POLITECNICO DI TORINO

Master's Degree in
Aerospace Engineering

Master's Degree Thesis

Analysis of a sustainable infrastructure to support commercial supersonic flight

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Alla mia famiglia,

unico supporto sempre presente,

ogni mio successo vi appartiene.

Summary

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Abstract-ENG

The aim of this thesis is to provide a green hydrogen production system. Dimensioning a solar arrays infrastructure and evaluating its feasibility in terms of power required is the first part of the conceptual design process. That power has to be enough to permit the process of liquefaction of the hydrogen, then storage it into pressurized tank which keep hydrogen at subfreezing temperature by means of high pressure, in order to maintain H_2 in a liquid state.

The second part of the treatment could be divided in two subsections:

- Subsonic case
- Supersonic case

In both case we will consider an airline company that operate in a specific airport. Passing through the calculation of the hydrogen needed by the aircraft, we will find the amount of daily fuel required to accomplish the mission, by each case considered.

After that, we will repeat previous calculation using as input parameter the daily liquid hydrogen needed and the energy required for each kg, in order to know how much wide our solar array infrastructure should be to make up for the daily power requirement.

Another aspect we must dwell on is the refueling operation of the hydrogen from the tank where the fuel is contained to the airplane aft-end. Because in many conceptual projects of LH_2 , the tank is situated in the rear part of the airplane due to the volume

required. We will evaluate another key role point of view that regard the refueling time using some equation and cross-checking calculation for the time needed to full the tank.

Last but not least, it is important to verify the feasibility of the project through the analysis of the direct operative cost, in order to compare the ticket price that passengers will pay using liquid Hydrogen instead of kerosene. To define that result, we have to frame which would be the price of the hydrogen, creating a trend to 2050 to foresee how much Hydrogen could be competitive in the future when the demand of that new fuel will increase and the efficiency of production process will be at the highest level.

Abstract-ITA

Lo scopo di questa tesi è quello di fornire un sistema di produzione di idrogeno verde. Dimensionare un sistema fotovoltaico e valutarne la fattibilità in termini di potenza richiesta è la prima parte del processo di progettazione concettuale. Tale potenza deve essere sufficiente per consentire il processo di liquefazione dell'idrogeno, quindi immagazzinarlo in serbatoi pressurizzati che mantengono l'idrogeno a temperatura criogenica e consentono all'idrogeno di rimanere nello stato liquido.

La seconda parte del percorso è suddivisa in due sottosezioni:

• Caso subsonico

• Caso supersonico

In entrambi i casi prenderemo in considerazione una compagnia aerea che opera in uno specifico aeroporto. Passando attraverso il calcolo dell'idrogeno necessario al velivolo, troveremo la quantità di carburante giornaliera necessaria per portare a termine la missione, caso per caso.

Dopodiché, ripeteremo il calcolo con un codice MATLAB utilizzando come parametro di input l'idrogeno liquido giornaliero necessario e l'energia richiesta per ogni kg, al fine di sapere quanto ampia dovrebbe essere la nostra infrastruttura di pannelli solari per compensare il fabbisogno energetico giornaliero.

Un altro aspetto su cui dobbiamo soffermarci è l'operazione di rifornimento dell'idrogeno dal serbatoio in cui è contenuto il carburante fino al tank

dell’aeromobile, situato nella coda dell'aereo. Solitamente il serbatoio è situato nelle ali dell’aeromobile, ma con le modifiche apportate, il serbatoio ad idrogeno avendo bisogno di ampio volume viene posizionato nella parte posteriore dell'aereo. Valuteremo un altro punto di vista del ruolo chiave per quanto concerne il tempo di rifornimento, utilizzando alcune equazioni e un cross check in merito al tempo necessario per riempire il serbatoio.

Infine, ma non per importanza, bisogna verificare la fattibilità del progetto attraverso l'analisi del costo operativo diretto per confrontare il prezzo del biglietto che i passeggeri pagheranno utilizzando Idrogeno liquido anziché kerosene. Per definire tale risultato, dobbiamo inquadrare quale sarebbe il prezzo dell'idrogeno, creando una tendenza al 2050 per prevedere quanto l’idrogeno potrebbe essere competitivo in futuro quando la richiesta di quel combustibile aumenterà e l'efficienza del processo produttivo sarà ad un livello più alto.

1 Introduction

This thesis consists in the development of an auto-sustainable airport infrastructure that could generate sufficient LH_2 to fulfill a daily request of fuel. It is developed in a scenario that has two important aspects to consider: on one hand there is the continuous growing of air traffic for many different reasons, considering people moving for job or just for holidays and, in the other hand, an urgent need for more effective and green transport base infrastructure for aircraft.

Air travel growth is due to many features such as low airfares, higher living standards, rise of tourism and travels and new airline business models. The need for a green aircraft stemmed from the worrying results of greenhouse gas emission analyses, such as CO_2 and NO_X. Airbus forecast shows an increase in air traffic of 4.3% over the next 20 years, through an RPK (Revenue Passenger Kilometers) analysis, and proves that commercial aviation industry and traffic are resilient to external shocks and doubles every 15 years.

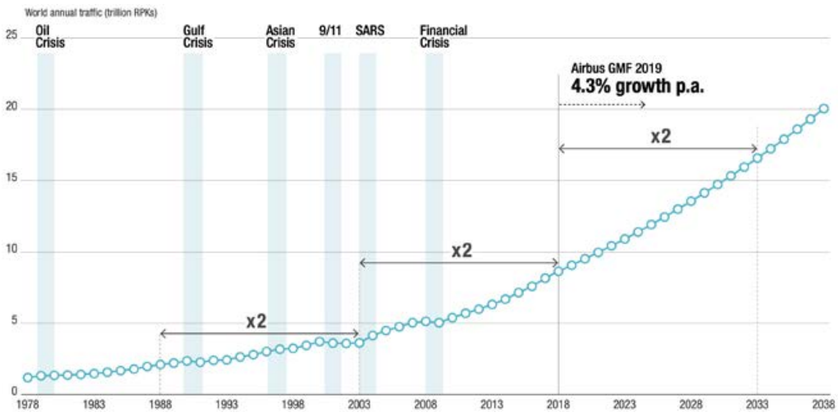

Figure 1-1 Air traffic increase along the year [1]

The sharp increase of traffic is strictly connected with the renewal and construction of airline fleets. Figure 1.1 shows Airbus' forecast for 2038: 36% of the new aircraft to be delivered will replace old airline aircraft, while 64% represents a growth. Asia-Pacific will account for 42% of deliveries while North America and Europe together for 36%, while a less percentage between 3% and 8% for Africa, CIS, Latin America and Middle est. In total 39210 aircraft units will be delivered. They will be divided in small (76%), medium (14%) and large (10%) aircraft.

The Intergovernmental Panel on Climate Change (IPCC), which is the international association responsible for assessing the science related to climate change, on October 2018 published its special report. This report deals with the impacts of global warming of 1.5°C compared to pre-industrial levels and supports the Paris Agreement. An increase of 0.2°C per decade is expected due to human activity as a result of past and current emissions. In order to stabilize warming at 1.5°C, global net CO2 emissions generated by human activities would have to decline to 45% of 2010 levels by 2030, reaching zero by around 2050. The IPCC considers carbon dioxide (CO2) as the principal greenhouse gas. Aviation represents approximately 2-3% of the total annual global CO2 emissions from human activities and, in addition to CO2, has an impact on climate from its non-CO2 emissions (e.g. NOX particles). CO2 emissions are projected to grow between two and four times by 2050 without policy interventions, because of the rapid growth of air transportation. Moreover, other aircraft pollutant emissions, including Nitrogen Oxides (NO_X), Unburned Hydrocarbons, Carbon Monoxide (CO) and

Sulphur Oxides (SO_X) are dispersed at all levels of atmosphere. This fact shows a worrying scenario: these substances directly or indirectly cause stratospheric ozone depletion (O_3), causing harmful effects on human health and the Earth's ecosystem.

Since aviation was born, the only type of propellant available was the kerosene, and all the aircraft project were thought around it, but through this process, the combustion of carbon-based fuel, we have the production of $CO + CO_2 + NO_x$ and other dangerous constitutive.

Nowadays, there are a lot of study-case to convert propulsion in a zero-emission way.

The aim of this thesis is to manage the infrastructural transition of an airport from the carbon-based fuel to a new type of propellant: Liquid Hydrogen (LH_2).

In 2020, the European Commission adopted a new dedicated strategy on hydrogen. It will bring together different strands of action from research and innovation via production and infrastructure to the international dimension.

The strategy will explore how producing and using renewable hydrogen can help decarbonize the EU economy in a cost-effective way, in line with the European Green Deal.

