Liquid Hydrogen Powered Commercial Aircraft

Analysis of the technical feasibility of sustainable liquid hydrogen powered commercial aircraft in 2040

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Preface

This report was written for the Space for Innovation competition organized by VSV 'Leonardo da Vinci', KLM (Royal Dutch Airlines) and Space Expedition Curacao (SXC). The competition is split up in two rounds with over 170 participants in the first round. A 500 word essay about an innovative concept that will change the aerospace world in 2040 was the initial requirement. Ten of these candidates were chosen to continue to the second and final round, including myself. The second and final assignment was to deliver a report of ten pages in which the concept is fully analyzed and elaborated upon. Detailed information about this contest and its requirements is found on the website: http://www.spaceforinnovation.nl. Furthermore the deliverables for the final phase also included a three minute filmed pitch, explaining the concept for the general public. One month was given for the ten finalists to complete and deliver both the report and film.

Abstract

The year 2040 is a realistic year to see liquid hydrogen powered aircraft transport passengers around the world. The properties of hydrogen, especially the lack of carbon emissions, are very promising and advantageous. Liquid hydrogen contains 2.8 times more energy than aircraft kerosene per kilogram. This means that for the same energy value great weight savings can be made. Furthermore the burning of hydrogen in aircraft engines produces no carbon dioxide and up to 80% less nitrogen emissions. With the environment and climate in need of urgent protection, hydrogen provides great benefits. Hydrogen is also one of the most abundant elements on the planet making it a renewable energy source without foreign dependance. The purpose of this report is to analyze the technical feasibility of using liquid hydrogen in aircraft. It will also look at the needed production and transport infrastructure required to make it affordable.

One of the reasons hydrogen is not used today is due to the much higher cost than using fossil fuels. As opposed to fossil fuels, hydrogen is not found but must be produced. Nearly all current production techniques use polluting fossil fuels and will therefore not contribute to a sustainable solution for air transport. Sustainable and environmentally friendly production processes including photolysis, electrolysis and biomass gasification are being developed and will produce 'green hydrogen' within the coming decades. Furthermore Munich Airport has built and proven, on a small-scale, that a hydrogen based infrastructure at an airport can run efficiently and affordably. Combined with innovative and currently working solutions for the transport of hydrogen a smooth transition to liquid hydrogen compatible airports and aircraft is expected during the period from 2025 to 2040. Twenty to thirty years will be needed to build prototype aircraft that can fully test a liquid hydrogen fuel and powerplant system. Overall there are two main requirements for successful implementation of this concept: the aircraft and airport must work on liquid hydrogen and the total cost must not be any higher than flying on kerosene. Given the diminishing fossil fuel reserves and expected advances in hydrogen technology the total cost of hydrogen is expected to become cheaper than kerosene by 2037. This will make liquid hydrogen powered commercial aircraft not only better for the environment but also an economically sustainable solution for airlines around the world.

Nomenclature

A/C	Aircraft	
APU	Auxiliary power unit	
C	Degrees centigrade (celsius)	
CO	Carbon monoxide	
CO_2	Carbon dioxide	
CSP	Concentrated Solar Power	
FL	Flight level	
GW	Gigawatt	
GWP	Global Warming Potential	
H_2	Hydrogen	
H_2O	Water vapor	
HP	High pressure	
K	Degrees kelvin	
kJ	Kilojoule	
kWh	Kilowatt hour	
IAE	International Aero Engines AG	
ICAO	International Civil Aviation Organization	
ISA	International standard atmosphere	
LH_2	Liquid hydrogen	
LP	Low pressure	
NO_X	Nitrogen oxides	
M_O	Mach number	
MPa	Megapascal	
SFC	Specific fuel consumption	[kg/Ns]
SEC	Specific energy consumption	[kJ/Ns]
SO_2	Sodium dioxide	
T/O	Takeoff	

