Production, Storage, Usage, Design, Economic and Emission Study for Hydrogen Powered Aircraft

Course: Emissions
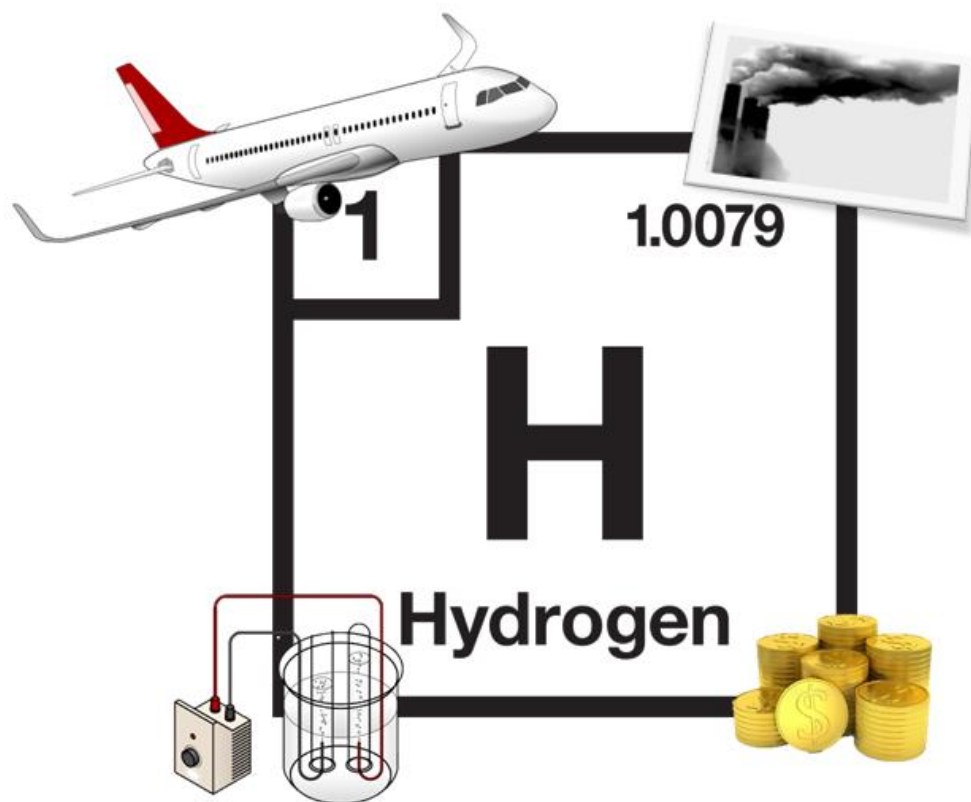
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1   Introduction

Aircraft usage has consistently increased over its history and continues to do so progressively faster. 3.8 billion passengers travelled in 2016 and the number is expected to double over the following 20 years. [1] Meaning a 4-5% traffic increase per annum prediction. As 2/3 of the aircraft produced will serve additional traffic and only 1/3 will replace old aircraft, manufacturers (both of airframes and engines) have a very strong interest in such continuing growth.

While the saturation of worldwide air traffic is still far away, the consequences of it is reaching a limit in environmental terms. Additionally, in this growing industry, the energy consumption is one of the main considerations both for its economic cost and environmental concerns. About 3% of total fossil fuel usage corresponds to consumption in aviation, where 80% of it is done by civil aviation. This links to 3% of total CO_2 emissions, of which this is emitted at high altitude.

As such, a major effort of improving fuel efficiency of aircrafts has been under way. Not only in modifying existing aircraft, but also in the design of more efficient ones. Especially considering the longer the range of the transportation, the higher importance of reducing fuel consumption.

The Advisory Council for Aviation Research and Innovation in Europe (ACARE) was created in order to improve the Strategic Research Agenda in accomplishing the targets of Vision 2020 and announced in 2001 the intent of reducing:

- Fuel consumption and CO_2 emissions by 50%
- NO_X emissions by 80%
- Perceived noise by 50%

per passenger kilometer in relation to the capabilities of new aircraft in 2000.

In addition, the long term aim of Flightpath 2050 increases the previous values to 75%, 90% and 65%, respectively. Not only that, but removing emissions when taxiing.

For all these reasons an alternative to fossil fuels is increasing in demand, especially considering their non-renewability. Therefore, new ways to store and produce energy that can be used in aircraft needs to be considered. This project will focus on the viability of using hydrogen as a method of providing energy to aircraft, from the methods available for its creation and storage, to its use in propulsion, such as combustion and turbines. Additionally a comparison in emissions between hydrogen and kerosene will be presented.

2   Hydrogen Production

Hydrogen is found in many substances in nature. It is most abundant in the water (sea water, rivers, lakes, rain water…), but it also exists in fossil fuels, organic material and in many other compounds. Despite that, it can rarely be found in nature in gas form. It's extracted by separation from its source. Next it is purified, pressurized and storage in tanks.

According with [12] it is estimated that "industrial plants produce about 55 million metric tons of hydrogen globally each year, with its increasing demand of 5% per year". There are many different methods of production of pure hydrogen in the gas form. Nowadays, the principal method is the steam reforming, abbreviated SR, of natural gas. A method that is less, but often used is the higher hydrocarbon reforming from refinery-chemical industrial off-gases. Other methods include coal gasification, water electrolysis and many others which are almost never industrially used.

This chapter is dedicated to explore the main methods of hydrogen production. Due to the chemical complexity of these methods only SR and Electrolysis will be described. However, it is made a comparison of these and other production methods in the following sections. The comparisons are made in various perspectives which include production efficiency, environmental impacts (see chapter "Emissions Study") and from an economical point of view.

2.1   Hydrogen production by natural gas steam reforming

Steam reforming is the present main technology and one of the most economical way of producing hydrogen. Usually this process uses natural gas as feedstock. There are others feedstocks used like methanol, Liquefied petroleum gas... The feedstock is chosen based on the intended end result, its chemical properties and global economy of the process (e.g. feedstock price). Being the most used way of hydrogen production, it is important that induces the least CO_2 emission of all industrial scale processes available at present.

This method can be divided in 7 units (figure 1):
- Pre-treatment unit (Desulfurization- figure 1)
- Pre-reformer
- Reformer
- High temperature water-gas-shift (HTWGS)
- Low temperature water-gas-shift (LTWGS)
- Hydrogen Purification

In the pre-reformer the high hydrocarbons are converted into carbon and methane oxides and have a temperature between 673 and 823K.

Next, these products are normally heated and their temperature rises up to nearly 1073K. The objective is reducing the risk of carbon formation from thermal cracking of the fuel before it reaches the reforming catalyst bed.

During steam reforming hydrocarbons are catalytically split in the presence of steam at high temperatures. Usually, the split occurs with the assistance of a nickel catalyst. During the catalytic split is produced syngas (hydrogen and carbon monoxide). The basic equation is

$$C_nH_m + nH_2O \rightarrow nCO + (n + m_2)\ H_2$$
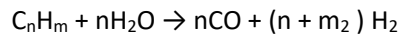
The carbon monoxide that is obtained is converted into additional hydrogen through a WGS reaction. This reaction has two catalytic stages: the first one with a high temperature shift (HTS) and the second with a low temperature shift (LTS). Carbon monoxide from the syngas is transferred according to the next equation into carbon dioxide and hydrogen

$$CO + H_2O \rightarrow CO_2 + H_2$$
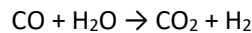
After this the percentage of CO is supposed to be less than 0.5% vol.

The H2 produced after WGS is still not pure, in other words it still contains some contaminants, mainly unconverted CH_4, minor mounts of CO and others in despicable quantities. Therefore, next, the impurities are removed in the purification unit. The process that is normally used is the pressure swing adsorption (PSA). What this process does is absorb the contaminant gases coming from the reformer at elevated pressure on activated carbon or molecular sieves. Next, these gases are desorbed by expanding the absorber tank to the approximately atmospheric pressure and finally returned to the reformer reactor as auxiliary fuel. The final result of the SRM is a purified H_2 with a high purity level.
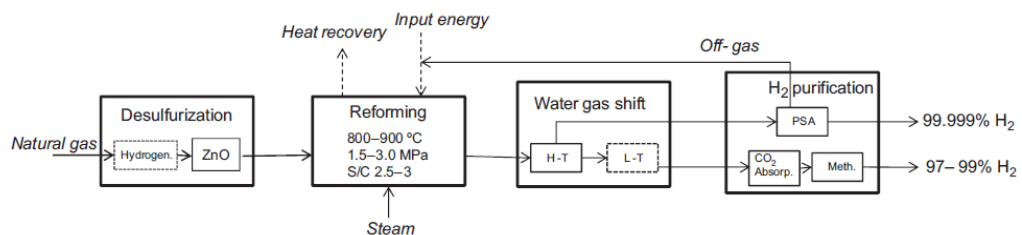

Figure 1 – Scheme of the Steam Reforming Process [12]

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2.2   Hydrogen Production by Water Electrolysis

Water electrolysis is another method to generate almost pure hydrogen. It's driven by the movement of electrons which are continuously circulated through an external circuit and uses electricity to split water molecules into the gaseous forms of hydrogen and oxygen. This is the overall chemical equation: $2 H_2O (l) \rightarrow 2 H_2 (g) + O_2 (g)$

There are two types of water electrolysis that nowadays we can consider: Alkaline and the Proton Exchange Membrane (PEM). Both processes obtain Pressurized hydrogen without a compressor and 99.999% pure, dry and carbon-free hydrogen.
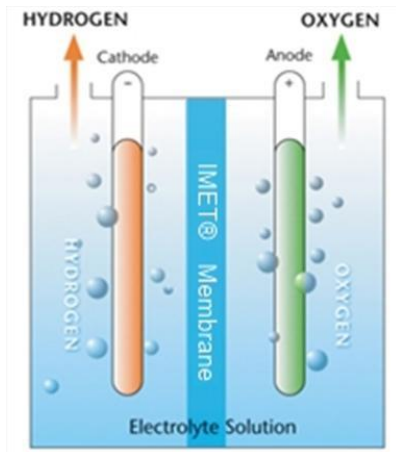
Figure 2 – Scheme of Alkaline Eletrolysis [13]

In alkaline electrolysis there is applied a voltage between two electrodes that are dived in a solution composed of water and liquid electrolyte (e.g. 30% KOH). The water molecules react with electrons giving origin to OH^- ions and H_2 molecule at the cathode ($4H_2O + 4e^- \rightarrow 4OH^- + 2H_2$). Simultaneously, at the anode the OH^- ions that have traveled through the electrolyte react and lose their extra electrons originate water, electrons, and O2 ($4OH^- \rightarrow 2H_2O + 4e^- +O_2$).