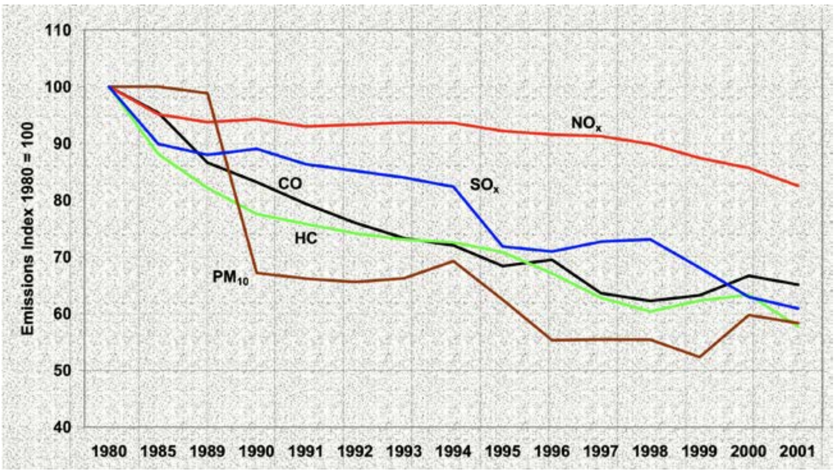

Figure 1-2 Pollutants trend evolution [2]

This table show how, thanks to evolution of technology, the level of pollution has always been in the spotlight by the slightly reducing of the pollutant's components. But this is not enough due to the increase of air traffic.

2 Hydrogen

2.1 Properties

Liquid hydrogen has been used as a fuel in space technology for several years directly mixed with liquid oxygen. It is lighter than kerosene and has fewer potential risks compared with compressed gas in terms of storage pressure. However, hydrogen liquefies at 20K. In the following table are showed all the properties of hydrogen:

Chemical Formula	H_2
Molecular Weight	2.016
Boiling Point @ 1 atm	−423.2°F (−252.9°C)
Freezing Point @ 1 atm	−434.8°F (−259.3°C)
Critical Temperature	−400.4°F (−240.2°C)
Critical Pressure	186 psia (12.7 atm)
Density, Liquid @ B.P., 1 atm	4.42 lb./cu.ft. (70.8 kg/cubic meter)
Density, Gas @ 68°F (20°C), 1 atm	0.005229 lb./cu.ft. (0.0838 kg/cubic meter)
Specific Gravity, Gas (air=1) @ 68°F (20°C), 1 atm	0.0696
Specific Gravity, Liquid @ B.P., [water=1 @ 68°F (20°C)]	0.0710
Specific Volume @ 68°F (20°C), 1 atm	191 cu. ft./lb.
Latent Heat of Vaporization	389 Btu/lb. mole
Flammable Limits @ 1 atm in air	4.00%–74.2% (by Volume)
Flammable Limits @ 1 atm in oxygen	3.90%–95.8% (by Volume)
Detonable Limits @ 1 atm in air	18.2%–58.9% (by Volume)
Detonable Limits @ 1 atm in oxygen	15%–90% (by Volume)
Autoignition Temperature @ 1 atm	1,060°F (571°C)
Expansion Ratio, Liquid to Gas, B.P. to 68°F (20°C)	1 to 845

Table 1- Hydrogen properties [3]

A state-of-the art technique for storing maximum hydrogen in a restricted volume is to convert hydrogen gas to liquid hydrogen by cooling it to a very low temperature. Hydrogen turns into a liquid when it is cooled to a temperature below 252°C and 1 atm, liquid hydrogen has a density of about 71 $\frac{kg}{m^3}$. At this pressure, 5 kg of hydrogen can be stored in a 75-liter tank. In order to maintain liquid hydrogen at this temperature, tanks must be perfectly isolated. That's why we need cryogenic tanks. LH2 is obtained from gaseous hydrogen by successive compression, cooling, and expansion processes. Hydrogen is produced by the steam reforming of natural gas, the electrolysis of water and the dissociation of ammonia. Hydrogen is also a by-product of petroleum distillation and chlorine manufacture.

Liquid hydrogen is used for rocket launch and is directly mixed with oxygen. The only exhaust product that came out from combustion is water vapor. Due to density, it requires larger volume to be contained. Whereas if it is combined with the air located in the atmosphere, there is NO_x need to be added to water vapor as waste gas.

Storage vessels require sophisticated insulation techniques to minimize unavoidable heat transfer leading to hydrogen loss via boil-off. Research in this area is focused on finding improved insulation and cooling methods. Hydrogen boil-off and the high cost of sophisticated insulating techniques required for maintaining very low temperatures coupled with the initial energy cost of creating liquid hydrogen make this method of hydrogen storage impractical for application in hydrogen fuel cell–powered vehicles.

Hydrogen is also one of the most abundant elements on the planet, so it would be very convenient to make it a renewable source of energy. Another important advantage is that LH2 contains 2.8 times more energy than aircraft kerosene per kilogram. This means that for the same energy value great weight savings can be achieved. The propellant combination (Hydrogen burning with oxygen) forms non-toxic and invisible exhaust gas. This combination has a high specific impulse and consequently payload capability increases.

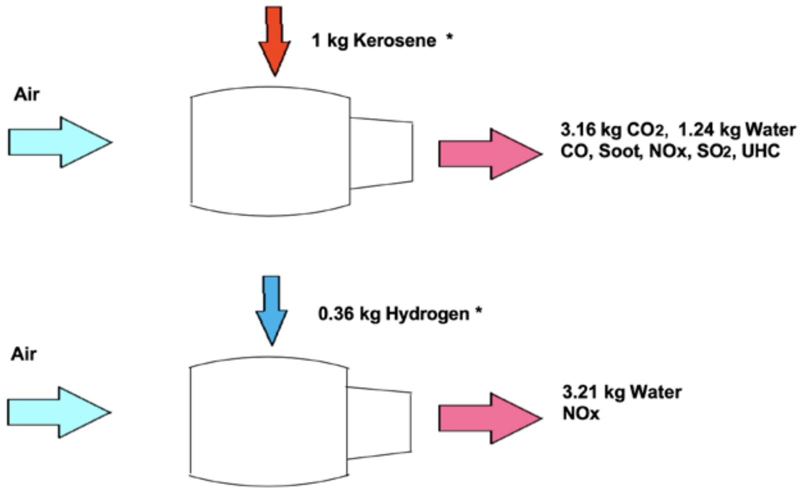

Figure 2-1 – Hydrogen efficiency compare with kerosene [4]

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2.2 Types of Production

Most commonly we hear of “grey”, “blue” and “green” hydrogen, produced using methane gas, methane gas with carbon capture and storage technology and renewable energy, respectively. However, there are also other colors in the hydrogen rainbow, which are:

- Grey – grey hydrogen is the most common form and is generated through steam reformation of natural gas or methane.
- Blue – blue hydrogen is generated from the same process as grey hydrogen, but the carbon is captured and stored. instead of being released into the atmosphere.
- Green – green hydrogen is produced by electrolysis using electricity generated by renewable sources such as wind and solar.
- Black – black hydrogen is extracted from fossil fuels, mainly coal.
- Turquoise – turquoise hydrogen is produced by a process known as “methane pyrolysis” which involves natural gas being passed through a molten metal. This process also produces solid carbon.
- Pink – pink hydrogen is generated via electrolysis using electricity generated from nuclear power.
- Purple – purple hydrogen is made using nuclear power and heat through combined chemo thermal electrolysis splitting of water.

- Red – red hydrogen is produced by a process known as “methane pyrolysis” which involves natural gas being passed through a molten metal. This process also produces solid carbon.
- White – white hydrogen is naturally-occurring geological hydrogen found in underground deposits and produced through fracking.
- Yellow – yellow hydrogen is produced by electrolysis using electricity generated by solar power.

The figure below shows all the possible process to product liquid hydrogen from each source of energy. Water for sure is the most abundant source from which generate the hydrogen, but it is also much expensive due to the cost of energy utilized for the electrolysis process.