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1. Introduction

With fossil fuels estimated to run out by 2040 and global warming becoming a growing issue the search for an alternative fuel for transport is of the utmost importance. A sustainable, environmentally friendly and affordable solution must be found to fuel the aerospace industry for the coming decades. Liquid hydrogen (hereinafter: LH2) has been of interest to the industry for nearly thirty years. LH2 is a type of cryogenic liquid, which are liquids that exist only at extremely low temperatures. In the 1980s the russian aircraft producer Tupolev experimented with the use of LH2 in their aircraft. A Tupolev Tu-155 was rebuilt to run on the cryogenic fuel and proved that LH2 can produce sufficient thrust to power a commercial aircraft [1]. Due to the extremely high hydrogen production prices present at that time, the project was unfortunately discontinued. The Tupolev study however did shed light on the great chemical properties of hydrogen. LH2 contains 2.8 times more energy than kerosene per unit mass and hence will save on aircraft weight. For the aerospace industry this is a great property as lightweight solutions are always highly preferred. On the other hand LH2 has very low energy density per unit volume meaning that for the same amount of energy LH2 will need four times more volume than kerosene [2]. Furthermore it must be noted that hydrogen boils at around minus 250 degrees celsius and hence must be kept at near absolute zero temperatures to avoid boil off (evaporation of LH2 into gaseous hydrogen) [2].

Figure 1: The Tupolev Tu-155 required a large tank (blue in illustration) to store the hydrogen fuel [1]

The purpose of this report is to investigate the technical feasibility of a LH2 propelled commercial aircraft. Whilst examining the technical challenges of a hydrogen aircraft, sustainability and environmental impacts will be assessed as well. In order to be the industry changing technology in aerospace by 2040, liquid hydrogen powered commercial aircraft and airports must must be compatible with the fuel and the fuel itself must be produced in a sustainable and affordable manner. Hence the scope of the report covers not only the operation of a hydrogen powered aircraft but also the production, transport and cost of such an airplane. The paper starts with looking at solutions to sustainably produce hydrogen and subsequently transporting it. Airport solutions, aircraft design and safety are then analyzed and finally a study is done into possible transition markets and the total costs of the project. The key challenges in this project are producing hydrogen without the emission of greenhouse gases in an affordable manner as well as creating appropriate aircraft systems and airport operations designed for safe operation of a liquid hydrogen commercial aircraft.

2. Sustainable Production

Unlike fossil fuels hydrogen must be produced in one of several processes currently used. In the United States approximately 500 billion cubic meters of hydrogen are already produced annually of which 96 percent is done using fossil fuels [3]. Current production of hydrogen, although affordable, is not sustainable nor environmentally friendly. Three innovative solutions to produce hydrogen sustainably and without carbon emissions are being developed.

2.1 Electrolysis

Electrolysis is a relatively simple process where electricity is passed through a liquid by placing two electrodes in the liquid and running direct current (DC) across them [4]. The result is the separation of oxygen and hydrogen molecules of the water used in the process. An advantage is that it produces hydrogen of high purity (over 99.99%) which leads to better performance during combustion in jet engines. The key to this process is the origin of the electricity used. If this was generated using carbon-based fuels, greenhouse gases will have been emitted during production making the entire process not environmentally friendly. Wind and solar power offer a good alternative sustainable solution to generating the electricity needed for electrolysis. A hundred percent efficient electrolysis process requires 39 kWh to produce one kilogram of hydrogen. Currently efficiencies up to eighty percent have been reached, a number likely to grow in the future [5]. Wind power resources in the United States today produce over 2800 GW, which is enough for 150 billion kilograms of hydrogen per year [6]. However the construction of wind turbines can be expensive and the availability of wind is never certain. Hence a better solution is to directly use the sun in a process called solar conversion.

2.2 Solar Conversion

Solar conversion contains two sustainable solutions to the production of hydrogen which are thermolysis and photolysis. Thermolysis uses heat produced from concentrated solar power (CSP) to drive electrolysis described in the previous section. As CSP is a renewable energy source and electrolysis produces no greenhouse gases in the process hydrogen can be produced without harming the atmosphere. New solar technologies are currently being developed that can yield up to thirty percent efficiency [7] making thermolysis a promising solution.

The second renewable solution using the sun as energy source is photolysis. Here solar photons are used to produce hydrogen using cyanobacteria or green algae in a biological process creating hydrogen [8] (process shown in figure 2). The great advantage of this solution is that no carbon-based molecules are emitted, hence not polluting the environment, and that it is a completely natural process. Further research and development is needed in this area before it can be used to mass produce hydrogen for air transport.

