired by a modern 300,000-ton long range wide body aircraft engine. Figure 5.7 represents the performance of a two-shaft geared turbofan with a take-off thrust of 116 kN ISA SLS to power the HMSR aircraft. Also, for this aircraft, same kerosene engine family that power the original aircraft can power the hydrogen

one. As it happens with the HMSR, engine can be derated and run at a lower TET level on the hydrogen aircraft due to lower MTOW.



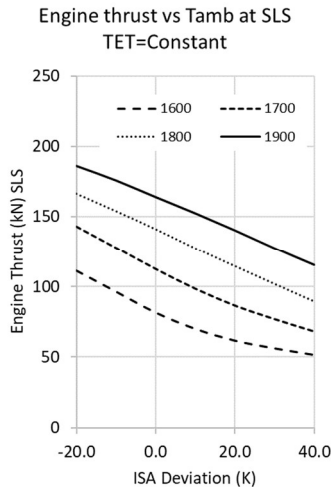


Fig 5.7a Thrust vs SLS ISA
Temp. Deviation
HMSR
TET1750K

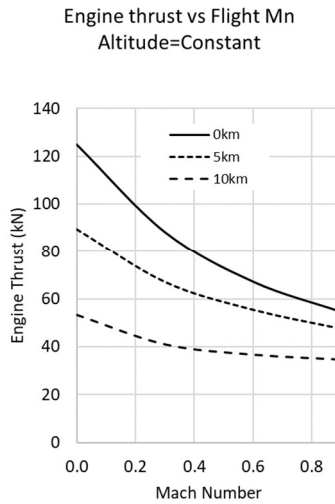


Fig 5.7b Thrust vs Flight
Mach Number
HMSR
TET1750K

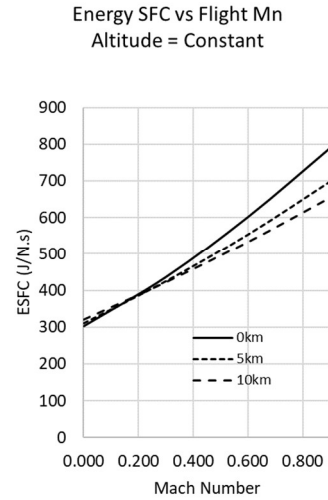


Fig 5.7c ESFC vs Flight
Mach Number
HMSR

A derivative of such engines may be easier performed if only changes addressed include a low NO_x combustion chamber, engine controls and hot low-pressure sections of the engine. It might be possible to obtain further benefits from the usage the liquid hydrogen storage and distribution system as a high-capacity heat sink, for example, to cool down de turbine blades and hot sections of the engine (Khandelwal et al., 2013). However, such changes would complicate further the development of the engine and have not been considered for the first innovation wave.

5.7 Aircraft family

While full decarbonization is the ultimate goal, this study focusses on a first wave of innovation and short-term goals. An aircraft family has been conceived based on existing aircraft or technology that either covers as much as possible of the contaminant segments or offers a low carbon business model alternative, shown Figure 5.8.

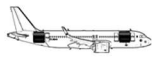
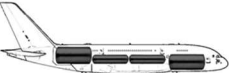
		
Range: 1,500 nm	Range: 3,500 nm	Range: 1,800 nm
Capacity: 138 – 2 class 144 – Economy + Premium	Capacity: 216 – 2 class 234 – Economy + Premium	Capacity: 720 – 2 class 680 – Economy + Premium
Weights and Capacity MTOW: 64.1 tons OEW: 43.1 tons Max Payload: 18.0 tons Fuel Capacity: 54 m3 Thrust (SLS): 2x116 kN	Weights and Capacity MTOW: 200.4 tons OEW: 146.6 tons Max Payload: 36.1 tons Fuel Capacity: 285 m3 Thrust (SLS): 2x281 kN	Weights and Capacity MTOW: 287.7 tons OEW: 194.3 tons Max Payload: 79.8 tons Fuel Capacity: 238 m3 Thrust (SLS): 2x421 kN
Performance Cruise Speed: 0.8M Landing: 69 m/s Take-off: 1,950 m	Performance Cruise Speed: 0.8M Landing: 69 m/s Take-off: 2,350 m	Performance Cruise Speed: 0.8M Landing: 77 m/s Take-off: 2,450 m
		
Range: 3,300 nm	Range: 4,800 nm	Range: 5,600 nm
Capacity: 372 – 2 class 388 – Economy + Premium	Capacity: 308 – 2 class 332 – Economy + Premium	Capacity: 208 – 2 class 232 – Economy + Premium
Weights and Capacity MTOW: 273.6 tons OEW: 200.5 tons Max Payload: 49.9 tons Fuel Capacity: 385 m3 Thrust (SLS): 2x406 kN	Weights and Capacity MTOW: 303.4 tons OEW: 228.6 tons Max Payload: 44.9 tons Fuel Capacity: 600 m3 Thrust (SLS): 2x441 kN	Weights and Capacity MTOW: 309.1 tons OEW: 238.5 tons Max Payload: 35.9 tons Fuel Capacity: 700 m3 Thrust (SLS): 2x448 kN
Performance Cruise Speed: 0.8M Landing: 74 m/s Take-off: 2,346 m	Performance Cruise Speed: 0.8M Landing: 77 m/s Take-off: 2,556 m	Performance Cruise Speed: 0.8M Landing: 78 m/s Take-off: 2,758 m

Figure 5.8: Main characteristics of aircraft family

Aircraft family is comprised by three subfamilies: a single aisle aircraft – HMSR – Hydrogen Medium [size] Short Range, a wide body aircraft – HLMR – Hydrogen Large [size] Medium Range, and a double deck aircraft – HVLSR/MR/LR/ER– Hydrogen Very Large [size] short/Medium/Long/Extended Range. While for a double deck aircraft several configurations have been assessed, for single aisle and wide body aircraft only one configuration has been envisioned. It would be

possible to consider additional derived versions of these, but with a much smaller payload/range elasticity as seen in the double deck design, since only a more limited trade-off between passenger and fuel volume is feasible.

To cover the standard capacity of current narrow body aircraft, the most demanded category, HLMR, inspired in 787-10 can carry 216 passengers over a 3,550 nm. Two tanks are placed at the front and rear of the passenger cabin and one in the forward cargo compartment. All the benefits pursued by fast-growing low-cost carriers in current single aisle aircraft – quick turnaround, high density, and flexibility up to 3,500 nm – can potentially be offered by HLMR.

A Very Large Aircraft, double decked, derived from an A380, may accommodate passengers in any of the decks, or in the cargo compartment. Existing wings of such a large aircraft proved to be too large for a hydrogen aircraft. Wings and engines from a 300-ton airliner were combined with the double deck fuselage, improving energy consumption and range. Several lay-out combinations lead to an Aircraft subfamily that covers part of the existing long-haul market. HVLLR, with hydrogen tanks in the main deck, has a capacity for 308 passengers on the upper deck, and 4,800 nm range. Although with a shorter range than existing wide body aircraft, real operations show that this aircraft can cover around 75% of current operations (AIRBUS, 2022). To cover the “one stop to anywhere” (Boeing, 2019) market, mostly encouraged by tourism and leisure travel, HVLER has the capacity to reach 5,500 nm with 232 passengers in a single class. To extend the range, additional tanks have been placed in part of the upper deck and the cargo compartment.

HMSR is a single aisle short range aircraft inspired in the A320-neo or the 737-max in which part of the fuselage has been cleared to install two hydrogen tanks, forward and abaft the passenger cabin. Maximum capacity for this narrow body aircraft becomes 140, compared to 200 from current aircraft. Maximum range also reduces to 1,500 nm, down from 3,500 nm of existing kerosene aircraft. Still, it could substitute more than 80% of forecasted aircraft demand bellow 150 passengers with data shown in (Airbus, 2019)

5.8 Conclusions

An aircraft family derived from existing aircraft or existing technology has been developed to address in a holistic way the first wave of decarbonisation of civil aviation. Figure 5.9 shows the existing aircraft and proposed aircraft family on a range passenger chart over the CO₂ emissions chart. Hydrogen aircraft will naturally have lower payload and range capabilities in the short term. This fact may push hot spots on Fig.5.9 to displace left and downwards as market matures and airports increase congestion.

In order to reduce the risks and enable an earlier accrual of decarbonisation, engine modification to burn hydrogen with low NO_x emission and fuel system may then become the most important research and development priority.

Narrow body aircraft operation emissions can be damped by an aircraft of similar size and technology to the 787 or the A330.

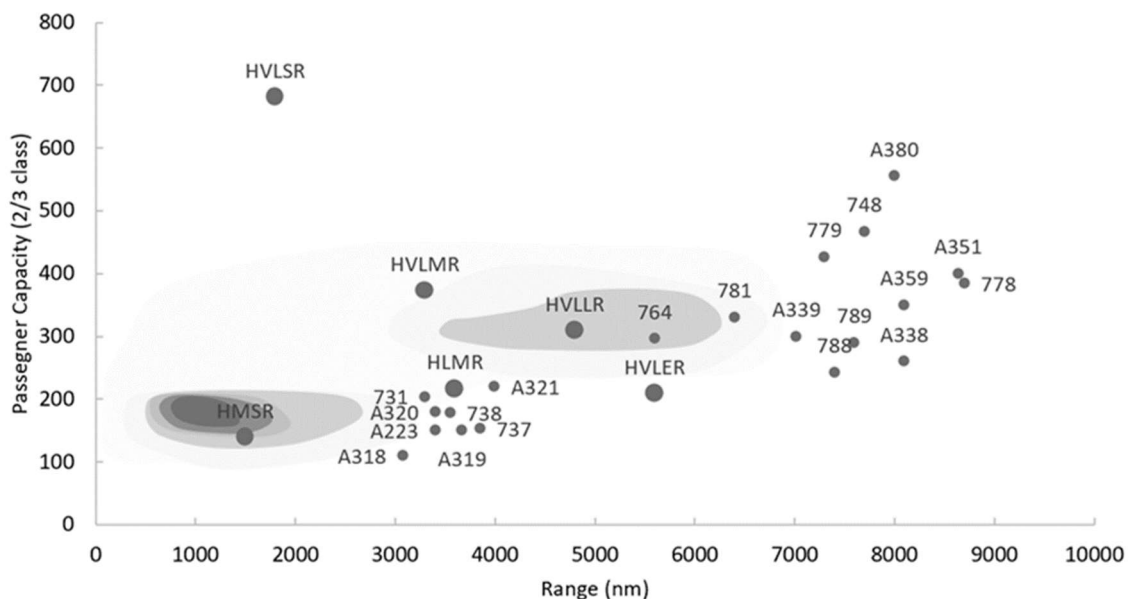


Figure 5.7: Range – Passenger position of hydrogen powered aircraft family

Current long-haul market cannot be completely covered by hydrogen powered aircraft if similar to existing aircraft are to be used as a first innovation wave. Only

part the long-range existing market can be attempted: that of medium size wide body aircraft at ranges below 5,500 nm. Nonetheless the addition of a stop in a few (maybe 2-3 % of aircraft movements according to Figure 5.1) very long journeys is considered acceptable. As Hydrogen aviation technology progresses, later innovation waves will deliver longer and longer range capability.

However, tourism and leisure travel, with a growth over 6% (Boeing, 2019) may give rise to new travel modes and business models. A larger capacity short haul aircraft may improve the profitability of low-cost carriers on short range flights and support aircraft congestion in network carrier operated hub to hub connection. HVLMR, with hydrogen tanks in the upper deck, can take up to 388 passengers in a single class over 3,300 nm. And HVLSR with passengers in both decks and fuel in the cargo compartment, covers 1,800 nm with 680 pax. These two new aircraft concepts may alleviate the higher congestion expected at some airports derived from higher number of operations due to reduced ranges of hydrogen powered aircraft.

This study reinforces the view of the authors that the switch to Hydrogen fuel is a very promising solution to decarbonising aviation. The concept of innovation waves is strongly advocated to enable a swift change. It is recognised that this change will need vast investments in technology and infrastructure that will require commitment and support similar to that devoted to decarbonising other industries. Nonetheless these costs are viewed as acceptable given the resulting employment, social and economic benefits they will bring.

5.9 Acknowledgement

The authors acknowledge the support of Lufthansa via the provision of artwork used in this paper and for their interest in this environment enhancing project.

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6 PROPULSION SYSTEM INTEGRATION FOR A FIRST-GENERATION HYDROGEN CIVIL AIRLINER?

Huete, J., Nalianda, D., & Pilidis, P. (2021). Propulsion system integration for a first-generation hydrogen civil airliner? The Aeronautical Journal, 125(1291), The 25th ISABE Conference special issue – Part I ,1654-1665. doi:10.1017/aer.2021.36

Paper published in Aeronautical Journal, ISABE Special Issue Part I

Presented at 25th ISABE Conference, 2022, Ottawa, September 2022

Awarded with a Bronze Written Paper Prize by the Royal Aeronautical Society, 2022

6.1 Abstract

An unusual philosophical approach is proposed here to decarbonise larger civil aircraft that fly long ranges and consume a large fraction of civil aviation fuel. These inject an important amount of carbon emissions into the atmosphere and holistic decarbonising solutions must consider this sector. A philosophical-analytical investigation is reported here on the feasibility of an airliner family to fly over long ranges and assist in the elimination of carbon dioxide emissions from civil aviation.

Backed by state-of-the-art correlations and engine performance integration analytical tools a family of large airliners is proposed based on the development and integration of the body of a very large two-deck four engine airliner with the engines, wings and flight control surfaces of a very long range twin widebody jet. The proposal is for a derivative design and not a retrofit. This derivative design may enable a swifter entry to service.

The main contribution of this study is a philosophical one: a carefully evaluated aircraft family that appears to have very good potential for first generation hydrogen fuelled airliners using gas turbine engines for propulsion. This family offers three variants: a 380-passenger aircraft with a range of 3300 nautical miles, a 330-passenger aircraft with a range of 4800 nautical miles and a 230-passenger aircraft with a range of 5500 nautical miles. The latter range is crucially important because it permits travel from anywhere in the globe to anywhere else with only one stop. The jet engine of choice is a 450kN high bypass turbofan.

Nomenclature

Δ	Change
BPR	Bypass Ratio
ESFC	Energy SFC (W/N)
FCV	Fuel Calorific Value (lower) (MJ/kg)
F_n	Nett Thrust (kN)
HVLER	Aircraft variant – Hydrogen Very Large Aircraft Extended Range
HVLLR	Aircraft variant – Hydrogen Very Large Aircraft Long Range
HVLMR	Aircraft variant – Hydrogen Very Large Aircraft Medium Range
ISA	International Standard Atmosphere
NO_x	Nitrogen Oxides
SFC	Specific Fuel consumption (kg/s/MN)
SLS	Sea Level Static
TET	Turbine Entry Temperature (K)

6.2 Introduction and analysis method

The use of hydrogen as a civil aviation fuel is an alternative to decarbonise aviation (ENABLEH2 2020, Cryoplane EU 2002, Verstraete 2009). Switching jet engine fuel to hydrogen promises to decarbonise civil aviation if hydrogen production is carbon-free and aircraft engines deliver very low NO_x. Hydrogen also removes other harmful emissions such as unburnt hydrocarbons, aromatic compounds, sulphur oxides, soot and smoke. However, hydrogen for civil aviation requires colossal changes in aircraft, infrastructure, management, safety and regulation. Such a change will be very expensive. However, the authors firmly believe that, socially and economically, it is a far superior alternative to the vast economic and social damage that will result from reducing air traffic. Hydrogen is a technology solution to provide combined sustainability in environmental, economic and social terms. With the appropriate (very large) investments an introduction in approximately 15 years is conceivable.

Many tests and evaluations of hydrogen-fuelled aircraft have been carried out. From von Ohain's hydrogen fuelled demonstrator in the late 1930s (Giffard 2016), the flight test of a B57-Canberra in the late 50s (Kaufman 1957), the TU-155 in the late 1980s (Tupolev 2020). More recently, significant tests at engine conditions to deliver hydrogen combustion with low NO_x are being carried out in the European project ENABLEH2 (ENABLEH2 2020).

For a swift change, several innovation waves are needed. For early service (2035?), the first wave must maximise the use of existing design and technology. Later innovation waves will deliver the full potential of hydrogen in the aircraft.

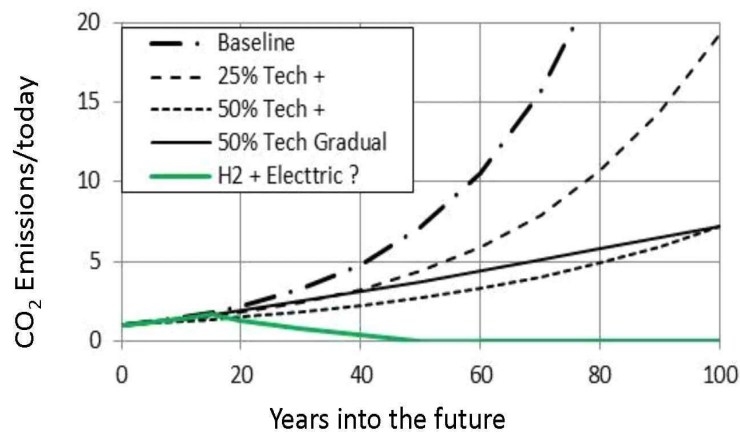


Figure 6.1: Comparison of five technology scenarios, all with the hypothesis of a continuous growth in air traffic of 4% p/a. Baseline shows CO₂ emissions with the continued use of current state of the art equipment. 25% and 50% show the benefits of immediate introductions of improved technology improvements that would yield, in 100 years these respective improvements. 50% gradual shows a gradual move to 50% and H2+Electric shows a fully decarbonised scenario.

This study examines a possible scenario into the first innovation wave to offer aircraft decarbonisation scenarios long before 2050 by maximising the use of current state of the art. This approach will enable a reduction of development costs, concentrate scarce research resources in the key hydrogen focused components. Such initial aircraft designs will not be optimal; but may reduce development time and risk. This could, hopefully, bring entry into service forward by 15 years or more. The carbon savings achieved would be colossal. The authors ask: why not fully decarbonise civil aviation in 50 years? Figure 1 shows a scenario, where five technology options are compared. The authors believe that the zero-carbon option in 50 years is feasible if decisive and wide-ranging international action is taken.

It is widely acknowledged that market forces alone will not bring the changes needed. It would be necessary to adopt direct international financial support or economic-taxation measures to enable the transition to zero-carbon aviation.

Techniques for evaluating the impact of different policy scenarios are available (Nalianda 2012).

Figure 2a shows air traffic characteristics (Schafer et al, 2016) where cumulative aircraft movements (departures), NO_x, Revenue Passenger Kilometres (RPK) and fuel used are shown on a basis of aircraft range. For large scale decarbonisation to take place, the whole range of operations needs to be addressed. A ‘portfolio approach’ is proposed.

Fast decarbonisation is possible if successive innovation waves are considered. In the first wave, for a fast implementation, Fig 2 b shows how such a first wave of innovation could be shared between electric (including all electric, fuel cell electric and hybrid) and hydrogen propulsion systems. This may give rise to an increase in popularity of hub and spoke systems (Figure 3) where inter-hub traffic is served by hydrogen fuelled transports with gas turbine engines and the spokes by all-electric, fuel-cell electric and hybrid electric aircraft.

The maximum estimated range of the ‘Hydrogen for GTs’ bubble in Figure 2b is shown at 5500 nm based on the results for the HVLER aircraft variant analysed here. In the longer term, third and fourth generation aircraft could be designed to exploit the synergies between electrical and hydrogen systems (Nalianda 2014) to deliver improved engine and aircraft performance.

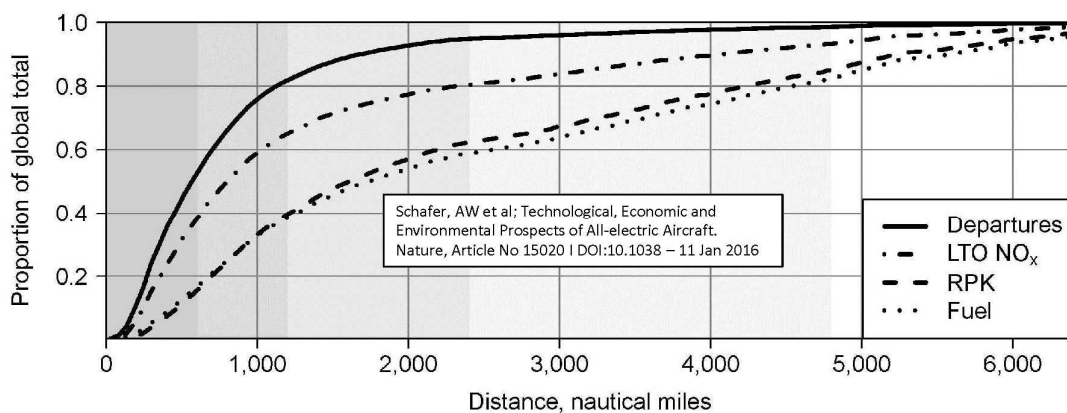


Figure 6.2a: Commercial Aircraft Traffic Characteristics (Schafer et al, 2016)

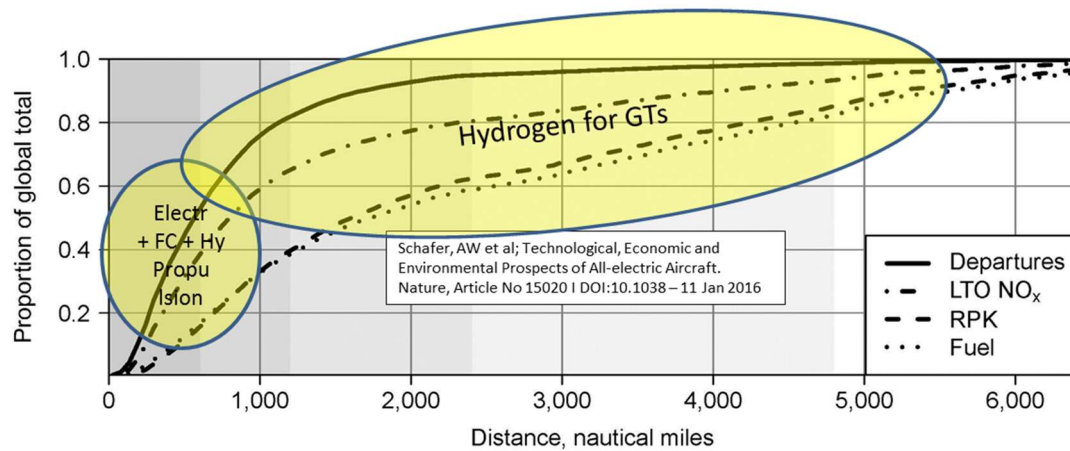


Figure 6.2b: Commercial Aircraft Traffic Characteristics (Schafer et al, 2016)
annotated by the authors on the basis of published electric propulsion capabilities and
H2 evaluation described here

The study described here follows such an approach for a propulsion system in a medium-long range aircraft design, where the focus is on the first wave of innovation aimed at a swift entry into service and the environmental reward is achieved by the faster deployment of carbon-free systems replacing carbon emitting equipment. An attempt is made, via a hypothetical but reasonable approach, to answer a key question: *What would a hydrogen fuelled propulsion system look like if integrated into existing airliner design experience?* A realistic option is proposed based on a derivative design inspired by existing technology for a wide body transport.

Through evaluation and analysis, the option of using an existing aircraft to achieve this objective was ruled out; it was apparent that such a vehicle would be very inefficient. A careful evaluation procedure was introduced (Huete et al, 2020-1) to downselect a reasonable vehicle from a wide range of options. It was concluded that the volume/mass relationships are such that a reasonable approach would be to consider a design that integrated the airframe of a 600 tonne double decker airliner (inspired by the Airbus A380, Lufthansa 2020), with

the wing and engines of a long range twin engine airliner (inspired by the Airbus A350-1000 with its Trent XWB turbofans, Jane's 2018). The evaluation was an iterative process and only the final result is shown here. This exercise gave rise to a family of three aircraft variants, labelled HVLMR, HVLLR and HVLER.

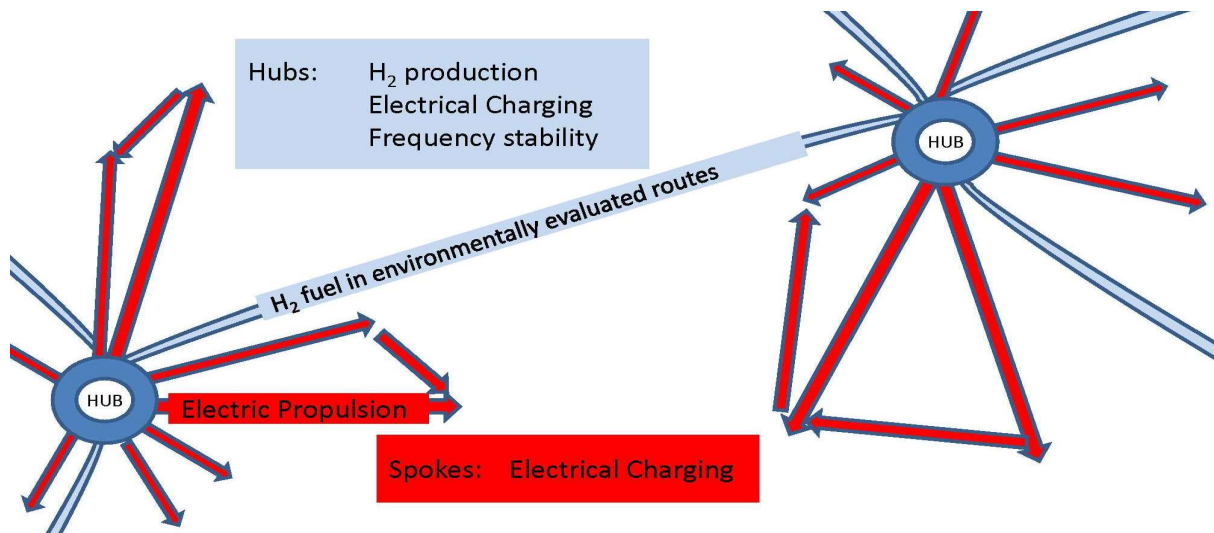


Figure 6.3: Schematic of Hydrogen Hub and Electric Propulsion Spoke Approach

It is clear that integrating the necessary components would not be a straightforward matter and the approach proposed here is a derivative design and not a retrofit. This could be accomplished within 15 years if sufficient research budgets are allocated very soon. It is also acknowledged that a significant challenge will arise from the systems needed to store, move and use hydrogen on board, the development of certification requirements, delivery of low NO_x systems and public support to decarbonise a sector. This public support is likely to be of a similar magnitude to the public investments and subsidies that underpinned the widespread use of Renewable Energy Systems in the electricity generation industry.

6.3 Engine characteristics

The evaluation was an iterative process, concluding with the selection of a baseline jet engine that is inspired by a state-of-the-art high bypass ratio three-spool turbofan (Trent XWB, Rolls-Royce 2020). Using TURBOMATCH (the

Cranfield gas turbine performance simulation code, (Nikolaidis 2017) the performance of turbofans using conventional and hydrogen fuels were evaluated. The TURBOMATCH analytical method uses gas turbine performance principles (Palmer & Pilidis 2013) and is an iterative method based in component characteristics.

	<i>Conv Fuel</i>	<i>H2 Same TET</i>	<i>H2 Same Fn</i>	<i>Conv Fuel</i>	<i>H2 Same TET</i>	<i>H2 Same Fn</i>
	Take-off			Cruise		
Mass Flow (kg/s)	1449.6	1449.6	1427.0	597.2	612.9	587.3
Fuel Flow (kg/s)	3.8159	1.488	1.4093	1.4400	0.6037	0.4999
Tubine Entry Temperature (K)	1865	1865	1837	1760	1760	1660
Nett Thrust (kN)	448.1	463.9	447.9	89.1	103.8	89.2
Exhaust Gas Temperature (K)	957	1016	998	893	947	885
Exhaust Mass Flow (kg/s)	155.6	153.3	148.8	61.1	65.9	59.9
Compressor Discharge Pressure (kPa)	4941	4941	4764	1882	2067	1830
Compressor Discharge Temperature	943	919	908	856	846	809
Compressor Mass Flow (kg/s)	149.5	149.5	145.1	58.8	64.4	58.5
Compressor Pressure Ratio	48.76	48.76	47.02	51.77	56.87	50.35

Table 6.1: Cycle characteristics of the turbofan engine

As expected, there are no major differences in engine performance arising from the use of hydrogen fuel, as shown in table 6.1. SFC is expressed in a conventional way and is also expressed as ESFC, philosophically akin to the concept of Heat Rate, in widespread use in land-based gas turbines. This is necessary because of the very large difference in the lower fuel calorific values, FCV, of conventional fuel and hydrogen, 43 and 120 MJ/kg respectively (Saravanamuttoo 2017). The engine used in the three aircraft variants described below is always the same. The engine is designed for the aircraft variant with the highest thrust requirement; the lower thrust requirement of the other variants is met by adjusting the engine power setting.

The next step was an assessment of engine performance throughout the flight envelope using TURBOMATCH with hydrogen fuel in the calculations. The outputs are in Figures 6.4, showing thrust variations with ambient temperature

(4a) and with altitude and flight Mach Number (4b). Figure 4c shows ESFC and its dependence on altitude and flight Mach Number.

