

Hydrogen Propulsion for Civil Aviation: An Introduction Scenario

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1- ABSTRACT

Civil aircraft that fly medium and 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 in a holistic manner. Hydrogen is increasingly seen as a key solution. There is a number of major issues to resolve. One of them is the provision of appropriate airport infrastructure.

A philosophical-analytical scenario feasibility is proposed here based on an airliner family, previously proposed by the authors to assist in the elimination of carbon dioxide emissions from civil aviation. The family comprises six airliner models derived (not retrofits) from existing state of the art airliners. The objective of the philosophical investigation presented here is to explore the gradual implementation of airport infrastructure considering geographical and traffic characteristics.

The outcome is a plausible and effective scenario where a gradual introduction of Hydrogen fuel is proposed where for a few decades Hydrogen will coexist with conventional fuels and drop-in Sustainable Aviation Fuels. This scenario proposes a first generation of six

very large hydrogen hubs to cover very large traffic centres to make in the first instance deep inroads into civil aviation carbon emissions. A second generation of 16 hydrogen hubs is also proposed that would enable a global span. These two generations of hydrogen hubs could enable a very wide introduction of hydrogen in the long term by catalysing cost reductions with volume and experience, in the long-term delivering 3rd, 4th and nth generations of hydrogen hubs where reliance on carbon fuels is gradually reduced until they have been fully displaced in the long term.

2- NOMENCLATURE

Δ	Change
BPR	Bypass Ratio
ESFC	Energy SFC (W/N)
FC	Fuel Cell
FCV	Fuel Calorific Value (lower) (MJ/kg)
F_n	Nett Thrust (kN)
GTs	Gas TRurbines
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
HY	Hybrid
ISA	International Standard Atmosphere
MLI	Multi Layer Insulation
MT	Megatonne
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)
Mt	Million (Metric) tonnes/ Megatonnes
CO ₂	Carbon Dioxide
MtCO ₂	Million tonnes of Carbon Dioxides
MtH ₂	Million Tonnes of Hydrogen
IFR	Instrument Flight rules
SID	Standard Instrument Departure
STAR	Standard Arrival
SARPs	Standard and recommended practices
EIS	Entry into Service

3 - INTRODUCTION

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 very substantial 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. There are many voices indicating that this could be an option. (BBC 2021 and many others). It is expected that there will be an acceleration of regulatory action and the industry needs to be ready (UNPRI, 2021). A wide community firmly believes (Parker & Pilidis 2021) that an industry contraction will be globally detrimental in social and economic terms, in particular for the less advantaged parts of humanity. For example in the EU in 2018, tourism accounted for 10% of GDP and 27.3 million workers (Europarl 2021). In some island nations tourism accounts for 50%, 60% and higher shares of employment (Visual capitalist 2021). Tourism is very dependent on aviation. These and many other statistics have persuaded the authors that positive climate action by civil aviation is needed to avoid the very damaging outcomes of an industry contraction and that Hydrogen is at the centre of the stage.

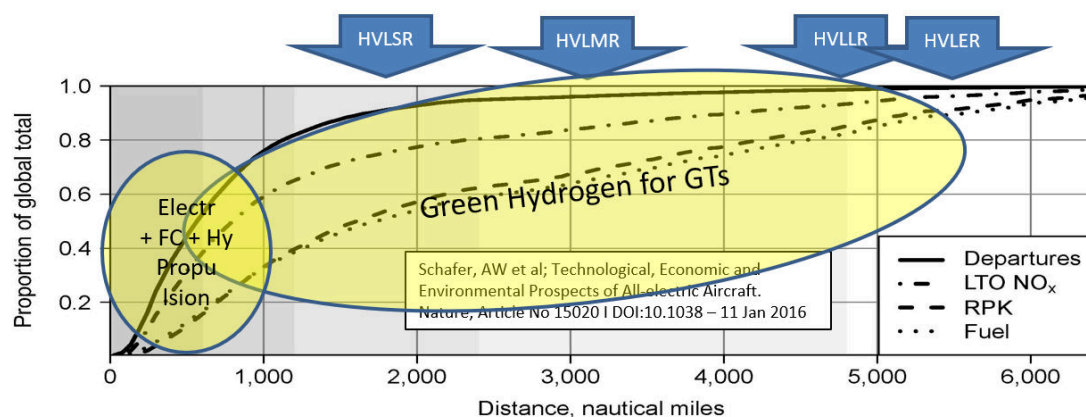


Figure 1 – HVLSR, HVLMR, HVLLR and HVLER capabilities with a baseline gravimetric efficiency of 0.45. (Schafer et al, 2016) annotated by the authors

The authors believe that with the appropriate investments and support, an introduction in approximately 15 years is conceivable. To achieve fast decarbonisation, the authors have proposed the concept of innovation waves. Hydrogen is a technology solution to provide combined sustainability in environmental, economic and social terms. The authors expect a synergistic development of electric technologies and hydrogen to replace carbon containing fuels in the long term. Figure 1 shows a vision for the first innovation wave. This concept of innovation waves will enable civil aviation decarbonisation early. There is an expectation that environmental regulations will develop swiftly (UNPRI, 2021); the industry should be ready for this.