The recombination of Hydrogen and Oxygen is avoided using a highly efficient ion-exchange membrane. The electrolyte remains in the system due to a closed-loop recirculation system.

The Proton Exchange Membrane (PEM) electrolysis is different from the previous one. It uses an ionically conductive solid polymer (so-called PEM) instead of a solution of water a liquid electrolyte. The electrolyte (conductive solid polymer) and two electrodes (anode and cathode) are placed between
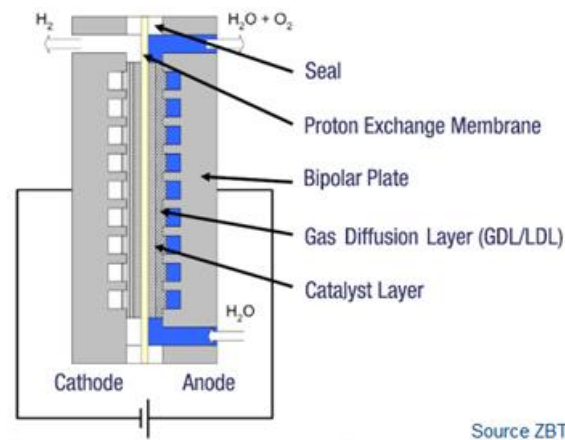
Figure 3 - Scheme of PEM Eletrolysis[13]

two bipolar plates. This set is the electrolyser cell.

The bipolar plate has four functions: to transport water to the plates; lead the product gases to the exterior of the fuel cell; conduct electricity; and finally, it's responsible for keeping a coolant fluid circulating with the objective of cooling down the process.

The water runs through the bipolar plate of the anode simultaneously as the voltage is applied between the two electrodes. Consequently, the negatively charged Oxygen present in the water molecules loses their electron and originates protons, electrons, and O2 at the anode ($2H_2O \rightarrow 4H^+ + 4e^- + O_2$). At the cathode, the H^+ ions that have traveled through the conductive polymer react; they acquire an electron becoming consequently neutral H atoms; finally, they combine resulting H2 ($4H^+ + 4e^- \rightarrow 2H_2$).

Each electrolyser single cell can be connected in series with others to make the core component of an electrolyser system, the cell stack.

Figure 4 – Serie of PEM eletrolysers[13]

2.3   Other Production Technologies

There are other Production Technologies such as: Biomass production methods, Coal and Oil gasification, some green methods for hydrogen production and other developing technologies. For more information consult [12], [18] and [19].

2.4   Economic Considerations of Hydrogen Production

One of the main deciding factors for choosing one technology over another is the economic factor, so the choice of hydrogen as fuel greatly depends on the cost of its production. This section is devoted to exploring hydrogen production from a purely economic perspective describing the various costs of hydrogen production. It also includes comparing the production costs of various hydrogen production technologies.

This study is only between Hydrogen Production methods and does not include a comparison with the costs of producing kerosene which would be rather interesting. The costs of producing kerosene are supposedly lower, which explains why it is the

most used jet fuel. However, it was not possible to obtain that data in order to make a precise economic analysis like the one made only between the H_2 producing methods.

2.4.1   Levelised cost of hydrogen production

In order to be able to compare the costs of producing hydrogen using different technologies it is used the "Levelised Cost of Hydrogen Production". This economic indicator includes the contribution of the "initial plant investment (annualised capital cost (ACC) over the economic lifetime of the plant), the fixed and variable operations and the maintenance costs (FOM and VOM) and the cost of feedstocks (e.g. electricity, natural gas; denoted FUEL)" [12]. It also takes into account the annual fuel consumption (FCONSUM) using the equation:

$$\text{Levelised cost} \;=\; \text{ACC} \;+\; \text{FOM} \;+\; (\text{VOM} \;+\; \text{FUEL}) \;\times\; \text{FCONSUM}$$

2.4.2   Sources of plant cost data

When estimating plant costs there are numerous inconveniences:

1. Estimating plant investment and operating and maintenance costs

There are different studies that estimate the sources of plant cost data in this matter. All off them take into account the direct costs, however the main difference between them is that they use different assumptions when it comes to the inclusion of the indirect costs. Some indirect costs can or cannot be included (e.g. the cost of licensing or land). Consequently, it's difficult to use a consistent approach for estimate the capital and operating and maintenance costs for each technology;

The direct plant investment costs are essentially the cost of the installed equipment. Plant construction projects also have considerable indirect costs (usually near one third of the total cost). These include "design, site preparation, contingency costs and profits for the construction contractor (direct costs implicitly include profits for equipment manufacturers)" [12] and the cost of land, licensing and permits that can vary with the country. Other costs can include additional financial costs to cover financing for up-front fees.

Most Operation and maintenance costs are variable costs and proportional to the plant output. These include "equipment, feedstock(s), outage costs, running costs, licensing costs and labour" [12]. There are also fixed ones such as annual costs ("e.g. Annual out-ages and for licensing" [12]).

2. Cost variations between countries

The costs vary with the country due to many factors (e.g. labour costs, environmental regulations, currency exchange rates …); For example: The plant

construction costs in USA are in average lower than in Europe due to less restrictive environmental regulations, lower taxes and lower labour and land costs.

It is not a simple task to compare costs in different countries and that must be taken into to account when "interpreting cost projections from different studies and when applying the cost projections (…) to a particular country". [12]

3. <u>Converting costs into consistent monetary units</u>

The monetary units used in investment costs are usually both dollars and euros. In addition, studies can have different base years; therefore, it is necessary to account for both currency conversion and inflation. In this study from [12] all costs are converted to US dollars in the year 2013.

There are two methods for this conversion:

I. First, adjust for inflation in the original currency and then apply the year 2013 currency exchange rate;

II. Vice versa: First, use the exchange rate in the study base year and then adjust for inflation using the inflation rate of the country in question.

<u>Note</u>: "Exchange rates are more volatile than inflation rates" [12], so the first option produces a more consistent conversion factor and it is the method that is going to be used from this point forward.

Summing up, it is necessary to convert the costs into consistent monetary units for a single currency and year.

4. <u>Estimating feedstock conversion efficiency</u>

The feedstock conversion efficiency of each technology, in other words, the energy that can be extracted from a fuel should be calculated consistently across the model.

The energy extracted is measured as "the energy released as heat when the fuel undergoes complete combustion or electrochemical conversion with oxygen."[12] More precisely, it is measured using one of the two reference points:

- The higher heating value (HHV) – "the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products."[16]

- the lower heating value (LHV) – "the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered."[16]

	Higher heating value	Lower heating value	HHV:LHV ratio
Hydrogen	142	121	1.17
Methane	56	50	1.12
Gasoline	47	44	1.07
Coal (anthracite)	27	27	1.00
Wood	15	15	1.00

Figure 5 - Heat of combustion of several fuels (MJ/kg). [12]

In this study, the HHV is the one used to estimate the efficiency of each feedstock/fuel and it can vary depending on their exact chemical composition. "For example, the efficiency of coal gasification is different for anthracite, lignite and other types of coal" [12].

2.4.3   Feedstock commodity price forecasts

	Price projections in 2010	Price projections in 2050		
	Central	Low	Central	High
Coal	4	4	5	7
Gas	10	7	12	17
Biomass	10	6	10	14
Electricity	14	14	29	33

Figure 6 - Feedstock prices and projections. All are converted into 2013 US dollars per GJ of embodied energy [12]

The main operating cost in hydrogen production is the cost of the feedstock(s) (figure 6). The future prices are highly uncertain. Therefore, price variations have a great impact in the total production cost. The projections used in this study taken from [12] are shown in the table above.

2.4.4   Cost components of principal hydrogen production technologies

This section is dedicated to compare the cost and operating efficiency of 4 hydrogen production methods: SMR, electrolysis, biomass and coal.

Estimates of the capital costs are compared in figure 7. Fixed operations and maintenance costs are expressed as a function of the capital costs in figure 8. The

feedstock conversion efficiency for hydrogen production by each technology is compared in figure 9.

In all figures, it's compared the costs for large centralised and small distributed plants and also the costs for centralised fossil plants both with and without Carbon Capture and Storage (CCS)[1] technologies. Most hydrogen for industrial applications is currently produced by cracking carbonaceous fossil fuels. Methane is the most common feedstock but coal has also been used. It would be necessary to deploy CCS systems on these plants to produce low-carbon hydrogen which would only be economic for large-scale production.
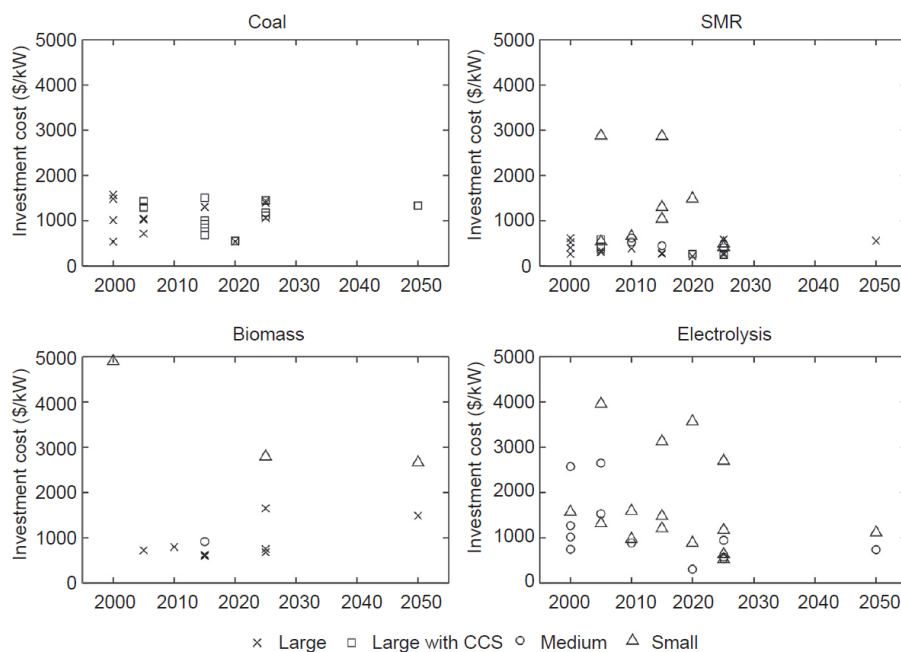
Figure 7 - Capital costs for hydrogen production technologies. Costs are from the studies cited and have been converted to US dollars in 2013.[12]