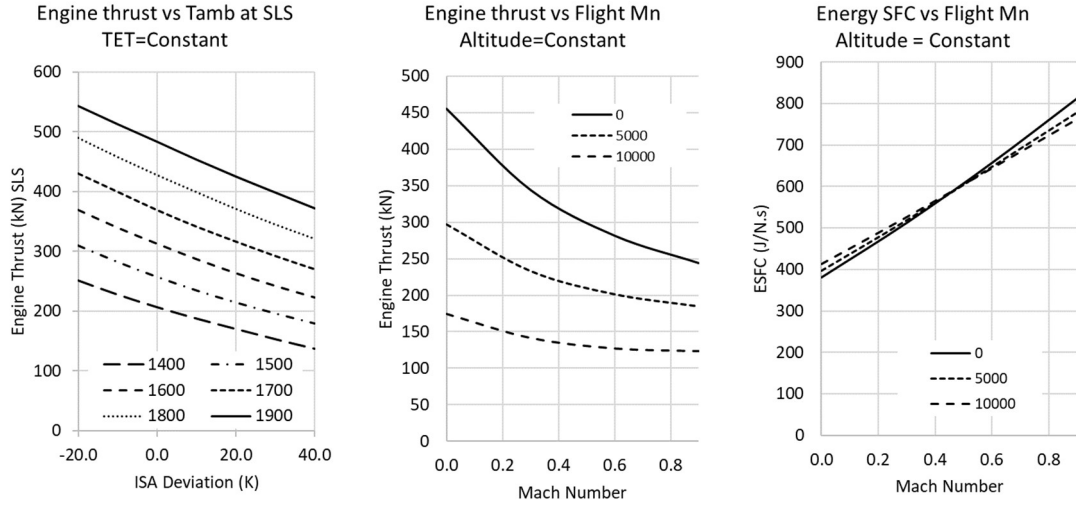


Fig 6.4a: Thrust vs SLS ISA
Temperature Deviation

Fig 6.4b: Thrust vs Flight
Mach Number

Fig 6.4c: ESFC vs Flight
Mach Number

6.4 Fuel tank integration

A major challenge with the use of hydrogen is the low density of the fuel, even in its liquid form. The fuel is to be stored at 21.5 K and 1.25 bar so insulation will require a great deal of attention. The authors-based tank design philosophy on expanded analytical studies based on previous Cranfield work (Goldberg 2017 and 2018, Goldberg et al 2018). Tanks need to be insulated to prevent heat leakages into the liquid hydrogen with no need for an active cooling system. Low pressure storage does not demand thick walls. Fuel withdrawals through engine feeding lines reduce tank pressure and temperature, while heat leakages increase them. Pressure and temperature are regulated through two mechanisms. To prevent excessive increase in pressure and temperature, due to heat leakages, a bleeding valve allows hydrogen to escape to a venting space in a safe way, restoring pressure and temperature inside the tank. To avoid undesirably low pressure inside the tanks, warmer or preheated hydrogen can be fed back into the tanks from feeding or venting lines.

Several design schemes are possible, either with single or double metallic or composite walls. A wide range of insulation materials from foam to vacuum jacketed multilayer insulation can be used. Resulting tanks, deliver insulation properties ranging from zero boil-off over extended periods of time, typically days, to short range tanks, which can accomplish a 6 hour mission with boil-off rates below 0.15% per hour (Goldberg 2018 and Verstraete, 2009). Tank selection depends not only on the mission, but on the infrastructure developed on airports for hydrogen aircraft. For airports without hydrogen infrastructure, requiring aircraft to arrive and park with large amounts of fuel, highly insulated tanks should be considered. For airports with a fully developed infrastructure, optimum tanks would require a much lighter insulation. Infrastructure plays a significant role in hydrogen development, not only because hydrogen needs to be produced onsite from renewable resources and would require safe storage and filling systems certified, but also due to the reutilisation system required for hydrogen left in the aircraft when stopped or parked overnight.

Due the uncertainty of pace at which such infrastructure will be developed, tanks considered in this paper are aluminium double walled foam insulated tanks where boil-off rates are below 0.15% per hour. The weight of the tanks considered here is 1,22 times the weight of the hydrogen contained. This results in a gravimetric efficiency (ratio of weight of hydrogen to weight of hydrogen plus tank) of around 0.45. Under optimum infrastructure development, gravimetric efficiency could be increased to the 0.7+ range.

The authors, based on established aircraft and engine design and performance correlations (Fielding 2017, Nikolaidis 2017, Raymer 1992 and Torenbeek 1982) developed a method for the evaluation of aircraft and engine performance (Huete et al 2020-1). Many iterations of different combinations were carried out. The final results of this analytical process are shown in Table 2 where the HVLMR, HVLLR and HVLER concepts are compared with the 'design donor' aircraft. These used this with the Cranfield propulsion system integration method Hermes/Orion (Nalianda et al 2020) to confirm the combined aircraft and engine performance. Hermes/Orion uses TURBOMATCH for engine performance calculations.

Figure 6.5a shows the airframe of the aircraft used for the study. The aircraft has two decks to carry passengers, the lower deck larger than the upper one. The authors examined three variants of a hydrogen fuelled airliner derived from this concept, HVLMR, HVLLR and HVLER; for hydrogen medium, hydrogen long and hydrogen extended range. The idea of long and extended range applies to hydrogen in this case and imply much shorter flights than the capabilities of a modern conventional airliner. The first, HVLMR, considers the use of the upper deck to house fuel tanks, HVLLR is conceived with the fuel tank in the lower deck and HVLER with a combination.

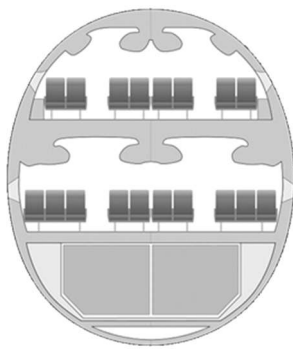


Figure 6.5a Baseline

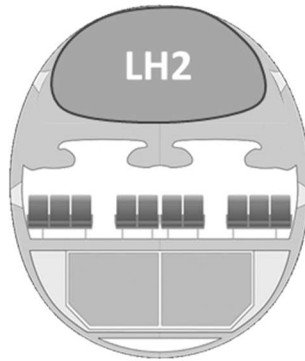


Figure 6.5b HVLMR layout

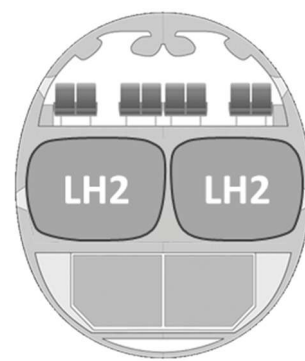


Figure 6.5c HVLLR layout

Image from Ssolbergj, Steff and Clem Tillier – Creative commons licenced modified by authors

	AIRBUS A350-1000	AIRBUS A380-800	HVLMR	HVLLR	HVLER
Mass (tonnes)					
Ramp	317	577	274	304	310
Max take-off	316	575	273	303	309
Max landing	236	394	251	275	276
Max payload	68	83	50	45	36
Operational Empty	155	276	200	229	238
H2 Tank (gravimetric eff 0.45)			33	51	59
Engines	2	4	2	2	2
Cruise thrust/engine kN	87	81	81	88	90
Static thrust/engine kN	432	374	406	441	448
Range (naut miles)	8700	8000	3300	4800	5600
Pax (2 class economy)	315	555	388	332	232

Table 6.2: Comparison HVLMR, HVLLR and HVLER with the ‘design donor’ aircraft

6.5 Integrated capability

To offer a visual expression of the aircraft concepts, the authors modified existing aircraft artwork (Lufthansa 2020) and produced authors impressions of HVLMR, HVLLR and HVLER. These are shown in Figure 6.6 with estimates of range and passenger capacity. Table 3 lists a compilation of distances between major cities obtained from Wikipedia to give a measure of the usefulness of the HVLMR, HVLLR and HVLER aircraft.

The estimated vehicle capability, for an introduction accelerator philosophy, is good. It does not match the payload or the very high ranges of current aircraft using conventional fuels, but it fares very well as an introductory accelerator technology to decarbonise aviation. Furthermore Figure 6.7 shows that the range offered covers more than 98% of existing aircraft departures and accounts for 90% of total fuel consumption. So, the remaining small fraction of very long-range flights could be carried out with one additional stop. It is expected that in this scenario the impact on fuel consumption will actually be beneficial because it is well known that significantly less fuel is required if a conventional aircraft flies two 8000 km legs instead of a 16000 km flight nonstop. Although in the case of hydrogen the benefit will be significantly smaller because of the much higher

energy density of the fuel, requiring a smaller fuel fraction of the total aircraft weight.

During this early investigation it became apparent that the tank gravimetric efficiency is a parameter that will very significantly influence the performance characteristics of the integrated aircraft and powerplant. A detailed evaluation is being pursued independently (Huete et al 2020-2)

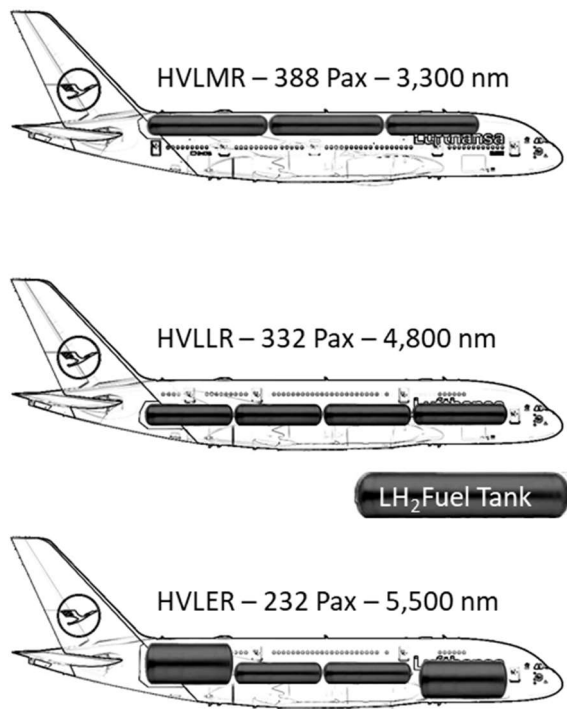


Figure 6.6: HVLMLR, HVLLR and HVLER concepts. Images courtesy Lufthansa (Lufthansa 2020) and modified by the authors

Table of Distances	nm	km
London - Athens	1293	2395
Dublin-Moscow	1514	2804
Singapore - Shanghai	2048	3792
New York - San Francisco	2235	4139
Boston - Los Angeles	2241	4150
Seattle - Honolulu	2329	4313
New York - London	3016	5585
Singapore - Sydney	3404	6305
Miami - Rio de Janeiro	3618	6700
Mumbai - Singapore	3697	6846
Madrid - Miami	3836	7105
Johannesburgh - Rio de J	3850	7130
London - Mumbai	3890	7204
Lagos - Mumbai	4116	7622
Shanghai - Sydney	4262	7893
Madrid - Johannesburg	4362	8078
Sydney - Honolulu	4401	8150
Dublin-San Francisco	4417	8180
Tokyo-San Francisco	4476	8290
London-Shanghai	4968	9201

Table 6.3: Distances between selected airports, a measure of the usefulness of HVLMLR, HVLLR and HVLE (Wikipedia)

6.6 Conclusions & recommendations

This paper describes an investigation into three hypothetical propulsion integration configurations with different tank locations for storing fuel. The investigation is philosophical in nature and is backed by detailed calculations. A family of civil aircraft using hydrogen fuel in gas turbine engines could be

developed using the main components of two existing aircraft as a basis for the design. A very large two deck transport design would provide the fuselage while the wings, engines and tail surfaces would be derived from a very long-range twin. The family would comprise three configurations, HVLMR, HVLLR and HVLER. This family exhibits a payload and range that is significantly smaller than the 'donor' aircraft, however its characteristics are sufficiently attractive to be considered as a launch option for a first generation zero carbon aircraft. The range of HVLER is strategically chosen to allow flights from any point on the planet to any other with just one stop. Figure 6.7 shows the strategic positioning of the family.

There may be many candidate aircraft to enter early service, HVLMR, HVLLR and HVLER appear to offer sufficient promise to be considered as first-generation candidates for the larger vehicles for the longer ranges. As technologies mature the performance of the aircraft of later generations would be better. In this context, a parameter of crucial importance, tank gravimetric efficiency is currently being evaluated by the authors examining proposed concepts (Verstraete 2009) and original analysis. Another aspect under investigation is the ability to burn hydrogen in the combustor with very low NO_x emissions (Enable H2, 2020). The approach in this investigation is to use combustors with very small orifices to mix air with fuel, procure good mixing characteristics delivering a lower primary zone fuel to air ratio and lower flame temperature, capitalising on the much wider flammability limits of hydrogen. This approach appears a good candidate solution at the expense of a small, acceptable weight and length penalty to the engine. Beyond carbon and NO_x , contrails deserve detailed consideration. It is anticipated that, initially, contrail mitigation will be via rerouting the flights (Nalianda, 2012). This approach is very promising to completely avoid persistent contrails at the expense of a few (1-3) additional percent in fuel burn. The integration of the fuel system and the components required is likely to follow known approaches (Brewer, 1978) updated. Given the reduced luminosity of hydrogen flames it is anticipated that heat transfer will be less aggressive than what is experienced with conventional fuels, so conventional combustor cooling

arrangements are probably adequate. The same is argued here for turbine cooling requirements. Nonetheless these matters deserve detailed examination.

Current detailed work is showing (Enable H2, 2020) that health and safety on airports and aircraft can be managed with careful attention to detail and appropriate investments. There will be many certification hurdles, in particular arising from the need to extensive changes of certification rules. The development process could comprise two parallel streams. The first would focus on the development of the aircraft and engines using conventional fuel to test the handling qualities of the vehicle. In parallel, a four-engine existing transport could be modified to use hydrogen fuel in two of the four engines to test all the systems associated with hydrogen in a twinjet; the remaining two engines would operate on conventional fuel while the hydrogen systems are developed to a high reliability and functionality. These parallel streams would probably last about a decade and serve as a platform for the dialogue with certification authorities to adapt rules to hydrogen fuel supporting a zero-carbon reality.

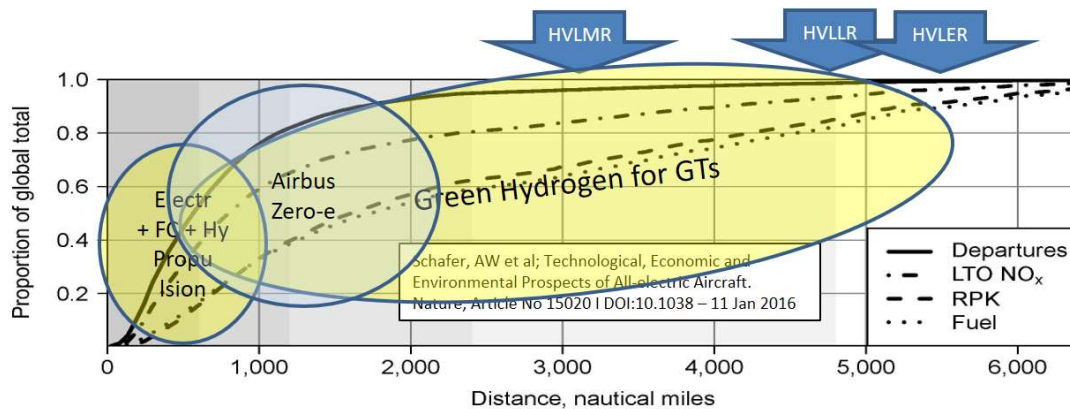


Figure 6.7: HVLMR, HVLLR and HVLER capabilities (Schafer et al, 2016) annotated by the authors and including the authors understanding of the Airbus Zero-e concepts (RAeS 2020)

Of course, there are the questions of airport infrastructure and the production of zero-carbon hydrogen in vast scales. This may be from sea water electrolysis to prevent unhelpful competition with scarce freshwater resources. Undoubtedly all these developments will cost hundreds of billions of pounds (or euros or US

dollars), however the authors firmly believe these costs are acceptable to migrate to zero-carbon an industry that brings so many technical, social and economic benefits.

6.7 Acknowledgement

The authors acknowledge the support of Lufthansa via the provision of artwork used in this paper and for their interest in this environment enhancing project.

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7 IMPACT OF TANK GRAVIMETRIC EFFICIENCY ON PROPULSION SYSTEM INTEGRATION FOR A FIRST-GENERATION HYDROGEN CIVIL AIRLINER

Huete, J., Nalianda, D., & Pilidis, P. (2022). Impact of tank gravimetric efficiency on propulsion system integration for a first-generation hydrogen civil airliner. The Aeronautical Journal, 126(1302), The 25th ISABE Conference special issue – Part II, 1324-1332. doi:10.1017/aer.2022.60

Paper published in Aeronautical Journal, ISABE Special Issue Part II

Presented at 25th ISABE Conference, 2022, Ottawa, September 2022

7.1 Abstract

Civil aircraft that fly long ranges consume a large fraction of civil aviation fuel, injecting an important amount of aviation carbon into the atmosphere. Decarbonising solutions must consider this sector. A philosophical-analytical feasibility of an airliner family to assist in the elimination of carbon dioxide emissions from civil aviation is proposed. It comprises four models based on the integration of the body of a very large two-deck airliner with the engines, wings and flight surfaces of a very long-range twin widebody jet.

The objective of the investigation presented here is to evaluate the impact of liquid hydrogen tank technology in terms of gravimetric efficiency. A range of hydrogen storage gravimetric efficiencies was evaluated; from a very pessimistic value of 0.30 to a futuristic value of 0.85. This parameter has a profound influence on the overall fuel system weight and an impact on the integrated performance.

The resulting impact is relatively small for the short-range aircraft, it increases with range and is very important for the longer-range aircraft. For shorter range

aircraft variants, the tanks needed to store the hydrogen are relatively small, so the impact of tank weight is not very significant. Longer range aircraft are weight constrained and the influence of tank weight is very important. In the case of the longest range, the deliverable distance increases from slightly over 4000 nautical miles, with a gravimetric efficiency of 0.3, to nearly 7000 with a gravimetric efficiency of 0.85.

Nomenclature

Δ	Change
BPR	Bypass Ratio
ESFC	Energy SFC (W/N)
FCV	Fuel Calorific Value (lower) (MJ/kg)
F_n	Nett Thrust (kN)
HVLER	Aircraft variant – Hydrogen Very Large Aircraft Extended Range
HVLLR	Aircraft variant – Hydrogen Very Large Aircraft Long Range
HVLMR	Aircraft variant – Hydrogen Very Large Aircraft Medium Range
HVLSR	Aircraft variant – Hydrogen Very Large Aircraft Short Range
ISA	International Standard Atmosphere
MLI	Multi-Layer Insulation
NO_x	Nitrogen Oxides
SFC	Specific Fuel consumption (kg/s/MN)
SLS	Sea Level Static
TET	Turbine Entry Temperature (K)
η_{grav}	Tank Gravimetric Efficiency = Fuel Weight / (Fuel + Tank Weight)

7.2 The aircraft family

Extreme decarbonisation is promised for 2050, but emerging is a strong consensus that this may be too late. The use of hydrogen as a civil aviation fuel is an alternative to decarbonise aviation (ENABLEH2 2020, Cryoplane EU 2002, Verstraete 2009). Switching jet engine fuel to hydrogen promises to decarbonise civil aviation if hydrogen production is carbon-free. Furthermore, hydrogen offers the challenge and potential to deliver much lower NO_x than hydrocarbon fuels (ENABLEH2 2020). Hydrogen also removes other harmful emissions such as unburnt hydrocarbons, aromatic compounds, sulphur oxides, soot and smoke. These plus careful flight management are expected to lead to contrail reduction (Nalianda 2012 and Voigt et al, 2021) Hydrogen for civil aviation is currently becoming increasingly popular but it requires large changes in aircraft, infrastructure, management, safety and regulation. Such a change will be very expensive. However, the authors firmly believe that, socially and economically, it is a far superior alternative to the vast economic damage that will result from reducing air traffic. Hydrogen is a technology solution to provide combined sustainability in environmental, economic and social terms. With the appropriate investments an introduction in approximately 15 years is conceivable.

A major challenge with the use of hydrogen is the low density of the fuel, even in its liquid form. For the present study, liquid hydrogen is stored at 21.5 K and 1.25 bar so insulation will require a great deal of attention. The authors based their tank design philosophy on expanded analytical studies informed by previous Cranfield work (Verstraete 2009, Goldberg 2017 and 2018, Goldberg et al 2018). Tanks need to be insulated to prevent heat leakages into the liquid hydrogen with no need for an active cooling system. Low pressure storage does not demand thick walls. Fuel withdrawals through engine feeding lines reduce tank pressure and temperature, while heat leakages increase them. Pressure and temperature are regulated through two mechanisms. To prevent excessive increase in pressure and temperature, due to heat leakages, a bleed valve lets hydrogen to escape to a venting space in a safe way, restoring pressure and temperature

inside the tank. To avoid undesirable low pressure inside the tanks, warmer or preheated hydrogen can be fed back into the tanks from feeding lines.

Figure 7.1 shows the cross-section of the fuselage of the aircraft used for the study; it also illustrates the cabin arrangements and tank locations of three of the four members of the family. The aircraft has two decks to carry passengers, the lower deck larger than the upper one. The aircraft also has large underdeck storage for storage and/or cargo. In Huete et al (2021) the authors proposed three variants of a hydrogen fuelled airliner derived from this concept, HVLMR, HVLLR and HVLER for medium, long and extended range capability respectively. The idea of long and extended range applies to hydrogen in this case and imply much shorter flights than the capabilities of a modern conventional airliner. The first, HVLMR, considers the use of the upper deck to house fuel tanks, HVLLR is conceived with the fuel tank in the lower deck and HVLER with a combination. The baseline weight of the tanks considered here is 1,22 times the weight of the hydrogen contained. These results were communicated in Huete et al (2021) for a baseline gravimetric efficiency (ratio of weight of hydrogen to weight of hydrogen plus tank) of around 0.45. The tank arrangement of HVLER, although not shown in Fig 1, can be implied from the arrangements of the other members of the family.

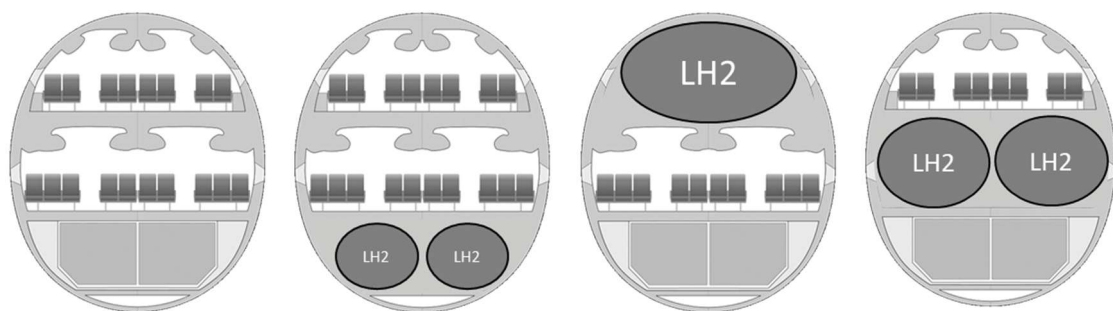


Figure 7.1a Baseline **7.1b** HVLSR layout **7.1c** HVLMR layout **7.1d** HVLLR layout

Image from Ssolbergj and Tillier – Creative commons licenced modified by authors

For the present study, a fourth member of the family is added: HVLSR. This aircraft is conceived as a ‘slot relief’ solution for very busy airports on the same

continent. It offers a useful transcontinental range and a very large capacity. In this design the storage or cargo space is used for liquid hydrogen, leaving the use of the two decks for passenger accommodation.

	AIRBUS A350- 1000	AIRBUS A380- 800	HVLSR	HVLMR	HVLLR	HVLER
Mass (tonnes)						
Ramp	317	577	288	274	304	310
Max. take-off	316	575	287	273	303	309
Max. landing	236	394	275	251	275	276
Max. payload	68	83	80	50	45	36
Operational empty	155	276	194	200	299	238
H2 Tank (gravimetric eff. 0.45)			20	33	51	59
Engines	2	4	2	2	2	2
Cruise thrust/engine (kN)	87	81	84	81	88	90
Static thrust/engine (kN)	432	374	421	406	441	448
Range (nm)	8700	8000	1800	3300	4800	5600
Pax (2 class)	315	555	720	388	332	232

Table 7.1: Comparison of HVLSR, HVLMR, HVLLR and HVLER with the ‘design donor’ aircraft. Baseline η_{grav} is 0.45 – Note magnitude of tank weight.

The estimated vehicle capability, for an introduction accelerator philosophy, is good and practical. It does not match the payload or the very high ranges of current aircraft using conventional fuels, but it fares very well as an introductory accelerator technology to decarbonise aviation. Table 7.1 shows details of the proposed aircraft and a comparison with the existing ‘technology donor aircraft’ (Huete et al 2021). Figure 7.2 shows a schematic arrangement of the four members of the family, figure 7.3 shows the payload-range diagrams of the members of the family and figure 7.4 shows the design range of the aircraft

against the backdrop of civil aviation characteristics (Schafer et al 2016). Figure 4 also shows, for the first innovation wave, the contributions of Hybrid, Electric and Fuel Cell Propulsion juxtaposed with Hydrogen Propulsion in Gas Turbines. With a modest tank gravimetric efficiency of 0.45, the range offered by the aircraft family HVLSR, HVLMR, HVLLR and HVLER, covers more than 97% of existing aircraft departures and accounts for 90% of total fuel consumption. Furthermore, the authors advocate that the remaining 2% of flights could be carried out adding a stop. In this context, the range of 5500 nautical miles was considered important because it allows to reach the other side the planet with a single stop.

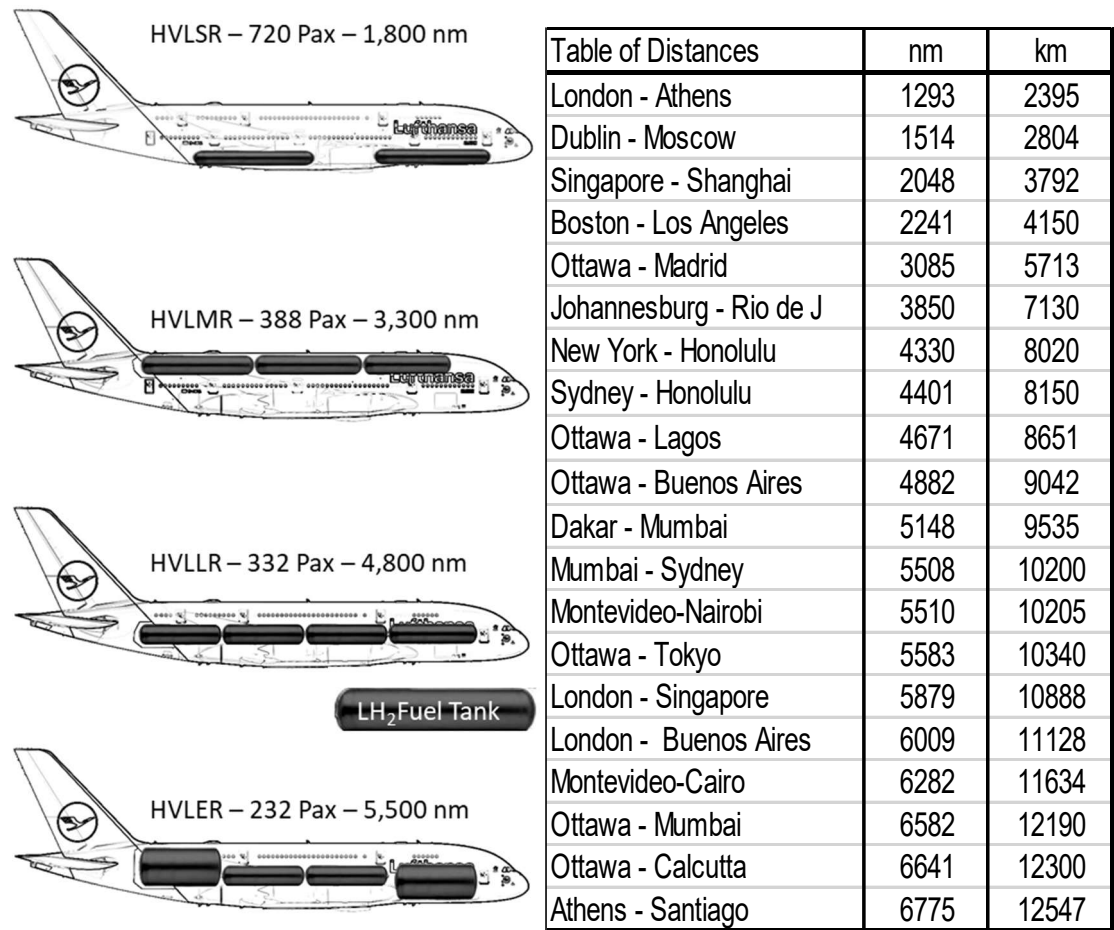


Figure 7.2: Four airliner family concepts. **Table 7.2:** Distances between some airports a measure of the usefulness of the aircraft family (Source Wikipedia)

Images courtesy (Lufthansa 2020) and modified by the authors.