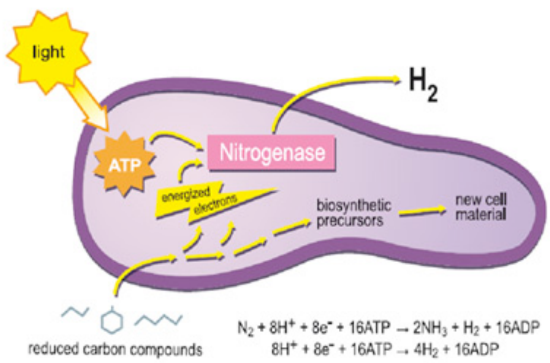

Figure 2: Diagram showing the basics of photolysis to produce hydrogen [8]

2.3 Biomass Gasification

Biomass gasification is another solution to producing hydrogen and offers a much greater economic benefit than electrolysis and solar conversion. Substantial research has already been done into biofuels including several successful commercial flights on biofuels with KLM [9] and Lufthansa [10]. Biofuels will therefore certainly play a great role in powering commercial aircraft in the coming decades. The same technology can be applied to a similar process that can produce hydrogen affordably.

During the process biomass is subjected to high temperatures and pressures in order to reduce the organic materials to hydrogen and subsequent carbon- monoxide and dioxide gases. These are then separated with membrane, chemical or catalytic steps [6]. Although some carbon emissions are created, the process is affordable and could realistically be feasible in the short-term. Furthermore an alternative method, also using biomass, is currently being developed in which the organic material is converted to bio-oil via pyrolysis followed by catalytic steam reforming of the liquid to produce hydrogen [6]. The great advantage of this method is that the bio-fuel has a very high energy density and thus can easily be transported to another site, near to the airport, where it is processed into liquid hydrogen.

2.4 Further Research and Development

Further research and development is needed into wind and solar power technologies. In order to use its power to drive electrolysis, wind and solar power technology will need to become much more efficient. Furthermore research and experimentation is also needed with the photolysis and biomass gasification methods as the exact process is not yet fully sustainable and economically viable. With further research the efficiency of these processes would increase, decreasing the total production price. As hydrogen is also required for industrial use and potentially in other automotive sectors by 2040 a combined effort for sustainable and renewable large-scale production of liquid hydrogen could further decrease the production price of hydrogen.

3. Hydrogen Transport

Hydrogen can be transported in both gaseous and liquid state. For both several solutions are already present and working. For example Germany already has 50 kilometers of safely working pipelines that transport gaseous hydrogen at a pressure of 2 MPa without an incident in the last 50 years [2]. A similar infrastructure can be built for the transport of hydrogen to airports. To transport hydrogen in liquid state high pressure and well insulated composite cylinder tanks would be used to insulate the cryogenic liquid. Air Liquide already has some working products for the transport of hydrogen in both gaseous and liquid state. The firm has a working infrastructure of 880 km hydrogen pipelines in northern europe for industrial use (red lines on figure 3) [11].

Figure 3 Northern Europe hydrogen transport infrastructure (red pipes)

Furthermore an innovative solution is emerging which could allow for faster transport of more hydrogen. The new technology allows hydrogen to be stored in solid form inside a chemical called sodium borohydride which is much denser than liquid hydrogen [12]. The great sustainable aspect is that when extracting the hydrogen to refuel an aircraft the chemical returns back to borax, the compound from which it is originally produced. As a result it is fully recyclable and therefore can be reused for further transport of hydrogen. Equation 3.1 [13] shows the chemical reaction that converts the sodium borohydride into the hydrogen used as a fuel and the borax that can then be recycled.

$$\mathrm{NaBH_4} + 2\ \mathrm{H_2O} \rightarrow 4\ \mathrm{H_2} + \mathrm{NaBO_2} + \sim 300\ \mathrm{kJ} \qquad 3.1$$

Further research is needed into this chemical solution however it already looks promising and should be technically feasible by 2040. Important to take into consideration is the probable transition to hydrogen power in other automotive industries as well. If cars, buses and other transport vehicles transition to liquid hydrogen as a power source a combined effort can result in a shared transport infrastructure decreasing the total costs and increasing the operating efficiency.