The concept of innovation waves is based on the premise that speed of implementation, to start decarbonising quickly, takes priority over efficiency; naturally the superb safety standards that characterise the civil aviation industry should not be compromised. Fig 2 offers a pictorial view of innovation waves. The first and the focus of this paper proposes derivative designs where the only disruptive feature is the introduction of hydrogen fuel. This is a vast change in itself. The aircraft family presented and analysed in Huete et al (ISABE 2020 and 2021) is a good candidate. The primary need for this innovation wave is the development of the derivative aircraft and engine designs, the fuel system and the parallel evolution of certification rules and airport infrastructure. The focus of the second innovation wave is on efficiency improvements and a better accommodation for the large volume requirements of the hydrogen on board. Naturally further adaptations of rules and infrastructure will be needed, but these will be of a lesser magnitude than those needed for the first innovation wave. The third and subsequent innovation waves will focus on efficiency enhancements capitalising on the properties of hydrogen; these include gas turbine pre-cooling and the synergies with superconductivity for the electrical system. For the third and subsequent waves the authors expect that there will be great synergies between hydrogen and electric propulsion.



Figure – 2 Aircraft for possible Innovation waves. The left image of this figure depicts the aircraft concepts proposed here. The centre and right images are from ENABLEH2 (2020).

A key cost item in the process will be the provision of the airport infrastructure for Hydrogen aircraft, especially in the context of the first innovation wave where a fuel transition is required. The objective of this techno-philosophical evaluation is to offer a plausible scenario for the entry into service based on the family of aircraft evaluated in Huete et al ISABE (2021 and 2022).

4 – THE AIRCRAFT FAMILY

The details of the aircraft family are explained in detail in Huete et al ISABE 2021, 2022, and are based on components (fuselage, wings, engine, tail), of two existing and operating aircraft models (Airbus A380, Airbus A350) comprising a total of four (4) different configurations, using hydrogen fuel in gas turbine engines: HVLSR, HVLMR, HVLLR & HVLER, as depicted in figure 4. Figure 1 shows the cross-section of the fuselage of the large aircraft used for the study; it also illustrates the cabin arrangements and tank locations of the four members of the family. The ‘donor’ aircraft has two decks to carry passengers, the lower deck larger than the upper one. The aircraft also has large underdeck storage for luggage 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. The HVLSR was conceived as a ‘slot relief’ solution (Huete et al ISABE 2022) for very busy airports in 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. Figure 2 offers a measure of their usefulness in terms of passenger capacity and range. Many more details are available in Huete et al (ISABE 2021). In Huete et al (ISABE 2022) a study of the influence of gravimetric efficiency was carried out that showed that as gravimetric efficiency increases, the range increased, improving usefulness. The range of the aircraft is shown also in Figure 1 to indicate that this family can make very significant inroads into carbon emissions, especially if very long-range non-stop flying is

replaced by one stop flights. The range of HVLER is carefully chosen to permit a flight from anywhere on the planet to anywhere else with a single stop.

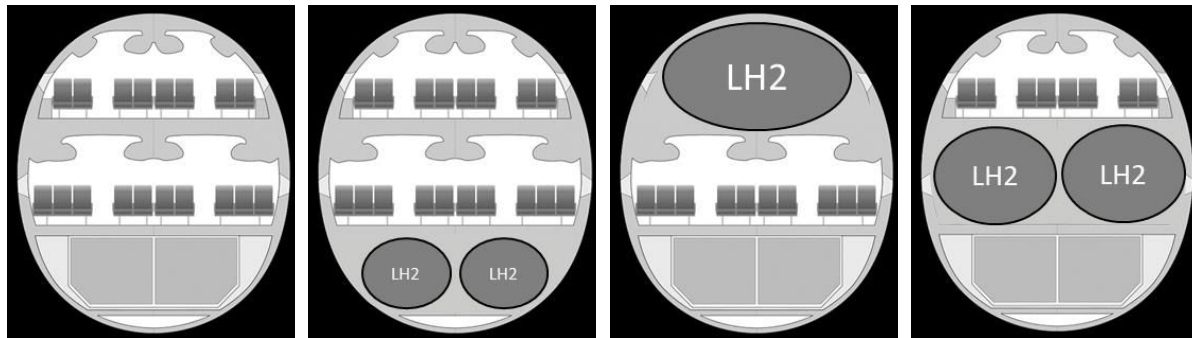


Figure 3a Baseline 3b HVLSR layout 3c HVLMR layout 3d HVLLR layout
Image from Ssolbergj and Tillier – Creative commons licenced modified by the authors.