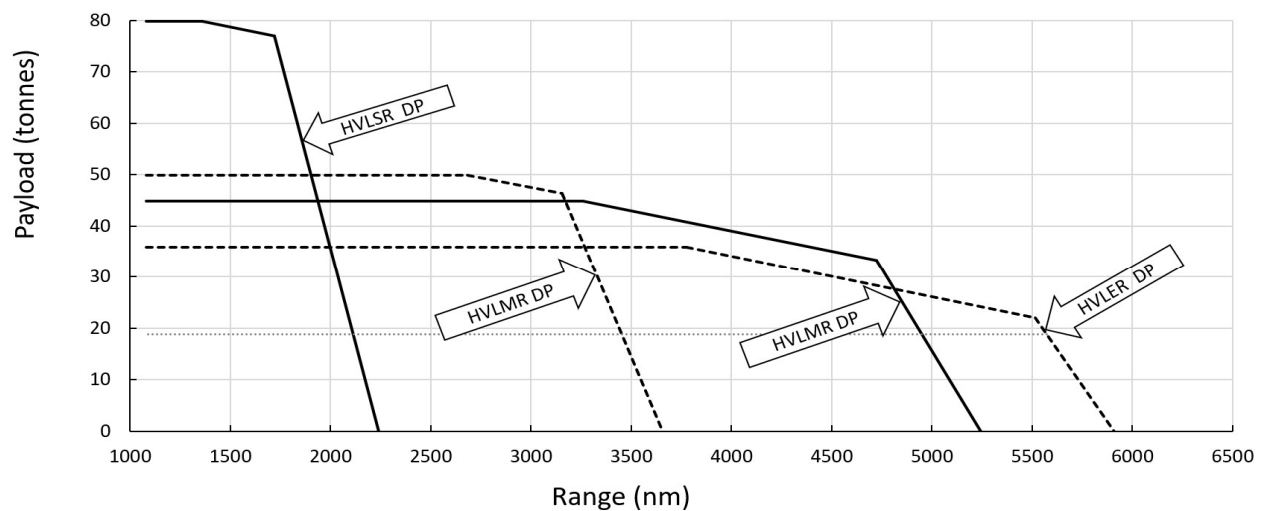


Figure 7.3: Payload range diagrams for the aircraft family, for a gravimetric efficiency of 0.45 with the design points of figure 2 indicated.

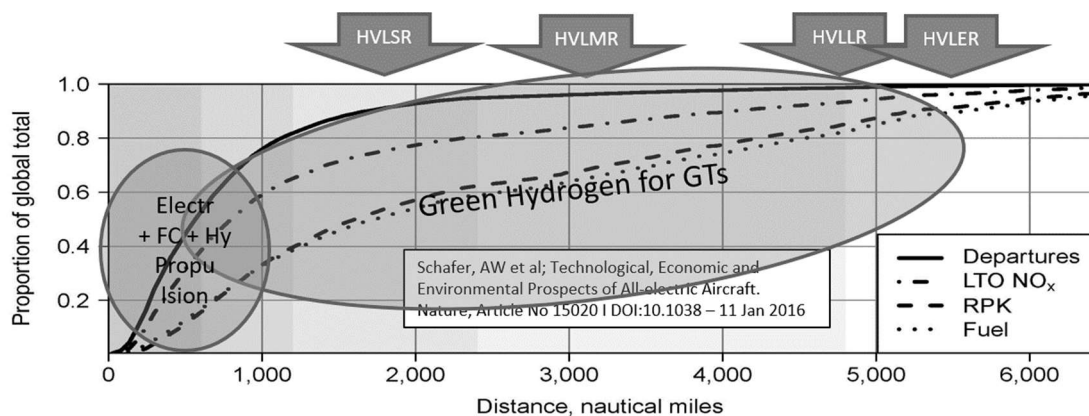


Figure 7.4: HVLSR, HVLMR, HVLLR and HVLER capabilities with a baseline gravimetric efficiency of 0.45. (Schafer et al, 2016) annotated by the authors

7.3 Impact of tank gravimetric efficiency

During this early investigation it became apparent that the tank gravimetric efficiency is a parameter that will significantly influence the performance characteristics of the integrated aircraft and powerplant. The objective of the work described here is to evaluate the impact of gravimetric efficiency on the integrated

performance of the vehicles. Using the methods established in (Huete and Pilidis 2021) a detailed parametric analysis was carried out.

In that study the gravimetric efficiency was evaluated for a range of considerations and design philosophies. Figure 7.5 shows some results of gravimetric efficiency for a particular tank design as a function of insulation philosophies. Given that the subject of the study is the first innovation wave, material properties are assumed to be conventional. Three cases were evaluated: A MLI (multi-layer insulation) arrangement and foam insulation with two different types of insulation.

In Figure 7.5, MLI indicates an arrangement with two containers, one inside the other and separated by a vacuum. Stiffened panels make the structure lighter. For this arrangement, the primary insulator is the vacuum layer and the weight of the tank increases as the maximum operating pressure increases. This is because the internal walls of the tank need to be made stronger and heavier to withstand the higher pressures. Thus, higher maximum operating pressure results in a lower gravimetric efficiency. The usefulness of a high-pressure capability is to contain the hydrogen boiloff without the need to vent during periods when the fuel demand for the engines is low or null. Venting the boiloff enables a lighter tank but it introduces other issues. This suggests a design dichotomy of lighter tanks with more complex boiloff management or heavier tanks with simpler boiloff management; this design dichotomy deserves detailed attention.

In the case of foam insulated tanks, there are two trends to consider. The first is the impact of insulation. Contrary to the case of vacuum insulated tanks, in which the minimum vacuum thickness provides enough insulation and takes hundreds of hours for the pressure to build up to reach the maximum value, foam insulated tanks have a limited time to maximum pressure or dormancy time. Thus, for a given dormancy time, the lower the maximum operating pressure, the thicker the insulation required to avoid heat influx and pressure increase. The second is the effect of internal wall of the tank, like vacuum insulated tanks. The sum of the weight of the insulation plus the wall shows a minimum value at some point, which

coincides with the highest value of gravimetric efficiency. Figure 5 shows that with relatively conservative technology, gravimetric efficiencies of 0.65~0.70 can be achieved

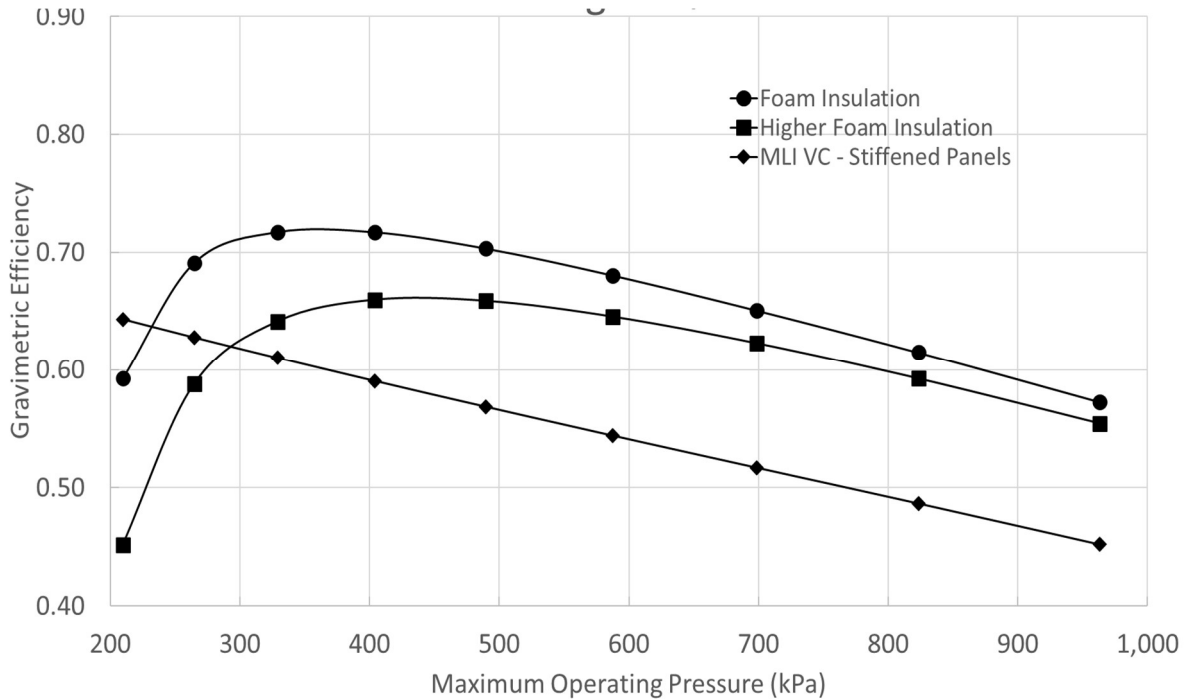


Figure 7.5: Gravimetric efficiency of tank options evaluated for a 100 m³ tank. The tank is cylindrical with hemispherical ends, a diameter of 4m and a length of 9.3m.

In Figure 7.5 the trend indicated for 'Foam Insulation' corresponds to a tank that takes 12 hrs for the pressure to build up from 160 kPa (representative of tank pressure at landing) to Maximum Operating Pressure in near-to-empty condition. This condition is the fastest pressure rise condition and it could happen on an overnight stop. The trend indicating 'Higher Foam Insulation' corresponds to a 24-hr dormancy time under the same circumstances. Tank wall weight is linearly dependent on maximum operating pressure and does not depend on dormancy time. Insulation thickness is dependent on both maximum operating pressure and dormancy time, and for a longer dormancy time, it moves the design to a lower value of gravimetric efficiency.

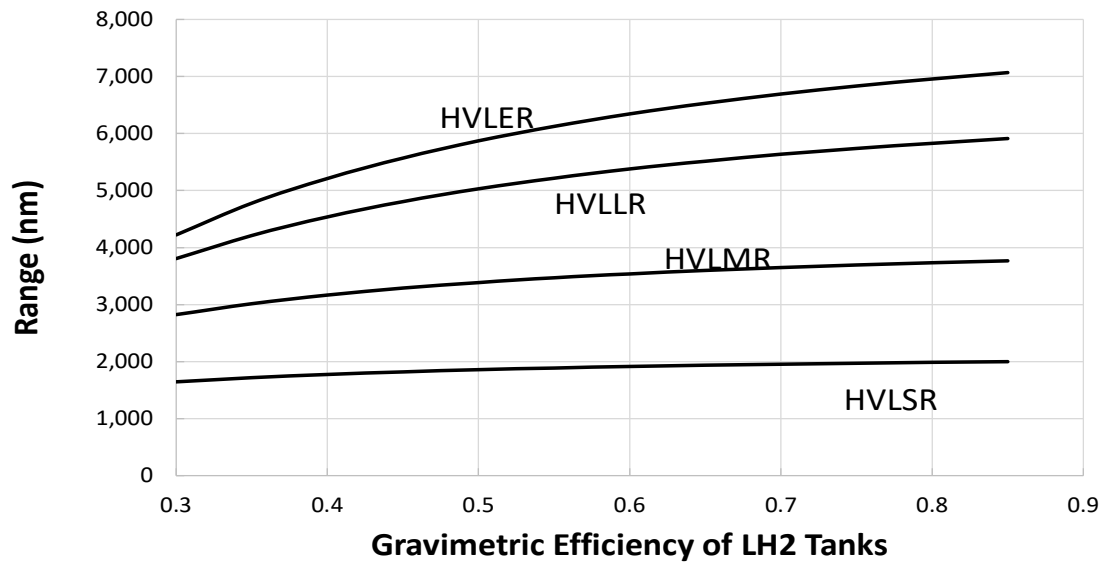


Figure 7.6: Impact of liquid hydrogen tank gravimetric efficiency on aircraft range

The above results were used to determine the range of gravimetric efficiencies to be used in the parametric evaluation. The lowest value and pessimistic boundary of the evaluation was chosen as 0.3. This is in line with McKinsey (2020). The results of the investigation outlined for Figure 7.5 coupled with an optimistic scenario for light material developments, were used to suggest a higher and optimistic gravimetric efficiency boundary of 0.85. These gravimetric efficiency results were then used in the integration evaluation method explained in Huete et al 2021. Essentially, an internally developed program evaluates the performance of the aircraft based on weight correlations by Torenbeek, 1982 and aerodynamic correlations by Raymer, 1992. Engines were assessed using Turbomatch (Nikolaidis, 2017). The program has been validated for large modern existing aircraft – A330/350/380 and B787/777 through several checks: aircraft drag and thrust, payload-range diagrams, and take-off and landing field length are contrasted with those published from the manufacturer. For the hydrogen aircraft, fuselage lay-out is modified to accommodate hydrogen tanks and a reduced passenger capacity is evaluated without exceeding the maximum structural load limit. In an iterative process, optimum wings and engines are down selected to match standard cruise conditions, take-off length and approach

speed. Only the impact of tank gravimetric efficiency in tank weight has been taken into account. Its indirect effect on aircraft operational empty weight through fuselage reinforcements and arrangements has not been accounted for. Therefore, the sensitivity to range shown in this paper should be considered a lower limit, being by and large the expected variation of aircraft performance larger than estimated here due to fuselage arrangement and other nonlinear effects. The results are shown at two levels: change of the design range for the designed Passenger capacity and modified payload range diagrams.

Figure 7.6 shows the range variation of the aircraft with gravimetric efficiency of the tanks. (for each aircraft, the amount of fuel does not change, only the weight of the tanks) For very small tanks, such as those of HVLSR, the impact of changing tank weight is very small because the tank weight is a small fraction of the total aircraft weight. This is shown in Table 1. As tanks become larger, heavier they comprise a larger weight fraction. So, for aircraft designs with longer range the increase in range due enhanced gravimetric efficiency is larger. In the case of HVLER the increase in design range is of about 20% from the baseline gravimetric efficiency of 0.45 to the optimistic value of 0.85.

Figure 7.7 shows three specific examples of the parametric evaluation for each member of the aircraft family and the impact of gravimetric efficiency on the payload range diagram. The cases shown correspond to three values of gravimetric efficiency. The first case is for 0.45; this is compatible with the first evaluation (Huete et al 2021) and what was used as a pessimistic baseline. The next value, of 0.60, corresponds to the value of gravimetric efficiency the authors believe is appropriate for the first generation of hydrogen fuelled aircraft to enter service. The third value of 0.75 corresponds to gravimetric efficiencies that could be implemented in the second or third generation of aircraft. This value of 0.75 is not considered a ceiling, it is rather viewed by the authors as a goal achievable after three decades of development and experience with hydrogen fuelled airliners. Beyond this the law of diminishing returns sets in and the curves shown in figure 6 flatten considerably.

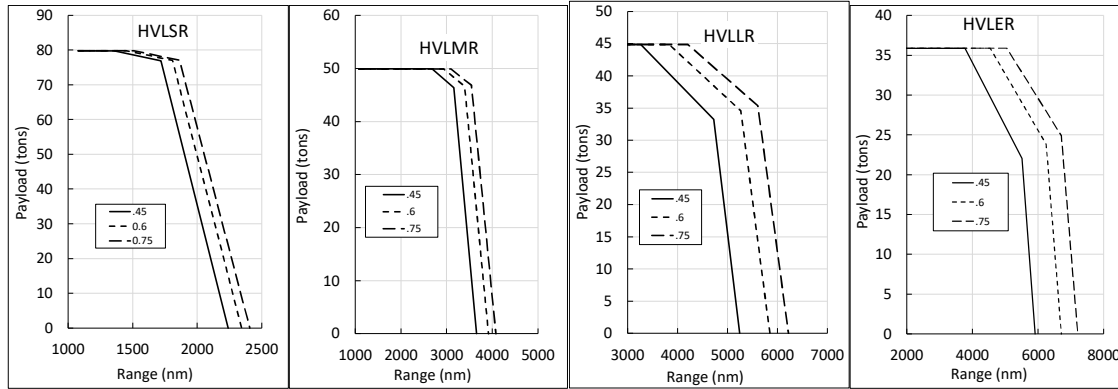


Figure 7.7: Influence of η_{grav} on the payload range diagrams of the aircraft family

7.4 Conclusion

This paper describes a techno-philosophical investigation into a family of four derivatives of a propulsion integration design for the first innovation wave. The models are based on the careful integration of a large twin deck civil transport with the wings and engines of a very long range widebody twinjet. The investigation is backed by detailed calculations. These four hypothetical configurations have different tank locations for storing liquid hydrogen fuel to achieve different payload range objectives. The impact of hydrogen tank weight on the attributes of this family of civil aircraft using hydrogen fuel in gas turbine engines is carried out. could be developed using the main components of two existing aircraft as a basis for the design. The baseline was conceived with a gravimetric efficiency of 0.45.

This family exhibits a payload and range that is significantly smaller than the 'donor' aircraft, however its characteristics are sufficiently attractive to be considered as a launch option for a first generation zero carbon aircraft. The baseline range of HVLER is strategically chosen to allow flights from any point on the planet to any other with just one stop. The focus of this study is the impact of the liquid hydrogen tank weight on the performance of the aircraft. A range of tank gravimetric efficiencies was analysed on the basis of a detailed evaluation and the parametric analysis. The range chosen was from a pessimistic 0.3 to an

optimistic of 0.85. The authors consider that a gravimetric efficiency of 0.7 is a feasible proposition for an entry into service in 12-15 years.

With a gravimetric efficiency of 0.7 the HVLLR would be able to have a range of over 5500 nm, giving it the capability of reaching any point on the planet with a single stop. With this gravimetric efficiency, HVLER's range would extend to more than 6500 nm, offer it a very wide scope for service. With this gravimetric efficiency the family would be able to cover nearly 98-99% of existing large capacity requirements.

It must be noted that safety on airports and aircraft can be managed with careful attention to detail and appropriate investments and there is the need to adapt certification rules. This will give rise to a longer platform development process because in parallel with the development of the aircraft, certification rules will need to be adapted. This family of aircraft could be of fundamental assistance in the certification process given that certification rules will need to be updated. Their similarity with existing platforms is such that it will allow the focus of adapting certification rules on the hydrogen related systems. This is, of course, not a trivial task, but the concept could give rise to the acceleration of decarbonisation.

At the beginning a very small number of hubs would be fitted with the capability of refuelling hydrogen. However, one useful feature of hydrogen is its light weight, so the penalty for carrying extra fuel is much smaller than that for conventional fuel. This would permit the aircraft to serve many destinations without refuelling, i.e., having pre-loaded the fuel at a hydrogen hub, land, disembark and embark passengers without refuelling in a conventional airport and flying on to another hydrogen hub. The authors strongly believe that seawater electrolysis with green electricity is required, requiring coastal hydrogen production stations. Preliminary investigations show that with two hubs whole continents can be covered with these arrangements and even single hub operations are very attractive. A certified inter aircraft refuelling kit for land operations would need to be designed to fit in the large cargo hold of HVLLR. This could be loaded onto an aircraft to rescue another in the case of a 'stranded' situation in a conventional airport.

Undoubtedly all these developments will cost hundreds of billions of pounds (or euros or US dollars). In fact, the more the details of this first generation of hydrogen aircraft are explored, the stronger becomes the view of the authors that the main obstacle for developing green civil aviation is the short-term cost of the transition. However, the authors firmly believe these costs are acceptable to migrate to zero-carbon an industry that brings so many technical, social and economic benefits.

7.5 Acknowledgement

The authors acknowledge and thank Lufthansa for the use of their artwork and their encouragement.

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8 PARAMETRIC STUDY ON TANK INTEGRATION FOR HYDROGEN CIVIL AVIATION PROPULSION

Huete, J. and Pilidis, P. (2021). Parametric study on tank integration for hydrogen civil aviation propulsion. International Journal of Hydrogen Energy, ISSN: 0360-3199, Vol: 46, Issue: 74, Page: 37049-37062

8.1 Abstract

Hydrogen powered gas turbine propulsion will play a central role in the decarbonisation of civil aviation. A key challenge is the integration of large liquid hydrogen tanks into the aircraft, given the low density of liquid hydrogen. Hydrogen offers a quarter of the energy content, per unit volume and one third of the fuel weight, when compared to a conventional fuel. Optimising tank weight is seen as key to aircraft usefulness. A detailed evaluation of tanks for civil aviation is presented here, covering a very wide range of sizes and design solutions.

For passenger air transport, if the choice is made not to vent, dormancy time (the time the tank can be allowed to operate without vapour or important fuel extraction) becomes a key design parameter. This paper highlights the interdependence of Maximum Allowable Operating Pressure and the amount of insulation with heating and venting, considering the influence of dormancy time.

The resulting tank gravimetric efficiency is presented for cylindrical tanks with hemispheric ends (a very likely choice for tank design). Notwithstanding conservative analysis, tank gravimetric efficiencies of 65-70% can be achieved. This permits combined fuel and tank weights that are less than half of those of current aircraft. The issue that then becomes critical is the resulting large tank and aircraft volume.

Nomenclature

Variables

E : Young's Modulus

h : Enthalpy

$\dot{m}$: Mass Flow

n : Number of Baffles

l : Length

P : Tank Pressure

$\dot{Q}$: Heat rate

R : Radius

SF : Safety Factor

t_d : Dormancy Time

u : Internal Energy

V : Tank Volume

x : Vapour Quality

w : Thickness

η : Efficiency

ρ : Density

σ : Stress

ν : Poisson's Ratio

Φ : Energy Derivative

Subscripts

b : Buckling

$grav$: Gravimetric

i : Inlet (for $\dot{m}$ and h) or Insulation (for w)

max : Maximum

l : Liquid Phase

o : Outlet

p : Pressure

v : Vapour Phase

w : Wall

ρ : Constant Density

Abbreviations

ERF Effective Radiating Forcing

LH₂ Liquid Hydrogen

MLI Multi-Layer Insulation

VC Vacuum

SAF Sustainable Aviation Fuel

8.2 Introduction

Hydrogen can be a sustainable fuel and a complete solution given the absence of carbon, aromatics, particle emissions and sulphur (Verstraete, 2009); there is very high potential for low NO_x (ENABLEH2, 2020) and contrails can be eliminated by careful rerouting (Teoh et al., 2020). Attention needs to be devoted to the emissions of large quantities of water vapour in the atmosphere.

Hydrogen aviation and aircraft concepts have been widely studied in a number of comprehensive studies (Brewer, 1991; Clean Sky 2 and European Commission, 2020; ENABLEH2, 2020; Huete, J; Nalianda, D, Pilidis, 2021; Khandelwal et al., 2013; Prewitz, Bardenhagen and Beck, 2020; Verstraete, 2009, 2015; Westenberger, 2003b). A challenge that always arises is storing a low energy density fuel and maintain aircraft usefulness. This yields high volume designs although with low take-off weight.

Hydrogen can be stored in a variety of ways, mainly, as a gas; as a liquid; and as part of a chemical compound (Colozza, 2002). In all cases, the challenge arises from its low volumetric density. Compressed hydrogen at 700 bars has a density of 42 kg/m^3 , about half of liquid hydrogen. Liquid hydrogen has a density of 70.8 kg/m^3 with 120 MJ/kg LHV, which results in 8.5 GJ/m^3 . Kerosene, with 33.6 GJ/m^3 (0.785 kg/m^3 and 42.8 MJ/kg) has approximately four times more energy per unit volume. Current research on hydrides, adsorption or chemical storage could improve the volumetric density, at a great cost in terms of added weight. The automobile industry has opted for gaseous hydrogen at high pressures (Nazir et al., 2020), after carefully examining liquid hydrogen (BMW, 2006) due to the complexity of producing, handling and storing liquid hydrogen for days or weeks inside a car. In aeronautics, liquid hydrogen has been the preferred option of studies to date, although research on how to diminish the high repulsive forces of hydrogen by means of porous carbon material (Agata Godula-Jopek et al., 2018), mycelium (Benjamin J. Stephenson and Jeffrey M. Hansen, 2017) or others (Züttel, 2003), in order to increase the volumetric density is still ongoing. Whatever technology is chosen for aircraft applications, the challenge is the same, integrating very large tanks in the aircraft.

Several studies focus on tank architecture, material and manufacturing technologies (Brewer, 1991; Colozza, 2002; Gomez and Smith, 2019; Mital et al., 2006; Sharifzadeh, Verstraete and Hendrick, 2015; Verstraete et al., 2010b), aiming to select the lightest solution. The figure of merit commonly accepted is the gravimetric efficiency, or weight of hydrogen per unit of fuel system weight, a similar concept to the weight fraction used in automobile tanks. One of the critical functions of a hydrogen tank is to keep it liquid at a temperature around 20K-30K for the whole mission. Heat leakages will try to increase the temperature while fuel withdrawals will reduce it due to the heat absorbed by a small fraction of the remaining liquid that vaporises and occupy the space that the withdrawal creates. These two phenomena fight against each other during the flight and the design of the tank must balance the overall effect. A large surface to volume ratio, would favour a higher heat leak, but it may be appropriate for short duration tanks with high rates of fuel mass flow. For long range flights, a higher maximum tank temperature (and pressure) can be designed at the cost of a thicker tank wall, or a higher insulation thickness may be placed, yielding to a heavier tank. Or the heat leakage be pursued through a reduction in surface to volume by increasing the tank diameter, reducing the curvature of the hoop stresses, and leading also to thicker walls. There is, however, a wide variety of estimation of tank gravimetric efficiency, ranging from 0.2 (Clean Sky 2 and European Commission, 2020) to above 0.7 (Brewer, 1991; Goldberg, 2018; Verstraete et al., 2010b), and many intermediate values (Marquardt et al., 2015; Sullivan et al., 2006; Winnefeld et al., 2018) with no evident explanation on the origin of the differences. The authors could not find a consistent and comprehensive evaluation covering the weight estimation from different sources to define a path for optimum design, considering implications at airport and airline level. A parametric study to understand the effect of tank size, diameter or length, design maximum operating pressure, wall material and tank architecture is performed. This is a central scientific contribution of this paper.

However, even with very heavy tanks, the overall weight of the tanks and fuel for a hydrogen system is lighter than a kerosene one. For example, 1 unit-weight of Kerosene is equivalent to 0.33 unit-weight of hydrogen on an energy basis. Hydrogen tanks can add an extra weight up to 0.66 unit-weight and still be lighter than the kerosene equivalent system. It has been assumed that integral kerosene tanks weight a negligible value compared to the kerosene weight they contain. The kerosene and hydrogen tank system will have equal weight for full tanks at a gravimetric efficiency of 0.33., For higher than this value, hydrogen aircraft will be lighter at take-off than conventional aircraft, but the volume will be much larger. For a gravimetric efficiency of 0.66, a full hydrogen tank weights half of a full kerosene tank with the same energy content. At landing, hydrogen tank adds a relatively small weight. In the very long term, designs capitalising on the careful balance of these two (larger volume lighter weight) conflicting characteristics plus the use of propulsion cycles that could be delivered with hydrogen but not with conventional fuels could yield more efficient aircraft designs.

Central to the design decisions that engender the tank weight are safety considerations, reliability, technology readiness level and venting (Momenthy, 1977). Venting is the process of safely releasing hydrogen vapour from the tank once it has reached the maximum allowable pressure due to heat leakage from the atmosphere into the cryogenic tank. Venting design guidelines can vary from venting at most flight segments a controlled amount to no venting at all throughout the flight and for a long time if parked. Venting is common process in all stationary applications. However, safety rules and airport specific constraints makes venting in aircraft applications more undesirable. In the long term, safety regulations may find the way to allow venting at or away from the gate, but it is likely that these approvals require time.

Therefore, a novel optimisation process based on the dormancy time (time for the tank pressure to reach venting pressure) as a main design parameter is suggested. Different tank architectures and insulation technologies are considered to explain the differences in tank gravimetric efficiencies found in previous research. Venting and its implications are analysed. Subsequently,

tanks for shorter and longer ranges of different sizes are studied, and limitations of hydrogen tank integration in aircraft are explored.

It is widely accepted that hydrogen have a different hazard behaviour than kerosene, being riskier in some situations and safer in others. For example, its low ignition energy and high volatility makes it more dangerous in confined spaces, while the lower flame emissivity or the higher lower-flammability limit makes it less damaging in open air. Main hazards are broadly represented by hydrogen related injuries, pressure hazard, and combustion hazard (Beeson and Woods, 2003).

Hydrogen related injuries refer to burns or frostbites under contact with cold fluid or burning fluid. A liquid hydrogen spill will fall down to the floor and air will condense on its surface with an oxygen concentration of around 50%. The rapid evaporation of hydrogen will originate flammable clouds that will travel mostly vertically due to low density of gaseous hydrogen. In order to prevent injuries, hydrogen tanks should be placed separately from the passenger cabin and confined in case of accidental spill.

Pressure hazard relates to the overpressure that could arise under vaporisation of liquid hydrogen in the tank or any closed section of the fuel system. Overpressure may lead to leak of the tank or the component, which represent a combustion hazard. In extreme cases, it may lead to burst of the component, with a massive release of liquid hydrogen. In all designs, the thermal insulation diminishes the heat influx, but there is always a boil-off rate inside the tank and system parts that increases the temperature and pressure of the liquid-vapour mixture. After certain period, the pressure would reach the maximum operating pressure, and venting becomes necessary. Since venting at the airport is not recommended at initial stages of hydrogen aviation, then it follows that vacuum insulated tanks, with a much longer dormancy time, will be preferred to first airliners' entry in to service. Vacuum insulated tanks lose most of the thermal insulation if vacuum is lost. Redundancy of the vacuum pumps and system will be required to mitigate this risk.