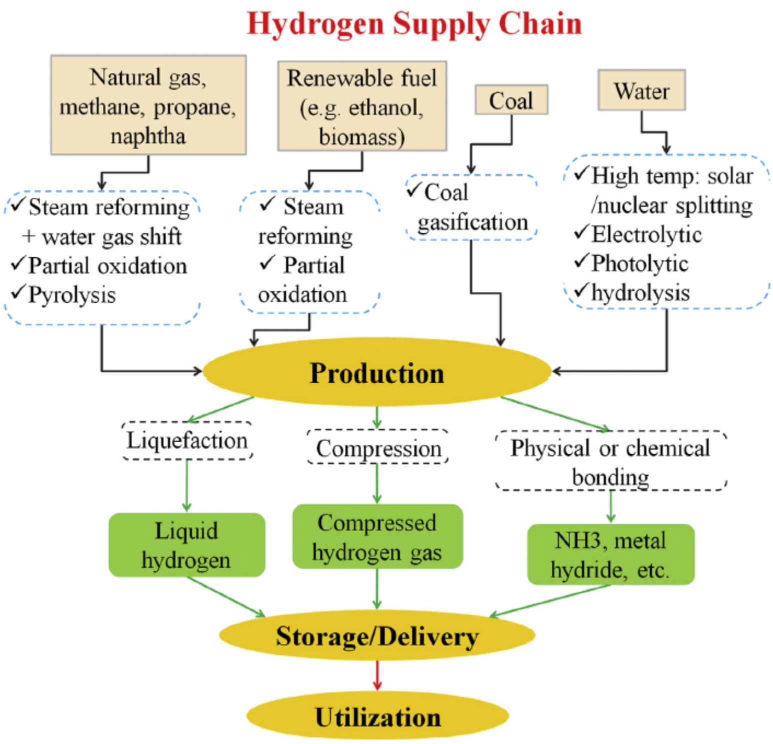

Figure 2-2 – Hydrogen supply methods [5]

2.2.1 Green hydrogen

In this essay we will consider only green production of hydrogen. This type of production is characterized by the absence of coal or other carbon-based fuel as power source.

The input power is only given by renewable energy source (e.g., solar, wind, hydroelectric). We will consider solar energy by means of solar array infrastructure. This type of energy sources is growing day by day spreading like wildfire. So, it would be easy to reach a big amount of energy without depending on the power line. The only cost we have to face off is a one-time amount for the infrastructure. But that cost could be amortized while using it and after the recovery of the initial investment, all the earnings will be a net income.

This process of productions take place thanks to electrolysis process in which an amount of energy is used to create a difference of potential is given at two electrodes trough the chemical reaction:

$$\textbf{Oxidation } 2H_2O \longrightarrow O_2 + 4H^+ + 4e$$

$$\textbf{Reduction } 4H_2O + 4e \longrightarrow 2H_2 + 4OH^-$$

$$6H_2O \longrightarrow 2H_2 + O_2 + 4H^+ + 4OH^-$$

$$2H_2O \longrightarrow 2H_2 + O_2$$

This reaction is guaranteed by strong acids such as sulfuric acid (H_2SO_4) and strong bases such as sodium hydroxide (or caustic soda, NaOH) and potassium hydroxide

(KOH) used as electrolytes. Their role is to increase the energy and the speed of the reaction producing as much hydrogen possible.

On average, 50 to 65 kWh of energy are required to produce one kg of hydrogen using the classic method. An ideal water electrolyzer with 100% efficiency would consume 39.4 kWh per kg of hydrogen.

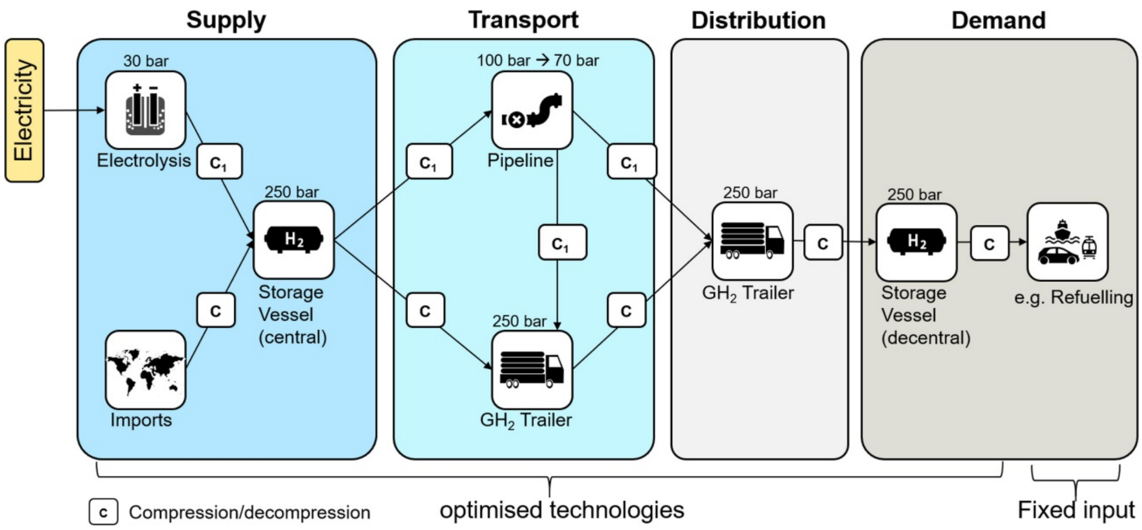

Figure 2-3 – Syntethic process for green hydrogen [6]

2.2.2 Blue hydrogen

Blue hydrogen is when natural gas is split into hydrogen and CO_2 either by Steam Methane Reforming (SMR) or Auto Thermal Reforming (ATR), but the CO_2 is captured and then stored. As the greenhouse gasses are captured, this mitigates the environmental impacts on the planet. The 'capturing' is done through a process called Carbon Capture Usage and Storage (CCUS).

Steam reforming of methane is a well-developed and highly commercialized process which produces about 48% of the world's hydrogen. This method can also be applied to other hydrocarbons such as ethane and naphtha. Heavier hydrocarbons cannot be used because they can contain. Other processes, however, such as partial oxidation, are more efficient with heavier hydrocarbons.

SMR involves the reaction of methane and vapor in the presence of catalysts. This process, on an industrial scale, requires an operating temperature of about 800 ° C and a pressure of 2.5 MPa. The first step is the decomposition of methane into hydrogen and carbon monoxide. In the second phase, called the "shift reaction", carbon monoxide and water are transformed into carbon dioxide and hydrogen. The energy content of the hydrogen produced is currently higher than that of the user methane but the enormous amount of energy required for the operation of the plants increases the efficiency of the process to about 65%. By adsorption or membrane separation, the carbon dioxide is separated from the gas mixture, which is further purified to remove other components. The remaining gas, formed by about 60% of combustible parts, is used to power the reformer. Processes of this type on an industrial scale occur at temperatures of 200 ° C or higher, and require the use of heat to start the process.

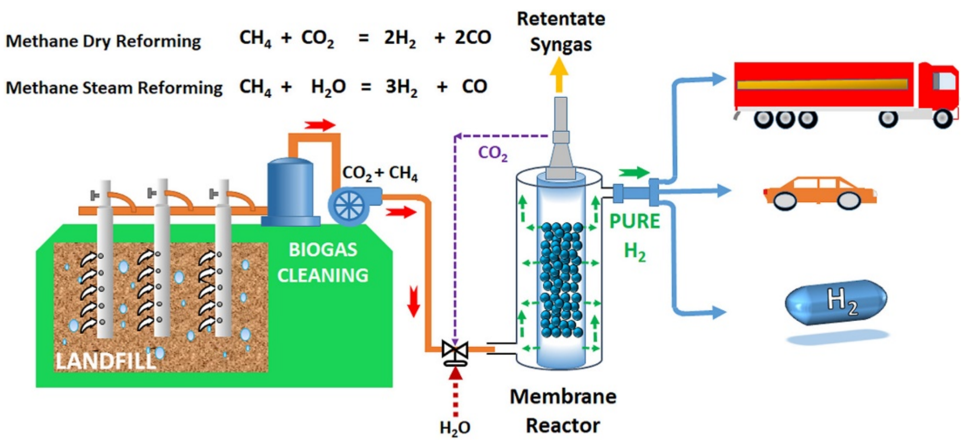

Figure 2-4 – Steam reforming process [7]

The cost of natural gas strongly affects the final price of hydrogen, according to some analyzes it constitutes 52% -68% of the total cost for large plants, and about 40% for smaller plants.

The costs of SMR are slightly lower than the one reached by electrolysis and competitive with lots of other technologies, it also involves a very low environmental impact. Some authors argue that SMR technology can be cost-effective, when combined with vehicle power, for application to small-scale production fuel cells.

2.3 Hydrogen transportation

The object of this task was to select a suitable and economic method for the supply of liquid hydrogen to the airport site in sufficient quantity to meet scheduled aircraft fueling requirements. The principal decision made was of locating the site for the hydrogen liquefaction facility. The required area for a plant of the capacity contemplated is quite large and for reasons of property availability and/or cost, the plant might have to be located at some distance from the airport.

Hydrogen is, for example, less flammable than petrol and its detonation is not easy (confined spaces and high concentrations are required, which can be avoided with the use of sensors). Natural gas is also more dangerous because, notoriously, it burns easily in presence of air, its spontaneous combustion temperature is lower and it explodes at lower concentrations. Yet, it is today one of the main sources for the production of electricity (gradually replacing oil) and (almost) all of us have it in our homes. Hydrogen, being very light (the lightest of the elements), when it burns it disperses quickly and the flame goes upwards. On the contrary, traditional fossil fuels do not disperse and are considered more dangerous.