The two smaller members of the family include the hydrogen tanks in the fuselage of existing airframe designs and the passenger carrying section of the fuselage remains unchanged, it is just somewhat shorter. They have passenger capacities of 70 and 130 passengers and a range of 1200 and 2000 nautical miles.

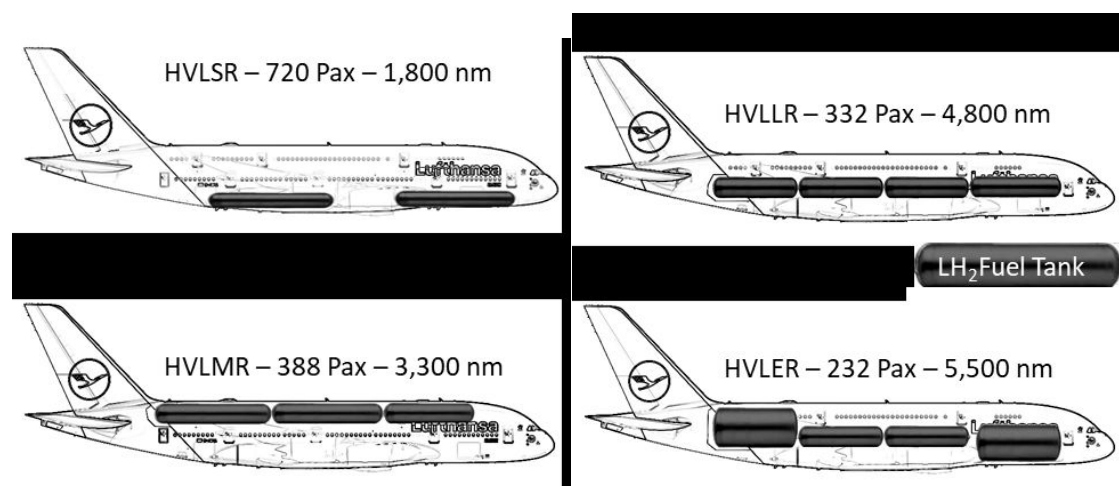


Figure 4 – Family of four very large airliner concepts. Images courtesy (Lufthansa 2020) and modified by the authors.

5.a – THE SIX HYDROGEN HUBS FOR THE FIRST GENERATION

There are more than 25000 commercial aircraft in service (Statista 2021) and production is of the order of 1500 each year (Statista 2021). Boeing foresees an approximate demand for 43,610 new airplane deliveries for the period between 2021 and 2040 (Boeing Commercial Outlook, 2021) and Airbus an approximate of 39,010 new deliveries until 2040 (Airbus GMF, 2021). Furthermore it is expected that hydrogen aircraft will coexist with those using conventional fuels and carbon containing sustainable aviation fuels. This will result a gradual introduction of the first innovation wave. A very high cost factor that will require also complex and costly R&D and certification is the provision of airport infrastructure to handle these aircraft. So the authors chose six hypothetical airports as the first generation. These were chosen on the basis of several criteria. Firstly they are busy airports. The objective here

is to enable a swift impact of decarbonisation. The airports selected are also close to a sea coast. This is on the premise that seawater will be used for electrolysis, to protect supplies of fresh water, so scarce in many places. Thirdly they were chosen at distances to enable successful hub and spoke operations using the aircraft family employed in the study. The airport choices apart from London are not based on any preference by the authors. These airports are: London, Neom, Singapore, New York, Los Angeles and Shanghai.

London was chosen because it is in the UK, the base of operation of the authors and it is a very useful airport for European and transatlantic operations. The 'London' of this study is an amalgamation of Heathrow and Gatwick Airport traffic.

Neom was chosen on the basis that it is a vast, brand new city project (Carnegie Endowment 2021), aiming to environmentally sound operations, is very large scale and it is very conveniently located. The authors make the hypothesis that a hydrogen hub could be located there.