Combustion – deflagration or detonation – in the aircraft can occur when there are leakages of hydrogen or air through the fuel system parts. This may occur through joints and valves, by a tank or piping wall failure, or by the filling process after an unsatisfactory purging. Deflagration is a minor problem if compared to detonation. Most incidents where ignition of hydrogen in open air has occurred have had limited damages, since hydrogen burns in a vertical buoyant flame. Only under a high ignition energy source or when in total or partial confinement, it has been reported that deflagration turns into detonation. (NASA, 1997, 2019)

Undesired combustion at the airport may be due to leakages of the fuel system or the refuelling system into the atmosphere or by spontaneous ignition of the venting system, when in operation. Vacuum insulated tanks have a much lower conductivity, and this leads to much longer dormancy times. From this point of view, foam insulated tanks show another disadvantage, particularly, if tanks are designed with a short dormancy time, so that venting becomes a usual procedure. Vented gas can eventually ignite and burn safely at the venting nozzle in stationary applications. Venting stacks up to 0.25kg/s are disposed at least 15 feet above a roof peak. For higher venting mass flows, flare stacks are recommended, but these need to be distanced 60 m from any occupied building (NASA, 2019). Therefore, venting in an airport environment will need to be avoided in first phases of operations.

Experience from other applications in relation to handling, purging procedures or other health and safety rules can be transferred and constitute a base for safe operation. Still there will be additional aspects that are specific to passenger transport. For example, the cohabitation of liquid hydrogen tanks and passengers in the small space of the fuselage may impose additional safety features; the requirement to have the lightest possible tanks may give rise to new tank architectures that have to demonstrate reliability and durability; a frequency of refilling of several times a day which may imply a higher likelihood of tank and system contamination, to name a few.

Vacuum insulated tanks and pipes offer a preferred short time solution for two reasons: enhanced safety through a double wall, usually with vacuum monitoring

and a vast and long experience in ground applications that foam insulated tanks lack. In all cases, fuel system pressure should never be sub-atmospheric since leakage of air into the tank could lead to a detonation of the mixture. Particular attention must be drawn to hydrogen detection in all confined spaces including the vacuum jacket. An inert gas atmosphere surrounding the tank can provide additional safety feature.

In a longer term, foam insulated tanks, when lighter, could be used, but there need to be enough experience built before then, that must be gained in other applications. Foam insulated tanks present several disadvantages with regards to the combustion hazard: if inner wall is not designed to sustain negative pressure, purging will need to be done by positive pressure purge procedure, typically with Helium. It requires more purging cycles than vacuum purging to reach the same residual concentration of oxygen and therefore will need higher purging gas flows to keep refuelling time acceptable; foam or aerogel must be enclosed and filled with an inert gas to avoid air condensation over the cold wall.

8.3 Integration of hydrogen tanks into the aircraft

Figure 8.1 shows a variety of proposed concepts. In all of them, evident is the challenge of integrating very large tanks within the airframe, leading to either an extension of the fuselage or a trade-off between passengers and fuel capacity, or both.

It is widely acknowledged that unconventional designs will ultimately deliver many of the potential benefits of hydrogen (Goldberg, 2018; Goldberg C, Nalianda D, Singh R, 2017). BWBs offer a more favourable configuration than the conventional tube and wing design. During the Cryoplane studies several non-conventional configurations were analysed at Cranfield University. A team of researchers and experts from Delft University, Sweden Defence Research Agency, DASA, Dornier and Cranfield University evaluated more than 20 unconventional concepts and concluded that Twin Tail-Boom and Tail-Tank concepts shown in Figure 8.2 were most appropriate configurations (SEFAIN, 2000).

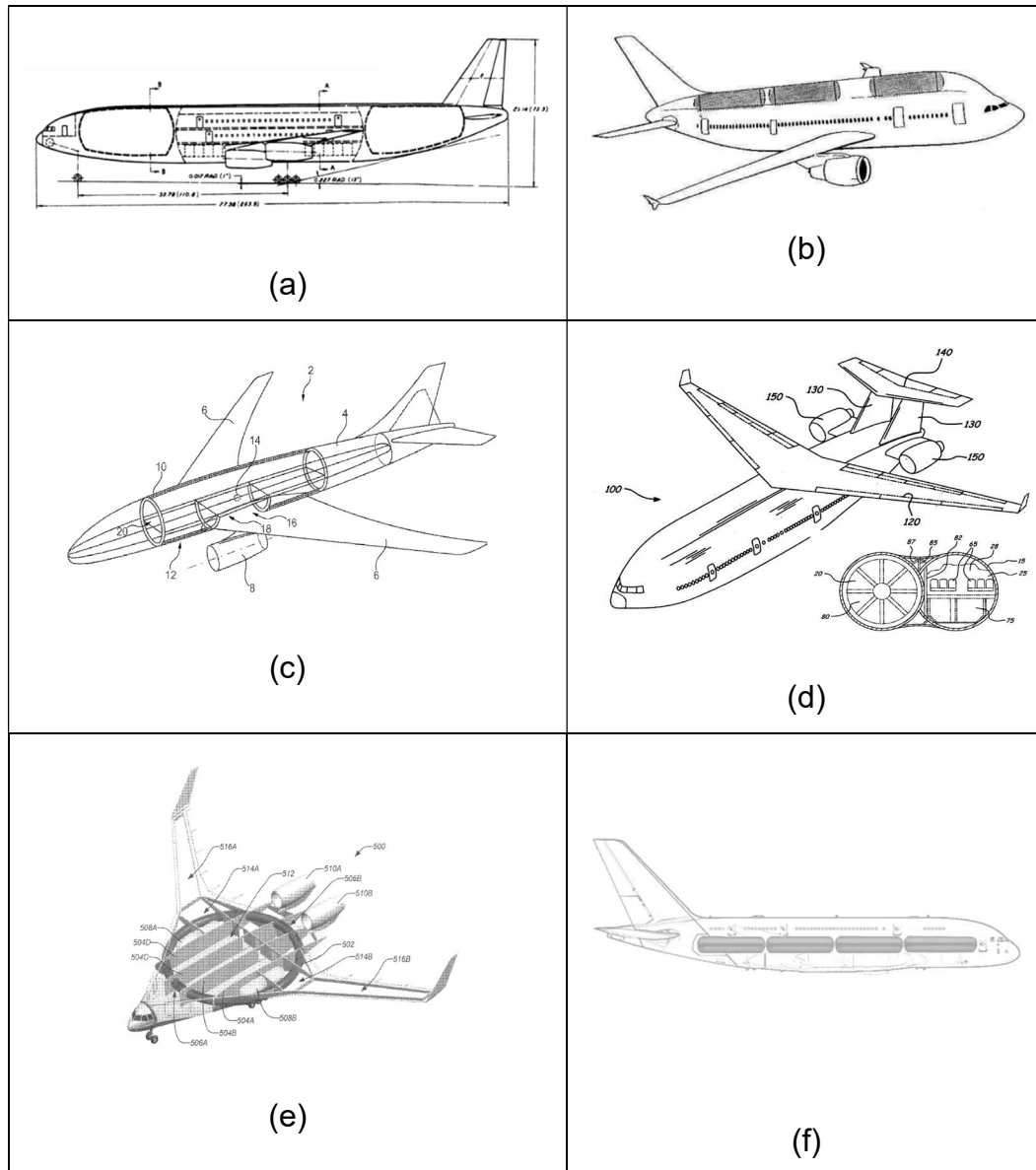


Figure 8.1: Main concepts of Hydrogen tanks in aircraft applications. (a) Fwd and Aft tank proposed by Brewer (Brewer, 1991), also adopted Airbus Zero-e concepts (AIRBUS, 2020b); (b) Upper tank proposed by Cryoplane (Cryoplane EU Consortium, 2003), also adopted by ENHABLEH2 (ENABLEH2, 2020); (c) Other Airbus concept (Schumacher, Hoffjann and Lehmberg, 2015); (d) Other *Boeing concept* (Seidel, 2003); (e) *Other Boeing concept* (Velicki and Hansen, 2006); (f) *Two deck Aircraft* (Huete, J; Mourouzidis, C; Nalianda, D, Pilidis, 2021).

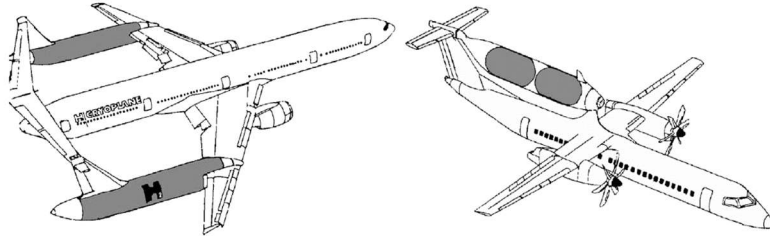


Figure 8.2: Unconventional concepts explored during the Cryoplane studies.

Recently, in ENHABLEH2, an EU funded consortium led by Cranfield University, 30 conventional and non-conventional configurations have been carefully assessed against 35 criteria for short- and long-range applications (Rompokos et al., 2021) concluding that configurations similar to Figure 8.1(b) and (e) are the most appropriate for long range aircraft.

The challenge of volume has led to designs with much lower stored energy than comparable conventional fuel aircraft. With a much lower energy onboard and an increased drag, the search for the lightest tanks has been one way to increase the range to acceptable values for airline operation.

8.4 Design guidelines and venting implications

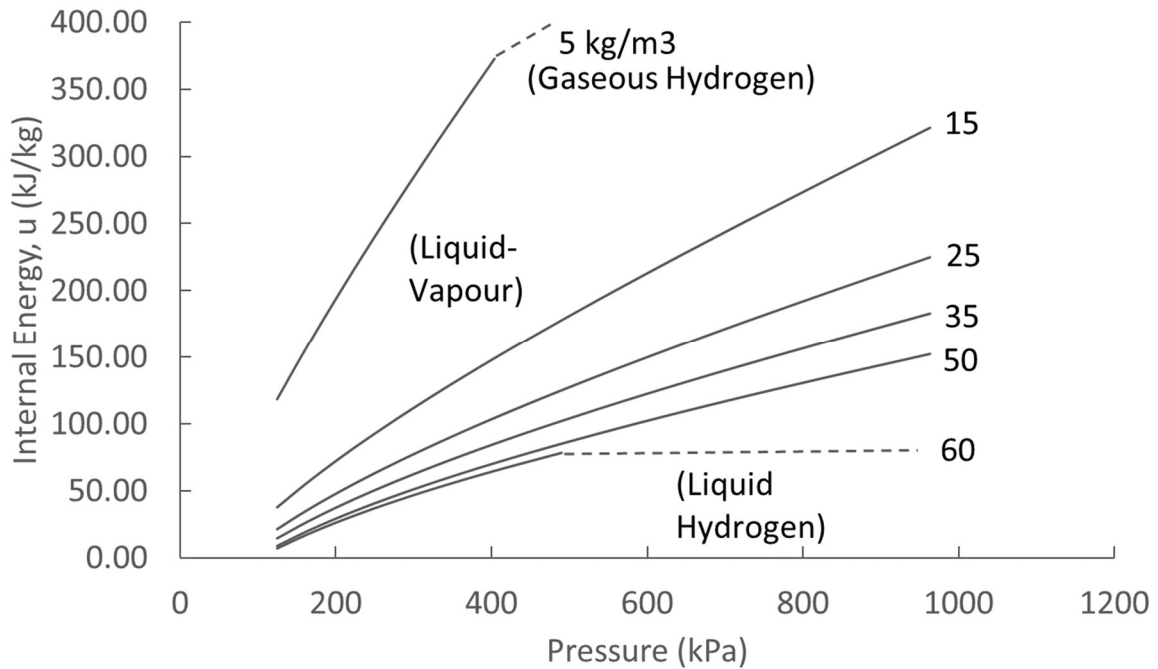
A well established method for tank design was introduced by (Brewer, 1991; Brewer and Morris, 1976) and is presented in (Colozza, 2002). The focus is to consider the hydrogen vented during the mission duration as a source of dead weight and minimise the sum of weight of tanks plus vented hydrogen. Usually, the maximum operating pressure of the tanks is chosen arbitrarily, commonly between 200 and 500 kPa. The process leads to an optimum insulation thickness, since for a low insulation thickness, tank weight is low and boil-off gas is high and for a high insulation thickness, the contrary applies. Somewhere in between there is an optimum that minimises the overall dead weight. Such a method is appropriate when the power requirement is low. Not considering the fuel flow to

the engines leads to an overestimation of boil-off, because hydrogen withdrawals reduce the pressure of the tank. Pressure variation in the tank is described in Eq.8.1 (Lin, 1991) :

$$\frac{dP}{dt} = \frac{\Phi}{V} \left\{ \dot{Q} + W + \dot{m}_i \left[h_i - h - \rho \left(\frac{\partial h}{\partial \rho} \right)_p \right] - \dot{m}_o \left[h_o - h - \rho \left(\frac{\partial h}{\partial \rho} \right)_p \right] + \rho^2 \left(\frac{\partial h}{\partial \rho} \right)_p \frac{dV}{dt} \right\} \quad (8.1)$$

where the energy derivative, Φ , is shown in Eq. 8.2 and Figure 8.3 from hydrogen vapour-liquid equilibrium data from (Leachman et al., 2009).

$$\Phi = \frac{1}{\rho \left(\frac{\partial u}{\partial P} \right)_\rho} \quad (8.2)$$



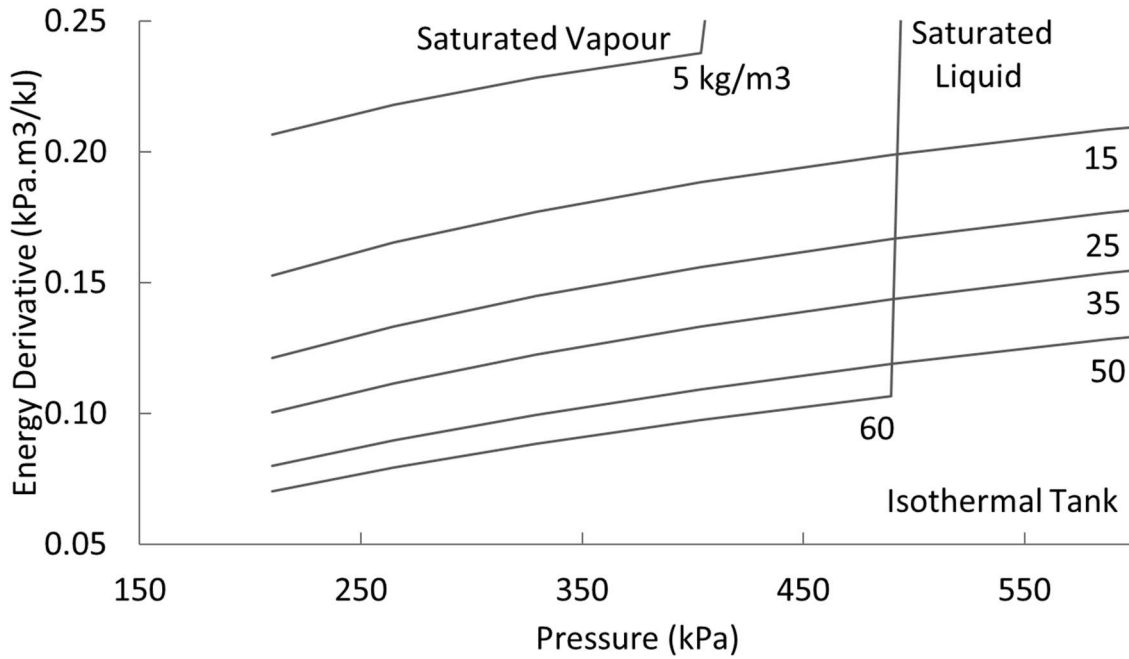


Figure 8.3: Internal Energy (top) and Energy Derivative (down) of Hydrogen at Liquid-Vapour Equilibrium

Eq. 8.1 can be rewritten, for a fixed volume tank with no inlet flow, as Eq. 8.3:

$$\begin{aligned} \frac{dP}{dt} &= \frac{\Phi}{V} \left\{ \dot{Q} + \dot{m}_o \left[h - (h_v - h_l) \left(x + \frac{\rho_v}{\rho_l - \rho_v} \right) \right] - \dot{m}_o h_o \right\} \\ &= \frac{\Phi}{V} \left\{ \dot{Q} - \dot{m}_o \left[h_o - \left(\frac{h_l \rho_l - h_v \rho_v}{\rho_l - \rho_v} \right) \right] \right\} \quad (8.3) \end{aligned}$$

For a stable steady-state condition to be reached ($dP/dt=0$) heat input must be balance by an enthalpy removal through an outlet flow – either fuel flow to the engine or venting some vapour flow out of the tank, as determined by Eq. 8.3. Otherwise, pressure would increase or decrease indefinitely. The transient pressure variation rate is also influenced by the energy derivative – with very low values as long as the vapour-liquid equilibrium exists. Pressure variation for a given heat input is damped by the liquid-vapour phase change equilibrium. Energy derivative grows quickly (nearly vertical) as soon as the vapour mixture

either fully evaporates (for densities lower than critical point density) or fully condenses (for densities higher than the critical point density), as can be observed in Figure 8.3.

For a preliminary thermal sizing, Q can be obtained from the steady-state isothermal model of the tank, considering convection and radiation from the surroundings and conduction through the insulation and the wall as described in (Colozza, 2002). For large tanks, consideration of conduction only, with tank external wall temperature equal to that of the surroundings leads to an error in the order of 1%. Further, conduction through the insulation can be approximated for, $w_i < 0.1R$ to:

$$\dot{Q} = kS \frac{dT}{dw_i} \approx kS \frac{\Delta T}{w_i} \quad (8.4)$$

Substituting Eq. 8.4 into Eq. 8.3 leads to an expression in which pressure variation depends on surface to volume ratio of the tank, insulation properties and tank duration time, t (taken as an approximation to flying time, shown in Eq. 8.5).

$$\frac{dP}{dt} = \Phi \left\{ k \frac{S}{V} \frac{\Delta T}{w_i} - \frac{\rho}{t} \left[h_o - \left(\frac{h_l \rho_l - h_v \rho_v}{\rho_l - \rho_v} \right) \right] \right\} \quad (8.5)$$

Surface to volume ratio is mostly dependent for any cylindrical tank with hemispherical ends on the radius of the tank, R . Surface to volume ratio has a minimum value of $2/R$ for a very long cylinder and $3/R$ for a sphere. For any given cylindrical tank with hemispherical ends, surface to volume ratio has a value between those.

Figure 8.4 shows Eq. 8.5 for various cases. '5hr tank' shadow area represents any cylindrical tank with hemispheric ends with a liquid withdrawal rate that makes the tank last for 5 hrs, and for a foam insulated thickness of 50 mm and various tank diameters (along horizontal axis). Thermal conductivity of foam has been taken 0.015 W/m.K. '2 hr tank' shadow area shows the equivalent area for a 2-hr lasting tank. The full line at the bottom (Spherical or Cylindrical Vacuum Insulated 2 hr tanks) shows Eq.5 for a MLI vacuum insulated tank with a thermal conductivity of 0.00015 W/m.K. It should be noted that such a low thermal conductivity makes the first term of Eq. 8.5 negligible against the second term.

By assimilating the duration of the tank as the flying time and the liquid withdrawal rate as the cruising hydrogen fuel flow, Figure 8.4 shows that smaller diameter tanks tend to have a pressure increase during cruise due to a high surface to volume ratio associated with a low diameter, and regardless of the length of the tank. Large diameter tanks and vacuum insulated tanks show pressure reduction during cruise and will need some sort of heat addition in order to limit the minimum pressure in the tank. For a 2 hrs medium haul flights, tanks can be in the 1.5-2 m diameter range for neutral pressure variation and between 3.5m and 5m for a 5 hrs long haul flight. Very small diameter tanks (< 1m) to optimise space use inside wings or in narrow spaces for any range application will require venting at cruise or vacuum insulation with heat addition. For tanks inscribed in current fuselage sizes, at any range, pressure can be designed to be more or less constant throughout the flight or slightly reducing. All lines in Figure 8.4 will shift to the left if a thicker insulation is considered.

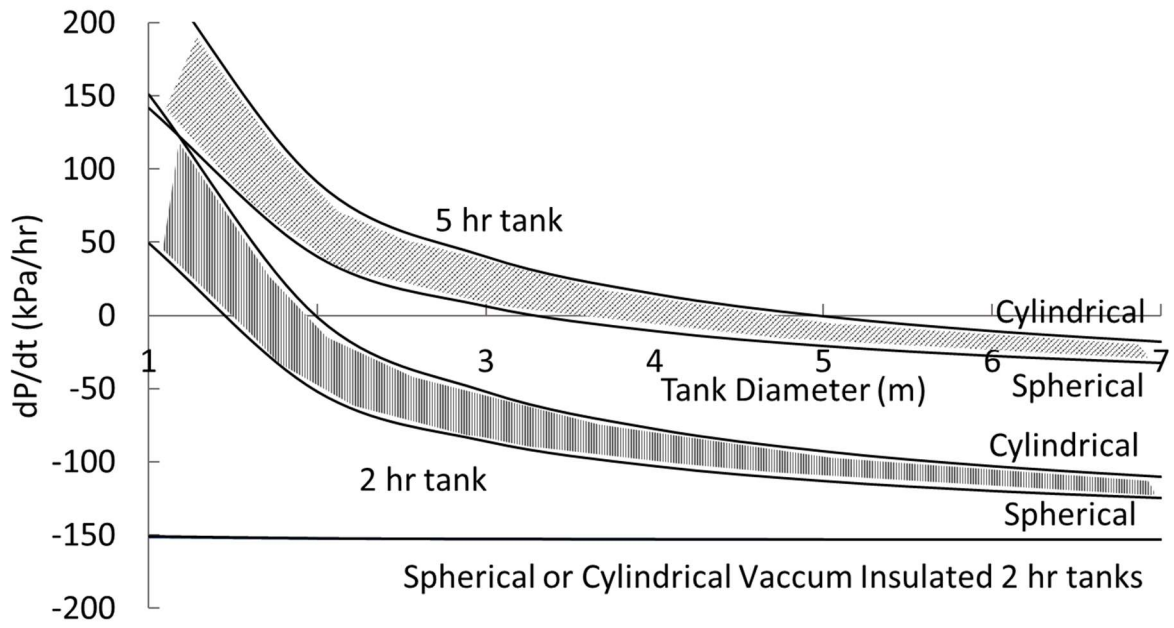


Figure 8.4: Effect of tank diameter and geometry on tank pressure variation during liquid withdrawals

When there is fuel withdrawal, the combined effect will be of a pressure decrease whenever the heat leakage is lower than the “corrected” enthalpy of outlet flow. Eq. 8.6 is derived from Eq. 8.3 and Eq. 8.4.

$$\dot{Q} = kS \frac{\Delta T}{w_i} < \dot{m}_o \left[h_o - \left(\frac{h_l \rho_l - h_v \rho_v}{\rho_l - \rho_v} \right) \right] \quad (6)$$

For civil passenger transports, at standard cruise fuel flow, tank pressure would typically fall because the fuel extraction will be much larger than the heat leakage, and heat must be added carefully to avoid decompression below ambient value. At airports, either on a long take-off delay or on a stop-over venting may become eventually necessary. The dormancy time, or time that the tank takes to increase the pressure from re-fill (P1) to venting (P2) can be derived from Eq. 8.3 since

energy derivative at constant density (closed tank with no outlet flow) is linearly dependant to pressure (see Figure 8.3). Eq. 8.7 shows the result of the integration after substitution of Eq. 8.4 and the implicit design trade-off between tank wall thickness and insulation thickness since either Q or P_2 can increase the dormancy time.

$$t_d = \frac{V}{\dot{Q}} \int_{P_1}^{P_2} \frac{dP}{\Phi} \cong \frac{V}{S} \frac{w_i}{k\Delta T(d\Phi/dP)_\rho} \ln\left(\frac{\Phi(P_2)}{\Phi(P_1)}\right) \quad (8.7)$$

It should be noted that dormancy time is dependent on the energy derivative “ratio” between initial and final pressure. Such ratio is about double for a full tank than for an empty tank, therefore, it should be expected a shorter time to venting after landing with a nearly empty tank than on a take-off delay.

Once maximum pressure is reached, hydrogen is then removed from the tank for pressure regulation (usually vapour, with a much higher enthalpy). In this case, necessary vented vapour to keep pressure constant is calculated in Eq.8, that also shows a simpler approximated expression, for pressures well below the critical pressure $\rho_l \gg \rho_v$.

$$Q = m_o \left[h_v - \left(\frac{h_l \rho_l - h_v \rho_v}{\rho_l - \rho_v} \right) \right] \cong m_o [h_v - h_l] \quad (8.8)$$

For a tank with no pressure variation during cruise, it can be deduced from Eq. 8.6, Eq.8.7, and values of energy derivative in the order of 300 to 500 kPa from Figure 8.5 that the dormancy time is around 0.6 of the cruising time, taking the cruising time as the duration of the tank at cruise fuel flow. For short and medium haul flights this value would be too low to avoid venting at the airport under a minimum delay. For long haul, it would still be too low for an overnight stop, increasing the insulation thickness requirement over that required to avoid

pressure increase during cruise. Therefore, it should be expected that for a non-venting tank at airport, pressure will reduce during cruise.

Figure 8.5 shows the pressure variation over the different flight segments for a generic case in which pressure reduces during cruise. The starting point in the figure (Refilling) represents the equilibrium of hydrogen mixture inside the tanks after filling. Pressure must be above atmospheric throughout, to avoid accidental air ingestion into the tanks. Since liquid hydrogen density increases with reducing temperature, it is desirable to fill the tank at the lowest possible temperature/pressure. As soon as the tank is closed, the density of the mixture will be fixed, and any variation in conditions will be along the horizontal line marked as “Take-Off Delay”. A small amount of vapour is needed – tank ullage – since any heat leakage before departure will increase the liquid volume fraction. Overfilling of the tank may lead to overpressure if all ullage is taken by the liquid phase expansion. A 5% ullage volume fraction has been considered along the work, offering an allowance for 2K or 150 kPa increase before departure. On departure, pressure starts dropping because of the fuel extraction to the engines, until it reaches a specified lower value above atmospheric. Then heat addition or any other process of heating up the mixture is necessary to prevent a reduction below this lower value. Possibly during descent, and certainly after landing when engines are turned off, pressure will start increasing again. Depending on tank pressure at landing and fill level, the tank will eventually reach to venting pressure.

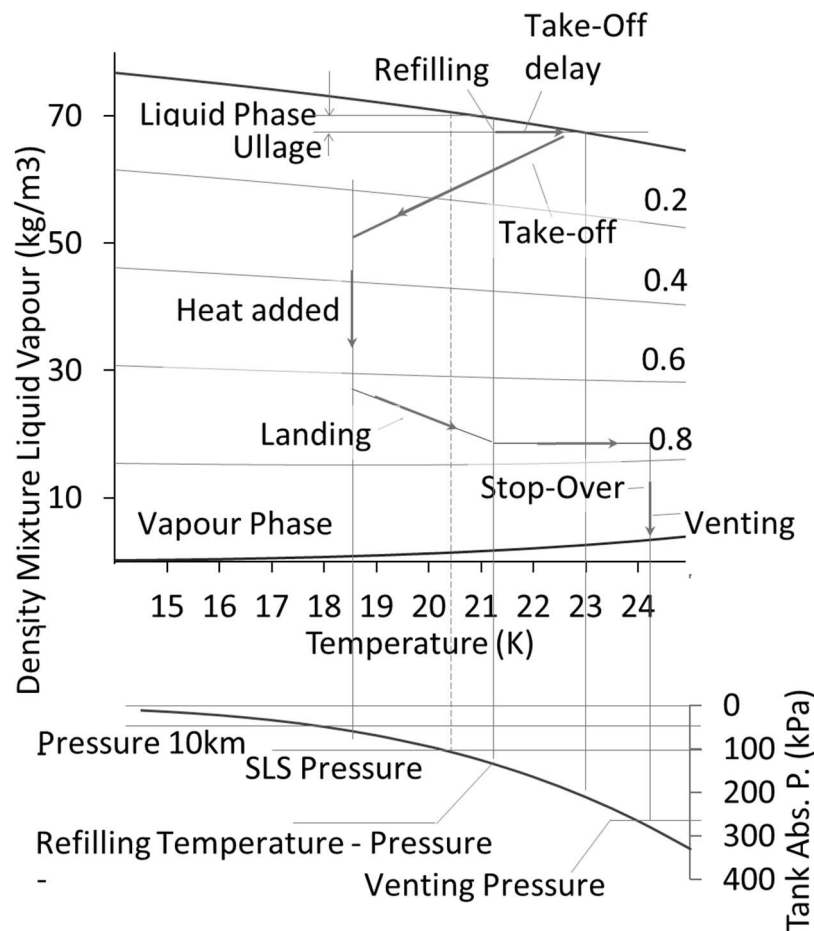


Figure.8.5: Tank pressure variation over the flight

Eq.8.1 provides accurate results for a static, isothermal tank – a tank with homogeneous temperature in all vapour and liquid contained. If the fluid inside the tank is not stirred, a temperature gradient will form due to convection of liquid and vapour in contact with the tank wall and pressure rise will be faster than a homogeneous temperature tank. References (van Dresar, Lin and Hasan, 1992; Hasan, Lin and van Dresar, 1991; Stewart and Moder, 2016) provide some experimental results that validate this statement. This is particularly relevant in a low heat efflux long storage tank. The higher the heat efflux, the higher the difference with the homogeneous assumption. Stirring carefully the fluid is an effective way of reducing pressure before venting is necessary at the cost of introducing additional energy to the tank. Mixing power is relatively low compared to heat efflux (Lin, 1991), so for the low dormancy times required for civil aviation

it can be assumed that dormancy time with mixing is approximately that of the homogeneous tank.