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[1] Carbon Capture and Storage (CCS) is a technology that can capture carbon dioxide ($CO2$) emissions produced from the use of fossil fuels in industrial processes, preventing the releasing of carbon dioxide to the atmosphere

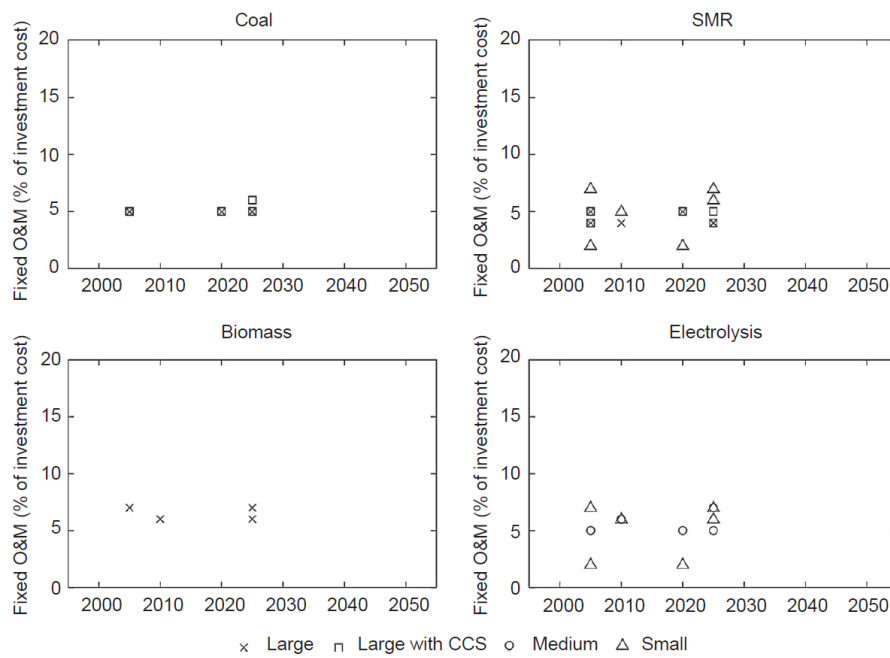*Figure 8 - Fixed operating and management (O&M) costs for hydrogen production technologies. Costs are from the studies cited and are presented as a percentage of the capital costs in each study. [12]*
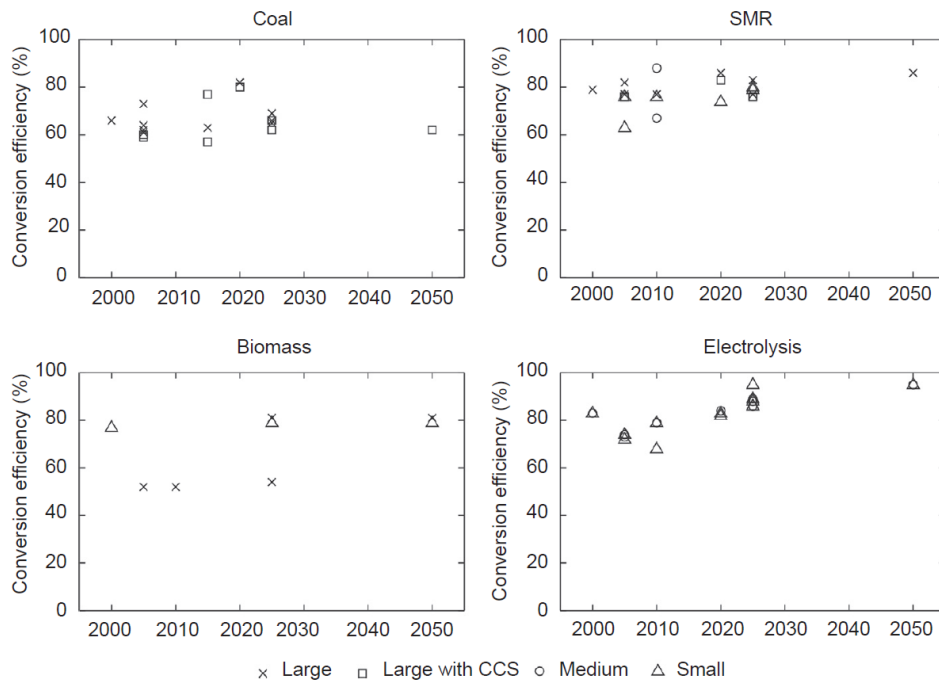

Figure 9 - Energy efficiencies of the principal hydrogen production technologies. [12]

1. Steam methane reforming

Natural gas steam reforming is the most developed technology to product Hydrogen. As a result, it is today the one that is usually utilized and has the lowest capital cost for large plants (figure 7). That is the main reason why it has been used globally for the past few years.

Nowadays, most SMR efficiency is between the 60% and 80%. By analysing the figure 3 it is possible to verify that it increases in average with the size of the plant. In the future the tendency is for the efficiency to slightly raise and to reduce the efficiency gap between the different size plants.

Feedstock costs are the most important economic factor, but SMR has high energy efficiency. In addition, these costs are expected to rise considerably in the future if CO2 emissions taxes rise. The CCS it's a potential solution because it would reduce the impact of such taxes. However, the plants become more expensive to build and it would also reduce plant energy efficiencies. The magnitude of the reduction would depend off course on the energy required to capture, compress and transport the CO2 to the underground storage site. So, in order to make CCS systems an economic viable solution for plants to produce low-carbon hydrogen the production needs to be in large-scale.

2. Coal and oil gasification

This technology had already other objectives as producing gas for lighting purposes. So, it is a mature technology like SMR. Although it has lower feedstock costs than the previous technology it is less but also widely used globally. That is because the average energy conversion efficiency is a bit lower and the capital costs are also in average a bit higher. The future tendency is for the differential use between these two technologies to be reduced because it is expected that the SMR's feedstock (gas) cost to have a more marked increase than coal.

The wide range of the energy efficiency is approximately between 50% and 80%. These values depend on the exact chemical composition of the coal. As it has been referred previously, the efficiency of coal gasification is different for anthracite, lignite and other types of coal.

In comparison with SMR the emissions of CO_2 are higher, so if CO_2 emissions taxes increase in the future, and they probably will, the CCS it's also a potential solution. The downside is that future expected energy conversion efficiency improvements in this technology will be minimized by CCS. Because of the higher CO_2 emissions, using CCS will inevitably cause a higher efficiency reduction to capture CO_2.

It is important to notice that oil, as opposed to coal, is unlikely to be used for hydrogen production. The reason behind it is that it is more valuable particularly for

transports applications. So, unless the transport sector changes for alternative fuels it is almost never considered in the context of hydrogen production.

3. Biomass-fuelled technologies

There are three main methods of producing hydrogen from biomass: thermochemical conversion (gasification or pyrolysis), biochemical/biological conversion and mechanical extraction. The figures only use data from gasification because the other processes are still at a laboratory stage of development.

Nowadays, there are no completed industrial-scale demonstrations of any biomass technology for producing hydrogen so cost and energy efficiency data presented are speculative. That is a consequence of the biomass low energy conversion efficiency. This can be explained by the fact that biomass has low hydrogen content (approximately 6%) and the 40% oxygen content which lowers the overall available energy.

Capital costs are expected to be similar to coal gasification costs because the conversion processes and plant requirements are identical (Figure 7). From all the technologies analysed Biomass is the one that has the wider range of energy conversion efficiency. The range is between the 45 and 80% (figure 9) due to the numerous potential feedstocks. For example, the conversion efficiency of wood is very low which can be derived by its low HHV (figure 5). The higher values are normally associated to steam reforming of biofuels which are processed prior to the hydrogen production plant. The principal advantage of such feedstocks would be to "reduce the feedstock transport costs from the farm gate to the hydrogen plant".

This study does not consider biomass technologies with CCS, but these plants have negative lifecycle emissions and "Biomass with CCS has been identified as a key technology for electricity production by several energy system models and hydrogen production from biomass offers similar advantages to the energy system."[12]

4. Electrolysis

Electrolysis is the only used method for producing hydrogen using water as feedstock. As it has been referred, it has the advantage of producing hydrogen with high purity and with zero CO2 emissions.

The principal drawback of this method is the high cost of electricity in comparison to other feedstocks. The near 100% pure hydrogen is produced but the cost is much higher than from SMR, especially with alkaline electrolysis. Low-temperature polymer electrolyte membrane (PEM) is the other electrolysis method and the one that is expected to be more efficient in the future. PEM electrolysers are suited to small-

scale hydrogen production and varying loads, for example from intermittent renewable electricity generation.

- The Capital costs are shown in the figure 10 for the year 2010 and a prediction for the year 2050. This data is annualised using an interest rate of 10% and assuming that the lifetime of the plant is 30 years.

	Capital costs in 2010			Capital costs in 2050		
	Low	Central	High	Low	Central	High
Coal	722	1056	1391	694	1056	1418
Coal + CCS	1045	1344	1642	926	1272	1618
Gas	288	409	530	233	409	585
Gas + CCS	361	468	575	321	409	585
Biomass	667	759	852	261	759	1257
Electricity	737	1522	2308	457	696	935

Figure 10 – Capital Costs in 2010 and predictions for 2050 [12]. These costs are US dollars 2013 per kW.