New York and Los Angeles are conveniently located straddling the North American continent and Shanghai and Singapore, with Neom, give good coverage of Asia. The authors emphasise that these choices are purely on a geographical basis and they do not imply any decision or commitment by the respective government, airport and/or business authorities. This arrangement leaves an important transpacific gap and the southern ends of Africa and Latin America to be covered, maybe, by the second generation of aircraft and airport development. Table 1 shows the distances between these six hubs, giving a view of the usefulness of the hub location. It is also worth noting that the flight ranges proposed here are well within the capabilities of the aircraft family of the study. Several cities have multiple airports, the assumption made here is that the hub is an amalgamation of some or all these airports.

From	To	nm	km
London	Neom	2106	3900
Los Angeles	New York	2160	4000
Neom	Shanghai	4374	8100
New York	London	3024	5600
Shanghai	Singapore	2052	3800
Singapore	Neom	4374	8100

Table 1 – Relevant distances between the hubs

5.b. – CARBON DIOXIDE EMISSIONS AND THE ENVIRONMENTAL IMPACT OF THE “SIX HUBS”:

In “Airport Tracker, uncovering aviation emissions” (Sam Pickard and Ipek Gençsü, September 2021) conducted an analysis covering 99% of the global Air Transportation (focusing mainly on the passenger transport sector) a considerable amount of the climate impact of the sector (27% of the CO₂ emissions) derives from a shortlist of 20 airports from the total research scope of 1,300 airports (airporttracker.org). Aviation emissions are unevenly distributed on the map, as they are unavoidably connected with the operation of the “busiest” hubs. They do coincide though with the initial main “Six Hubs”, speculated by the authors presented here as the pioneers of the hydrogen generation introduction, intended to be focused on this project.

According to the 2019 statistics (more representative of the global traffic, before the pandemic outbreak), present on the list of the 20 airports generating the majority of the sector’s “pollution” are (in sequence of MtCO₂ produced): Dubai International with 16.6 MtCO₂ (in our project substituted by the Neom), London Heathrow with 16.2 MtCO₂, Los Angeles International with 15.3 MtCO₂, New York JFK International with 12.9 MtCO₂ (Statista, 2021), Singapore Changi with 10.8 MtCO₂ and Shanghai Pudong International with 9.2 MtCO₂ (Sam Pickard and Ipek Gençsü, September 2021). The same airports with the exclusion of Shanghai occupy five (5) places in the list of the first ten (10) airports departure airports with the largest passenger CO₂ emissions from international operations in 2019 (ICCT, Statista, 2021).

The associated cities are also in the top 20 of the most polluting cities in the city-scale CO₂ emissions table for passenger aviation/ Civil Aviation Transportation, in the respective sums of their airports, with London occupying the 1st place emitting 23.5 million tonnes of carbon dioxide annually (Pickard, S. and Gençsü, 2021).

Aviation accounts for 8% of the global transportation sector emissions (Statista, 2021) and for the 2~3% of global anthropogenic emissions out of which the 1.3% is produced by international flights (ICAO, 2019). The Global Aviation Emissions exceeded the numerical value of 1000 million tonnes annually for the first time in 2018 (Lee et al., 2020), so using this number as a valid current approximate of the global aviation sector emission the six hubs referred to above, will account for approximately 8.1% of the global Carbon Dioxide emission transformed into net zero with the successful implementation and EIS of the Liquid Hydrogen as an ultimate scenario to tackle this problem.

The estimated values reported slightly vary between agencies, with IATA reporting a total CO₂ emission of 2019 to be 905 MT (IATA 2021) including freighter aircraft operations, and a similar number reported also by the ICCT (International Council of Clean Transportation), which both augment the proportion covered by the airports of the 1st wave. Hypothetically achieving the EIS in 2035, and considering the numbers by IATA and ATAG in the factsheet “Waypoint 2050”, in 2035 1,703MT of CO₂ will be produced by commercial aviation, rendering the actual “saved” amount of emitted CO₂ by the 1st generation of hubs to almost double due to the uneven distribution of passenger traffic.

6 – TRAFFIC ANALYSIS

Apart from the traffic analysis supporting the reasons behind the choice of the mentioned airports as the 1st generation of “Hubs” using primarily Liquid Hydrogen, data will be included in terms of operational efficiency in order to address the initial expected higher cost of liquid Hydrogen before its robust establishment into the market of transport. Airborne operational efficiency in terms of planning will be combined with analysis of the SFC (specific fuel consumption), taking into consideration all the existing SARPs (standard and recommended practices), and using unavoidably the method of “Tankering sectors” to facilitate and address the issue of limited supply (geographically). This solves part of the problem raised by ATAG (Air Transport Action Group) regarding the turnaround times and the associated costs and loss in revenue. The same was noted as one of the major challenges in the study of CleanSky 2 in May 2020, estimating an approximate 2-3 times longer refuelling times for medium and short-range aircraft (CleanSky 2, 2020).