8.5 Tank parametric study

In this parametric study, tanks are assumed to be cylindrical, with hemispherical ends. Figure 8.6 represents a generic tank with three layers: an inner wall (w) sustaining the hydrogen pressure, and intermediate insulation wall (i) reducing the heat leakage into the tank and an outer wall (b) sustaining the negative pressures (buckling) of the vacuum insulation or providing protection of foam insulation. It is assumed that integration of the tanks is possible any location since tanks of all sizes and aspect ratios will be analysed. For any given tank volume, tank shape can vary from a very low radius/long cylindrical tank to a maximum radius spherical tank.

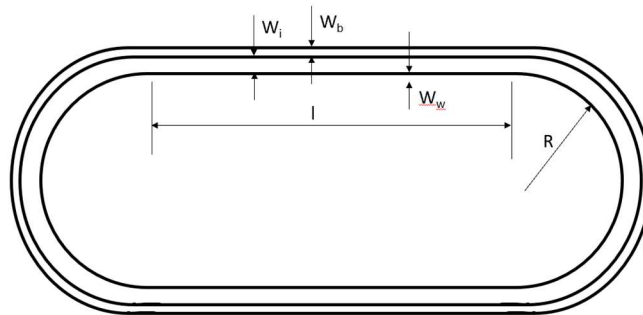


Figure 8.6: Tank Dimensions

Tank insulation may be provided by a layer of low conductivity material or by a vacuum jacket. Thermal radiation shields made of low emissivity material can be added to minimise radiation heat transfer. Low conductivity materials, commonly used, are foams and aerogels. Aerogels can improve their thermal conductivity further if operating in a vacuum. Vacuum based insulation has the disadvantage that an accidental loss of vacuum increases the thermal conductivity by several orders of magnitude. Additionally, the jacket external wall must sustain the external negative pressure. Design against buckling of the external wall usually requires a high thickness that ends up representing a high proportion of the

weight of the whole tank structure. Wall material can be made of metallic material or composites. In case composites are used, hydrogen diffusion through the wall or air permeation into the vacuum should be avoided or an additional liner should be placed, which will reduce the benefits of a light composite wall. An overview of insulation materials and properties is given in (Mital et al., 2006).

To compare the different tank architectures and conduct a parametric study and optimisation, three representative technologies will be considered:

- 1 - polyurethane foam insulation,
- 2 - MLI vacuum insulation
- 3 - Stiffened-panel MLI vacuum insulation.

Polyurethane foam has been selected as representative of foams and low-density aerogels with a range of thermal conductivities from 0.03 to 0.003 W/m.K and densities between 20 and 60 kg/m³. MLI insulation technology covers a range of different designs of vacuum multilayer insulated tanks from 0.0003 to 0.00003 W/m.K and densities between 10 and 100 kg/m³ without considering the outer tank. The density of the MLI insulation is not relevant due to the very low thickness required, being the outer wall the driver of the weight of the tank. Stiffened Panels MLI insulated tank have an outer wall either metallic or composite, but with a bi-grid structure that make the outer wall in the order of three times lighter than a flat panel wall (Sullivan et al., 2006). Table 8.1 summarises the insulation material properties.

A generic Aluminium alloy with a yield strength of 410 MPa and a density of 2,800 kg/m³ has been used. Preliminary mechanical sizing of the tank is calculated from the maximum operating pressure. Using Von-Misses criteria for radial and axial load of a thin-walled tank yields to Eq.9 for a cylinder and Eq.10 for a sphere.

A safety factor of 2.2 has been used to calculate the tank wall weight. Hemispheric ends are assumed to have the same thickness as the cylindrical section. For foam insulated tanks, an external protective wall of 0.8 mm has been added. This wall provides for mechanical and air contamination protection the

foam, preventing air condensation, loss of insulation properties over time or fire hazard under leakage failure.

	Thermal Conductivity (W/m.K) (Range Covered)	Density (kg/m ³) (Range Covered)	Construction Material
Polyurethane Foam Insulated	0.015 (0.003 - 0.03)	40 (20-60)	Inner tank: Al Outer Tank: N/A
MLI Vacuum Insulated	1.5.10 ⁻⁴ (3.10 ⁻⁵ - 3.10 ⁻⁴)	40 (10-100)	Inner Tank: Al Outer Tank: Al
Stiffened Panels MLI Vacuum Insulated			Inner Tank: Al Outer Tank: Al or Composite

Table 8.1: Insulation and tank materials properties considered.

$$P_{max}SF_P = \frac{w_w \sigma_{max}}{0.86 R} \quad (8.9)$$

$$P_{max}SF_P = \frac{w_w \sigma_{max}}{0.5 R} \quad (8.10)$$

For vacuum insulated tanks, the outer wall thickness has been dimensioned to prevent curved panel buckling. For a cylindrical tank with non-grid-stiffened wall subjected to uniform external pressure, the maximum allowable pressure, well correlated with experiments is given by Eq.8.10 (Timoshenko, Gere and Prager, 1962).

$$P_{atm}SF_B = \frac{E \frac{w_b}{R}}{1 + \frac{1}{2} \left(\frac{\pi R}{nl} \right)^2} \left\{ \frac{1}{n^2 \left[1 + \left(\frac{nl}{\pi R} \right)^2 \right]^2} + \frac{n^2 w_b^2}{12 R^2 (1 - \nu^2)} \left[1 + \left(\frac{nl}{\pi R} \right)^2 \right]^2 \right\} \quad (8.10)$$

For a better understanding of tank wall dependency on other design parameters as well as for parametric studies, the previous formula can be very well approximated by Eq. 8.11 (Budynas and Young, 1989).

$$P_{atm}SF_B = 0.807 \frac{E w_b^2}{lR} \sqrt{\left(\frac{1}{1 - \nu^2} \right)^3 \frac{w_b^2}{R^2}} \quad (8.11)$$

For spherical containers, experimental Eq.8.12 is used (Budynas and Young, 1989), which is equivalent to reduction of a factor of 3 to the theoretical value, due to a high sensitivity to manufacturing imperfections (Timoshenko, Gere and Prager, 1962). A comparison of results from Eq. 8.12 and a finite element analysis of a 2.5 m diameter tank external wall using experimental correlations as performed in (Sullivan et al., 2006) shows an error of 12%, Eq. 8.12 being more conservative.

$$P_{atm}SF_B = \frac{2E w_b^2}{R^2 \sqrt{3(1 - \nu^2)}} \cdot \frac{1}{3} \approx \frac{0.365 E w_b^2}{R^2} \quad (8.12)$$

Equations 8.4, 8.7, 8.9-12 can be used to calculate the weight of the walls and the insulation for different dormancy time requirements and for any insulation technology.

Figures 8.7(a) and (b) show graphically the trade-off between tank wall thickness and insulation thickness implicit in Eq. 8.7 for a $\phi 4\text{m}, 100\text{m}^3$ tank and for the technologies considered and described in Table 8.1. Such tank can be representative of a short-range airliner. The tank would have a net capacity (with 5% ullage) of 6128 kg of hydrogen at 329 kPa, with an energy content equivalent to around 20 tons or 25 m³ of kerosene. The fuselage dimensions for a typical short to medium range airliner are approximately 4 m in diameter and a length of 40 m, the tank being inscribed in the fuselage with a length of 9.3m. Figure 8.7(a) shows the tank weight and 8.7(b) shows the gravimetric efficiency of the tank. For a given venting pressure, Eq.8.9 determines the tank wall thickness, which grows linearly with the maximum operating pressure (line “Internal Tank Weight” in Figure 8.7(a)). Eq. 8.4 and 8.7 are used to calculate the required insulation thickness for a dormancy time of 12 hrs (empty tank), that reduces with increasing maximum operating pressure (line “Insulation Weight – Foam Insulated 12 hrs”). Total tank weight is the sum the internal and external wall, the insulation, and the accessories (line “Total Weight – Foam Insulated 12 hrs”). If dormancy time requirement is increased to 24 hrs the insulation weight line moves up in the graph to higher values (line “Insulation Weight –Foam Insulated 24 hrs”), and the total weight curve shifts accordingly with its minimum at a higher maximum operating pressure (line “Total Weight – Foam Insulated 24 hrs”). This same trade off, is used later, not only for maximum operating pressure, but for tank diameter and volume. Consideration of the variation of wall and insulation thickness separately, and the shift in the curves is key to understanding the optimisation process. For vacuum insulated tanks, Eq. 8.11 and 8.12 are used to calculate the external wall thickness, which is not dependant on internal pressure (line “External Wall Weight – MLI VC Insulation”). Vacuum insulated tanks offer more dormancy time than usually required at a minimum insulation thickness, so insulation weight is a horizontal line (line “MLI Insulation Weight”). Total weight for MLI VC insulated tanks is, therefore, a growing line parallel to the internal wall weight. (line “Total Weight – MLI VC Insulation”).

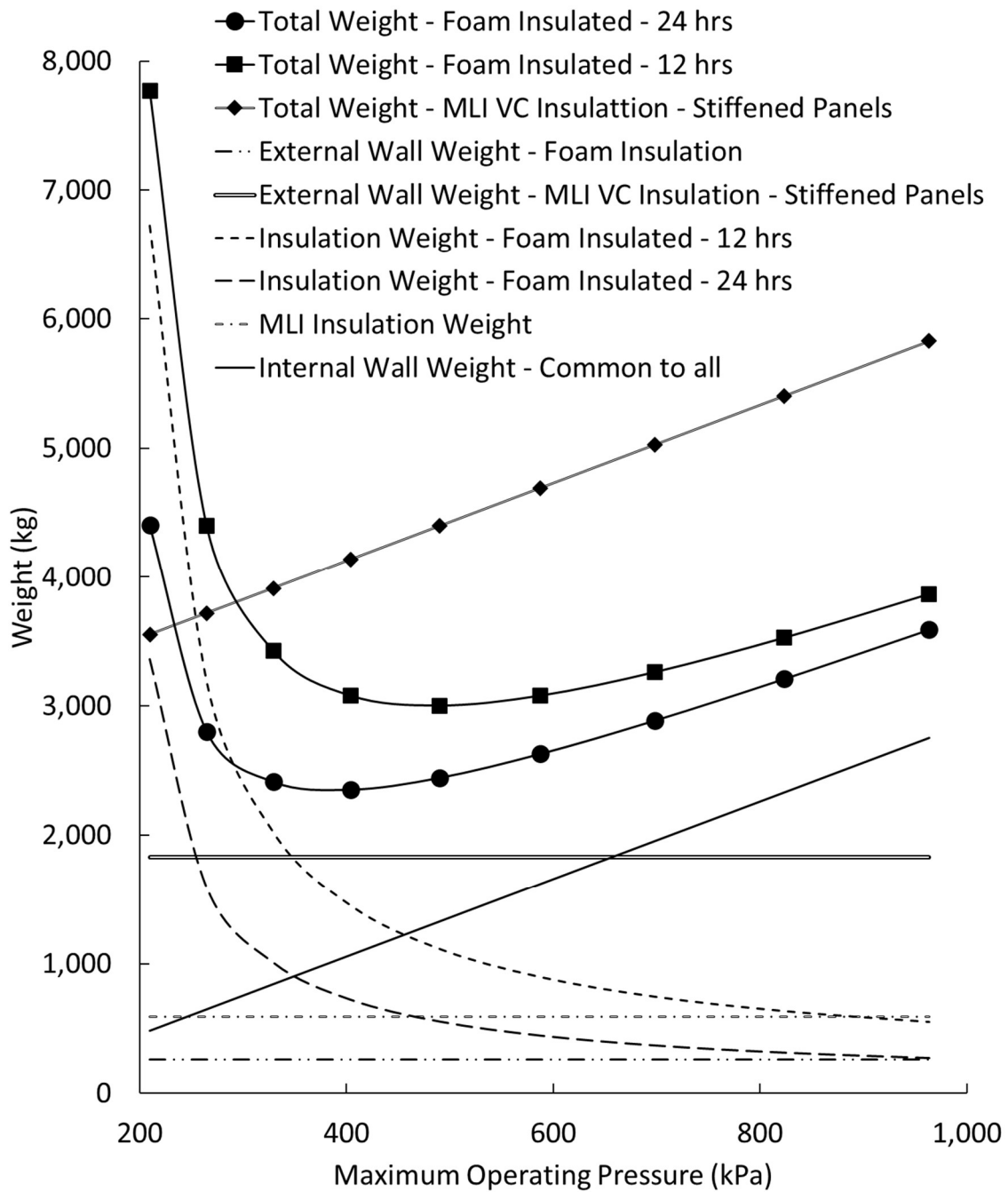


Figure 8.7(a): Tank Weight Trade-off for different architectures and technologies for a 100m³ cylindrical tank with hemispheric ends.

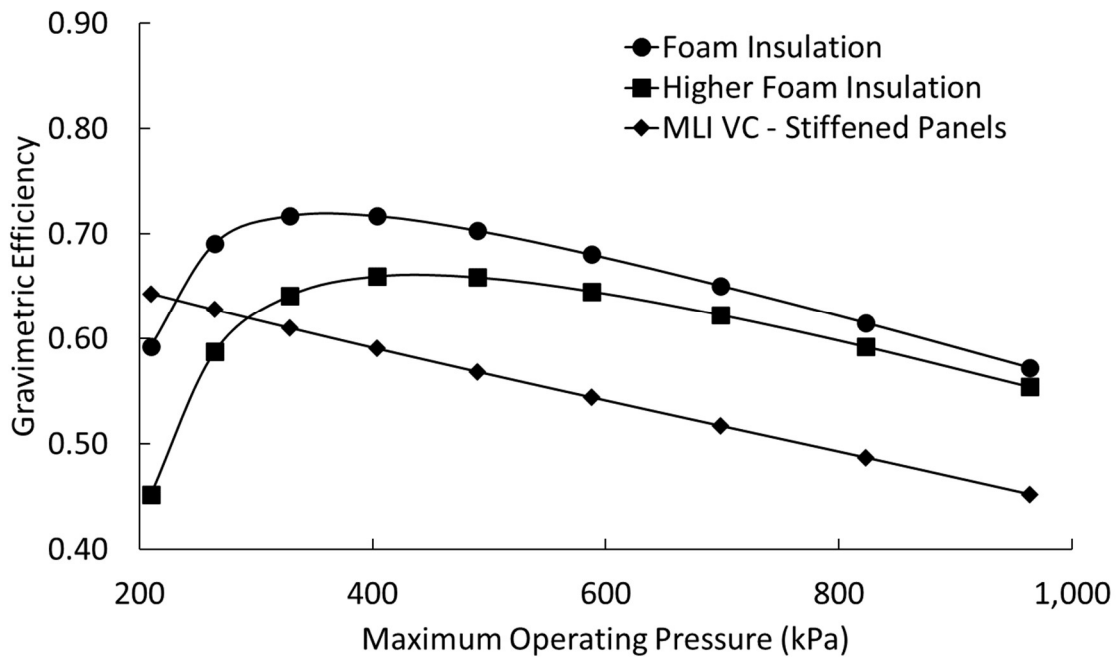


Figure 8.7(b): Tank Gravimetric Efficiency for different architectures and technologies.

Optimum radius

For a given volume, tank shape can vary between a long cylinder of small radius and hemispherical ends and a sphere. The surface of this shape will decrease asymptotically to that of the sphere with increasing radius. For a required dormancy time, Eq. 8.9 and 8.7 show that with increasing radius (decreasing surface to volume ratio), internal wall thickness will increase, and insulation thickness will decrease. For foam insulated tanks, it is expected therefore that there is an optimum radius in which tank weight is minimum. For vacuum insulated tanks, the external wall is subject to buckling and Eq. 8.11 can be used to deduct that thickness decreases with increasing radius. External wall weight is one order of magnitude higher than the internal wall weight, so that the sum of both walls weight decreases, leaving no optimum radius other than the sphere. Vacuum insulation is so efficient that lower than practical values are calculated for minimum insulation thickness, so it has been assumed a minimum MLI vacuum thickness safe value of 127 mm (5 in.) without any relevant incidence in weight. Figure 8.8 shows the gravimetric efficiency of the tank as a function of

the radius (radius) of the tank. Gravimetric efficiency has been calculated as the mass of stored hydrogen at the maximum allowable pressure or venting pressure divided by the mass of the tank plus the stored hydrogen. An additional 300 kg of accessories to make an allowance for buffers, instrumentation and fuel feed manifolds has been added. Other design parameters are as follow: Maximum allowable pressure: 329 kPa (equivalent to 25K vapour liquid equilibrium), Pressure at fill: 163.5 kPa (22K), Safety Factor Mechanical Design: 2.2, Minimum thickness of Al wall: 0.8 mm.

It should be noted the large difference in gravimetric efficiency obtained at different tank radius. This effect was also recognised by (Verstraete et al., 2010b) for foam insulated tanks. This fact underpins the large variation in gravimetric efficiencies found in the literature and explains the different optimum designs depending on range of the application and maximum fuselage size. The existence of an optimum radius for foam insulated tanks is also visible in (Verstraete et al., 2010b) and in (Winnefeld et al., 2018), although it is not discussed there. Optimum radius for a 100 m³ foam insulated cylindrical tank is between 2 and 2.5m, higher for longer dormancy times with thicker insulation. As the tank approaches a sphere (radius 2.88 m), there is a discontinuity since mechanical performance of the sphere is superior and gravimetric efficiency reaches an absolute maximum. Vacuum insulated tanks have a dormancy time in the order of hundreds of hours and therefore, only one line has been drawn for each type. In terms of weight, except for very low radius, they behave worse for dormancy time requirements lower than 24 hrs.

The effect of having multiple tanks rather than one for the same fuel capacity is now considered, as in Figure 8.1(f). Long tanks may be split into several tanks, each of them having the same diameter as the single tank but reduced length.” Foam insulated tanks weight more when split into several tanks of the same radius, since wall thickness would not vary, and total surface would increase (Winnefeld et al., 2018). Vacuum insulated tanks, on the contrary, can improve the weight, since buckling stress limit is dependent on length. This option also increases the tank volume compared to fuel volume since the cap envelope of

large diameter cylinders or spheres is unusable. Figure 8.8 also shows the improvement with multiple vacuum insulated tanks in the lines with the text ‘Split Tanks’. These lines represent the trend line of multiple tanks with a length to radius ratio of 4. For small diameter tanks, gain is larger. This trend is observed for all tank volumes. Longer length to radius ratio gives intermediate values between both cases (Winnefeld et al., 2018).

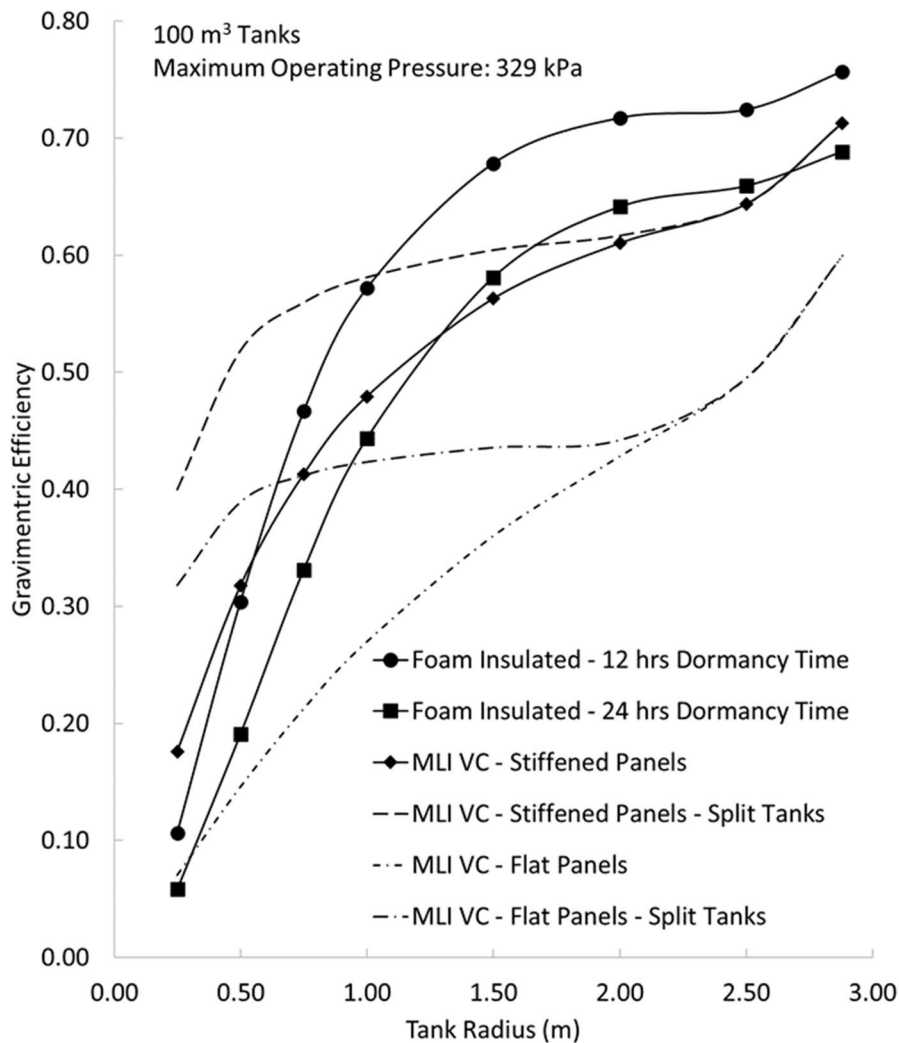


Figure 8.8: Effect of tank radius on gravimetric efficiency.

Consideration of elliptical tanks yield to same trends, but at a higher weight and lower gravimetric efficiency, due to a higher radius of curvature at the minor axis

points. A study on the sensitivity of elliptical foam insulated tank to longitudinal and cross section aspect ratios can be found in (Winnefeld et al., 2018).

Optimum Length

To understand the effect of length, a 2m radius tank and varying volumes has been studied. Results are plotted in Figure 8.9.

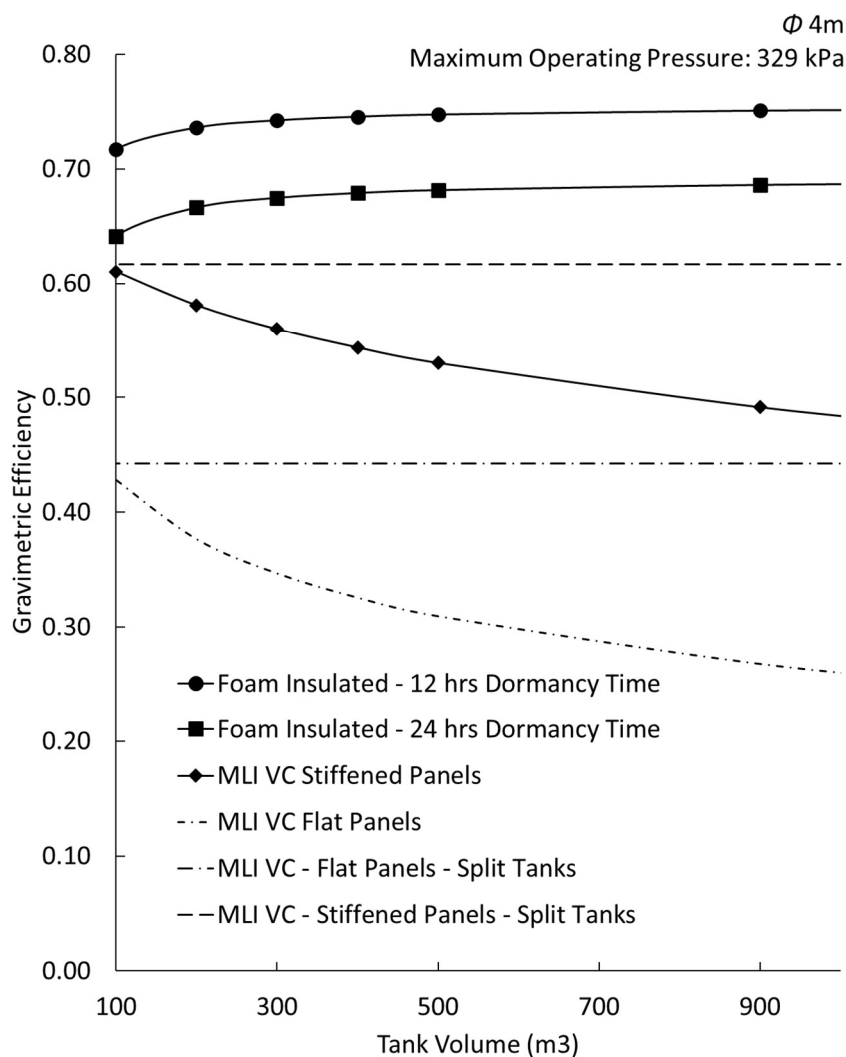


Figure 8.9: Effect of tank length on gravimetric efficiency for constant diameter tanks.

The effects of tank size can be explained through the surface to volume ratio of the tank. For any given volume, the lowest surface to volume ratio corresponds

to a sphere ($3/R$). For any given diameter, the longer the tank, the smaller the surface to volume ratio, with a rapid trend towards that of the cylinder ($2/R$). This asymptotic behaviour of the S/V ratio explains the small variation in gravimetric efficiency.

For foam insulated tanks, because the tank wall thickness depends only on diameter, it will not vary with tank length. Insulation thickness depends on S/V ratio, so the impact of volume variation in gravimetric efficiency is only that of the S/V ratio. Vacuum insulated tanks show the effect of increased external wall thickness with length. Splitting vacuum insulated tanks into multiple tanks improves the gravimetric efficiency and may ideally keep it constant for any tank volume, providing the same length to diameter ratio is kept constant.

The most important conclusion is that for large tanks, gravimetric efficiency is mostly affected by the radius of the tank, rather than by the length or the volume.

Optimum pressure

For any given tank size, tank wall thickness increases with maximum allowable pressure, as per Eq. 8.9. Heat leakage increases with increasing maximum allowable pressure as per Eq. 8.7 for a required dormancy time, and hence, insulation thickness requirement reduces. It is then expected that a trade-off exists, that shows a minimum value of tank weight at a certain pressure. Vacuum insulated tanks have a very low insulation weight and a very high external wall weight, neither of which depend on maximum operating pressure. Therefore, there minimum value occurs at the minimum pressure. Figure 8.10 shows the gravimetric efficiency of a 100 m^3 , both for a 2 m radius cylindrical, and for a 2.88 m radius spherical tank.

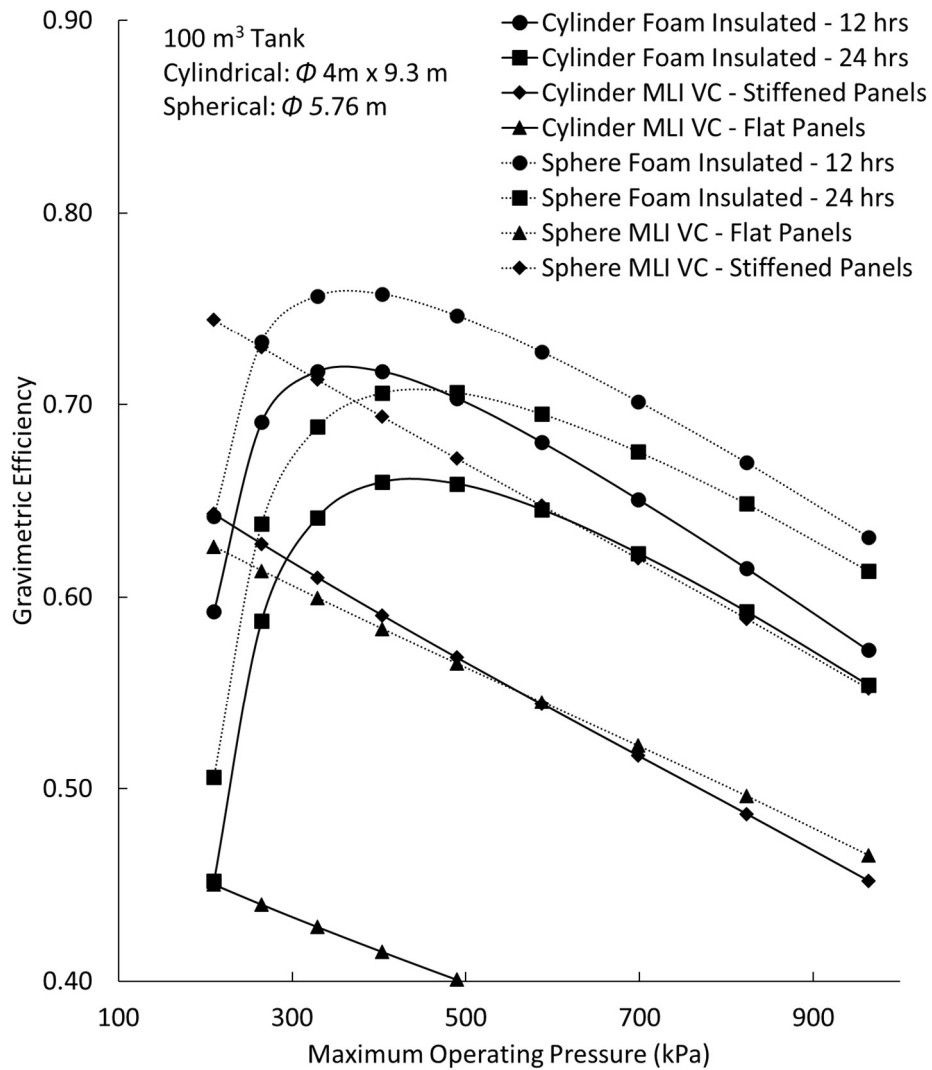


Figure 8.10: Effect of Maximum Operating Pressure on Tank Gravimetric Efficiency

Optimum pressure varies from 300 to 500 kPa, higher for longer dormancy times since insulation thickness is higher. Optimum pressure is slightly higher for the spherical tank as wall weight reduces compared to a cylinder.