Hydrogen is a fuel and, like all fuels, it brings with it a huge advantage: it can be stored for as long as you want and used when and where you want. Electricity, on the other hand, is not easy to store. Especially for long periods.

For the study, three different methods of transporting liquid hydrogen between the hydrogen liquefier and liquid hydrogen receiving-storage tanks located at the airport were considered [8]:

1. On-site liquefier - no transport
2. Vacuum jacketed pipeline
3. Truck-trailer
4. Railroad tank car

Since hydrogen is a gas, the first obvious solution is to use gas pipelines. Or, better, "hydrogen pipelines", which allow the transport of gas over long distances across entire continents. Here you have two alternatives: blended with natural gas using the existing network or by building a dedicated network.

3 Reference vehicles

For the reference vehicles utilized in this thesis, we have to consider them in two groups, supersonic and subsonic case. The supersonic case is a project of a supersonic airplane redesigned for LH2 usage. The trend of the aircraft manufacture is to bring aviation to a next level with projections to 2030 for the introduction of these new and innovative vehicles. This process took place for many manufacturers like Airbus and Boeing that respectively through the zero-e and net-zero carbon are redesigning their main airplanes to reach the zero-emission target. So, subsonic case was taking in consideration to make a clear comparison between the price of the ticket variation in LH2 usage between the two cases. In subsonic case were used as reference two medium range airplane such as: Boeing 737 and A-320.

3.1 Green Concorde

Taking as a reference the known Aerospatiale Concorde, using performances and features data from the existing project, it has been re-sized to make it eligible for liquid hydrogen application as propellant.

Figure 3-1 – Aerospatiale supersonic Concorde [9]

This supersonic civil aircraft is the basis from which the project “Green Concorde” takes inspiration. Our duty is to reinvent this type of airplane by using LH2 as fuel and this is the reason why most part of our decisions was made taking into account the solutions adopted by the Concorde. The Concorde production started in 1966 and only 20 specimens were built before the end of production in 1979. The first two prototypes never entered in services in order to act as a test bed for the production techniques and further development. Only British Airways and Air France bought the

Concorde and it officially become operational the 21st of January 1976. The principal routes were Paris - Dakar - Rio de Janeiro, London-- Bahrain and London/Paris - New York. Last flight happened the 26th of November in 2003.

The Concorde was unique considering the period when it was developed. Starting from the wing, it had an ogival delta wing designed to guarantee the best performances at high speeds. There were no horizontal control surfaces but only ailerons ensuring stability and longitudinal and lateral control. These aerodynamic characteristics forced flight at high angles of attack specially during take-off and landing manoeuvres: engineers adopted a variable trim nose to ensure visibility to pilots.

Talking about engines, the 4 Olympus 593 were designed to sustain supersonic speeds even without the utilisation of afterburners allowing reduced fuel consumption during cruise. They were positioned under the wing because variable shape intakes were required for supersonic flight.

Figure 3-2 Green Concorde

In our project the fuel used is LH2. In spite of this, a clear reference to the design choices made for the Concorde has been maintained as it is the aircraft already existing that comes closest to our requirements.

These are the main reasons why we choose as example the Concorde for our purpose of a new design for a civil supersonic aircraft using LH2 as fuel.

Through the estimation of the necessary thrust requirement, we decided the number and power of each thruster using as reference known propellers that could be converted for lh2 usage.

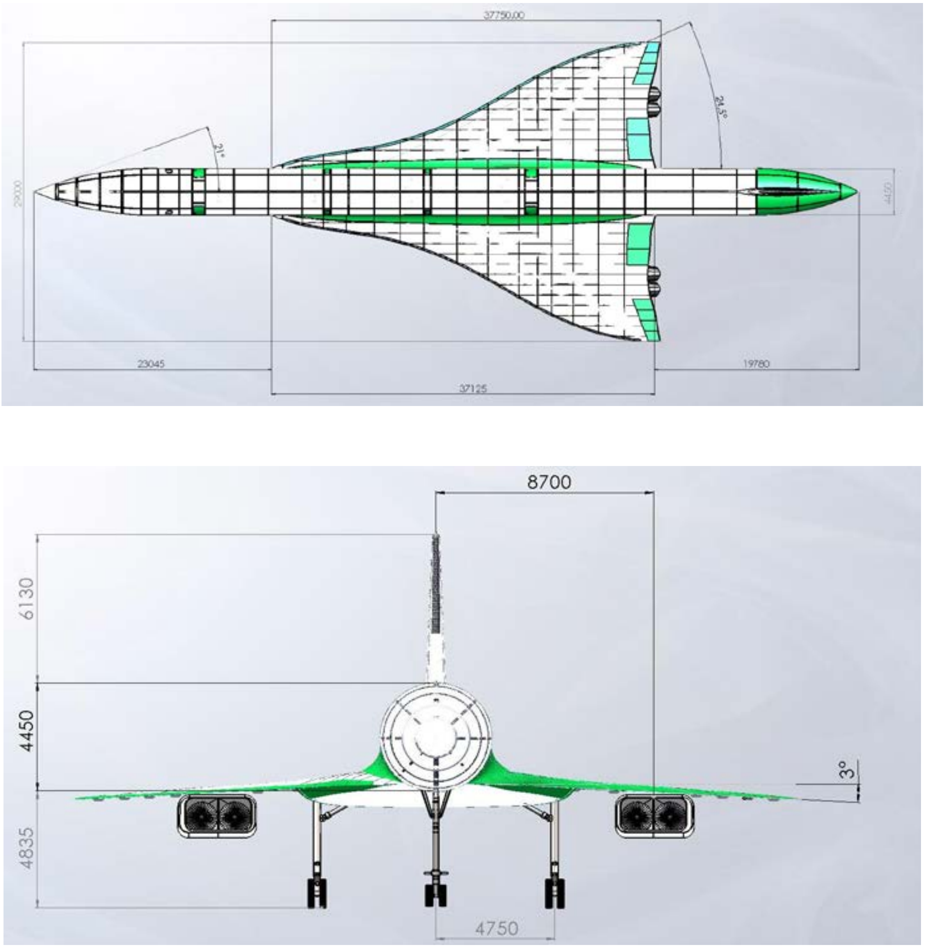

Figure 3-3 – Green-Hydrogen re-conversion project of Concorde [3]

This aircraft differs from the conventional ones for several reasons, including the fact that the cockpit is not located in the nose and that the fuel used is LH2. In fact, the fuel storage created many problems during this project phase because of its volume (about 333 m^3) and required a careful optimization. To be conservative and to consider the boil off problem even during the preliminary analysis phase, the fuel volume was increased by 5%, resulting 350 m^3.

Assuming that our aircraft is similar to the Concorde with ogival delta wing but without Canard.

Passing through Astrid (software under development by Politecnico di Torino), we insert all the known and calculated parameters to get the output of the Thrust-Weight-ratio curves. The last part of the conceptual design consisted in the evaluation of the final weight of our aircraft with all the various subsystems to be considered for the production of the aircraft and the definition of the mission profile with Astos. All the subsystems were sized, such as: landing gear, avionics system, anti and de-icing system, electrical system, and environmental system. Last but not least, a MATLAB file was generated for the sizing of the tanks and to optimize its distribution due to volumes occupied by hydrogen: three times higher than kerosene. Finally, the CAD of the whole plane was done and also renderings of the internal parts and facilities.

Wetted area estimated	1191.09 m^2
Oswald factor	0.85
C_f	0.0015
Mission type	Best range
Range (>8000km)	9000 km
Cruise speed (M>2)	2209 km/h
SFC (cruise)	0.6 kg/hour/kg
SFC (with afterburner)	1 kg/hour/kg
E (supposed)	18
Fuel weight	23600 kg
Fuel % during landing	5 %
Take off duration	30 s
SFC (TO)	0.4 kg/hour/kg
Throttle during climb	95%
Absolute Ceiling	18500 m
SFC (climb)	0.5 kg/hour/kg
RC at Absolute Climb	300 ft/min
Max turn load factor	2.8
Turn altitude	4000 m
Turn speed	650 km/h
Wing area	518.57 m^2
Sweep angle	24.5°
Cruise mach	2.2
Thrust per engine	11723.88 kg

Lift coefficient take off	0.69
Profile drag coefficient	0.03
Glide ratio in take off configuration	8.67
Climb gradient (≥ 0.024 for FAA)	0.03
Thrust to weight ratio	0.19
Thrust per engine [kg]	18992
Thrust to weight ratio	0.52
Wing weight	17696.17 kg
Tail weight	1769.67 kg
Fuselage weight	25870.91 kg
Installed engine weight	15000 kg
Gear weight	6607.58 kg
Total empty weight	106590.30 kg
Fuel Weight	23600 kg
Payload	24750 kg
Take off weight	154836 kg
FCS	3670.88 kg
Hydraulic system	1468.3 kg
EPS	7341.75 kg
Fuel system	2936.7 kg
Air conditioning	11746.81 kg
Avionic system	4405.05 kg
Engine system	2202.53 kg
Furnishing system	5873.4 kg

Table 2 – Green Concorde specifications [3]

Based on the requirements, in particular the type of aircraft and the range (about 8000 km), the information given in reference to the Concorde is perfectly suited to our needs. In order to solve a weak point of the Concorde, it was decided to provide a hold of up to 30 minutes in case of missed approach.