4. Airport Operations and Aircraft Design

4.1 Airport Operations and Safety

Given the cryogenic nature of liquid hydrogen (LH2) changes are required to airport operations. Because not all aircraft are going to change to LH2 overnight it must be kept in mind that during the transition period the airport must be able to handle both LH2 as well as kerosene aircraft. Most large airports have onsite kerosene fuel storage tanks. Similar tanks will need to be built to store LH2 below 25 degrees Kelvin. The easiest solution is to subsequently deliver the fuel to the aircraft via a well insulated refueling truck. Special care must be taken for airport vehicles servicing LH2 powered aircraft. A small leak of hydrogen into the air can occur and hence safety regulations must be adapted to ensure the small portion of hydrogen in the air is not ignited. For example airport service cars with spark ignition engines might pose a danger. An ideal solution would to convert all airport vehicles to hydrogen fuel cell cars, a technology most likely affordable by 2040 [14]. In fact Munich Airport has an ongoing project to power ground vehicles such as passenger busses by liquid hydrogen. Already more than 350,000 km have been covered by hydrogen powered buses at Munich Airport, driven by an efficient infrastructure directly at the airport [15]. The first public hydrogen filling station was built directly at Munich Airport and is found to run efficiently and competitively [16].

4.2 Installation of Fuel Tanks

Aircraft design will change depending on the size and type of airplane. Airbus completed extensive research in 2003 on aircraft design for liquid hydrogen [14]. For the medium range category the solution of installing tanks on top of the fuselage was found most efficient regardless of the 9 to 14% energy loss due to the extra bulky fuselage. This is made up for by the great specific weight properties of hydrogen, as it is substantially lighter than kerosene.

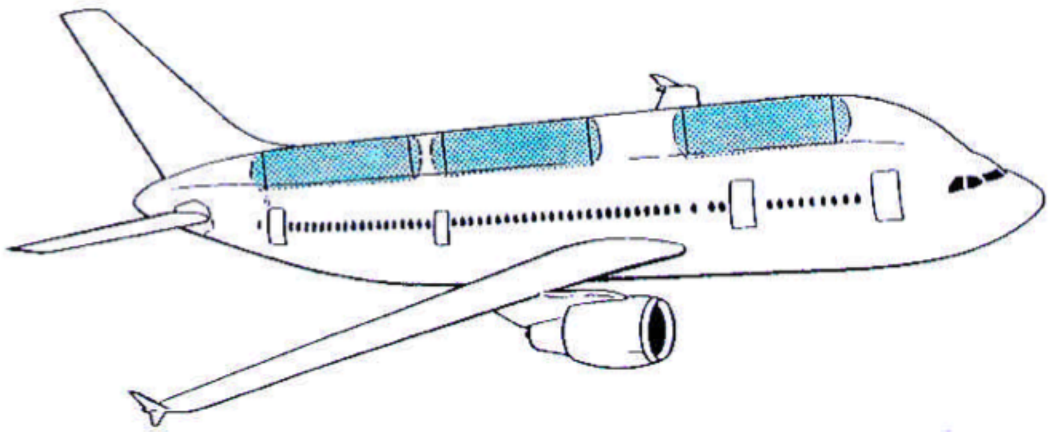

Figure 4 Airbus proposed tank installation for short/medium range aircraft [16]

Liquid hydrogen must be kept at extraordinary low temperatures and can therefore not be stored in the wings. Due to the large surface area the hydrogen will be very difficult to insulate. Furthermore hydrogen takes up four times more volume than kerosene for the same energy value and thus the space within the wing is insufficient. Placing the tanks above the passenger cabin, evenly spread out to avoid aircraft imbalance, is the most efficient solution. For very large aircraft, such as the Airbus A380, two large tanks could be installed just behind the cockpit and in the far aft of the passenger cabin without changing fuselage shape. With the solution presented in figure 4 the amount of passengers and cargo the aircraft can transport is only decrease a little due to the slightly lower maximum takeoff weight [2].