- The fixed Operation and Maintenance (O&M) costs are shown in figure 11 for the same years. The variable O&M costs are included into the fixed ones because they are very low in comparison. However, feedstock costs can be found in figure 6. Figure 11 has also the data relative to the energy efficiency conversion for each type of H_2 production plant.

	Fixed O&M costs	Energy efficiency in 2010	Energy efficiency in 2050
Coal	5%	65%	65%
Gas	4%	80%	85%
Biomass	7%	50%	50%
Electricity	5%	75%	85%

Figure 11 – Fixed O&M costs and assumed conversion efficiencies for the levelised cost comparison, as a function of the capital costs [12]

The following figure illustrates the levelised cost for the four Hydrogen production methods approached in this chapter. Both Steam Reforming and Coal gasification are shown with and without the CCS technology. Also, this figure doesn't have into account CO_2 emission taxes.
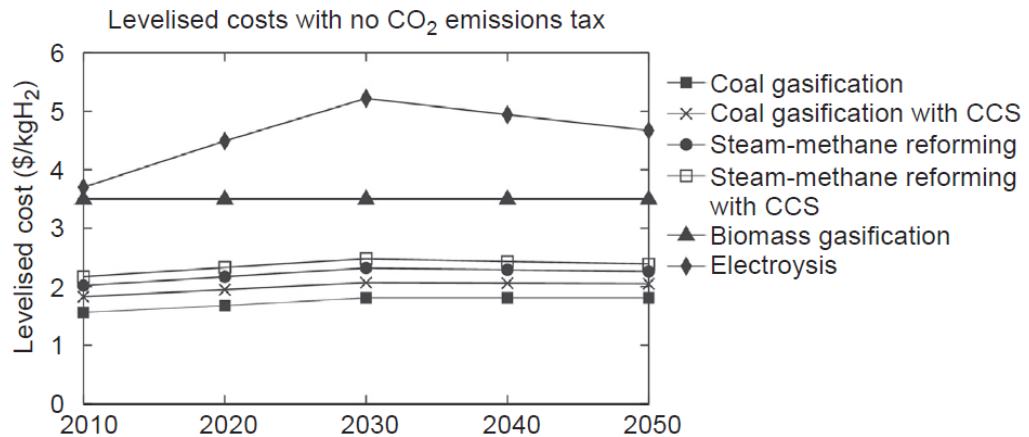
Figure 12 – Estimated Levelised cost projections for the Hydrogen Production technologies approached in this study. Costs are expressed in dollars/Kg using US dollars 2013

- o It is possible to verify that Coal gasification costs are a bit lower than SMR. That can be explained by the fact that gas prices are higher than coal and the future trend is for them to get even higher.
- o Biomass gasification is considerably more expensive than SMR and coal gasification, reflecting the higher feedstock cost and lower energy conversion efficiency.
- o Electrolysis is clearly the most expensive especially due to the high electricity costs. However, the hydrogen produced as a high purity level, so it has more value.

2.4.5 Uncertainties in technology costing

"The cost projections in Figure (12) are inherently uncertain. In Figure (13), cost ranges are estimated for the principal technologies in 2050. These ranges are calculated as follows:

1. The high and low capital costs are assumed to be one standard deviation from the best central cost, with the standard deviation calculated from the data presented in Figure 7.

2. The fixed O&M cost ranges are calculated from the capital cost ranges using the factors in figure 11.

3. Commodity (Feedstock) cost ranges are summarised in figure 6.

4. The upper and lower energy efficiencies of the plants are assumed to increase or decrease by 5% from the central estimates in figure 11."

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In Figure 13(a) it's possible to verify:

- The cost range is considerably higher for biomass and electrolysis.
- For electrolysis, the uncertainty over the future price of electricity is particularly important.
- There is substantial crossover between the ranges of all the technologies, which suggests that the most economic technology in the future is likely to depend on the success of technological developments and the evolution of feedstock prices.

The Figure 13 (b) analyses the impact of charging a $300/tCO2 tax on hydrogen production costs in 2050. As expected the use of SMR and coal gasification without CCS would be much higher and assuming that CCS only captures 85% of the CO_2 emissions the cost of these technologies with CCS would also increase a bit because of the other 15% that are still released into the atmosphere. This figure also assumes that Biomass feedstock is carbon-neutral; therefore, biomass costs are not affected by this tax.

It is possible to verify that coal and SMR with CCS are in this case, the most economic advantageous production methods. It is also possible to conclude that producing H_2 from fossil fuels without the using of CCS is economically impracticable considering the cost range of coal. There is a crossover between the ranges of all the other methods, therefore the cheapest technology will "depend on the success of technological developments and the evolution of feedstock prices" and "environmental legislation and taxation policies in each country."
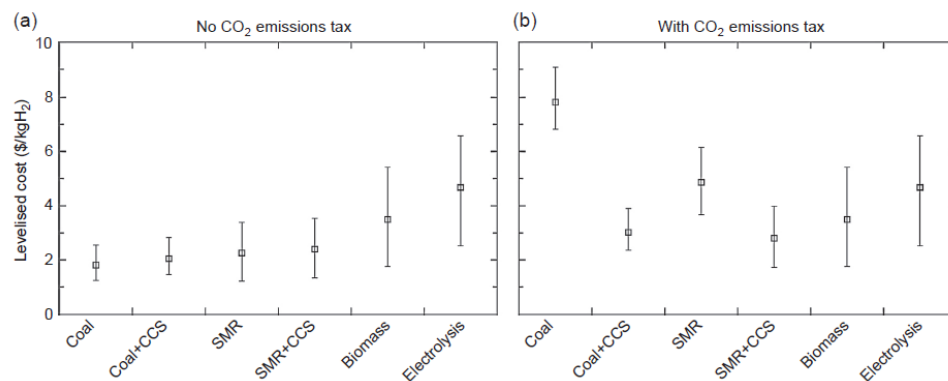

Figure 13 – Levelised Cost ranges for the hydrogen production technologies approached. In (a) costs are presented without CO_2 emissions tax and in (b) with that emissions tax. The Units are 2013 US dollars / Kg of produced H_2

2.4.6   Conclusions

Nowadays the Hydrogen production from SMR is the most used. The second one is coal gasification which is slightly increasing. They are both very mature and the most advantageous in an economic point a view. In the future the Biomass and Electrolysis are expected to have an important role depending on the technologies developments, uncertainties relative to the cost of the feedstocks and also due to the possible changes in the environmental legislation and taxation.

Another aspect that is important to highlight again is that in this study the Biomass technology hasn't been analysed with CCS. It can be an important fact to enable the production of low-carbon hydrogen from carbonaceous fuels and be treated as a future potential solution especially in case of the raise of CO_2 emission taxes.

Electrolysis is nowadays the technology with the higher capital and feedstock (electricity) costs in comparison with the others. Despite that, it is a technology that has the most potential to reduce its cost especially in the case of the PEM electrolysis with the advantage of obtaining almost pure hydrogen and with zero CO_2 emissions.

There are other technologies (not approached in this study) being developed in labs which can also be a future potential solution for minimize the costs of Hydrogen production.

The considerable crossover between the ranges of cost of the technologies approached implies that "the most economic technology in the future is likely to depend on the success of technological developments and the evolution of feedstock prices".

3   Hydrogen Storage in Aircraft

Once produced, the next step in the hydrogen life cycle is to be stored under specific conditions. The challenge in identifying an ideal hydrogen storage system is to meet simultaneously all the targets for practical applications. These are the current main objectives to improve hydrogen storage [17]:

- reducing weight and volume of thermal components;
- reducing the cost of hydrogen storage systems;
- increase the durability of hydrogen storage systems;
- diminish the hydrogen refuelling times;
- Find a solution for high-pressure containment of compressed gas. That's because the high pressure limits the choice of construction materials and fabrication techniques, within weight, volume, performance, and cost constraints.

3.1   Gaseous State Hydrogen Storage

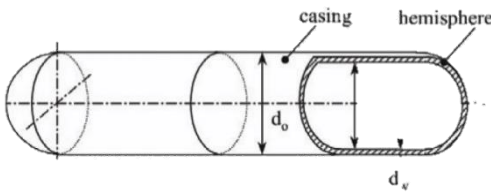The most common method used to store Hydrogen is high pressure (> 200 bars) compression of the gas phase.

Hydrogen can be compressed using mechanical compressors (piston-type). The theoretical work for the compression (admitting that is isothermal) of hydrogen is given by the following equation:

$$\Delta G = R \cdot T \cdot \ln(\frac{p}{p_0})$$

The variables have the following meanings: R - gas constant; T - absolute temperature; p - end pressure; p0 - starting pressure.

In fact, the process is not isothermal, which explains the discrepancy between the real and the theoretical values. Usually, the work consumption is a bit higher that the theoretical one. Despite that, this theoretical equation has an error of approximately 6% for the work calculated in the pressure range of 0.1-100 MPa, so it can be considered a good approximation.

Following the compression, hydrogen is stored (350 bars and 700 bar is used nowadays in hydrogen vehicles). The storage system use as vessel cylinders capped with two hemispheres. The wall thickness of this storage compartments is given by the following equation:

$$\frac{d_w}{d_o} = \frac{\Delta p}{2 \cdot \sigma_v + \Delta p}$$

The variables have the following meanings: d_w - wall thickness; d_o - outer diameter of the cylinder; Δp – overpressure; σ_V - tensile strength of the material.

<u>Materials</u>: The selected materials for this storage system should have a very high tensile strength, a low density, can't react with hydrogen and allow hydrogen to diffuse into them. Nowadays, pressure cylinders are usually made of "austenitic stainless steel (e.g. AISI 316 and 304 and AISI 316L and 304L above 300°C to avoid carbon grain-boundary segregation2), Cu, or Al alloys, which are largely immune to hydrogen effects at ambient temperatures".