Polygonal routes would permit significant traffic between airports where refuelling is not available (at least initially) in many airports. These are also known as “Tankering” sectors. Figure 7 shows some possibilities. Two routes are shown. One is a quadrilateral route serving four airports with refuelling only in London. The total length of the four legs of this route is slightly over 2500 nautical miles. (In the initial phase of the report here, air distances in straight level flight are shown, without the inclusion of the NM of the potential SIDs or STARs to be followed for operational reasons, as accurate calculations of air-distance based on an average seasonal estimation of winds, and hydrogen consumptions will be presented in the papers to follow. Those will be based on real IFR flight plans, from point-to-point navigation, and on an average weather condition prevailing per season.). The other route is a triangular route with refuelling in London with a total length of nearly 3000 nautical miles. So, these two polygonal routes could be served by the HVLLR, permitting quite a high capacity. This high capacity may mean that fewer flights may be required. Landing rights and competition issues could be mitigated by code-sharing.

The risk of an aircraft stranded in an airport unable to refuel hydrogen can be greatly mitigated by designing a kit for ground refuelling between aircraft to fit within the large cargo hold of HVLLR. This aircraft has a range that is significantly longer than any return flight within Europe. Thus, in the case of a stranded aircraft, a ‘donor’ HVLLR could carry out a revenue generating flight to the airport where the stranded aircraft is located, with the refuelling kit in the cargo hold. The ‘donor’ aircraft would then refuel the stranded aircraft to enable it fly to a

The map illustrates a hydrogen network centered on a London H₂ Hub. The following table summarizes the connections and distances shown:

Destination Country	Distance (nm)
Spain	655
Italy	729
Greece	783
Poland	864
Netherlands	504
Germany	648
France	1293

Table 2 shows the aircraft movements in the year referred (according to the data available) and the percentage of the global traffic that they represent. The first section includes the “Six Hubs” (first phase of introduction) and the second the additional ten (10) hubs, altogether composing the second phase of implementation. The statistics for Dubai are assumed to apply for Neom.

	Million flights	% of global total	Year	Sources
London Heathrow	0.476	1.224	2018	https://www.heathrow.com/companies/about-heathrow/facts-and-figures .
London Gatwick	0.281	0.722	2019	https://www.gatwickairport.co.uk/business-community/about-gatwick/company-information/gatwick-key-facts/
N York JFK	0.456	1.172	2019	file:///C:/Users/me072a/Desktop/ads/ATR2019.pdf NYNJ Port Authority 2019 Airport Traffic Report
N York - Newark	0.446	1.147	2019	file:///C:/Users/me072a/Desktop/ads/ATR2019.pdf NYNJ Port Authority 2019 Airport Traffic Report
N York - La Guardia	0.373	0.959	2019	file:///C:/Users/me072a/Desktop/ads/ATR2019.pdf NYNJ Port Authority 2019 Airport Traffic Report
Los Angeles	0.707	1.817	2019	https://en.wikipedia.org/wiki/Los_Angeles_International_Airport#Traffic_and_statistics
Shanghai Pudong	0.581	1.494	2019	https://en.wikipedia.org/wiki/Shanghai_Pudong_International_Airport#Statistics
Shanghai Hongqiao	0.349	0.896	2019	60 % of Pudong
Singapore Changi	0.386	0.992	2019	https://en.wikipedia.org/wiki/Changi_Airport#Operational_statistics
Neom (=Dubai)	0.418	1.075	2016	https://en.wikipedia.org/wiki/Dubai_International_Airport#Statistics
Global	38.9		2019	https://www.statista.com/statistics/564769/airline-industry-number-of-flights/
Total 6 hubs	4.4726	11.498		
Anchorage	0.114	0.293	2016	https://dot.alaska.gov/aas/assets/Activity_Summary_Report_current.pdf
Tokyo-Haneda	0.229	0.589	2019	https://www.statista.com/statistics/1242190/japan-to-kyo-haneda-airport landings-number/
Tokyo-Narita	0.35	0.900	2018	https://www.naa.jp/en/airport/pdf/statistics/t2t_030328.pdf
Honolulu - Inouye	0.163	0.419	2018	https://hidot.hawaii.gov/airports/files/2020/08/anua-kai-traffic-statistics-20200804.pdf
Honolulu - Kahului	0.080	0.204	2018	https://hidot.hawaii.gov/airports/files/2020/08/anua-kai-traffice-statistics-20200804.pdf
Chennai	0.178	0.458	2018-9	https://en.wikipedia.org/wiki/List_of_the_busiest_airports_in_India#April_2018_%E2%80%A3_March_2019
Oslo	0.25	0.643	2019	https://www.statista.com/statistics/797473/number-of-aircraft-movements-at-oslo-airport-in-norway/
Lagos	0.1	0.257	2019	estimated from https://www.nigerianstat.gov.ng/pdfuloads/AIR_TRANSPORTATION_DATA_Q2_2019.pdf
Johburg	0.2	0.514	2019	estimated from https://www.airports.co.za/airports/or-tambo-international-aiairport/statistics/airafrf
Lima	0.188	0.483	2019	https://www.lima-airport.com/Documents/Annual%20Traffic%20Stats%20Report.pdf
Rio	0.106	0.272	2019	estimated from https://en.wikipedia.org/wiki/Rio_de_Janeiro/Gale%C3%A3o_International_Airport
Sydney	0.346	0.889	2019	https://assets.ctfa.net/cvts/v228/b5k0x/4VvyuoCb3qhVBggCC/Vh3/5da8f884f3ac895b39M8ea459d50ff/SYD_Annual_Report_2019_FINAL.pdf
Total 10 hubs	2.3035	5.922		
Total 16 hubs	6.7761	17.419		