4.3 Fuel Supply System

Due to LH2 properties the fuel supply system requires a redesign from conventional kerosene systems. Similar to conventional aircraft a feed tank will be installed for each respective engine, within the aircraft wing. All fuselage fuel tanks will feed liquid hydrogen to the separate engine feed tanks keeping them filled. From the engine feed tank liquid hydrogen is passed through high pressure pumps and a subsequent heat exchanger. The heat exchanger is needed to heat liquid hydrogen at 20K to gaseous hydrogen at 150K after which it is injected into the combustion chamber of the engine [14]. Heat from the engine itself can be used for the heat exchanger to increase the temperature of the hydrogen. Experimentation shows that a return line from the engine to the feed tank is required to avoid high pressure fluctuations and cavitations in the engine fuel lines [14].

The engine specific fuel system is shown on figure 5 in purple. Both feed tanks consist of three low pressure pumps, two of which are active, the third running in standby. Furthermore a jet pump is installed to facilitate the filling of the feed tank with fuel from the remaining fuel tanks. The blue fuel lines belong to the fuel transfer system facilitating the filling of the feed tanks and possible cross-feed in case of fuel imbalance. The red pipelines allow for refueling of all tanks at the gate. The refuel connection is installed near the nose of the aircraft where a connection is made to the refuel truck. The orange lines found in the aft section of the fuselage correspond to the APU fuel system and the green lines facilitate fuel dumping in the case it is necessary. All valves and pumps will be controlled automatically or by the pilots via a panel in the cockpit.

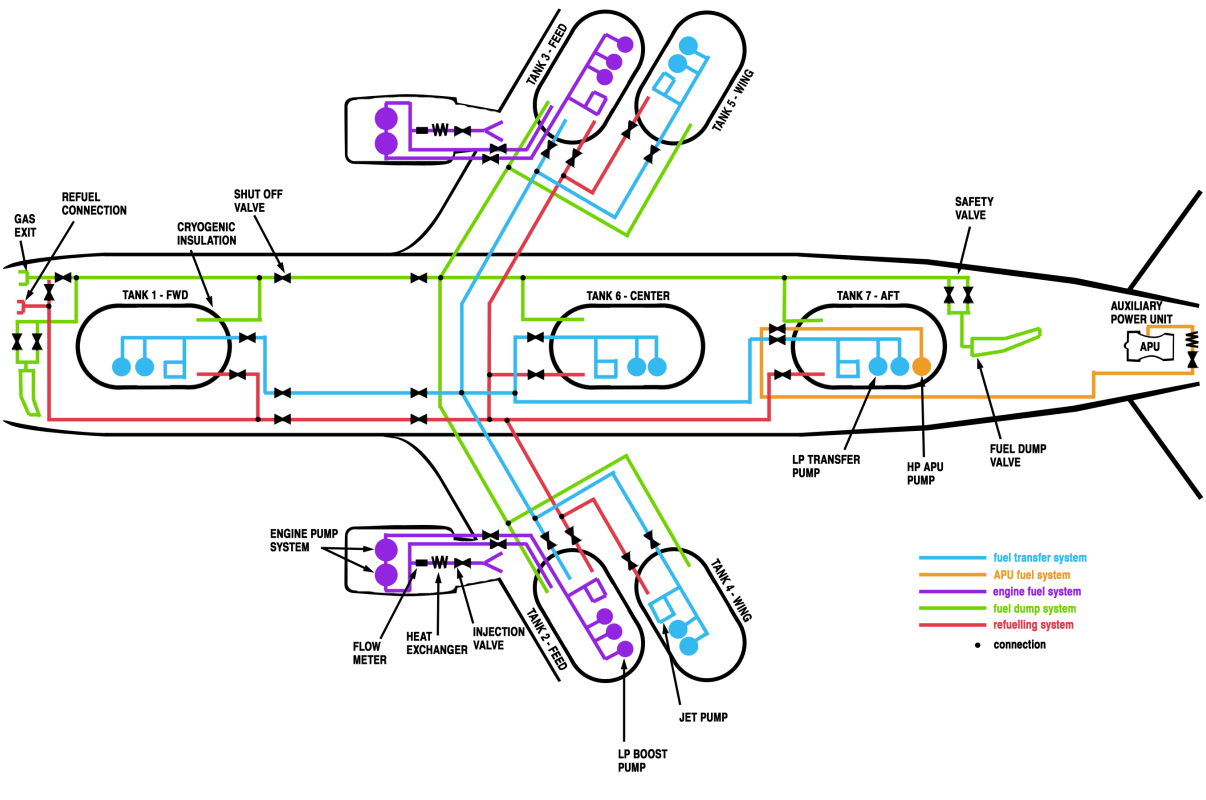

Figure 5 Possible fuel supply system for an Airbus A300 with liquid hydrogen [14]