Another major concern is its safety due to the embrittlement of the cylinder materials during charging and discharging cycles. Therefore, it is expected that future pressure cylinder walls to be made of new composites. One developing idea is a composite made of three layers: "an inner polymer liner over-wrapped with a carbon-fiber composite (which is the stress-bearing component) and an outer layer of an aramid-material capable of withstanding mechanical and corrosion damage. Industry has set itself a target of a 110 kg, 70 MPa cylinder with a gravimetric storage density of 6 mass% and a volumetric storage density of 30 kg·m^{-3}"
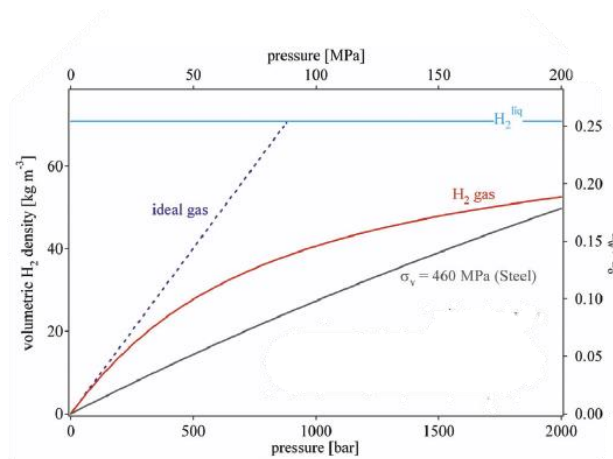

Figure 14 - Volumetric H$_2$ density.

This graph from [21] is referred to a stainless steel with a tensile strength of 460 MPa. It is possible to observe how the volumetric density of hydrogen inside the cylinder and the ratio of the wall thickness to the outer diameter vary with the pressure inside the cylinder. It is quite intuitive and can be verified that the volumetric

density increases with increasing pressure. It is not presented in the graph but the gravimetric density decreases with increasing pressure. So, increasing the volumetric density the gravimetric density (energy per mass) diminishes.

In order to increase both densities, one of the methods involves cryo-compressed tanks. Imagining that the pressure and volume are fixed, as the tank temperature decreases, the gas volumetric density increases which means the tank volumetric capacity increases. Therefore, cryo-compressed tanks have a low temperature (near 77K the liquid nitrogen temperature). On the other hand, the total system volumetric capacity is still less than one. That's because of the increased volume required for the cooling system.

This system is also limited by the energy needed to compression of the gas. It is estimated that 20 % of the energy content of hydrogen is lost due to this storage method. This problem can also be minimized by the development of new materials.

3.2   Liquid State Hydrogen Storage

Liquefaction was developed during the space age and today is used fundamentally on-board fuel cells. The liquid hydrogen (LH$_2$) is stored in cryogenic tanks with a temperature around 21.2 K and at ambient pressure. The principal advantage of this method compared to the previous one is the improvement of the energy density.
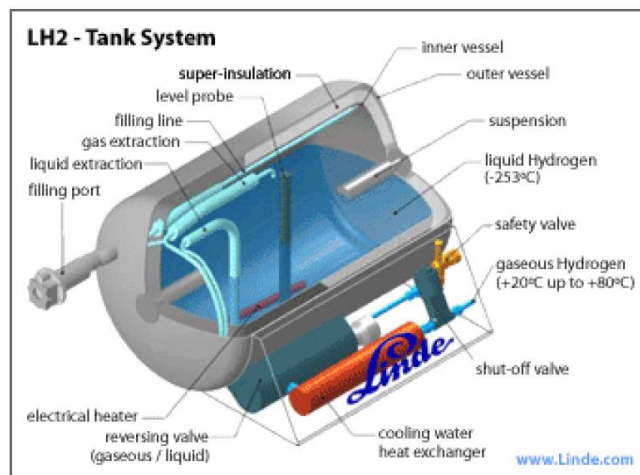
Figure 15 - Liquid Hydrogen Tank System. [17]

In the process the gas hydrogen phase is initially compressed at high pressure, liquefied at a cryogenic temperature and then stored in a liquid hydrogen tank. The low temperature is maintained using a liquid helium cylinder, but there are still problems due to the loss of hydrogen by boil-off. The boil-off rate because of heat leaks is a function of the size, shape, and thermal insulation of the tank. It is proportional to the surface-to-volume ratio, so the evaporation rate can be lowered if

the storage tank size (volume) is increased. Another strategy in order to minimize it is mixing hydrogen with a metal hydride (e.g. – Fe- Ti).

One of the main disadvantages is that the costs related to the energy required for hydrogen liquefaction, volume, weight, and tank are very high. It is also estimated that 40 % of the energy content of hydrogen is lost due to the storage methods. Other problems include safety with the handling of liquid hydrogen and also in storing, pressurizing and cooling it in such lower temperatures.

3.3   Other Storage Methods

There are other storage methods such as Solid State Hydrogen Storage. For more information about this consult [17], [20] and [21].

3.4   Design Changes due to Hydrogen Storage

As discussed previously the storage of hydrogen presents more challenges when compared to kerosene and those differences allow other non-traditional configurations to be considered.

One of the main differences when comparing the storage of both fuels is the weight and density since it affects the configuration of the aircraft. Since liquid hydrogen has more volumetric energy than in its gaseous state, it is the preferred method of storage in aircraft since reduces the needed volume for fuel storage.

	Kerosene	LH$_2$
Mass of equal energy	1 kg	0.357 kg
Density	804 kg/m^3	70.8 kg/m^3
Volume of equal energy	0.246 m^3	1 m^3
Global fuel consumption	270.1 Tg(Kerosene)/yr	96.4 Tg(LH$_2$)/yr

Table 1 - Properties of kerosene and LH$_2$.

Using table 1, when compared with an aircraft fueled with kerosene, an hydrogen fueled aircraft would have approximately 64% less weight in fuel, but it would occupy 4 times more space. Of course this is a rough estimate, since the aircraft would be bigger and the surface area of the aircraft would increase, the resulting drag would also increase, but since weight would be lower, a lighter aircraft might consume less fuel. Although since the storage equipment of LH$_2$ is heavier, the resulting total weight changes with the amount of fuel, making it is hard to calculate.

In traditional commercial jet aircraft the fuel is stored in the wings. This might not be viable as LH_2 storage. As such either the storage location must be changed to the fuselage or the wing shape must change to increase its volume.

Using the fuselage as storage, allocating certain parts of it, such as, in the back creates problems when considering the center of gravity, as the location is limited. Therefore the most viable way is storing along the span of the fuselage.

One of the options is the storage in the upper part of the fuselage, with the option of using part of the wing if the aircraft has a high wing. But the oversized wing can negate the benefit of the smaller top tanks (figure 16). [2]

Figure 16 - Concept of aircraft configuration with hydrogen storage in the back of the fuselage.
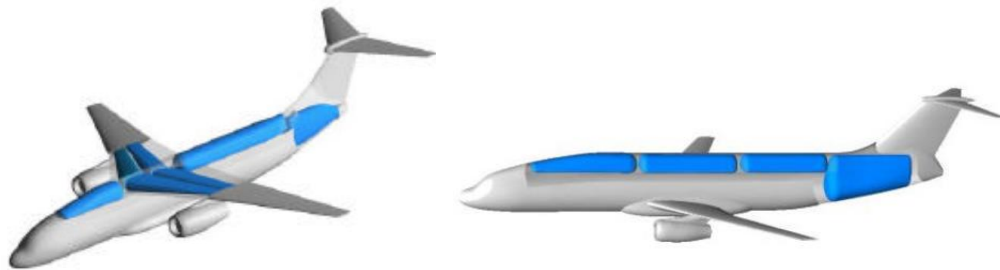
Figure 17 - Concepts of aircraft configurations with hydrogen storage along the fuselage.

Another option is a combination of the ones stated above, where the back is used for a large amount of the storage, but part of it is done along the fuselage. Keeping in mind that for the safety of the passengers, locating the hydrogen storage above allows, in the case of burst or rupture of the tanks, the evaporation of the hydrogen rising upwards.

Other unconventional configurations may become more viable with the usage of hydrogen. The blend wing body (BWB) by virtue of its profile shape has a lot of unused volume when the overall dimensions are small compared to the human being, which is one of the demands that hydrogen brings. Even so its viability may be conditioned to very large, long range flights. However, first the inherent problems of the BWB should be solved, for example emergency evacuation.
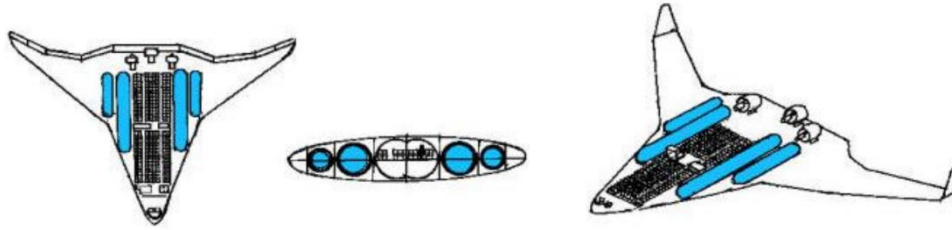
Figure 18 - Concept of aircraft configuration with hydrogen storage along the blended wing.

One of the aspects to be considered is the differences in certification for airworthiness, since liquid hydrogen has a different behavior than kerosene and the storage is done differently. LH_2 burns much faster than kerosene, but with a lower radiation heat and without making a fire carpet, as the kerosene does. LH_2 does not explode in open air, only in a confined space, so special attention must be paid to the design of the fuel system, making vents, security valves, etc., to prevent leakage into the passenger cabin. Studies reveal that passengers would have greater survival possibilities after a crash if they remained in the cabin and waited for the fuel to burn outside the aircraft.

4   Hydrogen Usage in Aircraft

This section proposes possible ways of using hydrogen to power aircraft. They will be introduced, briefly explained and then compared with the typical methods used at the moment both in the engineering and the consequent emissions.

Traditionally the methods of propulsion are based around the use of liquid hydrocarbons as fuel. Piston engines can use either kerosene (Jet-A), diesel or gasoline (Avgas), while turbine based propulsion, such as turboprops and turbofans use kerosene. These types of fuel have similar origins and have low price of production, as well as volumetric high energy content. Additionally, in atmospheric conditions these fuels have a small flammability window, with kerosene between 6-7.5%. All these characteristics make hydrocarbons the most used source of energy in military and commercial aviation.

Hydrogen on the other hand has both a chemical and physical behaviour that is different. It has the benefit of being usable in any of the types of engines mentioned previously, as well as, being converted into electricity using the chemical reaction in fuel cells making it very versatile. As mentioned in previous sections, the lower volumetric specific energy content, when compared to kerosene, makes the challenges of using it different.