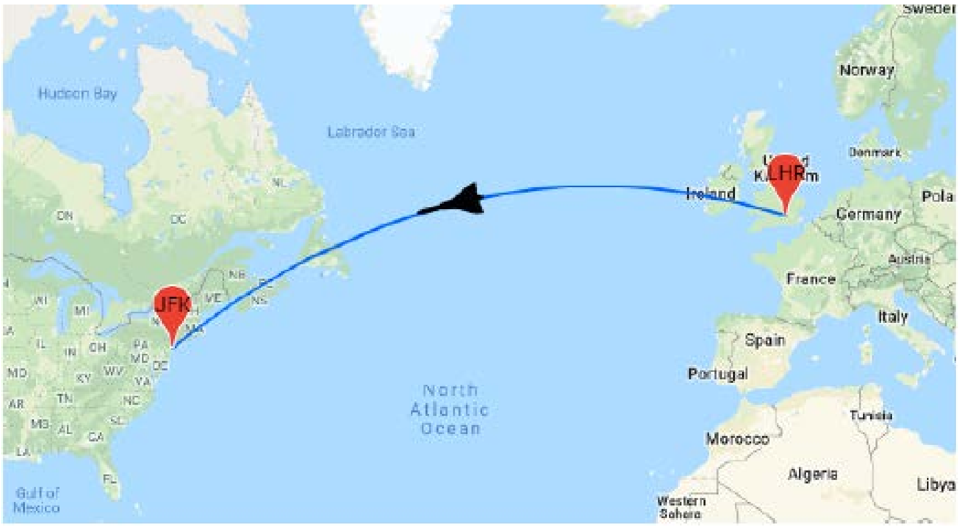

Figure 3-4 – Mission profile for Green Concorde [3]

The route that has been considered in order to define a realistic and economically interesting mission profile is London - New York. The aircraft is designed to meet the requirement in terms of range, but since the selected route is less than the requirements, as it is about 5500 km, it was possible to solve a weak point of Concorde, that is to increase its holding time from 10 to 35 minutes overall.

3.2 Airbus A-320

Airbus is for sure one of the most utilized airplanes in the aviation history. A-320 is the base of the 320 family in which figure some of the most known airplane worldwide like A-321 that is a bigger one and the A318-319 the smaller of the family. A320 create the base for the future economic success for Airbus. The aim of Airbus was to create different aircraft the share of components and design settings. This strategy gave to Airbus the possibility to compete with some other producer in the United States, in the economic and operative fields. Now Airbus is facing off its last project launched in 2020 called “Zero-E” to redesign some airplanes in LH_2 key. Two of the main challenges will be to store the fuel in the tank and to replace some components in the engine to maximize the output performances for hydrogen usage.

Figure 3-5 – Airbus A-320 [10]

In the table below, we can find some of the characteristics of the A-320 that we will need ahead about the treatment of some case related to ticket price and operative costs.

A320

Cruise speed	0,78 Mach
Endurance	6200 Km
MTOW	73000 Kg
Passengers	195
Fuel capacity	23859 L

Table 3- A320 specifications [10]

3.3 Boeing 737-800

The 737-800 is a fundamental piece of history aviation like the previous one. 737 is the best seller of his category in civil aviation. This airplane was born to be an economic airplane and all the work spent on it from Boeing has given to us an airplane capable of an incredible number of flight cycles thanks to a strengthened structure. An important factor is the easy maintainability which is a direct cost that could affect negatively the costs coming from the utilization of the vehicle. It is a medium range aircraft utilized by some many airline company around the world. Boeing give the possibility to company to acquire them in a leasing form and a direct maintenance service is fully given by the manufacturer. So that the possibility to utilized them without acquire the airplane in its full cost.

Figure 3-6 – Boeing 737-800 [10]

Following there are some specifications of the A320:

B737-800

Cruise speed	0,79 Mach
Endurance	5435 Km
MTOW	78245 Kg
Passengers	189
Fuel capacity	26022 L

Table 4 – B737-800 specifications [10]

4 Solar array dimensioning

In this chapter we will focus on the dimensioning of the solar array. But there are some preliminary assumptions to do before starting any calculation.

The idea is to create an infrastructure capable of producing liquid hydrogen directly on site. But one of the problems of the energy coming from renewable sources is that we cannot ensure a continue production, but we have to depend on the sun activity. For example, if it is a sunny day, we will have the maximum production expected, but if there will be some clouds our production will decrease proportionally.

The yield of solar panels is higher on sunny days with lower temperatures. In winter, when cloudy days, rains and fog appear, much depends on the sensitivity of your solar system. The latest generation photovoltaic cells are able to offer a good yield even on cloudy days, but most of the plants, in winter, with the presence of clouds and rain, manage to make only 25 - 30% of their normal production.

What should interest those who decide to invest in photovoltaics is not the yield of the solar panels in winter, but the overall yield over the year: if in that climatic zone in which you decide to install a solar system there are only a few days "Covered" per year, during the four seasons you will be able to meet your energy needs by compensating for the drop caused by adverse weather conditions. In Italy, two other geographical bands can be identified, an intermediate one which records between 2400 and 2600 hours of sunshine per year (between 6.5 and 7 hours per day) and one with fewer hours of sunshine but which nevertheless offers between 2200 and 2400 hours of sunshine per year (between 6 and 6.5 hours per day). For these reasons was intended to take as a reference the value of 6 hour of average sun per day. [11]

The conversion of solar radiation into electricity occurs thanks to the interaction between the luminous flow and a semiconductor material. To understand the conversion mechanism, one must recall the theory of energy bands for crystalline materials. A crystalline material has such a structure and compactness that it has an extensive superposition of valence orbitals of single atoms. In practice, an infinite set of energy levels to be constituted of continuous energy bands. By decreasing the distance between the atoms of the crystal, each atomic level originates a band that widens as the reciprocal increase's interaction. This widening can also cause the overlapping of the bands generated by different types of atomic orbitals. The band model can be applied to describe the properties crystalline solids of electrical conductors or insulators.

In general, an electrical conductor is characterized by partially filled valence bands or saturated with empty bands overlapping. The band of the crystal that exhibits energy levels vacuums accessible to electrons, thus making it possible for the metal to conduct electricity, is called conduction band. The valence band, on the other hand, is characterized by energy levels occupied by valence electrons. In the case of insulators, the valence band is saturated and is separated from the conduction band, empty, from a very high energy difference. This difference in height means that few electrons have energy enough to be promoted to the conduction band. For conductive materials, the two bands are overlaid, thus facilitating the passage of electrons.

Semiconductors have a band structure similar to an insulator, with the difference however that the energy difference between the full valence band and the empty conduction band is much smaller, of the order of 1eV.

Among the semiconductors most used in photovoltaic cells is silicon, whose lattice crystalline provides that each atom is surrounded by four other atoms, each of which puts in common one of the four valence electrons. With this type of bond, the structure of the silicon assumes a tetrahedral shape.