Due to the differences between a LH2 and kerosene fuel supply system it will be necessary to build a mockup system to throughly test the different components. After successful experimentation the system should not be installed in a prototype aircraft immediately. Given that the auxiliary power unit (APU) is not a flight safety item a LH2 powered APU and respective fuel tank should be installed first in an aircraft such as the Airbus A320 with subsequent inflight testing to see the behavior of liquid hydrogen during a real flight. The next step is to take an aircraft with four engines, for example the Boeing 747, and replace one engine with a LH2 powered counterpart. The subsequent fuel system components are then to be installed after which test flights will show the performance of a LH2 powered engine and its supporting fuel system. The reason for replacing only one engine is that in the case of failure, three kerosene powered engines remain functioning to continue flying the aircraft safely. Once engine performance experimentation is completed the final step is to convert a complete aircraft to be powered by liquid hydrogen and conduct a full-scale inflight test of the system.

4.4 Liquid Hydrogen Powerplant

Cranfield and Madrid Universities have conducted several experiments on jet engines including the V2527-A5 engine, a turbofan built by International Aero Engines for the Airbus A320 family. Two identical turbofans were used, powered by kerosene and hydrogen respectively. During the experiment they are run at equal thrust levels to compare the performance. Table 1 shows the positive results of the test.

Table 1 Comparison of hydrogen and kerosene fuel performance [17]

V2527-A5 (BASELINE ENGINE) AT SEA LEVEL STATIC, ISA+10C: OPR= 28.5, FOPR = 1.70, BPR = 4.8 Length = 3200 mm, Diameter = 1612 mm, Weight = 2370 kg				
	SEA LEVEL STATIC, ISA+10C		CRUISE, 11 km Mo=0.8, ISA	
	kerosene	H_2 (T_{fuel}=250K)	kerosene	H_2 (T_{fuel}=250K)
F_n (kN)	117.78	117.78	22.53	22.53
SFC (g/kNs)	9.6399	3.4077	16.5837	5.8898
W_2 (kg/s)	355.61	355.61	136.00	136.03
W_{fuel} (kg/s)	1.1354	0.4014	0.3736	0.1327
TET (K)	1472	1438	1288	1264
SEC (kJ/kNs)	415.48	408.92	714.76	706.78
SFC_{CH}/SFC_{H2}	2.829		2.816	
SEC_{CH}/SEC_{H2}	1.016		1.011	
*Engine data comparison, for V2527-A5, when working with kerosene and hydrogen. Engine is running at the **same thrust** for both fuels. External heat exchanger assumed when using H_2.*				

The hydrogen powered engine has a much lower specific fuel consumption meaning a significantly lower fuel fraction (the fraction of total aircraft weight that is aircraft fuel. A lower fuel fraction allows the payload weight to be increased or aircraft range to be extended). Hence even though the operational empty weight of the aircraft increases by approximately 23 percent due to the added hydrogen fuel tanks [14] this is compensated by a decrease in fuel weight. As a result using liquid hydrogen should only have a small impact on the amount of payload that can be transported subsequently not hurting the profitability for the operator.

5. Sustainability and Safety

5.1 Emissions and Cruise Flight level

There are two reasons for switching to liquid hydrogen. One of them is the running out of oil and subsequent need for a new fuel, the other reason is to limit the carbon footprint of the aviation industry. Hydrogen does just that. Combustion of hydrogen emits zero carbon dioxide gases and up to 80% reduction in nitrogen oxide emissions compared to kerosene. A slight increase in water vapor is emitted [2].