4.1   Piston based

The use of hydrogen in piston-based engines is extremely old. In 1806 Francois Isaac de Rivaz developed the first internal combustion engine which ran on a hydrogen/oxygen mixture. But due to the ease of use of fuel fossils, the widespread use of hydrogen in internal combustion engines never occurred.

Even so, due to the versatility of hydrogen, conversion of nowadays fossil fueled internal combustion engines to hydrogen is possible and it was patented by Paul Dieges in 1970. Additionally, many automobile companies are considering the use of hydrogen as fuel and even the hybrid use of gasoline and hydrogen. [3]

Figure 19 - Hydrogen internal combustion engine inside a transit bus

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The differences between a hydrogen internal combustion engine and a traditional aviation gasoline engine include: [4]

- hardened valves and valve seats, stronger connecting rods, due to the higher compression ratio
- non-platinum tipped spark plugs, since platinum is a catalyst causing hydrogen to oxidize with air
- fuel injectors designed for a gas instead of a liquid
- required turbo or supercharger to achieve full power

It is important to consider that due to the lower volumetric energy content of hydrogen the output power will be less when compared to the size of the engines. This means that engine sizes would need to increase to output the same power.

On the other hand, hydrogen's energy efficiency is 20 to 25% better than that of a gasoline in an internal combustion engine due to leaner air to fuel ration and higher compression ratio achieving over 40% energy efficiency.

In terms of emissions the main components are water and NO_x. For each kg of hydrogen, it is expected 9 kg of water, although the NO_x emission depends on the temperature and fuel to air ratio. This relation will be explored in the turbine section.

The big drawback when considering the use of these engines in aviation is the comparison with electric engines that can use hydrogen fuel cells since they are more energy efficient.

4.2   Electric

4.2.1   Fuel Cell

Hydrogen can also be used to power electric engines with the use of a fuel cell. A fuel cell is an electrochemical cell, that is, it converts the chemical energy from a fuel into electricity through an electrochemical reaction of hydrogen with oxygen or another oxidizing agent. The main characteristic that makes it different from a battery is the need for constant input of the hydrogen and oxygen, whereas the chemical components are usually already part of
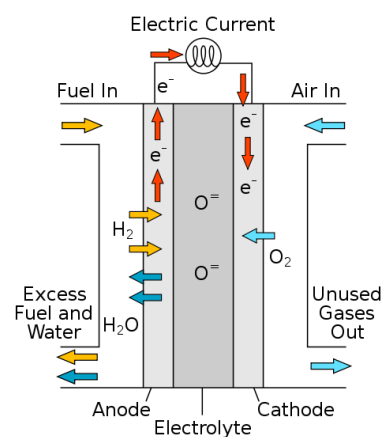

Figure 20 - Scheme of a fuel cell.

the battery.

While the invention of the fuel cell is dated in 1838, its commercial use started with the space program with NASA to generate electric power for satellites. Since then its use has increased, especially when backup power usage is needed.

Like the effects of combustion, fuel cells release H_2O as emissions in the resulting operation. On the other hand, unlike turbines and other high temperature operations there is no emission of NO_x. This is a great advantage and the consequences of NO_x released at high altitude will be discussed later.

4.2.2   Fuel Cell vs Battery

Commercially available fuel cells generally have an efficiency between 40%-60%, although since the waste is heat it can have uses in the aircraft operation. Batteries, on the other hand, offer much greater efficiency in chemical to electric conversion, but when combined the hydrogen storage with the fuel cells, the total energy per weight and per volume is actually much higher.

The comparison is then dependent on the range of the aircraft, since if a low range is acceptable a battery-based source, with its higher efficiency becomes more attractive.

While for long range and because of the battery's characteristic size and weight, the fuel fraction of the aircraft becomes much higher. Additionally, a battery's weight is the same during the flight, but with fuel cells, hydrogen is being consumed and released to the atmosphere as water, reducing the aircraft's weight with time with the rate indicated by the Breguet equation. Therefore, a less efficient in power conversion, but much more space and weight efficient method, like fuel cells can become more efficient overall.

This relation and its range breakpoint are dependent on many factors, some of them in constant change as the engineering of these parts evolves. In the beginning of 2018 Norway announced the aim of all flights up to 1.5 hours to be flown using electric power by 2040. This can be the beginning of the creation of those breakpoints.

4.2.3   Electric Motor

The conversion of the electric power obtained with the power cell to thrust is done with and electric motor attached to a propeller. With that in mind, propeller-

based thrust is usually used in regional aviation and so the thrust required of the engines is comparable to piston-based engines, up to turboprops, outside the transonic regime.

Figure 21 - Airbus E-fan's ducted fan

Electric engines can have high energy efficiencies. A brushless DC motor can have up to 90% and has the added benefit of it being possible to work as a generator. When compared with the other used engines it has no atmospheric emissions and lower noise emissions.

The range of operations of piston and electric motors is similar as both frequently have propellers at similar rotation speeds. When considering a fuel cell with an electric motor total energy efficiency can be over 50%, while internal combustion piston engines reach lower values. In addition, electric engines have easier maintenance and allow the option of either fuel cells or batteries as an energy source, including hybrid options.

The use of electric motors in unmanned aviation is now common, but in manned aviation it is still rare. The main engineering reason discussed previously, regarding the low range achievable by battery usage.

4.3   Turbine

Gas turbines are the most used method of thrust generation in commercial aircraft. They are based in the Brayton cycle with continuous internal combustion. Gas turbines have in common the use of a compressor upstream of a combustion area and followed downstream by a turbine. In addition, regional aircraft usually have a propeller to more efficiently achieve thrust making it a turboprop, while longer ranger aircraft have a fan to operate at higher Mach Number, usually with high bypass ratio.

Turbines have the benefit of generating large amounts of thrust per weight and volume when compared with piston and electric engines at the range of power needed for long range commercial aviation (MW of power). Therefore, the use of turbofans in commercial aviation is still unmatched in its operation range.

Kerosene is the most common fuel used in the combustion area of a turbine, but in theory any source of heat that works in the conditions required of that area will work. This includes hydrogen and in fact, both can be mixed for a hybrid result.

According to both numerical and experimental studies the design of hydrogen fueled turbines is possible and similar to kerosene fueled ones. In fact a conventional gas turbine operated with fossil fuel oil could be converted with the minimum effort to use hydrogen as an alternative fuel.

One of the main differences with the use of LH_2 is the need to vaporize the fuel. That is possible with heat exchange which, like with rocket engines might be done using the combustion area's heat. Additionally the cold sink provided by the hydrogen fuel can be utilized in unconventional forms of turbofan engines.

An important parameter in design of the turbine's combustion area is the combustion efficiency and one of its main influences is the excess air ratio (EAR).
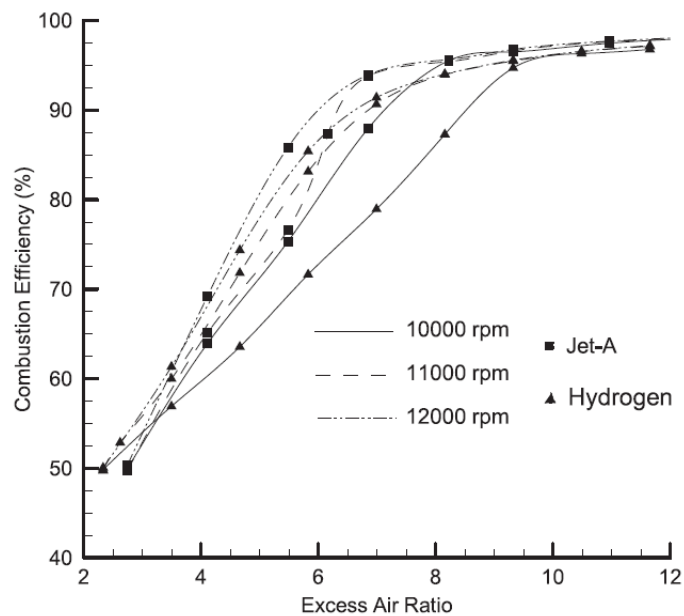

Figure 22 - Combustion efficiency versus the EAR.

While EAR has a large influence in combustion efficiency it also affects the emissions of NO_x. NO_x originates from oxidation of ambient nitrogen at high temperature in the combustors of aircraft. Aircraft NO_x emissions have a considerable environmental impact by leading to the formation of O_3. This effect is discussed in the following section regarding emissions.

On a numerical analysis of a gas turbine combustor fueled by hydrogen in comparison with kerosene analyzed in the range of excess air ratios from 2 to 12 for

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10000, 11000 and 12000 rpm engine speeds [5], "the conclusions can be summarized as follows;