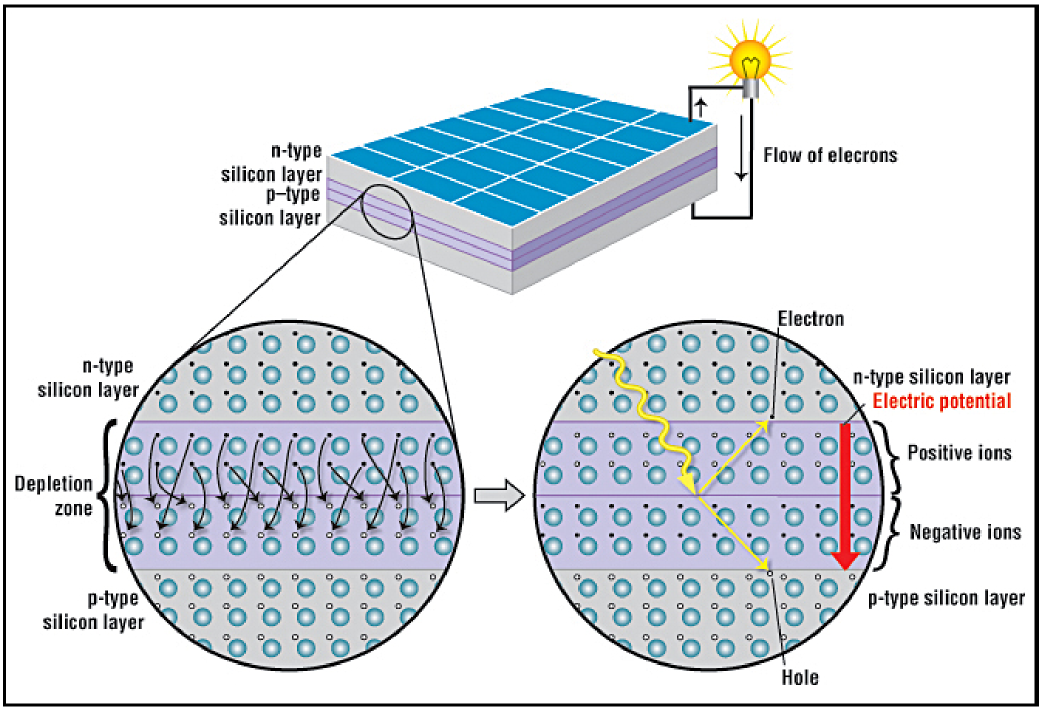

Figure 4-1 – Solar cell detail working process [12]

A photovoltaic panel transform solar energy into electric energy by means of silicon photovoltaic cell that absorb photon coming from the sunrays. Solar photons interact with the electrons in the atoms of silicon, some of these electrons are divided generating a flux of electric energy in a semiconductor material. Each photovoltaic panel has a cabled circuit on each cell that direct the energy flux to an inverter. The energy flux is in CC, but the inverter purpose is to convert it in AC to be unified to the current coming from every electric line. Then we have the transformer that increase the voltage of the current to keep it at the desired value for the purpose it has been thought for.

Figure 4-2 – Solar array example

There are essentially three types of photovoltaic panel:

- Mono-crystal
- Compact mono-crystal
- Thin film

Each of these types has its own characteristic in energy production. For this essay the panel with the best production of energy per m^2 has been chosen in order to take up the minimum possible area.

The best solution for our case was represented by a panel production of 370 W of energy with dimension of 1,55 m x 1,05 m. This panel has a production for m^2 of about 230 kW.

At the end of these preliminary assumptions we can go through the calculation starting from the fuel weight required in each study case:

- Subsonic case
- Supersonic case

The energy required for the electrolysis has been fixed at 50 Kwh for each kg of hydrogen produced based on some existing infrastructure that produce liquid hydrogen. But this value depends on the efficiency of the reaction. In the future this value could go down to product much hydrogen from the same energy.

Equation 1

$$Power\ required = fuel\ weight * \frac{electrolysis\ power}{kg}$$

Equation 2

$$Power\ required\ for\ hour = \frac{power\ required}{electrolyzer\ operative}$$

Where the value of electolyzer operative are the hour of working of the whole production infrastructure. In this case we assumed 16 hours operating. It is different from the average sun time because we are going to storage the energy during the day to guarantee at the system to work for the expected amount of time. The production has been thought to take place in the night because in case of lack of energy it could be replaced from the current coming from the electric line. That energy has the minor cost during the night according to furnishing zone cost of every provider.

Photovoltaic panels have to be a certain inclination to perform in the best way due to the incidence of solar rays and so their own efficiency. We consider a 36% of panel loss due to inclination and other factor that may affect energy production.

Equation 3

$$Solar\ array\ power\left[\frac{kW}{m^2}\right] = \frac{Power\ required\ for\ hour}{Avarage\ sun\ time * efficiency}$$

The efficiency is $1 - 0{,}36 = 0{,}64$

After that we can evaluate how much wider our solar array should be to accomplish the role that it has been thought for, through the relation:

Equation 4

$$Array\ dimension[m^2] = \frac{solar\ array\ power}{panel\ specific\ power}$$

4.1 Supersonic case

For the supersonic case we took in consideration the aircraft that came out from a project called "Green Concorde" in which the amount of fuel was evaluated in order to comply a flight from London to New York. The tanks in this case are located into the fuselage and not as always in the wing. This configuration has been adopted because the thickness of the tank needs to be higher than kerosene and the structure of the wing could not support that weight. So, the decision to place them under the passenger cabin and a big one in the aft-end.

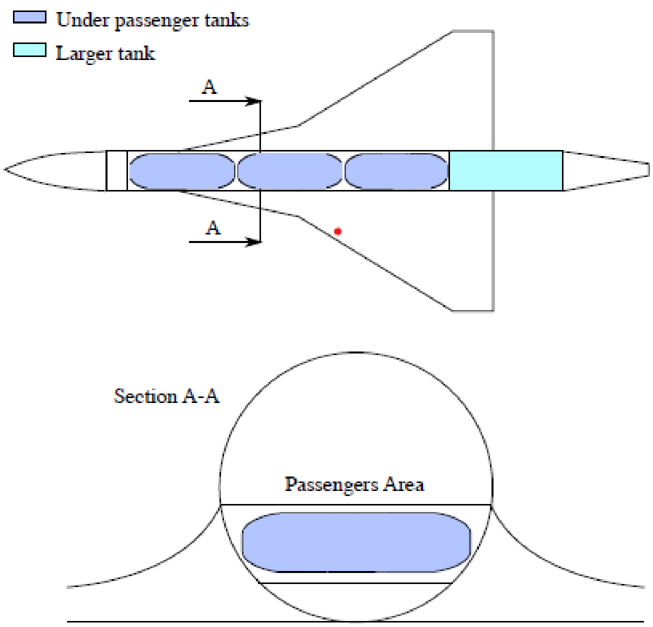

Figure 4-3 – Green Concorde tank distribution [3]

This configuration is designed on the basis of the criticisms of the previous one. It is characterized by a large rear tank with the fuselage diameter and by a parallelepiped shaped tank adequately rounded at the corners located under passengers. The latter was divided into 3 parts for construction and maintenance reasons. In the front part, between the nose and the passenger area, there is a free volume that could be used to store the luggage or some subsystems.

But the fuel capacity is intended to cover a flight of 9000 km. We are going to take in consideration the value of the distance between London and New York: $5500km$, also to report the comparison with the subsonic case in number of flying ours: 10hours. With the endurance considered, “Green Concorde” need a quantity of LH_2, equal to:

Equation 5

$$Liquid\ hydrogen\ required\ = \mathbf{17000}\ [kg]$$

The solar array power needed by the fleet to ensure a full day of work is:

Equation 6

$$Solar\ array\ power\ required\ per\ hour = \mathbf{5,66}\ [MW]$$

To meet that request of power our solar array dimension should be of:

Equation 7

$$Solar\ array\ dimension = \mathbf{24926}[m^2]$$

4.2 Subsonic case

An important aspect to underline is how to evaluate the fuel quantity that has to be produced by the whole system. For the subsonic case starting from the fuel quantity in liters and simply converting it passing through the density.

As said in section 2.1 we need almost 0.3256 kg of hydrogen for each kg of kerosene. This relation came out from the comparison of the two calorific energies owned by each type of fuel taken in consideration. The dimensionless number:

Equation 8

$$Calorific\ factor = \frac{calorific\ value\ kerosene}{calorific\ value\ H_2} = \frac{46.2}{141.9} = 0.3256$$

Create a direct relation to estimate how much fuel should we have onboard to evaluate the starting point from which our MATLAB code is written around.

Taking in consideration two of the most used airplane worldwide for the subsonic case and a medium range of flight Airbus 320 and Boeing 737-800, through the correct conversion of the fuel quantity into kilograms of hydrogen we could know how many kilograms of hydrogen will be necessary for each airplane.

4.2.1 A320

From the datasheet of the airplane in section 3.1, the fuel capacity of the tank using kerosene is around:

Equation 9

$$Kerosene\ capacity[l] = \mathbf{23859}\ liters;$$

The density of the kerosene assumed is 0,786;

Equation 10

$$Kerosene[kg] = Kerosene[l] * kerosene\ density\left[\frac{kg}{dm^3}\right] = \mathbf{18753}[kg]$$

Equation 11

$$H_2[kg] = Kerosene[kg] * calorific\ factor = \mathbf{6105}[kg]$$

4.2.2 B737-800

Equation 12

$$Kerosene\ capacity[l] = \mathbf{22596}\ [l]$$

Equation 13

$$Kerosene[kg] = Kerosene[l] * Kerosene\ density\left[\frac{kg}{dm^3}\right] = \mathbf{17760}[kg]$$

Equation 14

$$H_2[kg] = Kerosene[kg] * calorific\ factor = \mathbf{5782}[kg];$$

After that preliminary calculation, we have to assume how many refuel, a fleet of these two airplanes have to do to fulfill a day of operation of these airplanes.