Table 2 Flights from the selected airport hubs

In the year 2019 (pre-COVID 19), the number of scheduled passengers reached the value of $\leq 4,5$ billion (IATA, 2020, Statista, 2021). Dubai, London and Singapore are three of the leading airports for international air passenger traffic also in the year of 2020 (Statista, 2021).

Total calculated passenger traffic is in the region of: 62.5 million pax in JFK (Airport Traffic report, 2020), 80.9 millions in LHR, 87 millions in LAX, 76 million pax in Shanghai Pudong and 97.3 million in Dubai and finally 68.3 millions of passengers in 2019 at Singapore Changi airport (Statista, 2021). The summary of the traffic serviced through these airports during the period of 2019, is of a total of 472 million passengers, accounting for the 1/5th of total passenger traffic worldwide. Ideally a substantial percentage of this proportion will be serviced exclusively by hydrogen powered aircraft in an inter-hub connectivity approach (for LR international flights) in the first phase of implementation, and subsequently been transported to the desired destination (short haul flights).

7 - HYDROGEN DEMAND, COST AND ANALYSIS:

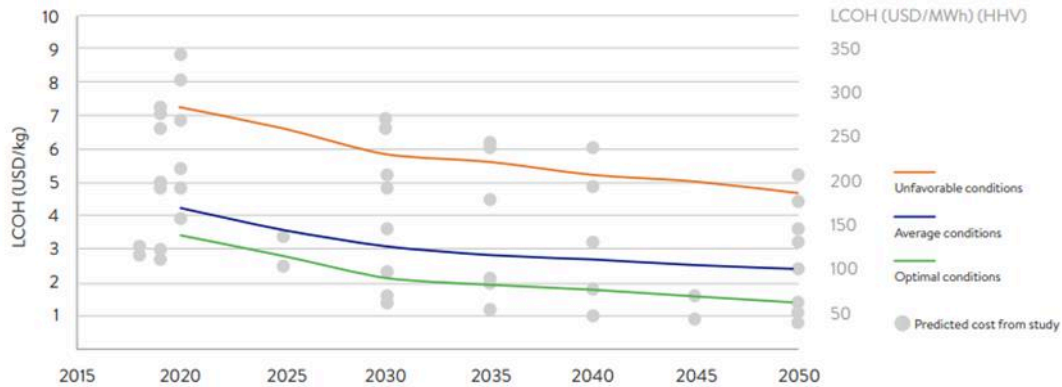
Approximately 95 billion gallons of fuel (~300MT) were consumed in commercial aviation in 2019 (IATA, 2021, ICAO, 2021). Jet fuel price reached 2.32 \$/gallon in 2018 and an average of 1.95\$/gallon in 2019. In 2019 the fuel expenses of commercial aviation have been reported as 186 billion dollars (IATA, 2021).

By 2050, the hydrogen demand for aviation, representing 20% of the sector's need is estimated to be 43Mth₂ (ATAG,2021), coinciding with the figures published in 2020 by CleanSky, giving an approximate of 40Mth₂ as a base in the case of a minimum EIS scenario (CleanSky, 2020). The authors believe (and hope) that this is a great underestimate because by 2050 decarbonisation should be much more significant, including zero tailpipe carbon emissions, to avoid the risk of sector contraction on environmental grounds. Operational costs can only be roughly estimated as energy costs have been constantly reconfigured and adapted to the needs, directly dependent also on the mandating rules that will be imposed and the governmental regulations in place at the respective times.