- When jet-A was used, the temperature values at the combustion chamber outlet were validated with those in the literature.
- When the EAR is increased, the combustion efficiency values increased.
- When the EAR is increased, the pressure drop percentage values increased.
- The percentage values of UHC and CO2 emissions for jet-A decreases with an increasing of EAR values.
- The maximum NO values were obtained at 10000 rpm for hydrogen fuel. The minimum NO values were found at 12000 rpm for jet-A fuel.
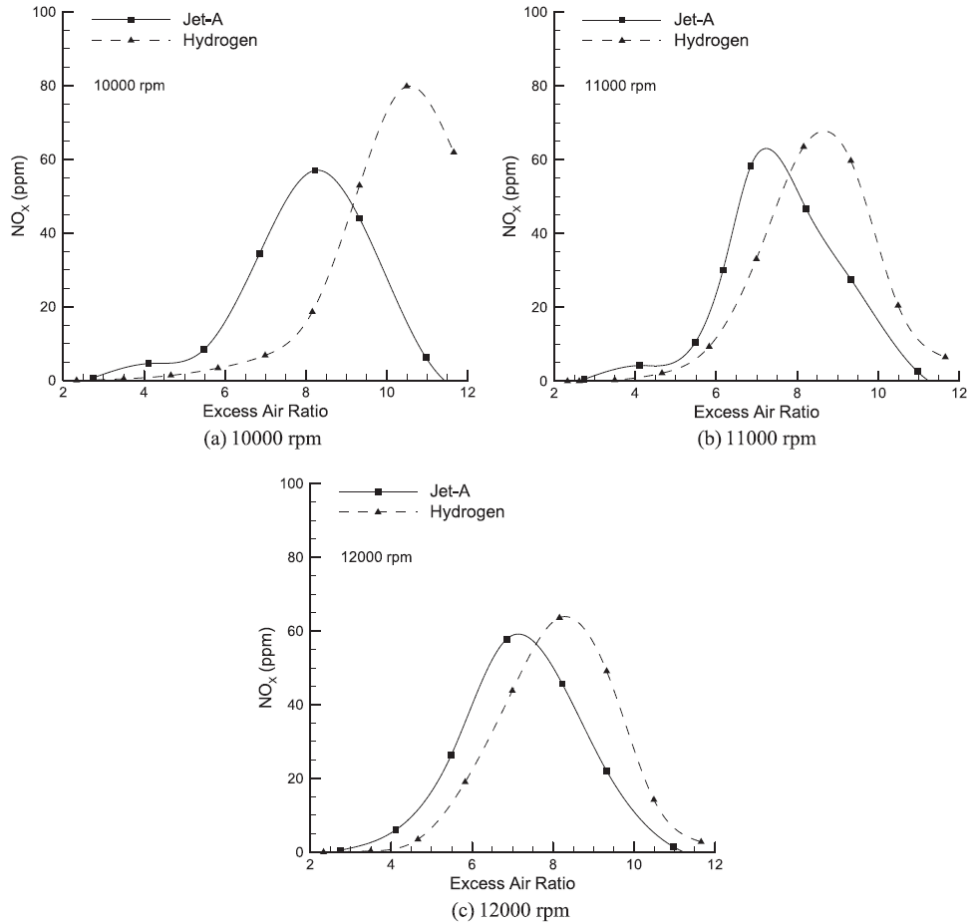- The engine speed values in the studied combustor did not affect in the UHC and CO2 emissions.

Figure 23 - NOx values in combustion outlet vs EAR in a numerical analysis

In this study, when hydrogen was compared with jet-A, many aspects of hydrogen fuel were deemed to be superior. Hydrogen burning was seen as advantageous in terms of pressure drop (15–30%), temperature values at the combustion chamber outlet (3–10%) and CO_2 and unburned hidrocarbonates emission values (100%). It was seen as advantageous in terms of NO_x emission values at low EAR values, but it was seen as disadvantageous at high EAR values."

Turbofans generally work with EAR of 4 to 5 [6], which when relating figure 23, it is also possible to verify that a hydrogen powered turbofan would have a lower NO_x emission in that EAR range.

Finally, while it does not impact the direct usage of hydrogen, the fact that the chemical reactions are much simpler than the ones obtained with kerosene, since hydrogen has no carbon component, allows an easier and computationally simpler CFD analysis.

5   Emission Study

The next chapter focuses on the comparison of emissions between kerosene and hydrogen as fuel in long range commercial operations. An account of total emissions release in production and usage of both fuels will be attempted along with the global values in the atmosphere. Ending with possible consequences of the change of the present fleet using kerosene to hydrogen.

5.1   Production of kerosene vs hydrogen

This part of the paper is reserved to analyze the emissions of some forms of hydrogen production and kerosene production. This approach enables us to estimate the environmental impact of each production method according to [15] in the references. In this article there is not sufficient data to compare the emissions from all the hydrogen production technologies. The comparison is between the H_2 from Natural Gas (Steam reforming), H_2 from Hydrolyses and other renewables energies and H_2 from Biomass in addition to the Kerosene Production.

5.1.1   Greenhouse Effect

Global Warming Potential (GWP) is used by the Intergovernmental Planet on Climate Change (IPCC) to integrate the overall climate impacts of well mixed-greenhouse gases. In simpler words, measures how much heat a greenhouse gas traps in the atmosphere.

The CO_2 is the number one responsible for the greenhouse effect but there are others that also contribute for this effect. That is relevant because GWP is normalized to CO_2 equivalent emissions and is expressed as a factor of CO_2 whose GWP is standardized to 1. It compares the heat trapped by a certain mass of gas with the heat trapped by an equal mass of CO_2. It is also calculated during a time interval that needs to be specified.

For example, these are the three main greenhouse gases and their 100 year global warming potential (GWP): Carbon dioxide (CO2) which GWP=1; Methane (CH4) which GWP=25 (releasing 1 kg of CH4 into the atmosphere is about equivalent to releasing 25 kg of CO2); Nitrous oxide (N2O) which GWP=298 (releasing 1 kg of N2O into the atmosphere is about equivalent to releasing 298 kg of CO2). [14]

The following graph exemplifies that on each hydrogen production process. It can be used as a tool to draw some conclusions.
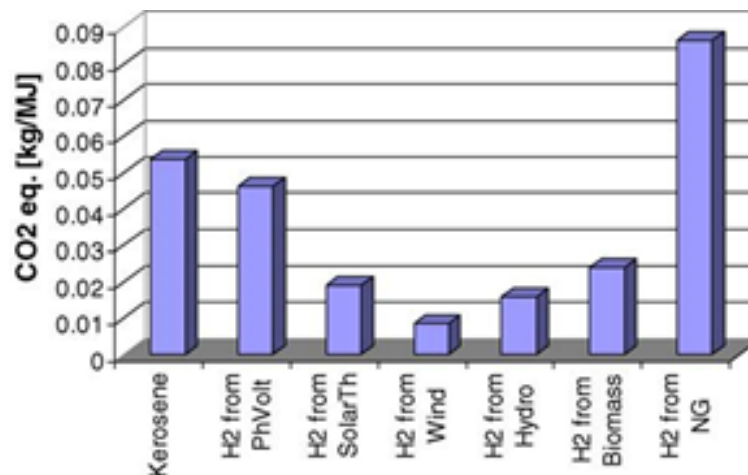
Figure 24 – CO2 equivalent emissions of aviation fuel production [15]

It can be verified that hydrogen production from natural gas steam reforming is clearly the one who contributes the most for the GWP. The Kerosene production and hydrogen production from photovoltaic energy are the second and third main contributors and the others have much less influence on GWP. It's also relevant to notice that H_2 from natural gas (steam reforming) is the more economical way to product H_2 and the one by far that has the biggest negative impact on global warming.

5.1.2   Acidification and Acid Rain Formation

Nitrogen oxides, sulphur oxides and ammonia gaseous emissions when dissolved in water react and form acids. When formed, Acid rain can cause serious damages for example: corroding human infrastructures, damaging the vegetation…

When dissolved, Acid substances are characterized by the quantity of H^+ protons released. Another way is using the SO_4 equivalent which compares the acidification effects of a certain mass of gas with the ones caused by an equal mass of SO_4. It is used to compare the relative importance of some gases to the acidification process.

The following graph exemplifies that on each hydrogen production process. It can be used as a tool to draw some conclusions.
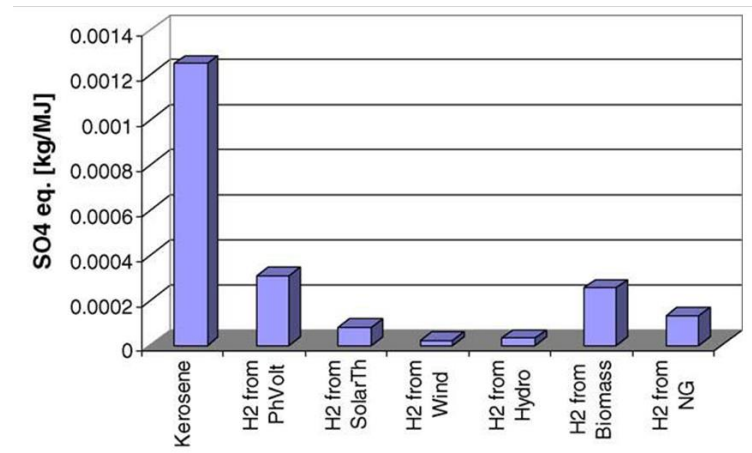
Figure 25 – SO$_4$ equivalent emissions of aviation fuel production [15]

The kerosene production technology is clearly the one which has the greatest acidification impact, due to very high SO$_2$ emissions during its production. All the other H$_2$ producing technologies have much less impact in this matter.

5.2   Combustion of kerosene vs hydrogen

The comparison of the emissions will be done considering the global emission values, assuming the energetic requirements are constant. The method used is radiative forcing (RF). RF [W/m^2] is defined as the change in the net (solar + terrestrial) radiative flux due to a change in the atmospheric composition (such as an enhanced level of a greenhouse gas) or due to a change in the solar irradiance. A positive RF leads to a global warming. For simplification, an assumption is made of a complete replacement of the fleet of conventional aircraft to hydrogen powered aircraft in 2015. For additional simplification it is assumed the consumption and emissions to stay constant after that point. The main contributions considered to radiative forcing (RF) arise directly or indirectly from the emissions of CO2, H2O, NOx, Sulphur products and soot. [7]

	Kerosene	LH$_2$
Mass of equal energy	1 kg	0.357 kg
Emission Index (H$_2$O)	1.26 kg(H$_2$O)/kg(ke)	3.21 kg(H$_2$O)/kg(ke)
Emission Index (NO$_x$)	12.6 g(NO$_x$)/kg(ke)	1.1 to 5.0 g(NO$_x$)/kg(ke)
Global Fuel Consumption	270.1 Tg(kerosene)/yr	96.4 Tg(LH$_2$)/yr
Global H$_2$O emissions	340.4 Tg(H$_2$O)/yr	868.0 Tg(H$_2$O)/yr
Global NO$_x$ emissions	1.04 Tg(N)/yr	0.088 to 0.411 Tg(N)/yr

Table 2 - Fuel and emission properties of kerosene and LH$_2$.