Optimum architecture

In this section, a comparison of optimum tanks for the different architectures described previously is performed. A 100 m³ tank is taken as an example but general conclusions for larger tanks are also given.

An optimum 100 m³ foam insulated tank will be spherical or cylindrical with radius above 2 m, with a small loss of gravimetric efficiency between 2 and 2.5m. A 24 hrs dormancy time (full tank condition) has been used leading to an optimum Maximum Operating Pressure around 400 kPa. Optimum vacuum insulated tanks have also the largest possible radius, with diminishing returns as the tank approached a sphere, and a discontinuity at the spherical shape due to the double curvature. Since the optimum Maximum operating pressure is the lowest possible, 200 kPa has been considered as a safe value above atmospheric. Table 8.2 summarises optimum tank designs. Two options for cylindrical tanks with a radius of 2 m with optimum insulation based on foam and vacuum, and a 2.88m radius optimum spherical tank are compared.

Both cylindrical options have a very similar result. The spherical option is superior, but difficult to integrate in common short to medium range aircraft designs, with a fuselage diameter of around 4 m.

For larger tanks, physical limitations for fuselage integration restrict the maximum radius to that of the fuselage. As per Fig.8.8 and 8.9, optimum tanks will have the largest possible radius and gravimetric efficiency will not vary significantly with tank length. Due to thicker required walls, optimum Maximum Operating Pressure will be lower than the 100m³ tank given as an example, but to give an order of magnitude, still in the range of 300 kPa for a 900 m³ tank. As it can be observed in Fig.8.9, the farther from a spherical shape the tank is (or the higher the length to radius ratio), the larger the difference in gravimetric efficiency between foam and vacuum insulated tanks. Since large tanks with limited maximum radius will have a higher length to radius ratio, the larger the tank, the more favourable will be the foam insulated construction. This fact is observed in Figure 8.11 (a) for a 6m diameter 300m³ tank and Figure 8.11(b) for a 7 m diameter 900 m³ tank. For medium and large size tanks foam insulation is the preferable option. As expected from Figure 8.8 and 8.9, foam insulated tanks behave better for long haul capacity. As it also can be deduced from Figure 8.9, vacuum insulated tanks for long haul can be improved by splitting the volume into 3 tanks, leading to maximum values similar to the 300 m³ tank, but still lower than foam insulation.

100 m³ Tank	Cylinder	Cylinder	Sphere
	Foam	Stiffened Panels MLI Vacuum	Stiffened Panels MLI Vacuum
Diameter (m)	4	4	5.76
Dormancy Time (hrs)	24	200	240
Total Length (m)	9.29	9.29	
Maximum Operating Pressure (kPa)	404	210	210
Useful LH ₂ Capacity (kg)	5969	6405	6405
Inner Wall			
Material	Aluminium		
Thickness (mm)	3.27	1.94	1.62
Weight (kg)	1,068	633	473
Insulation			
Material	Foam	MLI Vacuum	MLI Vacuum
Thickness (mm)	310	127	127
Weight (kg)	1450	593	529
Outer Wall			
Material	Al	Al (bi-grid panel)	
Weight (kg)	262	1,828	696
Accessories (kg)	300	500	500
Total Weight (kg)	3,079	3,554	2,199
Gravimetric Efficiency	0.660	0.643	0.744

Table 8.2: Short/Medium Haul Transport Aircraft Optimum Tanks

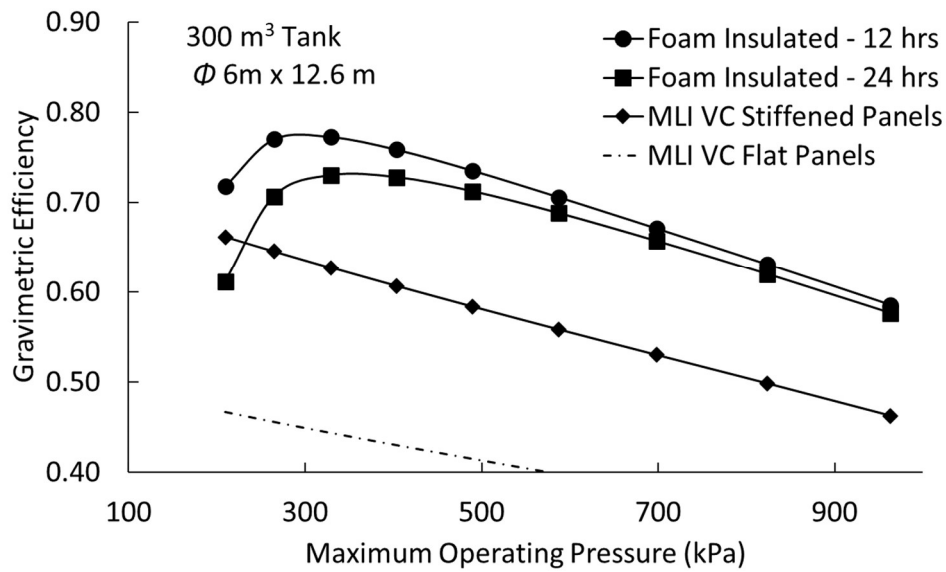


Figure 8.11(a): Gravimetric efficiency for medium size tanks.

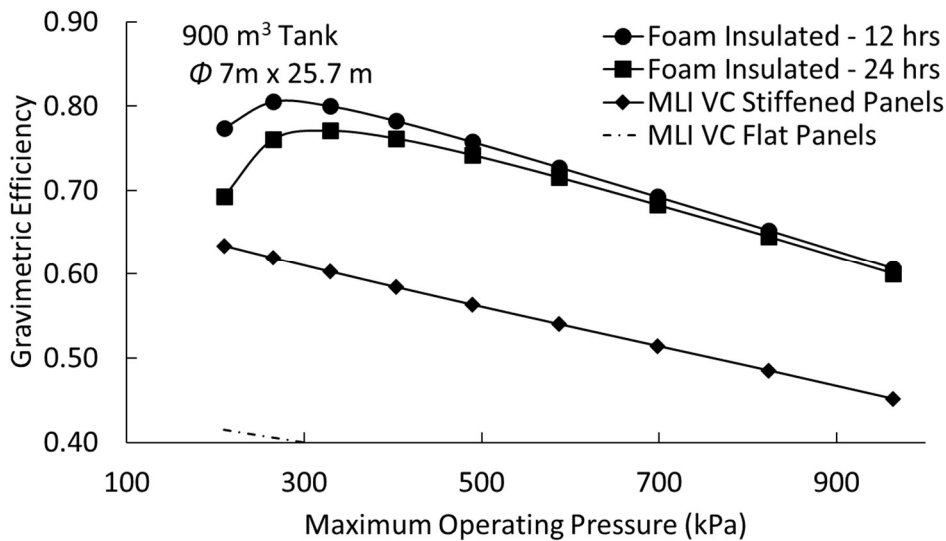


Figure 8.11(b): Gravimetric efficiency for large tanks.

8.6 Conclusions

A comprehensive review of tank design criteria provides an explanation for the large variety of quoted gravimetric efficiency of tanks in previous literature.

The gravimetric efficiency of liquid hydrogen tanks shows a wide variation, mainly, with tank diameter, yielding values as low as 0.1 for 0.5m tanks, up to nearly 0.8 for very large tanks. Increasing the length of the cylindrical tank at any given diameter, does not significantly affect the gravimetric efficiency. Optimum tanks are, therefore, those with maximum diameter that can be inscribed into the aircraft fuselage. Tanks designed to be fit into the wings or in smaller compartments will be heavier or require venting at cruise. For tanks below 2-3m diameter, MLI vacuum insulated tanks with an external wall with stiffened panels offer the lowest weight. For larger diameters, foam insulated tanks are lighter.

The low density of liquid Hydrogen requires aircraft tanks with four times the volume of those used in an equivalent conventional aircraft. For existing aircraft fuselage diameters, and for all ranges above regional aircraft, tank gravimetric efficiency calculated is higher than 66% w. hydrogen, meaning that weight of tank is half the weight of hydrogen stored or lower. Being hydrogen three times lighter per unit of energy content, the weight of the full tank will be lower for a hydrogen aircraft than for a kerosene equivalent aircraft. This conclusion suggests that the main challenge to the design of a hydrogen fuelled aircraft is the volume of the tank rather the weight.

Large capacity insulated tanks required for hydrogen aviation show increasing gravimetric efficiency with growing diameters. Regardless of the technology used for insulation, an increase in diameter results in a reduction of surface to volume ratio that makes the tank weight in relation to stored hydrogen to drop. Being the tank diameter limited by aerodynamic design of aircraft, lightest tanks will be the largest that can be inscribed into the airframe.

Foam insulated tanks are generally superior to MLI Vacuum Insulated tanks, even if stiffened panels are used for the external wall subject to negative pressure. Vacuum insulated tank weight can be reduced if tank is split into several tanks of same diameter and a smaller length to diameter ratio is used. On the contrary, splitting foam insulated tanks deteriorate the total weight. Only for very small tanks, such as automobile applications or long endurance missions, vacuum insulated tanks offer a better solution. Optimum maximum operating pressure is

between 3 and 5 bar for foam insulated tanks and around 2 bar for vacuum insulated.

Optimum tank size and architecture will depend on the mission and should be evaluated in each case. However, there are some trends observed in this research. Short range aircraft will be less affected by the gravimetric efficiency of the tanks, since the amount of stored hydrogen and hence the weight of the tanks are a minor fraction of the aircraft weight. MLI vacuum insulated tanks, even at low diameter could provide a compromise solution. Long range aircraft, on the contrary, will be heavily penalised by low gravimetric efficiency tank. For those, large diameter foam insulated tanks, such as those depicted in Fig.1 (a) and (d) could lead to lightest tanks. Still, the impact of reduced aerodynamic efficiency of these may balance the optimum towards a compromise solution such as Fig1. (b), (c), (f) or any of the unconventional concepts depicted in Fig.2. Optimum tank configuration cannot be determined but at a system level.

A novel method was developed to enable to optimise lightweight tanks for hydrogen fuelled airliners. This method considers the dormancy time as a principal design parameter and considers the evolution of mass, pressure, temperature, and phase change of hydrogen during a flight. It is also shown that the type of aircraft and its mission will have a profound influence on tank design. One of the key conclusions of the study is that there is a very large design space to be explored. When the considerations of heating, stirring, and venting are added this offers many opportunities for optimisation that comprise the aircraft and airport systems and includes aircraft performance and economic dimensions. It is the expectation of the authors that, as successive innovation waves are implemented, these opportunities will give rise to very efficient hydrogen aircraft and propulsion systems.

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9 EMISSION SCENARIOS AND HYDROGEN AIRLINER MARKET ENTRY

Aviation sector is committed to achieve net zero by 2050 (ATAG, 2021c; Graver et al., 2022; IATA, 2021; ICAO, 2022b, 2022a), but the route to reach there is not clear yet. The plans produced by institutions like ICCT, ATAG or ICAO leave a significant fraction of the CO₂ emitted to be offset by other means through carbon credits.

Year 2050 will see around 22,500 billion RPK, estimated from 8,700 billion in 2019 at a compounded annual growth rate of 3.1% (AIRBUS, 2022; ATAG, 2021c; BOEING, 2022; Clean Sky 2 and European Commission, 2020; Graver et al., 2022). At a today's average emission levels of 90 grCO₂/RPK (ICCT, 2020), aviation would release 2,000 million tonnes of CO₂ to the atmosphere and will consume 641 million tonnes of Jet A-1 or 800 billion litres (27.45 EJ).

In 2019, aviation emitted 920 million tonnes of CO₂ (ICCT, 2020), of which 785 million are attributed to passenger transport and the remaining to freight transport. Passenger transport used around 250 million tonnes of Jet A-1 or 310 billion litres (5.8 EJ).

Table 9.1 shows the calculated production of sustainable aviation fuels (SAFs) for the different scenarios published by the aviation institutions and the residual value of CO₂ that needs to be compensated through direct additional removals of CO₂ from the atmosphere or through carbon credits. It should be noted that ICAO only deals with international aviation, which accounted for 61% of global aviation in 2019 (ICCT, 2020).

Despite investment level estimates in the order of several trillion, none of the drawn scenarios, except for ICCT#3 meet the Paris agreement without the need of other sectors credits or direct CO₂ removals. For example, ICAO#3 proposal, assumes \$950 billion for SAF biomass-based fuels, \$1,700 billion for SAF from gaseous waste (other sectors' CO₂), \$460 billion for SAF from atmospheric CO₂ and \$60 billion for low carbon fuels, addressed to mitigate greenhouse gas (GHG)

emissions from conventional refinery processes and \$50 billion for hydrogen infrastructure development (ICAO, 2022b).

		SAF(Mt)	Residual CO ₂ (Mt)
ATAG#1	Pushing technology and operations	380	135
ATAG#2	Aggressive SAF development	445	155
ATAG#2	Aggressive technology - Hydrogen	330	115
ICAO#1	High readiness technologies	200	244
ICAO#2	Push on SAFs	467	228
ICAO#3	Push on SAFs+ No LCAF	423	203
ICCT#1	SAFs	220	950
ICCT#2	SAFs + Electric + Hydrogen	250	450
ICCT#3	SAFs + Electric + Max Hydrogen	315	0

* Assumes a 100% emission reduction factor for SAFs by 2050

** Only considers international operations

Table 9.1: SAF production scale and residual emissions for scenarios drafted by most relevant institutions

The main reason behind the difficulty to meet the Paris agreement lies in the consideration of fuels that are not net zero but have relevant life cycle emissions (Table 9.2). While using fuels that reduce the CO₂ signature along the life cycle can reduce substantially the net emissions, they are insufficient to achieve net zero.

			Biogenic Carbon Growth	Cultivation / Transportation / Conversion	ILUC	WTT	TTW	WTW
Jet A-1				15.7	0	15.7	73.83	89.53
Agricultural / forestry residues	ETJ		-73.83	39.7	0	39.7	73.83	39.70
	FT		-73.83	7.7	0	7.7	73.83	7.70
Vegetable oil crops	HEFA	Brassica Carinata	-73.83	34.4	-12.7	21.7	73.83	21.70
	HEFA	Palm Oil	-73.83	37.4	39.1	76.5	73.83	76.50
Lignocellulosic energy crops	ATJ	Switch grass	-73.83	43.4	5.4	48.8	73.83	48.80
	FT	Miscanthus	-73.83	10.4	-12.6	-2.2	73.83	-2.20
Sugary energy crops	SIP	Sugarcane	-73.83	32.8	11.1	43.9	73.83	43.90
	ATJ	Sugarcane	-73.83	24	7.3	31.3	73.83	31.30
MSW	FT	0% non-biogenic carbon	-73.83	5.2	0	5.2	73.83	5.20
	FT	50% non-biogenic carbon	-36.92	53.5	0	53.5	73.83	90.42
Synthetic Kerosene	FT + DAC		-73.83	0	0	0	73.83	0
	FT + industrial source		0	0	0	0	73.83	73.83
Liquid Hydrogen	Renewable Powered Electrolysis		0	0	0	0	0.00	0

ILUC: Indirect land used change; WTT: Well to tank; TTW: Tank to wake; WTW: Well to wake; ETJ: Ethanol to jet; FT: Fischer Tropsch; HEFA: Hydro processed esters and fatty acids; ATJ: Alcohol to jet; SIP: Synthesized iso-paraffins; DAC: Direct air capture

Table 9.2: CO₂ Climate impact intensity (gr CO₂ per MJ) of selected biofuels and alternative fuels (ICAO, 2019b, 2019c)

Only a few of the biofuels have a close to zero impact on CO₂ emissions. Some species, like *Miscanthus* may have a negative impact due to soil organic carbon stock sequestration associated with land use. But this will depend on the chosen land and therefore the scalability of production should be analysed further. The same happens with residues, either from agriculture or forestry, since from the moment its usage affects investment decision it should not be considered a residue anymore but a by-product and should share the emissions with the main product. MSW can have low impact if the residues are free of non-biogenic content.

Synthetic kerosene may have a net zero impact if produced with CO₂ captured from the air. If produced from CO₂ directly captured from other industrial processes either the industry assumes the emission or aviation does. It is considered double counting practice to attribute the zero emissions to both sectors, since it would not be true. Even if CO₂ is available from an industrial process that is not suitable for decarbonization, it should be sequestered or stored permanently in some stable form and CO₂ newly captured from the atmosphere should be used to produce synthetic fuel if true net zero is to be met.

Hydrogen has net zero CO₂ emissions, and it is the only fuel that has zero CO₂ emissions. This is only possible if renewable energy is used all along the process.

Warming effect of non-CO₂ emissions can be higher than CO₂ emissions as reported by (Lee et al., 2021) due mainly to contrail and induced cloudiness. The scientific understanding of contrail formation and its warming impact is not yet clearly understood and is a topic widely researched. There are some studies that show significant reduction of contrail formation with aromatic content of fuel is reduced (Voigt et al., 2021) to less particle and soot emissions that act as nuclei for the condensation. Until experimental research allows the understanding of contrail formation with SAFs and Hydrogen, this will remain unknown, or anything said will need to be said with low confidence.

It is well known that conditions for contrail formation are local in the skies, and these localities can be avoided. Typically, conditions extend for various tens or

hundreds of kilometres but the thickness (height) of the adverse conditions is only a few hundred meters (Dray et al., 2022). Some researchers have published studies in which these areas are avoided, reducing altitude, showing increased fuel consumption of 5-6% of the total aviation consumption if contrails are to be completely avoided (Dray et al., 2022; Noppel and Singh, 2007; Yin et al., 2018). The trade-off between CO₂ and non-CO₂ emissions is controversial and it is not clear what metric should be used (Lee et al., 2021) since the former stays in the atmosphere for hundreds of years and the latter only hours. The increased fuel consumption releases additional CO₂ if a carbon-based fuel is used and its warming effect will not be nil. If additional fuel consumption is hydrogen, there will be no further impact in global warming.

NO_x global warming effect is also polemic. While (Lee et al., 2021) reduced its impact in their latest report to an insignificant level, (Grewe, Matthes and Dahlmann, 2019) are claiming methodological flaws in the impact that NO_x emissions have on methane lifetime. Although there is some debate in this, its impact is of a significantly lower magnitude to contrails. SAFs can be burnt with low NO_x combustors at an expense of a small efficiency penalty. Hydrogen can produce lower NO_x emissions due to a lower flammability limit and a higher flame speed, which allows the maximum temperature of the primary zone to be lower than kerosene or SAFs and reduces the residence time of air at high temperatures. Experimental research is being carried out at Cranfield on low NO_x hydrogen combustion based on micromix technology. NO_x reduction is also essential at lower altitudes to avoid other health problems arising from high NO_x pollution.

To draw a fair picture of the global warming impact of the different fuels, non-CO₂ effects should be accounted for. Some researchers have proposed the use of the GTP100 as the most relevant metric to compare CO₂ and non-CO₂ effects. In this metric, the effect of contrails and NO_x is only 9% and 1.9% of CO₂, respectively (Lee et al., 2021). Due to the uncertainty on the impact of non-CO₂ emissions and the possibility to make drastic reductions with today's technology, this research will focus on CO₂ emissions only. It should be noted that eliminating the contrail

formation increases the CO₂ emissions in the case of SAFs or synthetic fuels by around 5%, while it does not have a CO₂ effect in the case of hydrogen.

The alternative fuels may also have a strong effect in the fuel bill of the airlines and hence, on the price of flight tickets. The cost of production of the different fuels has been analysed widely in the literature. (Pavlenko, Searle and Christensen, 2019) analyses the cost of SAFs showing prices ranging from 1€/lt. for the higher CO₂ emission vegetable oil crops feedstock HEFA fuels to 2€/lt. for the lower CO₂ emissions energy crops FT fuels. This figure should be compared to around 0.4€/lt. for Jet A-1. Table 9.3 shows the price for the previous categories cross checked with carbon intensities from ICAO (ICAO, 2019b). The energy bill grows as the level of decarbonization increases.

For a typical medium range flight operating cost of 80\$ per passenger, the new operating costs have been calculated assuming an average energy intensity of 1.22 MJ/RPK, as reported by (ICCT, 2020). Energy bill and CO₂ emissions just calculate the amounts for 641 mt of fuel, representative of mid-century. Last row in Table 9.3 indicates the cost for synthetic fuel using single point capture of CO₂, i.e., from another industrial process. As discussed before, either the credit is used to decarbonise the industry it comes from or aviation, but it cannot be both (European Commission, 2020). In a world that is requiring net zero in all economic activities, this is not considered an option here.

	\$/lt	Well To Tank (gr CO ₂ /MJ)	Tank To Wake (gr CO ₂ /MJ)	Well to Wake (gr CO ₂ /MJ)	Op Costs Medium range flight 2000 km (\$/pax)	Energy bill for 641mt fuel (billion\$)	CO ₂ emissions for 641 mt fuel (mt)
Jet A-1	0.35	15.7	73.83	89.53	80.00	280.44	2456.29
Vegetable oil crops	1.15	2.67	73.83	76.5	125.60	921.44	2098.76
MSW	1.61	-43.40	73.83	30.43	151.82	1290.01	834.95
Sugary energy crops	1.96	-42.53	73.83	31.3	171.49	1566.44	858.71
Agricultural / forestry residues	2.07	-66.13	73.83	7.70	178.04	1658.59	211.25
Lignocellulosic energy crops	2.19	-76.03	73.83	-2.20	184.60	1750.73	-60.36
Synthetic Kerosene (CO ₂ industry)	2.76	0.00	73.83	73.83	217.37	2211.45	2025.56

Table 9.3: Biofuels price from ICCT estimate (Pavlenko, Searle and Christensen, 2019) cross checked with carbon intensities from ICAO (ICAO, 2019b)

	\$/lt	Well to Wake (gr CO ₂ /MJ)	Op Costs Medium range flight 2000 km (\$/pax)	Energy bill for 641mt fuel (billion\$)	CO ₂ emissions for 641 mt fuel (mt)
Jet A-1	0.35	89.53	80.00	280.44	2456.29
Today					
CO ₂ removal @ 332\$/tCO ₂	1.20	0	128.45	961.44	0.00
Synthetic Kerosene (DAC)	3.50	0	259.45	2802.91	0.00
LH ₂ (kerosene equivalence)	2.77	0	218.17	2222.67	0.00
Future					
CO ₂ removal @ 92\$/tCO ₂	0.59	0	93.42	469.15	0.00
Synthetic Kerosene (DAC)	1.58	0	150.19	1267.14	0.00
LH ₂ (kerosene equivalence)	0.82	0	106.65	655.10	0.00

Table 9.4: Zero emission fuel carbon intensities

There are other decarbonization options: removing CO₂ from the atmosphere to compensate for the CO₂ emissions of Jet A-1, or use of alternative fuels like synthetic fuels or hydrogen. Table 9.4 shows prices for these options. CO₂ removal costs have been taken from (Fasihi, Efimova and Breyer, 2019) for a 4,000 full load hour photovoltaic powered low temperature solid solvent facility. Future value corresponds to 2050, where it is assumed a total installed cumulative capacity of 15,356 MtCO₂/a with a learning rate of 3%. Initial capex for the mentioned DAC plant is 730€/tCO₂. Synthetic fuel is calculated by ICCT (Pavlenko, Searle and Christensen, 2019) at 2.5€/lt. Another working paper by ICCT (Zhou, Searle and Pavlenko, 2022), shows the price of synthetic fuels in the US and Europe using single point source of CO₂ (from industrial process) at 40\$/t CO₂. Their estimate is 2.11\$/lt. in the US and 3.17\$/lt. in Europe mainly due to difference in the cost of electricity. Costs reduce to 1\$/lt. and 1.85\$/lt. in US and Europe by 2050 as technology matures. For Table 9.4, an average value for US and EU as estimated by Zhuo has been used where DAC costs have been adjusted to (Fasihi, Efimova and Breyer, 2019). LH₂ costs are taken from (Dray et al., 2022; iea, 2019) in agreement with most recent publications.

At reported prices, best option is to remove CO₂ by direct capture in an equivalent amount that it is going to be emitted by the standard Jet-A fuel. From a logical point of view, this would be feasible if the technologies mature. The cost given by (Fasihi, Efimova and Breyer, 2019) is based a deep literature review and data from pilot plants working in the US and EU. However, the technology is at development stage and needs to demonstrate scalability. CO₂ dynamics in the lower atmosphere may also impose limitations to the technology and need to be understood (Johnston et al., 2003).

Relying on direct air capture may be controversial for other technical reasons: it needs to be sequestered in a permanent safe manner, may perpetuate fossil fuel industry, may create an unfeasible demand from other sectors and restrictions on emissions may still be in force despite of a massive capacity of direct air capture. Synthetic kerosene is an alternative that requires the successful development of DAC technology. Hydrogen can provide an alternative to synthetic fuels at a lower

cost, although at same level of power requirements (Table 9.5), calculated from (Albrecht et al., 2017; Dray et al., 2022).

	Electric Power Demand MJ / MJ fuel	Heat Power Demand / MJ / MJ fuel	Distilled water demand (gr H2O/MJ)	Renewable Power 45% cap. for 641 mt fuel eq (GW)
Future				
CO ₂ removal	0.07	0.47		131.71
Synthetic Kerosene (DAC)	2.07	0.47	256.00	4,095.91
LH ₂	1.80	0	75.00	3,567.78

Table 9.5: Energy requirements to decarbonise aviation

From the first order estimations given here, it has become clear that decarbonising aviation may not be possible within the timeframe specified by the Paris agreement and subscribed by the institutions. Even with a maximum effort in SAF development, decarbonization is not possible. It is proposed that the time constraints are first removed to make the most reasonable decision in the long term, and a transitory plan is drafted afterwards, avoiding incurring in massive investments (in the order of trillions) just to meet an unfeasible target.

Today's installed wind energy worldwide sums 825GW (IRENA, 2022) and installed nuclear capacity 358 GW (IAEA, 2022). The power requirements are an additional major challenge for aviation industry to decarbonise.

It is imperative new technologies that favour the energy efficiency, not only providing a sustainable and carbon free footprint but a significant reduction in energy consumption. Hydrogen has potential to provide addition fuel savings through its sink potential. It may add cooling power to the aircraft to increase the operating temperature of the turbines or reduce the cooling air. It could enable the usage of superconducting technology that requires very low operating temperatures. With it, a blended wing body aircraft may be powered by two main turbogenerators that electrically drive distributed fans mounted close to the trailing edge of the body, benefitting from boundary layer ingestion. Such

advanced concept has been studied offering fuel savings in excess of 60% (ENABLEH2, 2020; Goldberg, 2018). This is one of the areas of further research.

The technology to produce hydrogen from renewable resources by electrolysis of water is quite mature (iea, 2019), although some advances are expected in terms of efficiency and cost, particularly for PEM and SOEC electrolyzers. The improvement in efficiency would drive down the power requirements calculated in table 9.5, but not significantly, since the power requirements have been calculated with an efficiency of 67%. Liquefaction technology is also a mature technology that today requires around 30% of the hydrogen heating value to cool it down to 20K. This represents the 16% of the total energy requirement to produce LH₂. Further advances are possible, but it is not expected to impact in the overall power requirements meaningfully. Storage of hydrogen in liquid state in big, heavily insulated tanks at the airport is also a mature technology with a very small fraction, if any, of boil off.

Nevertheless, hydrogen is not an easy option for civil aviation institutions. The main obstacles are the following, in order of perceived importance (ICAO, 2022b):

1. Challenges related to infrastructure – hydrogen in the airport, operations, safety
2. Certification of aircraft
3. Cryogenic storage and thermal management in the aircraft
4. Public perception of risk and stakeholder acceptability
5. Reduced ranges, reduction of non-stop flights
6. Operators and leasers less asset range flexibility
7. Hydrogen availability
8. Increased cost of all aircraft operations

The most mentioned challenge is infrastructure (1). It should be noted that operating long range aircraft with hydrogen reduces the need to equip many

airports and simplifies the logistics of hydrogen availability (7). A few airport hubs could give coverage to the worldwide operations.

Narrowbody aircraft, as described in Chapter 3 presents an additional challenge in terms of reduced range (5) and flexibility (6). The longitudinal stability issues arising from rear tank installation could difficult the certification of the aircraft (2) and complicates the thermal management system (3), due to higher heat ingress per unit of stored mass.

For these reasons, the present work studies the early introduction a long-range airliner.

It should be noted that as presented in Chapter 6, approximately one third of the fuel consumption is subject to electrification, perhaps with some hydrogen powered hybrid fuel cell system assistance. Medium range aircraft accounts for another third, up to 2,500 nm approximately, and the remaining third is long range.

An airport like Heathrow consumes 5Mt of fuel in international operations. Producing synthetic fuel or LH₂, at 2MJ of energy per MJ of fuel requires around 0.428EJ. This could be produced with 13.6GW of nuclear power to produce the fuel (2 nuclear plants of today's average size) or with 34GW of wind at a load factor of 40%.