Average Daily Block Hour Utilization of Total Large Narrowbody Fleet
(Seat Size 150+, Single Aisle)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
American	9.96	9.80	9.71	9.66	9.51	9.88	10.04	10.26	10.35	10.08	10.38	10.97
Continental	11.46	10.50	10.52	10.40	-	-	-	-	-	-	-	-
Delta	11.23	10.70	10.49	10.59	10.41	10.45	10.49	10.67	10.72	10.26	10.43	10.64
Northwest	10.03	9.59	-	-	-	-	-	-	-	-	-	-
United	10.41	10.24	10.43	10.06	10.30	10.14	10.14	10.26	10.16	10.26	13.33	10.48
US Airways	10.53	9.98	10.19	10.37	10.34	10.37	10.38	-	-	-	-	-
America West	-	-	-	-	-	-	-	-	-	-	-	-
--sub Network	**10.62**	**10.18**	**10.27**	**10.21**	**10.14**	**10.19**	**10.23**	**10.36**	**10.38**	**10.18**	**11.18**	**10.72**
Southwest	-	-	-	-	12.09	11.68	11.01	11.53	11.45	11.42	11.28	10.66
AirTran	-	-	-	-	-	-	-	-	-	-	-	-
jetBlue	10.19	8.17	12.43	12.51	12.69	12.91	12.67	12.72	12.92	12.42	12.40	12.51
Alaska	12.02	11.07	11.06	11.62	11.75	11.59	11.23	13.41	11.59	11.83	11.31	10.23
Virgin America	12.48	12.66	12.66	12.29	13.80	12.47	11.37	10.93	10.95	11.12	-	-
Hawaiian	-	-	-	-	-	-	-	-	-	-	8.83	10.18
-- sub Hybrid	**10.80**	**9.22**	**11.99**	**12.19**	**12.53**	**12.30**	**11.79**	**12.37**	**11.95**	**11.82**	**11.55**	**10.85**
Allegiant	-	-	-	5.90	4.49	4.70	6.09	8.09	7.64	7.58	7.72	8.08
Frontier	226.68	10.39	12.68	11.65	10.09	10.06	11.83	12.32	12.18	14.34	13.06	11.65
Spirit	14.51	14.40	15.11	13.86	12.78	12.38	12.75	13.17	13.52	11.54	12.74	12.24
-- sub ULCC	**113.07**	**11.80**	**13.64**	**12.40**	**10.77**	**10.37**	**11.05**	**12.04**	**11.97**	**11.71**	**11.79**	**11.17**
Total All Sectors	**10.94**	**10.01**	**10.55**	**10.55**	**10.55**	**10.58**	**10.57**	**10.88**	**10.84**	**10.70**	**11.33**	**10.80**

Table 5 – Block hour utilization Narrow-bodies [13]

According with the previous picture we can assume 10 hours of flight on average for each airplane. After that every aircraft should need two full refueling operations.

The fuel consumption per hour of each plane is around 2000 $[l * hr]$ in the kerosene version and about 511 kg for the H_2 version. The value about the consumption takes in consideration the endurance of the airplane in full tank condition. We will take in consideration two airplanes of each type. Every airplane could manage an entire day of flight for each refuel.

Through a simple calculation the amount of fuel needed is:

Equation 15

$$Subsonic\ case[kg] = 2 * (5782 + 6105) = \mathbf{23774}[kg]$$

Finally, this is the input parameter for the MATLAB code for the solar array described previously will gave to us the amount of power required and how much wider our solar array should be to ensure a full operative situation according with the previously assumption and formula shown.

The solar array power needed by the fleet to ensure a full day of work is:

Equation 16

$$Solar\ array\ power\ required\ per\ hour = \mathbf{7,92}[MW]$$

To meet that request of power our solar array dimension should be of:

Equazione 17

$$Solar\ array\ dimension = \mathbf{34861}\ [m^2]$$

5 Refueling

The refueling is, for sure, another aspect to evaluate in terms of security of the air man, passengers and the whole structure of the airport. Hydrogen is a very flammable element and need to be treated with accuracy by trained staff to avoid unexpected accident. Even though operations must be complied in fast way possible to permit to the airline company to do not miss its slot.

Refueling could be done in two different ways:

1. Underground pipeline
2. Tanker

In both of them a pump is required to refill the tank of the airplane. Hydrogen need to be compressed at high pressure (almost 700 bar) to keep it in liquid state and to avoid boil-off. Without these precautions hydrogen due to its volatility will leave the tank.

In terms of time required for the full refill a MATLAB code will help us to understand which are the pressure to manage the refueling system.

For this case we assume a pump of a diameter of 0.1 m and we can find the value of the exit velocity of the hydrogen through the pump. Then we can find thanks to the section and the density the flow that could pass through the pump.

Equazione 18

$$\Delta p_{H_2} = 150[bar]$$

$$\Delta p = difference\ of\ pressure\ between\ tanker\ and\ aircraft\ tank$$

$\rho_{H_2} = 0.071[\frac{kg}{dm^3}]$

$g = 9.8\ [\frac{m}{s^2}]$

Equation 19

$$V_{exit} = \sqrt{\left(2 * g * \left(\left(\frac{p_{H_2} * 100000}{g}\right) + 10\right)\right)} = 5477[\frac{m}{s}]$$

Equation 20

$$Pump\ section = 0.10^2 * \frac{pi}{4} = 0.0079[m^2]$$

Equation 21

$$Flow\ rate = \left(S_{pump} * V_{exit} * \rho_{H_2}\right) * 60 = 183.25[kg/min]$$

This flow could ensure a refueling time of:

Aircraft	Hydrogen quantity [kg]	Time refuel [min]
Boeing 737-800	5782	**31.55**
Airbus A320	6105	**33.31**

Table 6 – Refueling time for subsonic case

For the case of the Green Concorde we must change the pump section due to the different size of the tank. For this case the right section to be utilized is:

Equation 22

$$Pump\ diameter = \mathbf{0.15}[m]$$

Equation 23

$$Pump\ section = 0.15^2 * \frac{pi}{4} = \mathbf{0.0177}[m^2]$$

With a new flow rate for this case of:

Equation 24

$$Flow\ rate = \left(S_{pump} * V_{exit} * \rho_{H_2}\right) * 60 = \mathbf{412.32}[\frac{kg}{min}]$$

So, the required time to complete refuel our airplane, with a tank of 17000 kg of dimension will be of:

Equation 25

$$Time\ refuel = \mathbf{41\ minutes}$$

Using underground pipelines, the configuration for the refueling would be the one shown in picture; where the operator by means of a telescopic boom inflate Liquid Hydrogen from the aft end of the airplane, an easy access to the tank which as shown before are located in the tail of the vehicle and under the passenger's cabin.

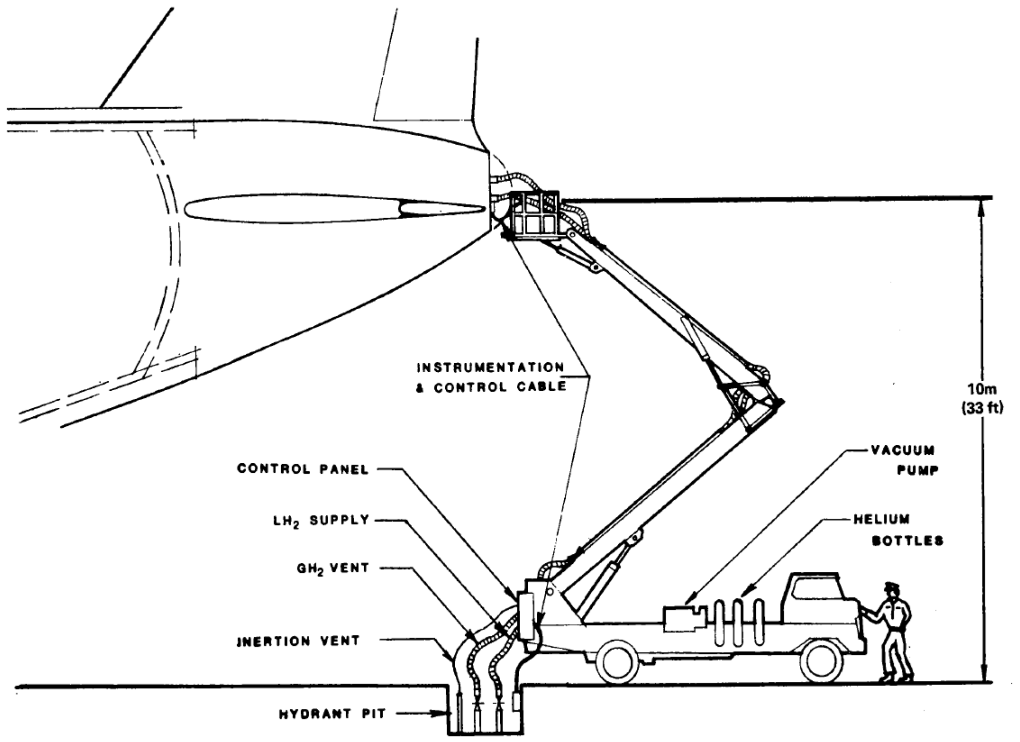

Figure 5-1 – Hydrogen refuelling from underground pipeline [8]

6 Hydrogen production cost trend

Hydrogen could represent a new era for the entire aviation industry. Since 2020, every manufacturer decision is moving towards in this way. From the evaluation of the energy amount required from the infrastructure, is shown the area needed for the solar array infrastructure it's not too easy to comply. To reach these objectives all the system will need to move in this direction in order to spread all around the world airport facilities or something connected with the airport environment.