5.2.1 Carbon Dioxide

While hydrogen combustion does not emit CO_2, it is necessary to take CO_2 into account, as CO_2 has an atmospheric lifetime of several decades. Therefore, in the situation in study of instantaneous substitution of the entire fleet, the effect of aviation CO_2 previously emitted will be felt long time after the substitution. In fact, the amount of aircraft CO_2 emissions in such a scenario would prevail more than 100 years after the end of its emission, including the consequent change in radiative
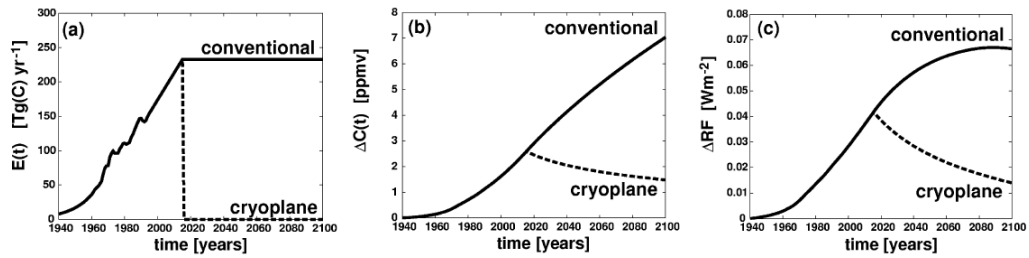

Figure 26 - (a) Aircraft CO2 emissions E(t), (b) Aircraft contributions to the atmospheric CO2 concentration C(t), (c) consequent RF(t)

forcing it brings. [7]

	Kerosene	Hydrogen
2015	0.041 W/m^2	0.041 W/m^2
2050	0.061 W/m^2	0.025 W/m^2
2100	0.066 W/m^2	0.014 W/m^2

Table 3 – Aircraft-induced RF change done by CO2. [7]

5.2.2 Nitrogen Oxides

NO_x originates from oxidation of ambient nitrogen at high temperature in the combustors of aircraft. This means that it is dependent on the temperature and both combustion of kerosene and hydrogen will produce it at the temperatures reached in a turbofan's combustion chamber.

These emissions modify the climate by producing O_3. The relation of increase in O_3 seems consistent
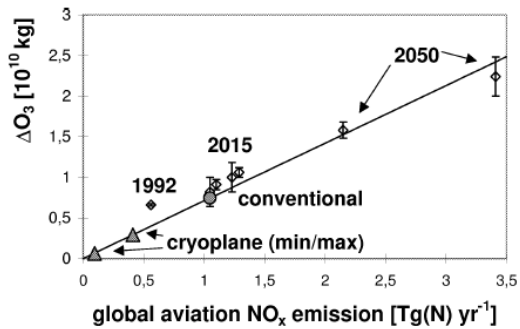

Figure 27 - Annual mean changes of the total O3 mass in the troposphere (up to 100 hPa) of the northern hemisphere due to aircraft NOx emissions.

with the emission of NO_x from aviation in the troposphere of the northern hemisphere. [8]

NO_x not only disturbs the atmospheric O_3 balance but also affect the CH_4 abundance. Since an increase in O_3 leads to an increase in atmospheric OH, and as the reaction with OH is the major sink of CH_4, aviation causes a reduction of the atmospheric CH_4 abundance. [7]

Both computational [5] and experimental [7] attempts show that hydrogen usage reduces the emission of NO_x in turbofans. The value is still estimated, but a reduction of 60% is expected.

	Kerosene (measured)	Hydrogen (estimated)
NO_x consequent O_3-RF	0.054 W/m^2	0.021 W/m^2
NO_x consequent CH_4-RF	-0.036 W/m^2	-0.014 W/m^2

Table 4 - Comparison of the consequences of different NO_x emissions in O_3-RF and CH_4-RF in 2015 [7]

5.2.3   Water Vapor

Water Vapor is the main emission of hydrogen-powered aircraft. Unlike other types of emissions, H_2O emission would increase in this scenario, 2 to 3 times more.

While water vapor is a greenhouse gas, it remains in the atmosphere only days to weeks and the total water emissions of aircraft amount to a change in water concentration in the troposphere of approximately 0.4%. Additionally, its direct influence on radiative forcing is much smaller. The highest estimates amount to a change from 0.0008 to 0.0019 W/m^2 in H_2O-RF with the complete replacement of the fleet. [7]

5.2.4　Contrails

While the direct effects of the increases water vapor are of smaller amplitude, the indirect consequences are of importance. One of them in the formation of contrails which are screated in sufficiently cold and moist ambient air as an indirect result of the release of aircraft water vapor. As additional high and thin clouds, contrails affect the radiation balance of the Earth's atmosphere.

Contrail formation depends on many characteristics, such as: H_2O emission index, combustion heat (per unit of fuel) and the overall propulsion efficiency, as well as the conditions of the atmosphere, such as: temperature, humidity and pressure.

All of those characteristics are used on a global fuel consumption map. [9] Allowing to notice the areas of densest air traffic with the highest contrail coverage.

In terms of global mean changes in RF, conventional fleets have a change of 0.052 W/m^2 while a hydrogen fleet has an increase to 0.081 W/m^2. [7] A point to keep in mind is that this change in RF is constant. As contrails last minutes to hours.
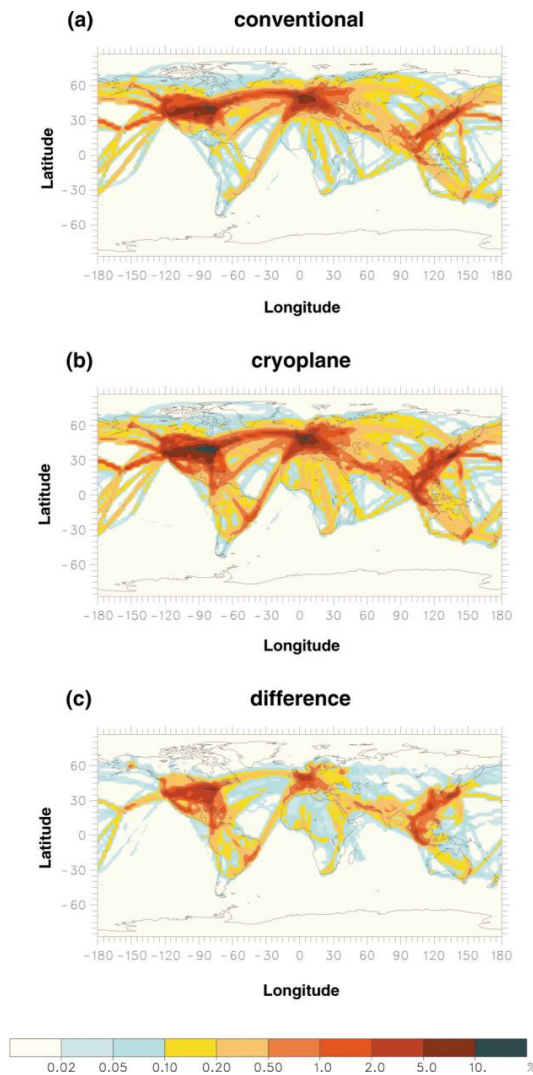

Figure 28 - Annual mean of the total actual contrail coverage (in%) for the (a) conventional and (b) hydrogen fleets in 2015. (c) difference between (a) and (b). [7]

5.2.5   Total effects

Table 5 shows the study's results with a total radiative forcing. Since CO_2, the component emitted by kerosene use, has over 100 year of permanence in the atmosphere, while the contrails, the RF component that increases by the use of hydrogen, has an instant, but minutes long influence, the result is an instant increase of RF with the instant change to hydrogen. As the years pass and the CO_2 is removed from the atmosphere, the values will lower until the only components emitted by the aircraft have a small permanence time in the atmosphere, nullifying the long term effects.

		Kerosene	Hydrogen
CO_2	2015	0.041	0.041
	2050	0.061	0.025
	2100	0.066	0.014
NO_x	CH_4	0.054	0.021
consequent	O_3	-0.036	-0.014
H_2O		0.0008	0.0019
Contrails		0.052	0.081
Total	2015	**0.111**	**0.131**
	2050	**0.132**	**0.115**
	2100	**0.137**	**0.104**

Table 5 - Contributions to RF [W/m2] for the conventional and hydrogen scenarios for 2015, 2050 and 2100

This shows that kerosene use has long term consequences in the atmosphere that cannot be ignored. On the other hand, while hydrogen combustion has an immediate impact on the atmosphere, the effect has considerable less long term impact.

Of course, this is simply a study with high limitations. It is not expected an instant change in the global aircraft fleet. In fact, it is possible to have aircraft using both fuel types with a natural progression towards a full hydrogen only fleet. In fact, such a scenario allows for a smoother transition, allowing a reduction in the spike in RF of a fast fleet transformation.

6 Conclusions

This study allowed an insight of the production, storage and consumption of hydrogen in aircraft. It showed the actual commercial methods of production and its viability along with its competitiveness with fossil fuels. At this point the main factor against it is economical, although there are additional difficulties regarding infrastructure.

In terms of production, the cheapest ways of producing hydrogen are also the ones which have greater environmental harm. Nowadays, with the growing concern about the environmental impacts of gaseous emissions, there are expected possible changes in the environmental legislation and taxation. Therefore, and taking into account uncertainties relative to, for example, feedstock prices, the H_2 production methods more utilised will be the ones which will have more technological developments, having the lowest environmental impact and costs.

The storage methods for aircraft is at this point the main engineering challenge in design when compared with conventional aircraft. This is due to complexity of the storage as well as the low energy per volume characteristic of the hydrogen. This fact might encourage new configurations of aircraft that have an increased relation of volume per surface to reduce drag, such as blended wing body.

In term of propulsion is where hydrogen shines with it high versatility, being able to be used with any of the traditional propulsion methods such as turboprops and turbofans, even when mixed with kerosene. As well as being used for generation of electricity for electric motors, that being also possible to be hybrid with both hydrogen tanks with fuel cells and batteries.

This fact makes it so hydrogen can be used with versatility as it is the middle point in performance between kerosene and batteries. As such, it can allow a smoother transition from fossil fuels to renewable energies. Especially considering that it is obtainable from both fossil fuels, such as natural gas reforming and renewable energies such as electrolysis.

Finally, the study of emissions shows that the changes to the environment are different with a change to hydrogen as fuel. The reduction of CO_2 must be balanced with the increase of contrails, characteristic of the high water vapor emissions of hydrogen.

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