9.1 Long range aircraft development

It is estimated that development of a hydrogen airliner will have its major research and development efforts in technologies and safety not related to the aircraft. The long-range aircraft is usually seen as riskier since the integration of the hydrogen tanks may turn more complex. As discussed in Chapter 3 this may not be the case, since the aircraft stability is enhanced with top tanks, or a double deck design, and tank construction and thermal management is easier with larger diameter tanks (Chapter 7). Development of a hydrogen aircraft will require an important development in the following aspects:

- Safety standards
- Operation and training of personnel – ground support
- Storage technology
- Gas turbine combustion chamber and adaptation of gas turbine designs
- Certification of materials in potential contact with hydrogen

Due to the novel nature of the aircraft probably any R&D effort calculation is very uncertain. The certification costs of the hot section materials and coatings in the engine should be analysed and discussed among the industry experts. The development of a cryogenic tank and fuel system for operation in civil aviation may be in the order of billions, perhaps not even tens of billions. A new aircraft using conventional design and manufacturing tools, will take some tens (low tens) of billions to develop in the worst-case scenario. More uncertain it is the development of safety standards, but probably the order of magnitude will be in the worst-case scenario in the tens of billions. Such an uncertainty may seem useless, but it is not, since it gives an order of magnitude which could be utilised for first order trade-offs. It is estimated that the development of the technology and certification cost of the first widebody product will be of the order of \$100 billion.

For an aircraft with a target price of around \$200 million, the breakeven is just 500 aircraft. The \$100 billion amount for research and development is well below many military programmes. This probes that the investment costs are not a showstopper for the hydrogen aircraft.

9.2 Market Entry Scenario

A market entry scenario is drafted assuming that priority is given to development of decarbonizing solutions in the long term, and not in technologies that could reduce the environmental impact in the short term but could not decarbonise aviation in the long term. Such technologies include most SAFs as depicted in Table 9.2.

With the main research institutions and industrial stakeholders focused on the minimum required technologies to safely fly on hydrogen, it is estimated that a hydrogen freighter could enter into service around 2032-2035. Following two years of experience with freight operations, a passenger widebody airliner could start operations after 2035.

The following Figures 9.1 and 9.2 shows the deliveries and cumulative fleet of freighters and widebody aircraft assuming a 3.1% traffic per annum. It is also estimated that 100% of new freighter deliveries will be hydrogen powered from 2035 onwards. For the widebody aircraft, a 3.1% traffic growth has been assumed and with a ramp up in hydrogen aircraft deliveries that ranges from 10% in 2025 to 100% in 2050. Projections are concerned with production ramp up and consider complete market pull/adoption. Assuming growth rates of 4.1% for cargo, as the latest Boeing market forecast do (BOEING, 2022) or 3.2% as per Airbus (AIRBUS, 2022) will result in a slightly increase in the numbers, mainly in the long term, but does not vary the conclusions of the study. In both cases a retirement age for old and new aircraft has been set at 25 years of operation.

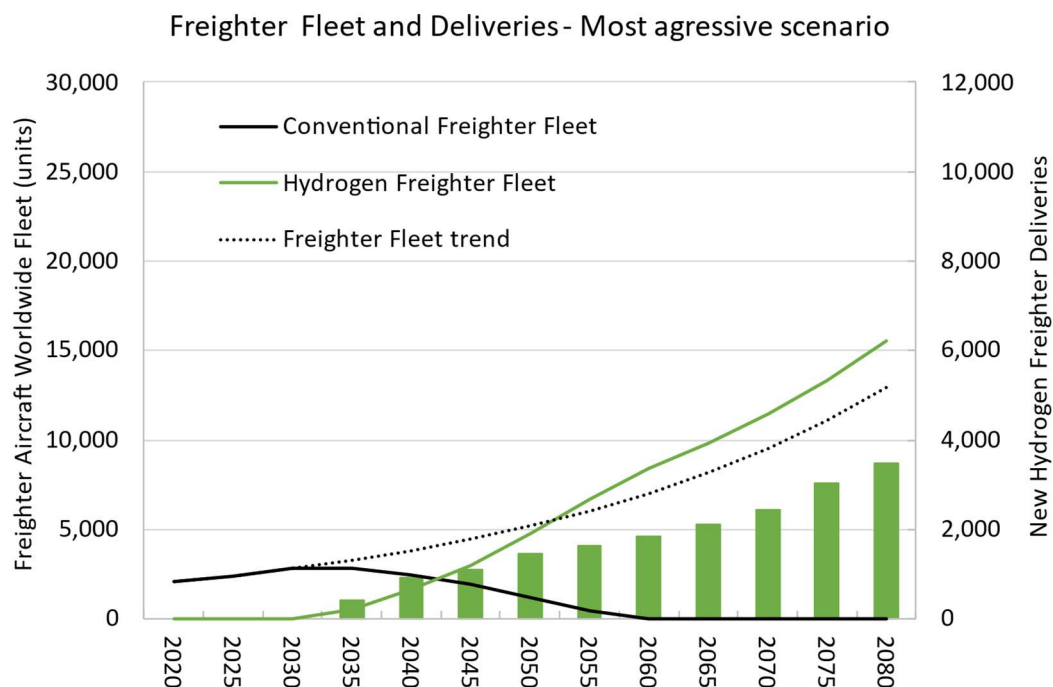


Figure 9.1: Fleet composition by technology forecast of Freighter aircraft

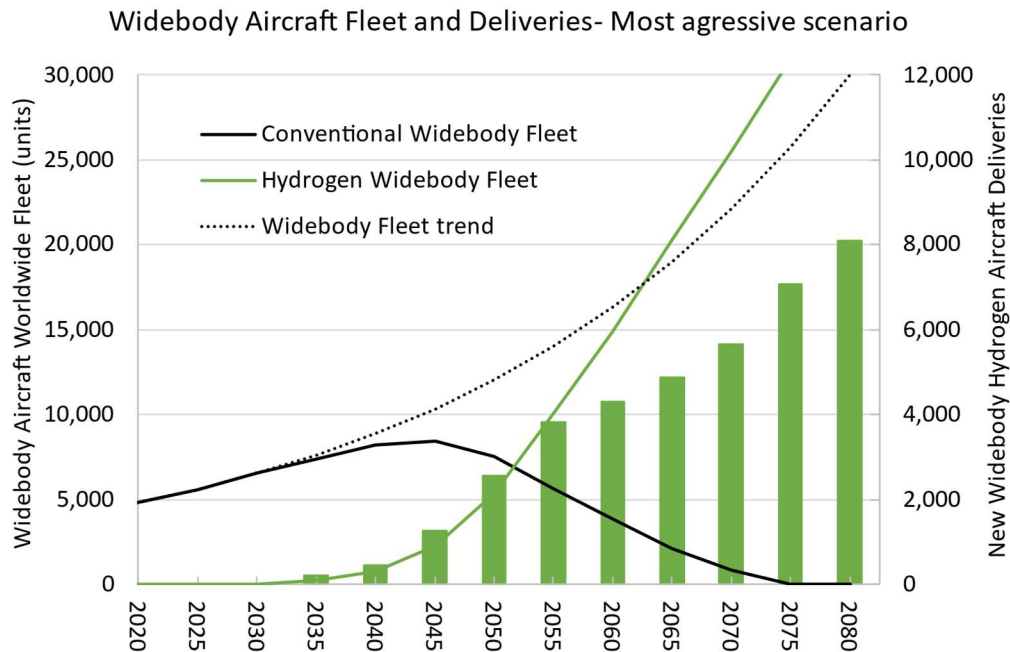


Figure 9.2: Fleet composition by technology forecast of widebody aircraft

It should be noted that decarbonization of the long-range market cannot not be completed by 2050, since the fleet in operation will be mostly conventional. It is only from 2075 that the segment will have all zero-emission aircraft in operation. This unfortunate conclusion is a necessary outcome considering the development lead times and lifetimes of the sector.

In order to estimate the global sector decarbonization, regional and narrowbody aircraft have been assessed. For the ‘most aggressive scenario’ simulation, it has been assumed that all regional aircraft are electric from 2030, and that 50% of the narrowbody sold during the period 2030-2035 are electric. The lower range of the electric aircraft can still take a portion of the narrowbody market, with a typical mission of 850 nm, which represents around 50% of total operations (Beddoes et al., 2022b). For longer ranges, hydrogen is employed, estimating that entry into service could occur between 2035 and 2040, mostly limited by the infrastructure development in smaller airports. A ramp up for the hydrogen

narrowbody aircraft ranging from 10% in 2035 to 100% of the new aircraft sold in 2055 has been assumed. Fig. 9.3. shows the narrowbody aircraft composition by technology with an estimated lifetime of the aircraft of 25 years.

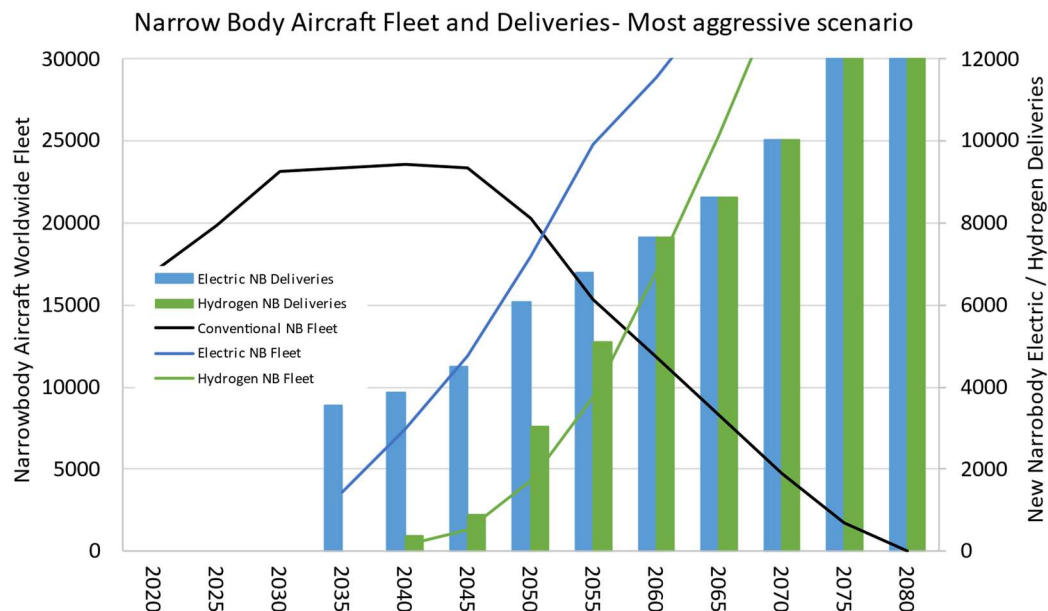


Figure 9.3: Fleet composition by technology forecast of narrowbody aircraft

With these assumptions an estimation of the sector emissions has been performed (Figure 9.4).

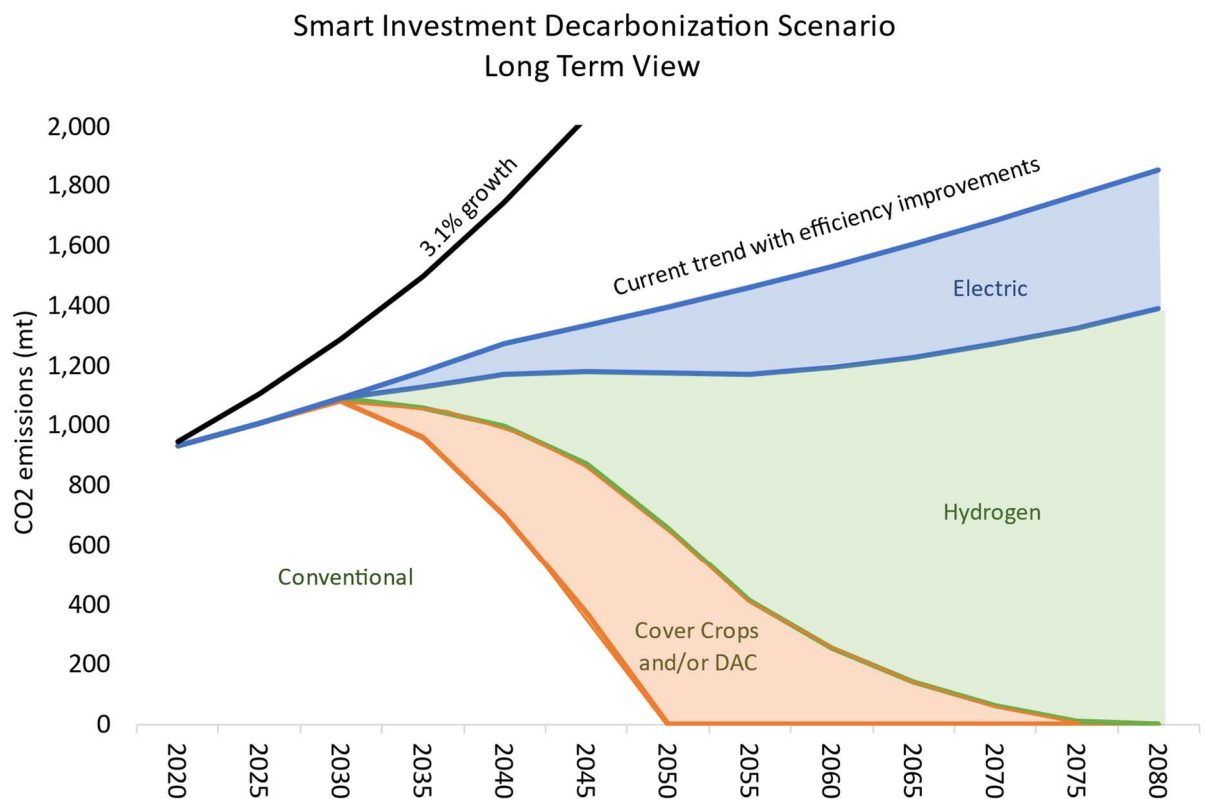


Figure 9.4: Aviation emissions for the most aggressive scenario, 'Smart Investment' scenario

Complete decarbonization does not occur until 2080, mostly due to the convenience of employing the whole life of aircraft. Since the delivery of new aircraft is not 100% hydrogen until 2055, it follows that decarbonization cannot occur until 25 years later. An early retirement of the fleet is possible, and it will reduce the emissions, but it cannot be an airline decision, which could not cope with the extra cost of early retirement. For this reason, it has not been considered here.

Emissions continue to grow until year 2030, where the combination of efficiency improvements and the entry into service of electric aircraft shift the curve. If is mostly hydrogen the fuel that is responsible for a major part of the decarbonization. It could not be otherwise with the assumptions made in this research.

The utilization of net zero sustainable aviation fuels and synthetic fuels with direct air capture could alleviate the emissions, but it is believed that it will not do it significantly. The very long lead times of biomass FT plants, which could take more than 15 years from conception to start delivering fuel, and the uncertainties of the direct air capture technology, could situate aviation in this scenario in which the public perception management becomes a priority.

The aviation sector should start today working with maximum intensity and focus on decarbonization, but this may not occur until 2080. Technology improvements, reduction of non-CO₂ emissions is of paramount importance in the short term. Development of electric and Hydrogen propulsion technologies and aircraft must be a priority. A significant investment in Direct Air Capture, could not only open new possibilities for future synthetic fuels, but could demonstrate the commitment of the sector with decarbonization and will contribute to the withdrawal of CO₂ emissions during the transition period.

Meanwhile, institutions, operators and manufacturers should focus on compensating for emissions by other means and become extremely transparent to manage the public perception to avoid a demand driven reduction of aircraft operations.

10 CONCLUSIONS

Transformation of aviation to hydrogen propulsion will prompt many changes in aircraft and infrastructure. Aircraft will need to incorporate cryogenic tanks that store the hydrogen in liquid state. Spherical or large diameter tanks, inside the fuselage, are preferred, since they result lighter, but they take volume traditionally designed for passengers. There is a trade-off between passenger capacity and fuel capacity (range) that is novel to hydrogen power aviation. For tube and wing designs this sets a limit in the capacity-range space.

A Hydrogen powered narrow body aircraft would reduce its capacity to around 100 passengers if the same 3,000 nm range is to be achieved. The trade-off allows an alternative design point of in the 150 passengers / 2,000 nm. The substitute of the existing kerosene powered narrowbody aircraft, with a capacity of 200 pax and 3,300 nm, would need to be an 8 abreast of the size of an Airbus 330 or a Boeing 787.

In the largest size of the spectrum, single deck tube and wing designs shows a trade-off that goes from 250 pax/6,000nm to 350 pax/4,000 nm. Longer ranges or capacities would need to be covered by double deck designs or non-conventional configurations.

Placing the tanks at the back of the passenger cabin, introduces another challenge: that of the centre of gravity shift between a full aircraft at landing (forward) and an empty aircraft with max fuel (aft). If no additional control surfaces are to be considered to manage a larger shift than the conventional kerosene aircraft, the tube and wing designs with tanks at the back show a maximum range just above 2,000 nm, regardless of the diameter of the fuselage, except for narrowbodies, which is below 1,500 nm.

These limitations suggest that the optimum hydrogen aircraft might not be a tube and wing with single empennage as the existing kerosene aircraft. Several innovation waves may sequentially improve the performance of the hydrogen aircraft. The first one, focused on existing configurations and technology, focused on gaining aircraft certification and building experience, and with limited

capability. A second innovation wave could focus on increasing the capacity by adding features and new technology developments that would increase the range. These include dry wings, laminar flow control in the wings, foam insulated tanks, shape-conforming tanks, top tanks, additional control surfaces, apart from expected improvements in aerodynamics, composite content and weight and engine efficiency. A third generation would exploit the benefits of the heat sink hydrogen provided by the cryogenic storage of hydrogen in non-conventional configurations that would be powered by a turboelectric distributed propulsion system with BLI, make use of superconducting technology or improve the cooling of the hot section of the engine.

The energy efficiency of the hydrogen aircraft would be penalised in the first generation, mainly due to heavy vacuum insulated tanks that demand fuselage arrangements that increase the weight of the aircraft. For the second generation, with lighter designs, the energy efficiency would improve and could eventually be better than the kerosene aircraft, depending on the tank added weight and the fuselage arrangements. For very light designs, the efficiency improves with the design range of the hydrogen aircraft.

Existing technology can be employed, and it is sufficient, to cover most of the today's civil air traffic. A Boeing 787 size aircraft could transport 200 passengers 3,500 nm but would require tanks forward and aft the passenger compartment to keep the stability limits. An Airbus 380 size aircraft allows several configurations if one of the decks is used for hydrogen storage, or if the hydrogen is stored in the cargo space. Wings would need to be resized significantly to the size of an Airbus 350 wings. The capability of the aircraft is above 300 passenger and 4,800 nm, and it can be modified to hold 200 passengers for 5,500 nm, allowing to flight anywhere in the world with one single stop. Higher capacity aircraft are possible for saturated corridors between important city pairs.

The gravimetric efficiency of the tanks is one of the aspects that have the highest impact in aircraft performance. Even for low gravimetric efficiency tanks, the aircraft based on existing technology show extremely useful ranges to accelerate decarbonization of civil aviation. Tanks inscribed in the fuselage, with the

maximum possible diameter, show an increase in gravimetric efficiency due to the improvement of the surface to volume ratio of the tank, and the corresponding reduction in required insulation.

The limitations in range or capacity suggest that flying habits may shift towards hub-and-spoke systems, in which hubs could offer hydrogen powered flights between hubs, leaving a shorter distance to the destination to be covered by electric or hybrid electric smaller aircraft.

The development of operations of hydrogen aviation based on hubs simplifies the challenge by reducing the number of airports to be provisioned with hydrogen infrastructure and risks associated with a massive deployment of hydrogen operations.

Sustainable aviation fuels could provide emission savings to aviation but could not lead aviation to net zero emissions, unless sustainable aviation fuels are restricted to several technologies and the technology for capturing CO₂ from the atmosphere can be successfully developed and scaled. Hydrogen allows another path for decarbonization of aviation by using a zero-emission fuel.

The development lead times, however, delay the decarbonization to 2080, even in the most aggressive scenario, leaving the Paris agreement and the commitments to reach to net-zero by 2050 unfulfilled.

Should the sector fail to effectively communicate the challenge at all levels, the aviation industry is bound to shrink due to the unlikelihood of significantly reducing the emissions in the short and medium term.

11 INTELLECTUAL CONTRIBUTION

Following the research questions introduced in Chapter 2 – Aim and Objectives, the following intellectual contributions have been made:

Is it possible to fly on Hydrogen with today's technology?

- Yes, it is, with limitations. Single deck designs can flight 2,000 nm, double decks up to 5,500 with reasonable payload
- A second generation could focus on improving performance, and extending the range through top tanks, perhaps foam insulated and improved materials, aerodynamics and engine efficiency
- A third innovation wave could bring maximum synergy to the hydrogen aircraft in large volumetric fuselages like BWB and turboelectric superconducting distributed propulsion.

What minimum technology developments are necessary?

- Storage tanks – MLI vacuum insulated tanks are at high TRL, but need further developments for aviation, mainly lighter weight, and considerations of flight specific phenomena, like sloshing or zero/negative G situations.
- Hydrogen fuel system – optimum architecture is still to be understood
- Combustion Chamber – Low NO_x – Micromix or Lean Direct Injection TRL3

What are the implications a first generation of hydrogen airliner has on customers, operators, and airports?

- Hydrogen power aviation may bring to an end the narrowbody aircraft
- Gates C (<36m) will be under-utilised for regional and electric aircraft only
New Slots D and E will be needed

- Passengers will be required to pay extra \$200 for a 2,000 nm flight
- Lower capacity and range will increase pressure on airport capacity. Large capacity Hydrogen airliners could provide slot alleviation in high density routes
- Massive power generation capacity will need to be built at airports. A combination of renewable and nuclear – Small modular reactors may be needed.
- 1/3 of the fuel cost in a long-range flight is due to restriction not to vent at the airport

What are the changes required to the design tanks if a dormancy time requirement is added?

- In space, pressure is selected to optimise density and insulation to minimise weight of tank plus mission vented vapour. In civil aviation, dormancy time links pressure and insulation since both increase dormancy time.
- Vacuum insulated tanks have so low thermal conductivity that minimum pressure is acceptable.
- Foam insulated tanks have an optimum pressure at around 3 bar for medium dormancy times and around 6 bar for long dormancy times.

‘To vent or Not to Vent’ at the airport is a critical dilemma with paramount implications

Other intellectual contributions not part of the research questions

- A dual fuel aircraft that burns the kerosene first have better energy efficiency than only kerosene and only hydrogen aircraft
- The energy efficiency of the hydrogen aircraft does not always improve with range, and it depends largely on the

12 DISSEMINATION AND IMPACT

The knowledge developed within this thesis allowed the Centre for Propulsion and Thermal Power Engineering to win and successfully deliver three work packages for ATI managed FlyZero project.

- Tank Design, in which FlyZero adopted the methodology developed in the thesis for dormancy-time driven tank design. Due to the conclusions explained in chapter 8, tank gravimetric efficiencies considered by FlyZero team around 0.65. This figured should be compared with 0.35-0.38 used by Clean Sky report 'Hydrogen Powered Aviation', published in May 2020.
- Fuel System and Combustion consultancy, in which the implications of not venting at airport was deeply discussed and different fuel system architectures were explored. One of the selected fuel system architectures was proposed by Cranfield University team.
- Advance propulsion work-package, in which aircraft design and performance estimation for propulsion evaluation was done with the tools developed in this thesis. The pressure to increase the aircraft range led to the discovery by the author of the benefits of the dual fuel aircraft.

Several papers were presented in ISABE 2022 and ICAS 2022 with strong engagement from the audience. The papers 'Propulsion System Integration for a First-Generation Hydrogen Airliner' and 'Impact of Tank Gravimetric Efficiency on Propulsion System Integration for a First-Generation Hydrogen Airliner' were presented in ISABE 2022. The former also was presented as ISABE invited paper in ICAS 2022 with strong engagement from the audience. Both were selected by RAeS for publication in the Special Issue of the Aeronautical Journal where the best 23 papers from ISABE were published.

The paper 'Propulsion System Integration for a First-Generation Hydrogen Airliner' was awarded a Bronze Prize by the RAeS in 2022 and was the 5th most downloaded paper in 2022 in the Aeronautical Journal with 1599 downloads.

13 FURTHER RESEARCH

The present research has been done with low fidelity models, using experimental correlations for weight and drag estimations and conceptual designs that lack detail in many instances. The priority in further research should be, therefore, to improve the accuracy of the models. The proper simulation of the elimination of wing bending relief in the hydrogen aircraft and structural considerations regarding the tank placement in the fuselage and the loads supported by the wings may have the highest impact in the conclusions.

Non cylindrical tanks that could be placed in more suitable spaces with less impact in passenger capacity should be investigated. The challenge is to give these tanks a sufficiently lengthy period of time before venting becomes necessary when parked empty at the airport. Advanced pressure management systems, active venting systems, new insulation concepts or the utilization of the boil-off vapour in the aircraft would bring important benefits to the hydrogen aircraft, although these are unlikely to be installed in the first generation of hydrogen aircraft.

A dual fuel aircraft, which utilises the fuels sequentially, burning the heavy kerosene first and the hydrogen later, offers energy efficiency improvements against the kerosene and the hydrogen aircraft and should be considered an option for the transition. Additionally, the possibility to power the aircraft with kerosene reduces the risks of the introduction of a novel hydrogen fuel system and perhaps contribute positively to the public perception of risk. A dual fuel combustion chamber should be designed. The challenge is to design a combustion chamber that have low NO_x emissions on both fuels separately.

Further research should be done on tank integration, particularly on crash worthiness and leak management.

Uncertainties on the tank performance and fluid behaviour could only be solved by testing due to lack of codes that predict liquid hydrogen behaviour. Testing of materials and insulation will clarify the gravimetric efficiencies achievable for large tanks when design for the long lives required in civil aviation. Foam insulated

tanks seem to offer the highest potential in weight reduction and aircraft performance improvement. However, foam and adherence performance over time with a large number of thermal cycles needs to be investigated through experimentation. Lightweight tanks designs, without a heavy vacuum jacket, will likely be preferred in the future. Foam or aerogel solutions should be developed in conjunction with the tank and thermal insulation manufacturers.

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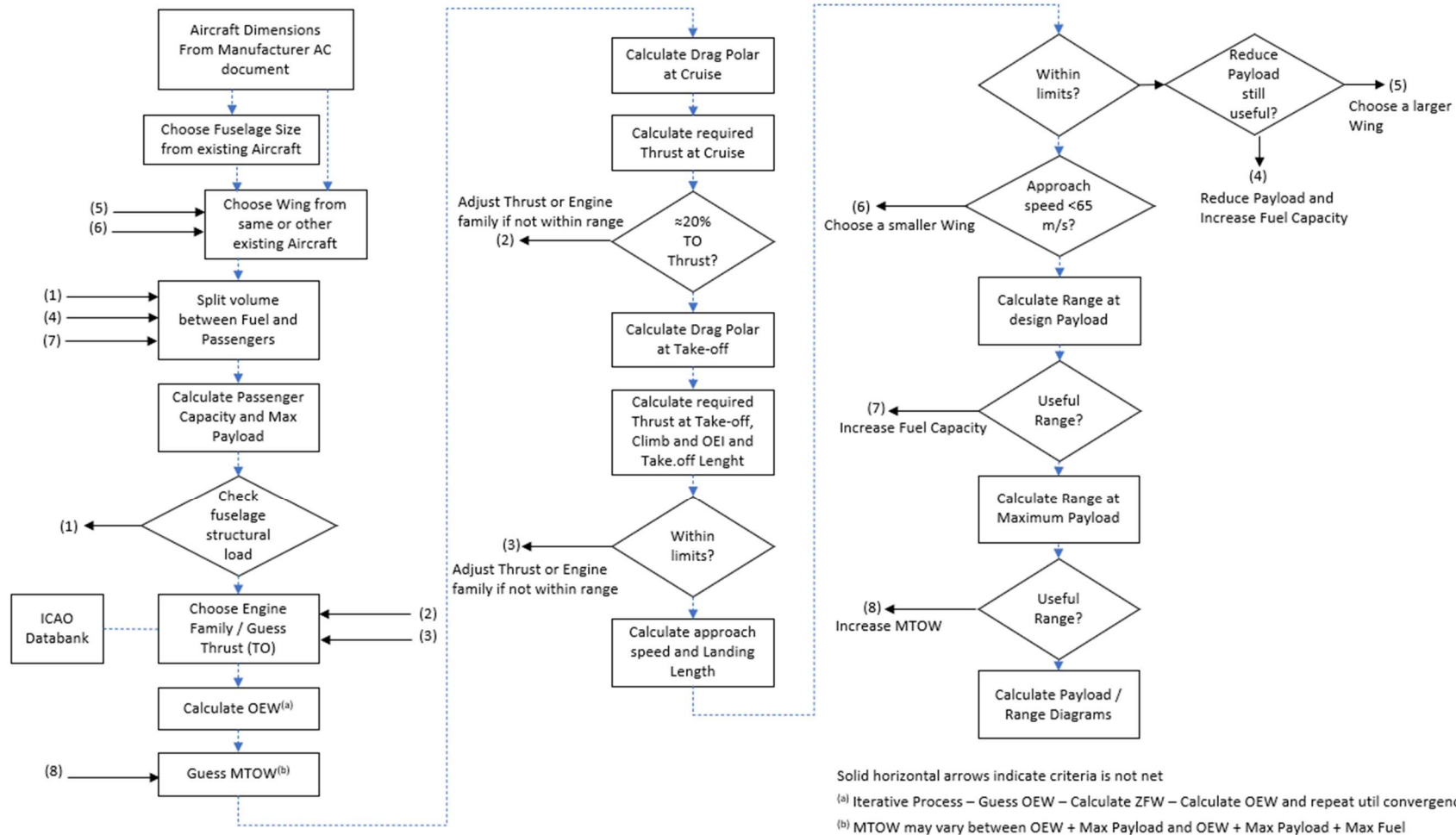
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Appendix A : Hydrogen Powered Aircraft Evaluation Using Existing Technology



Appendix B : A Strategy to Decarbonise Civil Aviation

J. Huete, D. Nalianda, B. Zaghari and P. Pilidis, "A Strategy to Decarbonize Civil Aviation: A phased innovation approach to hydrogen technologies," in IEEE Electrification Magazine, vol. 10, no. 2, pp. 27-33, June 2022, doi: 10.1109/MELE.2022.3166245

Paper published in IEEE Electrification Magazine

B.1 Abstract

Greening aviation is key to our global future. However, reducing aircraft operations would severely impact economics globally. Therefore, it is imperative that radical and green propulsion alternatives are developed quickly. The most likely approaches to succeed in this grand challenge are hydrogen (H₂) and electrification, which hold the promise of complete decarbonisation. H₂ is an inevitable solution for a fully sustainable aviation future, via hybrid/fuel cell technologies for short to medium range and direct H₂ combustion in gas turbine engines for longer missions. However, the huge financial investments required to make this a reality will not be considered until a few technical challenges can be overcome. Given the pressure to start decarbonising quickly, a philosophy of innovation waves is proposed on the basis that to accelerate the implementation of decarbonising technologies it is beneficial to develop quickly sub-optimal solutions and with time to improve efficiency as experience is accrued.