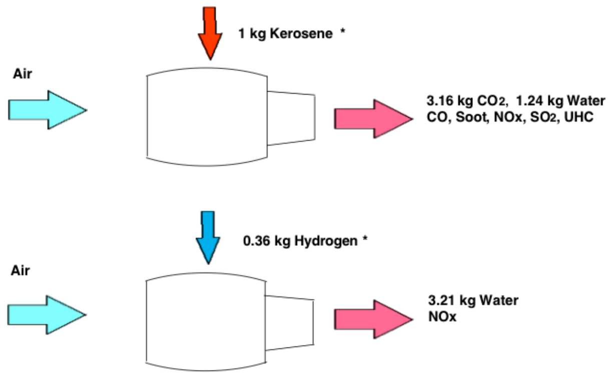

Figure 6 Comparison of emissions for kerosene and hydrogen of equal energy content [16]

Aircraft contrails are created due to water vapor and can harm the atmosphere. The damage it does depends on the altitude at which the contrails are created. For conventional aircraft the difference with respect to flight level is not very large as seen in figure 7. However for hydrogen powered aircraft decreasing the flight level from 390 to 350 cuts the effect of water vapor emissions by two thirds.

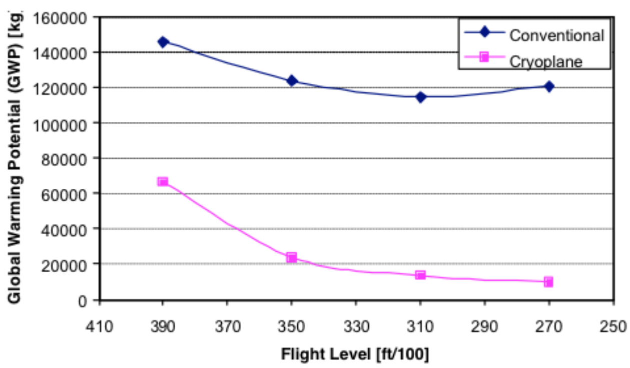

Figure 7 Effect of cruise flight level on GWP for both aircraft [14]

Hence to further decrease the impact of hydrogen powered aircraft on the environment, regulations need to be changed with respect to hydrogen cruise flight levels. For conventional aircraft it is normal to fly at cruise levels of 390. Hydrogen aircraft will need to fly at 350 or less for the largest environmental benefit, although even at current levels of 390 they are significantly better than conventional aircraft.

5.2 Safety of Hydrogen Engines

Research by Airbus and other companies shows that hydrogen aircraft are just as safe as kerosene and no large regulatory actions need to be taken due to the new fuel. Given the installation of hydrogen tanks above the passenger cabin and the fact that the gas is lighter than air will mean that any leaked gas will rise up, immediately away from the aircraft. Furthermore the combustion of hydrogen occurs at concentrations significantly below the detonation limit and will not produce any toxic gases in the process [16].

6. Transition Markets and Costs

Four factors will influence the time frame for the transition to hydrogen. The future cost of liquid hydrogen, advances in hydrogen technologies, potential long-term international restrictions on aircraft emissions and the cost of kerosene. As long as kerosene remains cheaper than the production of hydrogen the chances of seeing a large transition are small. With oil prices rising and advances in hydrogen technologies pushing down its price it is estimated to see a cross-over around 2037 [14] after which the production of hydrogen will be cheaper than that of kerosene. This date may be shifted forward if regulatory actions are taken by governments in the form of carbon taxes or hydrogen subsidies. The majority of airlines will not freely transition to hydrogen if it does not provide any economic benefit over kerosene. Furthermore by sharing the hydrogen infrastructure with other modes of transport and industries the cost for the aviation sector may decrease. By 2037, as LH2 aircraft do not suffer from carbon taxes and hydrogen becomes cheaper to produce, little increase should be seen in ticket prices. Passengers should be able to fly at the same price.