Additionally, energy cost is directly proportional to the demand and "mass-production" is lowering the costs. Present estimates give hydrogen a price of three (3) to six (6) times higher than jet fuel with production, liquefaction and distribution costs included, dropping to approximately 1.4 to 2.4 times the cost of jet fuel by 2050, according to the projected cost arrangements (ATAG,2021).

In this specific paradigm though, this cost is estimated to be reduced by an approximate of 35% as part of the production cost and the distribution cost will ideally be absorbed by the installation of producing units in the airports situated in coastal areas. In Statista's Green Hydrogen production cost (differing by country according to the facilities available), costs are at a present average of 4,5€/kg and predicted to drop to an average worldwide price of 1.7€/kg by the year 2050.

The same approximate costs are reported in the paper of World Energy Council in collaboration with PwC (PriceWaterhouseCoopers) and EPRI (Electric Power Research Institute) (World Energy Council,2021). It is essential understanding that even though Hydrogen may seem initially more expensive, the significantly reduced CO₂ abatement cost of operation renders it more competitive than presented.



Source: World Energy Council in collaboration with PwC and EPRI, paper: "Hydrogen Demand and cost dynamics", World Energy Council, September 2021
 'Used by permission of the World Energy Council'

There is also a more optimistic approach by the reducing the cost of electrolytic hydrogen to 2.16\$/kg already by the year 2030 (Fuel Cell and Hydrogen Energy Association (FCHEA), 2021). This comes close to the cost of liquid Hydrogen estimated in the project of CleanSky2 placing the total cost of liquid Hydrogen "to nozzle" at 3\$/kg when produced in Europe and 2.60\$/kg when produced in the Middle East (and shipped to EU included) (CleanSky2, 2020).

8 – CONCLUSION

This paper offers an analytical-philosophical scenario, with a feasible implementation of Hydrogen technology in the years to come. The introduction of the mentioned aircraft family, as the first wave of Hydrogen aircraft will be combined with a calculated gradual entry into service in different phases on a timeline from 2035 to 2050. This entry into service on this specific timeline is meant to cover, operationally beneficial geographical locations and airports, aiming to decarbonise effectively already from the first generation of the "Six Hubs" operating on Hydrogen technology. In the following phases, more airports investing in the new technologies will assist in covering a higher percentage over time aiming for an actual "Net Zero" by 2050.

On the first attempt to conceptualize how the traffic will be distributed between the hubs, according to the needs and demands of present air traffic predictions, it has been noted that by conducting the aforementioned "tankering sectors", there is a potential to actually decarbonise a significantly larger number of flights than the one mentioned in the first phase of this paper. A flight dispatching from an airport and executing a "polygonal" or "triple/quadruple sector" cannot be accounted and compared only for the CO₂ emissions saved from the initial airport but a more complex analysis needs to be done, as fuel is saved also from the expected values that it would refuel in the intermediate destinations. So, the aforementioned numbers become approximately double in an optimistic approach, and the facilitated traffic is not sourcing only from the "Six Hubs" but also from the connected destinations. Moreover, tankering strategies may indeed add a very small amount of fuel burned enroute to account for the extra weight carried by the extra fuel (Hydrogen in this example), but this "fuel burn bias" is insignificant if we add to these estimate calculations the CO₂ emissions saved from the avoided refuelling procedures during ground time that would normally take place in the intermediate stops (refuelling trucks emissions on an environmental perspective, plus the advantage of less handling costs associated with refuelling procedures for the operators, and finally the reduced ground time and the carbon taxes saved).

Considering all these, we ideally set the initially supported numbers as the lower boundary of the first phase of De-carbonisation and with the addition of the regional traffic polygonal routes and an efficient planning to facilitate a tankering strategy in place we can aim

for the Higher boundary numbers that will be presented on the next paper together with the accurate numbers of the first planning phase.

The six hubs proposed here cover primarily the Northern Hemisphere and leave a large trans-Pacific gap. For global coverage an extension of the study is planned considering sixteen hubs, these comprise the six listed above plus: Anchorage, Tokyo, Honolulu, Madras, Oslo, Lagos, Johannesburg, Lima, Rio and Sydney.