B.2 Introduction

Most institutions point to 2050 for a complete decarbonisation, though there is a growing feeling among these same institutions and the population that it will be already late. Hydrogen as a fuel for civil aviation can fully decarbonise aviation (Brewer 1975, ENABLEH2 2020, Cryoplane EU 2002, Verstraete 2009). Providing hydrogen is produced in a clean way – through electrolysis with renewable energy, so called green hydrogen – a fuel change from kerosene to hydrogen can eliminate all carbon emissions. Furthermore, hydrogen combustion can also reduce NO_x levels significantly, since lower flammability limit of hydrogen combustion is leaner (less fuel concentration), and this allows a lower local maximum combustion temperature and a possibly shorter combustion chamber and residence time. Other particulate emissions – hydrocarbons, sulphur, aromatics, smoke – are also eliminated. Except for contrails, the use of hydrogen for civil aviation can have no impact on the environment. Transition to hydrogen usage will be expensive but reducing flight travel will be more detrimental to the global economy. Hydrogen can become a solution to keeping to global competitiveness in Europe, and a worthwhile investment support to economic growth in the era after COVID, the current oil crisis and Ukrainian war. In such sense, Hydrogen is a well compromised solution. Assuming enough investment is secured, and technology development is rightly phased, hydrogen powered civil commercial aviation can enter service in 15 years.

The emphasis on suitable investments is emphasised given that technology adaptations and certification will require parallel development. The authors maintain that with a decade (plus) and appropriate R&D/Certification programmes civil aviation decarbonisation is a real prospect. It is imperative to succeed without blocking economic growth. Great strides have been made against poverty in the last century. There is a great deal of progress needed here and we must not go back in this context.

Gradual development of hydrogen aviation could accelerate decarbonisation, and for that, a few waves of innovation are required. First innovation wave could make use of as much existing technology as possible, targeting an entry into service in around 15 years. Future innovation waves will unlock the full potential of hydrogen in aircraft

Research on the potential of using existing technology has been carried out, leading to the definition of a scenario in which decarbonization starts as soon as possible. By doing this, minimum R&D costs to launch hydrogen aviation are also reduced, and the scarce resources available focused on hydrogen specific topics, leaving for future times fuselage, wing and subsystems optimisation. Aircraft will not be optimum for hydrogen use but development lead time and risk will be drastically reduced. With such conception, perhaps entry into service could be accelerated 15 years or more from the original 2050. Carbon reduction will be massive. Would it be possible to decarbonise aviation fully in 50 years? 5 technological options investigated by the authors are shown in Figure A.1. Complete decarbonization is possible if right wide, international decisions are made.

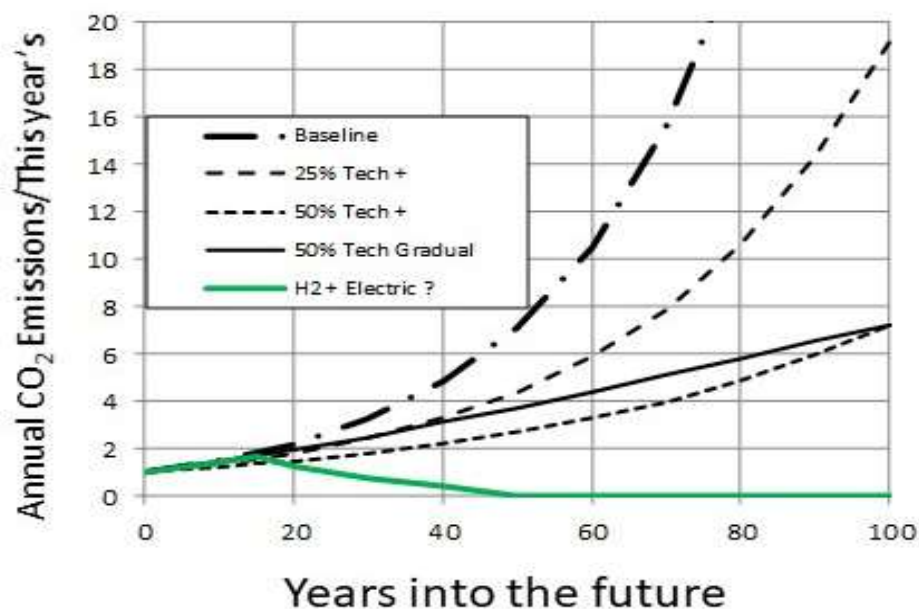


Figure A.1: Comparison of five technology scenarios, all with the hypothesis of a continuous growth in air traffic of 4% p/a. Baseline shows CO₂ emissions with the

continued use of current state of the art equipment. 25% and 50% show the benefits of immediate introductions of improved technology improvements that would yield, in 100 years these respective improvements. 50% gradual shows a gradual move to 50% and H2+Electric shows a fully decarbonised scenario.

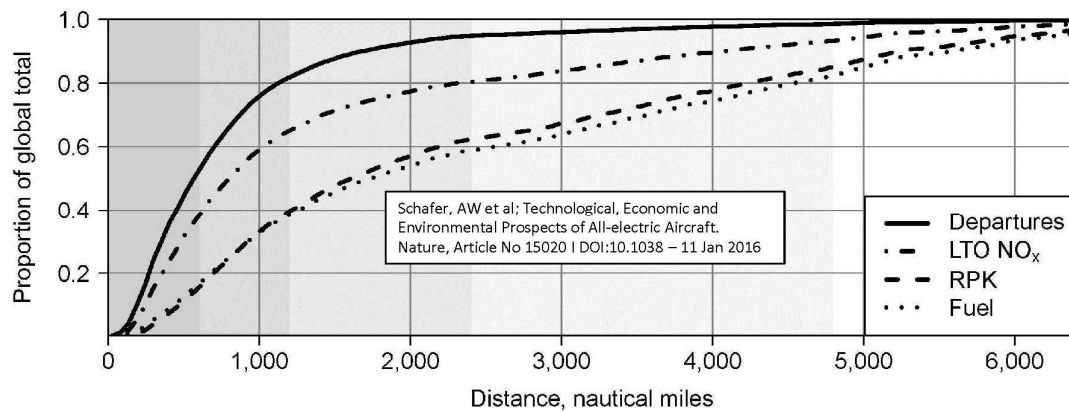


Figure A.2a: Commercial Aircraft Traffic Characteristics (Schafer et al, 2016)

Economic considerations do not lead to the selection of hydrogen as a fuel for aviation, especially in the lack of economies of scale, therefore, very likely, economic forces will not bring hydrogen to the sector. Such transition will require enormous incentives, such as other sectors have required in the past to be carried out. Nailanda, 2012 develops several tools to evaluate the effectiveness of the different policies.

Figure A.2a shows air traffic characteristics (Schafer et al, 2016) where cumulative aircraft movements (departures), NO_x, Revenue Passenger Kilometres (RPK) and fuel used are shown on a basis of aircraft range. For large scale decarbonisation to take place, the whole range of operations needs to be addressed. A 'portfolio approach' is proposed.

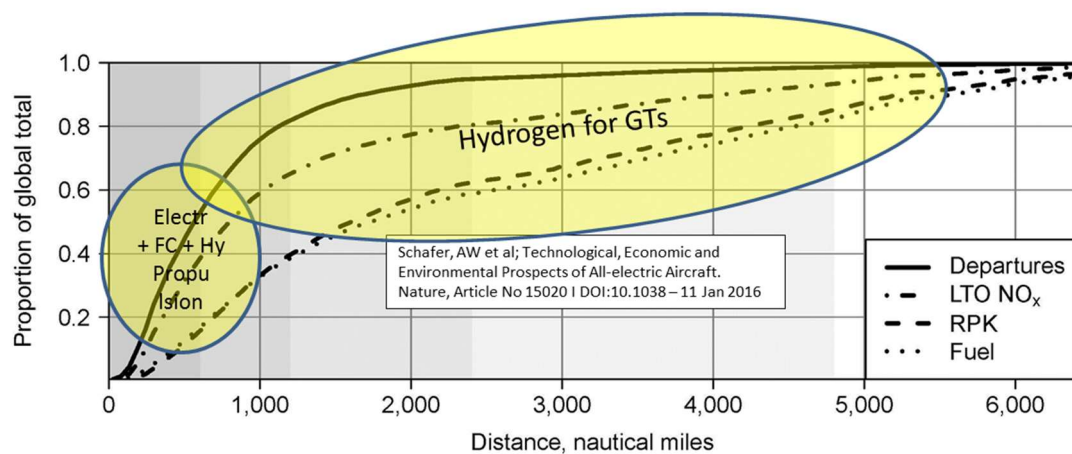


Figure A.2b: Commercial Aircraft Traffic Characteristics (Schafer et al, 2016) annotated by the authors based on published electric propulsion capabilities and H2 evaluation described here.

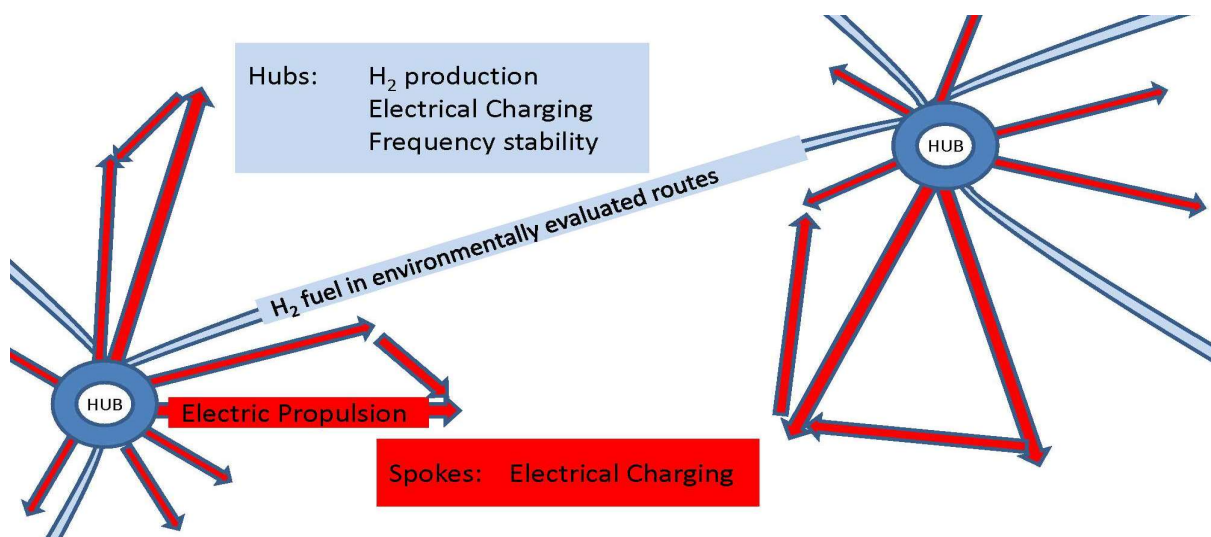


Figure A.3: Schematic of Hydrogen Hub and Electric Propulsion Spoke Approach

B.3 Innovation waves

A much higher impact on aviation greenhouse emissions can be achieved when successive waves of innovation are considered. Figure B.2b shows how a first innovation wave could be shared between electric propulsion and hydrogen systems. Within electric propulsion, all electric, fuel cell electric and hybrid electric can be contemplated. This could provoke a boost of hub and spoke flight approach, where traffic to hubs is performed with electric propulsion aircraft and traffic between hubs is done with hydrogen. See Figure A.3.

Maximum range for Hydrogen aircraft shown in Figure A.2b is 5,500 nm, according to maximum range of HVLER (Huete et al 2021). In a longer term, hydrogen aircraft of second, third and fourth generation could offer significantly ampler missions in terms of passenger capacity and or range through improved technologies.

The focus of the first innovation wave will be twofold. A primary objective will be to offer to the market a hydrogen aircraft family comprising a family of aircraft, described in a later section. The other key objective will be the adaptation of certification rules to cope with the new electrical and hydrogen technologies. This concurrent aircraft/engine development and adaptation of the certification rules must be very closely coordinated and is likely to form the backbone of the critical path of the entry into service of zero/near zero carbon aircraft. This will permit operation without any backward drift of the superb safety record of the industry. Simultaneously green hydrogen production and airport infrastructure will need to secure certification and be commissioned. The authors would expect hydrogen fuelling and electrical charging would take place in different terminals of an airport. A capable aircraft family comprising hydrogen aircraft concepts working synergistically with a significant Hybrid Electric Fleet (Figure A.4) could offer a holistic solution. With the varied electric and hydrogen fleets envisaged and the deployment of six carefully selected international hydrogen hubs the first innovation wave could provide a realistic start and proper civil aviation decarbonisation could start in 10-15 years.



Figure A.4: Concept of Innovation Waves.

The primary objective of the first innovation wave would be to press into service safe aircraft to start decarbonising as quickly as possible. This would inevitably yield knowledge to improve the vehicles and make them more efficient. These improvements in efficiency to better accommodate the electrical and hydrogen requirements of the aircraft fleet would be the primary focus of the second innovation wave. Within the second innovation wave the authors are currently exploring the feasibility of 17 hydrogen hubs to offer global coverage for the hydrogen fleet. This is based on the concept of ‘tankering’. I.e. carrying fuel for more than one journey. So, an aircraft could take from a hydrogen hub with enough fuel for two flights. The aircraft would then land in an airport where the airplane would be unloaded and reloaded without refuelling and take off to reach another hydrogen hub to refuel for further flights. Hydrogen, given its very high energy content per unit of mass is much more attractive than conventional fuels for the ‘tankering’ concept. In the second innovation wave some adaptations to

certification rules are expected. These will be much more modest than those foreseen for the first and third innovation waves.

In the third innovation wave the authors expect a very close synergistic integration of hydrogen with the electrical components. Hydrogen is anticipated to be carried as a liquid at temperatures of about -250°C ($\sim 25\text{K}$) to enable an efficient hydrogen system. At these temperatures there is an opportunity to exploit hydrogen cryogenics to enable superconducting electrical systems. These opportunities are very likely to give rise to much more efficient aircraft designs that what would be possible with hydrocarbon fuels. These major innovations would require very substantial adaptations to the certification rule needed to exploit the synergies between electrical and hydrogen systems (Nalianda 2014) to deliver improved engine and aircraft performance.

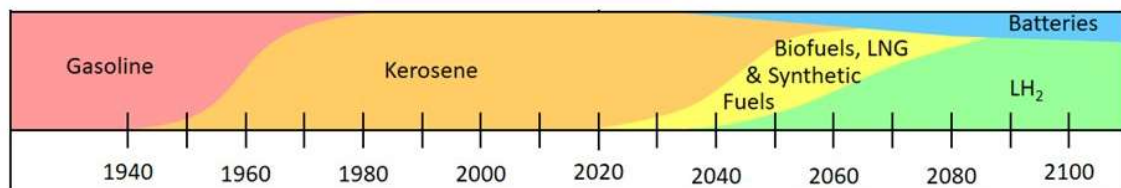


Figure B.5: Decarbonisation pathway

Even for the first generation of hydrogen aircraft, a retrofitting or a derivative was ruled out. High-capacity aircraft need large wings to take-off and land, and it comes with a thick wing capable of storing a large amount of fuel. Such a heavy wing is not used at all in a hydrogen aircraft, where fuel is installed in the fuselage. A procedure to evaluate best existing wing and powerplant for a given fuselage was described in (Huete et al, 2020-1). It was concluded that for long ranges, a reasonable sizing would be that of the fuselage of a double deck 600 t airline, inspired by A380, (Lufthansa, 2020) with the wings and engines of a twin-engine long-range aircraft, inspired by A350-1000 with Trent XWB engines. Although evaluation process was iterative and many other options were evaluated, here it

is presented the final iteration only. This research originated a family of three aircraft – HVLMR, HVLLR and HVLER.

B.4 Fuel tank integration

Major research investments will need to be made to address the two primary features of hydrogen as an aviation fuel. These are the large volume and the low temperature.

For the same energy content as conventional aviation fuel, liquid hydrogen is approximately a third of the weight and four times the volume. To reduce the volume storage as a liquid is essential, this means that the hydrogen temperature will need to be 25 K (-250 C approximately). The authors consider this as a surmountable challenge that will require about a decade to resolve and to allow the consequent adaptation of the certification rules. The authors adopted an analytical tank design approach based on earlier Cranfield University research (Goldberg 2017 and 2018, Goldberg et al 2018). A passive design is adopted where heat transfer and heating of the fuel is prevented using appropriate insulation. Given the relatively low pressure (between 1 and 2 bar) of the fuel the walls can be relatively thin. Fuel removed into the engine will reduce pressure levels, while heat ingress will raise pressure levels.

To protect from the risk of inappropriately high pressure and temperature, due to heat leakages, a bleed valve allows hydrogen to safely escape into a venting volume. This will lower, the tank pressure and temperature. To remove the risk of very low pressure inside the tanks, due to large and fast hydrogen removals to feed the engine, warmer or preheated hydrogen can be returned into the tanks, maybe from the venting volume.

Figure A.5a shows an image of the aircraft used for the study. The aircraft has two passenger decks, the upper deck is smaller than the lower one. The authors thereby propose three designs of a hydrogen fuelled civil transport derived from this concept, HVLMR, HVLLR and HVLER; for hydrogen medium, hydrogen long and hydrogen extended range. The idea of long and extended range is specific to the use of hydrogen in this exercise, and they correspond to shorter flights than

those possible with an advanced conventional civil aircraft. The first, HVLMR, considers the use of the upper deck to locate the hydrogen tanks, HVLLR is conceived with the fuel tank in the lower deck and HVLER with a combination of fuel tanks, primarily in the main deck and some on the upper deck and the cargo space.

B.5 Integrated capability

To understand the concepts studies, please refer to Figure A.6, in which two of the options are schematised: HVLMR, with hydrogen tanks in the upper deck and HVLLR with hydrogen tanks in the main deck, larger than the upper deck. The extended range version, HVLER, is like Fig. A.6c plus additional tanks in the back of the aircraft as in Figure A.6b. Table A.2 shows a list of city pairs that the proposed aircraft could serve to illustrate the high utility of such aircraft.

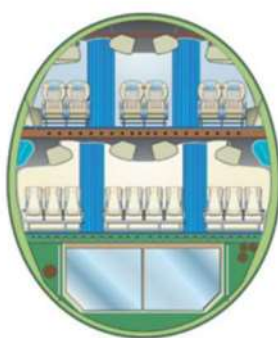


Figure A.6a Baseline

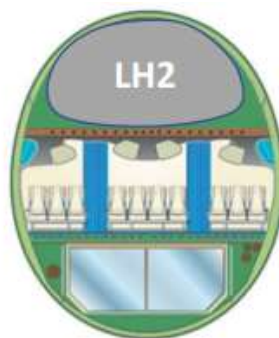


Figure A.6b HVLMR

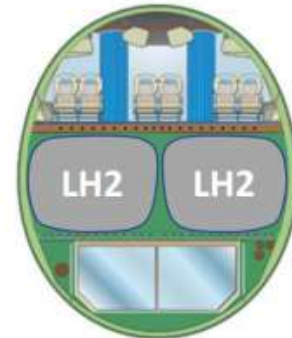


Figure A.6c HVLLR

Images courtesy Lufthansa (Lufthansa 2020) and modified by the authors.

Passenger capacity is quite close to current aircraft. Range is not as high as kerosene aircraft, but it is good enough to the purpose it has been thought for – a quicker decarbonisation. A comparison of Table A.1 and Figure A.2 shows that aircraft family covers more than 98% of departures and 90% of fuel burnt. The remaining flights, those with a very long range, could still be performed with these aircraft with one stop.

Most sensible parameter to aircraft performance was found to be the tank weight, usually expressed as ratio of useful hydrogen divided by the weight of the tank plus the stored hydrogen – the gravimetric efficiency. The impact of the gravimetric efficiency on the aircraft family performance is being evaluated (Huete et al 2020-2). A gravimetric efficiency of 0.45 has been assumed, as quite a conservative value. A detail analysis of the tank design, sizing and implications has been performed by Huete and Pilidis, 2021.

	AIRBUS A350-1000	AIRBUS A380-800	HVLMR	HVLLR	HVLER
Mass (tonnes)					
Ramp	317	577	274	304	310
Max take-off	316	575	273	303	309
Max landing	236	394	251	275	286
Max payload	68	83	50	45	36
Operational Empty	155	276	200	229	238
H2 Tank (gravimetric eff 0.45)			33	51	59
Engines	2	4	2	2	2
Cruise thrust/engine kN	87	81	81	88	90
Static thrust/engine kN	432	374	406	441	448
Range (naut miles)	8700	8000	3300	4800	5600
Pax (2 class economy)	315	555	388	332	232

Table A.1: Comparison HVLMR, HVLLR and HVLER with the ‘design donor’ aircraft. H2 tank gravimetric efficiency is a conservative 0.45

B.6 Conclusions & recommendations

In order to address the urgency of developing viable and cost-effective passenger aircraft concepts to address climate change, the paper intends to propose ideas, which while being philosophical in nature, are supported with detailed investigations. Through informed analysis the paper proposes the idea that a family of hydrogen fuelled civil aircraft could be developed using conventional design rules and pre-existing components of two existing aircraft. For this the fuselage will be adapted from a very large two deck (4 engine) transport aircraft

design, while the wings, engines and tail surfaces would be derived from a long-range twin-engine aircraft. This philosophy could be used to further derive a family of Hydrogen fuelled Very Large (HVL) aircraft which could be specifically configured to achieve medium, long and extra-long ranges (designated as HVLMR, HVLLR and HVLER respectively), through configuration and integration of appropriately sized cryogenic tanks storing LH₂. This family is expected to exhibit payload-range capabilities that are limited when compared to the original aircraft from which they have been derived, but will necessarily have sufficiently attractive performance characteristics to be considered as a launch option for a first generation zero carbon aircraft.

While the concepts being proposed are the first generation, it is expected that as technologies mature, the performance of the aircraft would certainly improve. These investigations, in conjunction with further research undertaken by the author (Huete et al 2020-2) have shown that in addition to improvements in the integrated aircraft concept, the gravimetric efficiency of the cryogenic tank and the design of suitable low NO_x emission combustors with an ability to efficiently burn hydrogen are of paramount importance.

The authors do not foresee any major technology hurdles that suitable, large and timely investments in research and development cannot resolve. Although hydrogen presents many challenges, possible solutions are visible for these. The vehicle development process may require a concurrent technology acquisition programme intimately interlinked with the adaptation of the certification rules. The objective here is to ensure the continuation of the superb safety track record of civil aviation. A possible path to deployment could comprise a first phase with two parallel tracks. In one a faithful replica of the aircraft is made to test aerodynamic qualities using conventional fuel. The other track would comprise a four-engine aircraft to test the hydrogen fuel system in two of the engines while the other two used conventional fuel. The duration of this first phase could be 7-8 years and would encompass a close and detailed dialogue with the certification authorities to bring in the bulk of the new certification rules required. The outcome of these two phases would be a solid confidence in the aircraft as a vehicle and

of the complete hydrogen system. In the second phase that would have started before the end of the first one, the combination of the two streams of the first phase would deliver a certifiable hydrogen airliner along with the rules to certify it; all this within a decade.

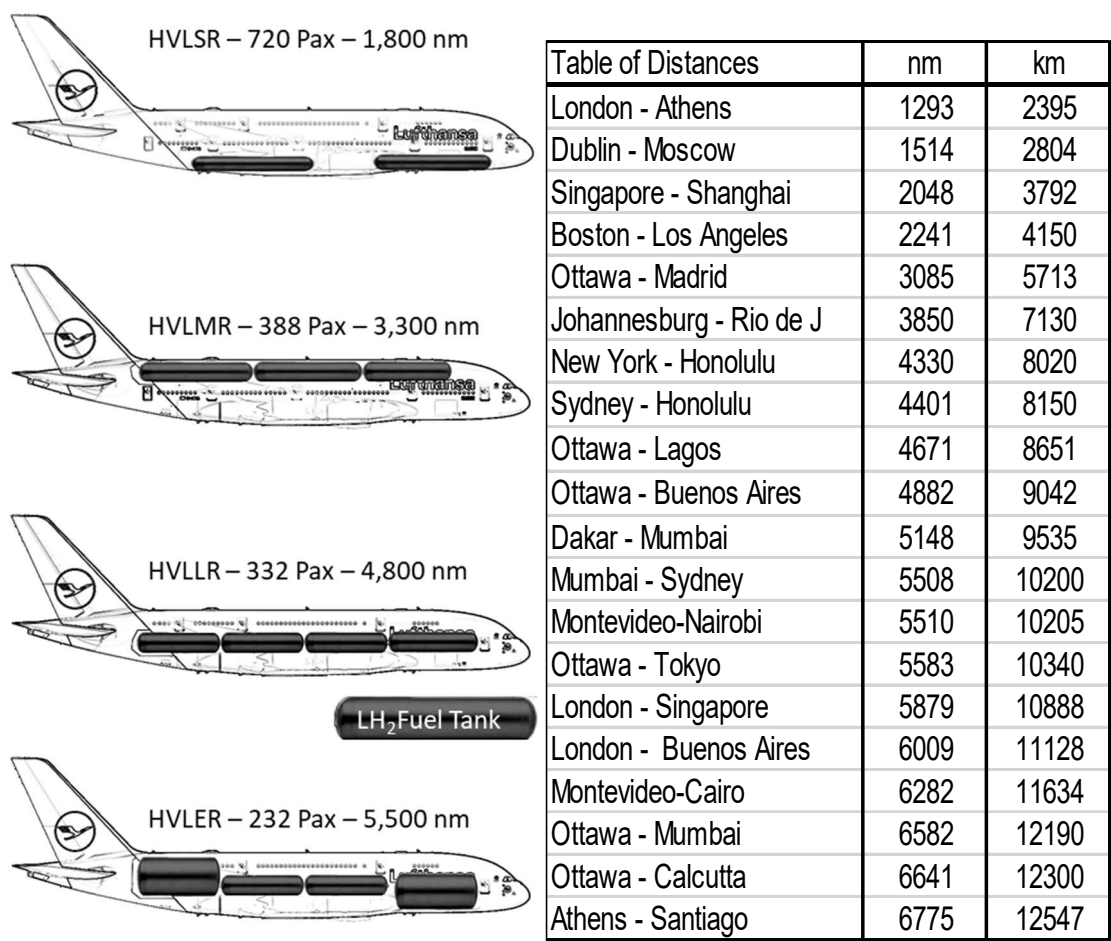


Figure A.7: Four airliner family concepts. **Table A.2:** Distances between some airports, a measure of the usefulness of the aircraft family (Source Wikipedia)

Images courtesy (Lufthansa 2020) and modified by the authors

It is not only the aircraft that needs attention. Airport infrastructure will experience vast changes. However, the very low weight of hydrogen makes the concept of tankering (loading in one airport the fuel needed for two or more consecutive flights) much more attractive than in conventional aircraft. This would permit a gradual airport development because, initially, a very small number of hydrogen fuel hubs would permit these aircraft to serve a very large number of airports enabling a very wide reach for decarbonisation. Another matter to resolve is the provision of prodigious amounts of green hydrogen. This will require significant investments on zero carbon electricity generation. Furthermore, hydrogen may need to be produced from sea water electrolysis to prevent unhelpful competition with scarce freshwater resources. These developments will be expensive, needing tens, possibly hundreds of billions of pounds (or euros or US dollars), however the authors firmly believe these investments are valuable to migrate to zero-carbon an industry that brings so many technical, social and economic benefits. The alternative, an industry contraction, will be vastly more expensive and damaging.

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