A case study has been done on the potential of transitioning to liquid hydrogen in Sweden. The study, conducted by Cranfield University, looks at Scandinavian Airlines (SAS) specifically for a possible transition scenario. The national carrier operates around 70% of Swedish domestic air traffic [18]. As Stockholm's Arlanda is the airline hub almost all domestic flights pass through the airport and hence LH2 refueling facilities could most effectively be installed at this airport. SAS' fleet is expected to rise in future decades as a result of an increase in passengers. As older aircraft phase out and retire these will be replaced by liquid hydrogen powered jets that fly within the domestic SAS network by refueling in Stockholm. Once the fleet increases, LH2 refueling facilities will be installed at other swedish airports to increase flexibility for the airline. With a domestic network in mind the size of these hydrogen aircraft is in the small to medium range ranging between 150 and 220 passengers. Figure 8 shows one of many transition scenarios looked at in the case study and assumes that all aircraft introduced from 2025 are hydrogen fueled. Although some aircraft may remain flying on kerosene by 2040, the majority of aircraft should be flying on liquid hydrogen.

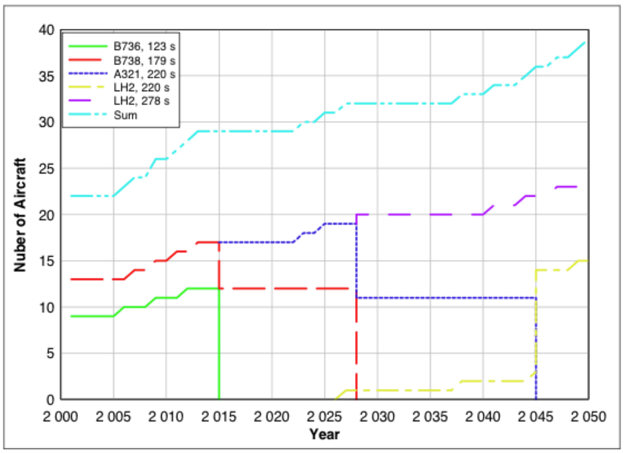

Figure 8 Possible transition scenario for SAS Swedish domestic fleet [18]

Another sector that could see the transition earlier than others is the United States Air Force (USAF). Given the heavy reliance on oil from outside american borders hydrogen looks very appealing. Hydrogen is one of the most abundant elements in our planet [2] and hence a transition to a LH2 powered Air Force would significantly decrease foreign reliance. Furthermore it is difficult to fully quantify the costs of the complete research, development and transition to LH2 powered aircraft. The aerospace industry is known for its high research and development (R&D) costs and, similar to past R&D projects, financial assistance from governments will be needed. If the USAF shows interest in LH2 powered military aircraft, United States (US) financial aid could lessen the economic burden on aircraft producers in developing a LH2 prototype aircraft. Therefore a possible entry market could be the US, starting with LH2 powered military aircraft only to continue and build liquid hydrogen powered commercial aircraft for the US domestic and international fleet.

7. Conclusion

The technical feasibility of cryogenic liquid hydrogen powered commercial aircraft is not in question. By 2040 it will definitely be possible, in fact it can already be done today. What is crucial is to produce hydrogen in a sustainable and economically viable way without harming the environment. This is the greatest bottleneck at the moment but one that is likely to be overcome by the year 2040. With new solar power technologies emerging, photolysis and electrolysis should become much more efficient and cheaper. Furthermore with current ongoing research into biomass and their use as fuels biomass gasification is another, potentially cheaper, production method that could produce hydrogen without a carbon footprint by 2040.

Munich Airport has built and proven, on a small-scale, that a hydrogen based infrastructure at an airport can run efficiently and competitively. Combined with innovative and current working solutions for the transport of liquid hydrogen a smooth transition to liquid hydrogen based airports is expected during the period from 2025 to 2040. Research and development for at least 10 to 15 years will be needed to build and test a prototype aircraft with working and efficient liquid hydrogen fuel system and engines. 2030 is a realistic year to see a small to medium range aircraft fully powered by hydrogen fly for the first time.

With carbon emissions fully cut and nitrogen oxides decreased by up to 80% the use of hydrogen provides great environmental benefits whilst being just as safe as conventional kerosene based aircraft. Some further research is needed into the remaining water vapor emissions and effect of aircraft cruise altitude. With fossil fuels expected to completely dry out by the end of the century it is essential to find a new fuel for not only the aerospace sector, but also other automotive industries. With hydrogen technologies becoming more and more efficient and the added cost-benefit of a shared infrastructure with the automobile and industry sectors the use of liquid hydrogen can be made affordable and technically feasible in the coming 20 to 30 years.

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