9 - ACKNOWLEDGEMENT

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10 – REFERENCES

- [1] ATAG, Air Transport Action Group, Waypoint 2050, Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century, second edition, September 2021
- [2] ATAG, Blueprint for a Green Recovery, A sustainable growth plan for building global connectivity following the worst crisis in aviation history, September 2020
- [3] BBC - <https://www.bbc.com/future/article/20190909-why-flight-shame-is-making-people-swap-planes-for-trains>; accessed 23 Sept 2021
- [4] Carnegie Endowment <https://carnegieendowment.org/sada/83975> accessed 23 Sept 2021
- [5] CleanSky2 JU & Fuel Cells and Hydrogen 2 JU, prepared by McKinsey & Company, Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050, First Edition, May 2020
- [6] Cryoplane Project, EU Press Release, Meeting the challenges in aircraft emissions: Commission looks into clean alternatives to fossil fuel –2002, https://ec.europa.eu/commission/presscorner/detail/en/IP_02_769
- [7] Enable H2 Website - <https://www.enableh2.eu/> accessed 11th April 2020
- [8] EU Parliament <https://www.europarl.europa.eu/factsheets/en/sheet/126/tourism>, accessed 23 Sept 2021
- [9] European Commission, Flightpath 2050 Europe's Vision for Aviation Maintaining global leadership and serving society's needs Report of the High-Level Group on Aviation Research, European Union 2011
- [10] Goldberg C, Nalianda D, Singh R, Pilidis P; (2017) Turbo-electric Distributed Propulsion (TeDP) Vehicle Study, including Techno-economic, environment and risk analysis (TERA) Final Research Grant (NNX13AI78G) Report to NASA, Cranfield University (Confidential)
- [11] Goldberg C (2018) Techno-economic, Environment and Risk Analysis of an Aircraft Concept with Turbo-electric Distributed Propulsion, Doctoral Thesis, Cranfield University
- [12] Goldberg C, Nalianda D, MacManus D, Pilidis P & Felder J (2018) Method for simulating the performance of a boundary layer ingesting propulsion system at design and off-design, Aerospace Science and Technology, 78 (July) 312-319.
- [13] Huete, J; Nalianda, D, Pilidis, P. Propulsion system integration for a first-generation hydrogen civil airliner? The Aeronautical Journal, ISABE Special Issue 2021, DOI: <https://doi.org/10.1017/aer.2021.36>

- [14] Huete, J; Pilidis P. Parametric Studies on Tank Integration for Hydrogen Civil Aviation Propulsion. Paper under review in International Journal of Hydrogen Energy, 2021.
- [15] Huete, J et al; Impact of Tank Gravimetric Efficiency on Propulsion System Integration for a First Generation Hydrogen Civil Airliner, Under Review ISABE 2022
- [16] IATA, Economic Performance of the Airline Industry, December 2019
- [17] IATA, Industry Statistics Fact Sheet, October 2021
- [18] IATA, FlyNetZero, Net zero carbon 2050 resolution Fact sheet, 2021
<https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/>
- [19] ICAO, 2019 Environmental Report Aviation and Environment, 2019
- [20] Lufthansa, <https://www.lufthansa.com/us/en/388> , accessed 20 April 2020
- [21] Nalianda D (2012) Impact of environmental taxation policies on civil aviation - a technoeconomic environmental risk assessment, Doctoral Thesis, Cranfield University
- [22] Nalianda,D; Goldberg, C; and Mastropierro, F; Hermes / Orion aircraft performance and propulsion system integration model, Cranfield University Manual (2020)
- [23] Nikolaidis, T; TURBOMATCH– Gas Turbine Performance Simulation –User Manual, unpublished, Cranfield University 2017
- [24] Parker, RJ and Pilidis, P; The Light Beyond the Clouds, The Aeronautical Journal , Volume 125 , Issue 1291: The 25th ISABE Conference special issue , September 2021 , pp. 1467 – 1468 DOI: <https://doi.org/10.1017/aer.2021.81>
- [25] Pickard, S. and Gençsü, I. (2021) ‘The Airport Tracker: uncovering aviation emissions’. ODI policy brief. London: ODI (www.odi.org/en/publications/the-airport-tracker-uncoveringaviation-emissions).
- [26] Schafer, AW; Barrett, SRH; Doyme, K; Dray, LM; Gnadt, AR; Self, R; O’Sullivan, A; Synodinos, AP; Torija; Technological, Economic and Environmental Prospects of All-electric Aircraft. Nature, Article No 15020 | DOI:10.1038 – 11 January 2016
- [27] Statista <https://www.statista.com/statistics/262971/aircraft-fleets-by-region-worldwide/> accessed 23 Sept 2021
- [28] Statista, Air Transportation Worldwide - dossier, 2021/ accessed January 2022
- [29] UNPRI <https://www.unpri.org/inevitable-policy-response/what-is-the-inevitable-policy-response/4787.article>; accessed 23 Sept 2021
- [30] Visual Capitalist <https://www.visualcapitalist.com/countries-reliant-tourism/> accessed 23 Sept 2021
- [31] World Energy Council (in collaboration with PwC & EPRI), Working Paper: Hydrogen demand and cost dynamics, September 2021

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