The price is a factor to do not underestimate because now its demand and naturally also its offer it's not at the level to compete with the most used kerosene. The cost of the aviation kerosene (Jet A-1) in those years is around 0.7€ and might be difficult to compete with those prices. But a key aspect of the Hydrogen to do not forget could be the energy that it could express while burnt. That energy is three times higher than kerosene.

Almost five years ago when the first green LH_2 production site infrastructure for terrestrial use was born, the price of Hydrogen was around 13 €/kg. Nowadays in which there are a lot of opened projects to make this type of fuel the most used, all the producers will try to maximize the efficiency of the chemical reaction to keep up the daily quantity produced.

In the following table is shown which could be the trend for the price of the hydrogen in the following years until 2050.

Liquid hydrogen total cost [€2019/kg]				
Electricity from grid [%]	**Electricity from renewables [%]**	**Current Scenario (2020)**	**Near Future Scenario (2030)**	**Long-term Future Scenario (2050)**
100	0	6.8	5.1	4.4
90	10	6.3	4.7	4.1
80	20	5.9	4.4	3.7
70	30	5.4	4.0	3.4
60	40	4.9	3.6	3.0
50	50	4.4	3.3	2.7
40	60	4.0	2.9	2.4
30	70	3.5	2.5	2.0
20	80	3.0	2.1	1.7
10	90	2.5	1.8	1.4
0	**100**	**2.1**	**1.4**	**1.0**

Table 7 – Hydrogen trend for mixed sources of energy percentual [14]

For our treatment we will take in consideration a starting cost of 3€/kg considering that the initial cost of the infrastructure needs to be amortized for some years. The provision is that the value of the hydrogen will go down for the increasing supply.

7 Direct operative cost

Direct operative cost (DOC) is the cost of the entire aircraft system when it is utilized and when it’s not. All of these costs are the bases on which an airline company define the passengers ticket price before the upcoming of the low-cost company. Whereas an IOC is an indirect operative cost that depends on the passengers onboard and it is a fix cost in €/km. This value depends on the type of the airplane and facilities on board: in Reskim is given as a percentual, from the 15% to 50%, of the TOC. In our study case for indirect operative costs was valued around the 45% of the TOC (Total operative costs).

Aircraft Cost and Operations
Narrow-bodies

	Cost Per Block Hour	Cost Per ASM	Daily Hours Utilization
Small Narrow-bodies	$4,032	7.8¢	9.8 hrs.
Large Narrow-bodies	$4,302	6.3¢	10.8 hrs.

Table 8 – Narrow bodies average data [15]

The costs that afflict for the major part in the Direct operative cost is the fuel that could be even half of the amount spent to manage a flight. But in the cost of the fuel are included also the cost to transport it.

Our solar infrastructure will solve the problem of fuel transportation. These facilities will permit the refueling directly on site by means of underground pipelines, or by moving in a default area of the airport for the passenger's safety.

In the following picture, we can see how vacuum-jacket pipe is the best way to cover small distances in order to not exceed in costs due to transportation. All these informations are useful to realize the refueling as seen in previous chapter.

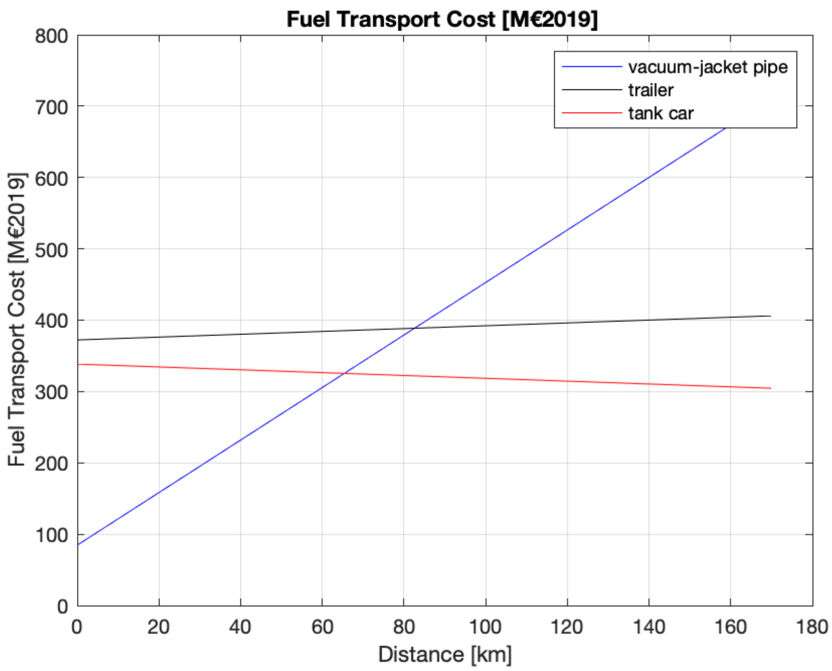

Figure 7-1 – Fuel transport type cost [14]

7.1 Supersonic study case

For the supersonic study case we took in consideration the table below, thanks to the work of my colleague Francesco Frascella and its thesis work on direct operative costs of the "Green Concorde", a project that we had carried on together in 2020. In that table we will focus on the direct cost of the fuel. Utilizing the previous data that came out from this thesis, we will evaluate which would be the cost of the fuel for an airline company for the London-New York route taking in consideration the proposed model of hydrogen self-production of fuel done in the airport infrastructure. The cost in the table below include all the operating costs that every day airman has to face off to bring to its destination a long-range flight as the re-configuration of the Concorde.

DIRECT OPERATIVE COST PER FLIGHT	
[$/flight]	GREEN CONCORDE
DOC_fuel	85020
DOC_crew	12071
DOC_insurance	10954
DOC_depreciation	36434
DOC_M_AF_L	1621
DOC_M_AF_M	8371
DOC_M_TJ_L	816
DOC_M_TJ_M	25696
DOC_Maintenance	36503
DOC	180982

Table 9 – Green Concorde Direct operative cost per flight [16]

From this table the value that we are interested in is the DOC_fuel that is of $85020\$$. This value of DOC is referred to the fuel needed but at the cost of $5\$/kg$. This cost of fuel is referred to a mixed production type of sources, that is an energy coming from renewable and also from the electric line, the last one type of production is different from green energy. The exact percentage utilized to produce the needed fuel is made by 30% of electricity from grid and 70% of renewable energies. In our case the incoming electricity will be 100% from renewable sources, so the price of hydrogen will be less than before.

The aim, now, of this chapter is to re-evaluate that direct cost but considering a complete green production following the future trends seen in chapter 6. The cost of transportation of fuel will be not accounted also.

The considered cost of fuel in the current scenario is of 3,4$/kg, whereas the previous one utilized in the treatment of the Direct cost reported in table 7.1, converted in our currency was of 5$/kg.

After this assumption the direct cost of fuel for the flight taken in account is of:

Equation 26

$$DOC_{fuel} = 51012€ = 57968\$$$

Resulting in a total DOC of: 153930$

With the previsions of costs trend in the future this cost will tend slightly to go down with the increasing demand of that new fuel. According with the table at chapter 6 the cost of hydrogen will tend to 1.4€/kg in 2030 and to 1€/kg in 2050.

Assuming this trend, the Direct Operative Cost will further decrease proportionally with that price.

Equation 27

In 2030: $$DOC_{fuel} = 23805€ = 27051\$$$

Equation 28

In 2050: $$DOC_{fuel} = 17005€ = 19323\$$$

Interpolating the data coming from the Table 7 with the value just calculated, the trend is the following one.

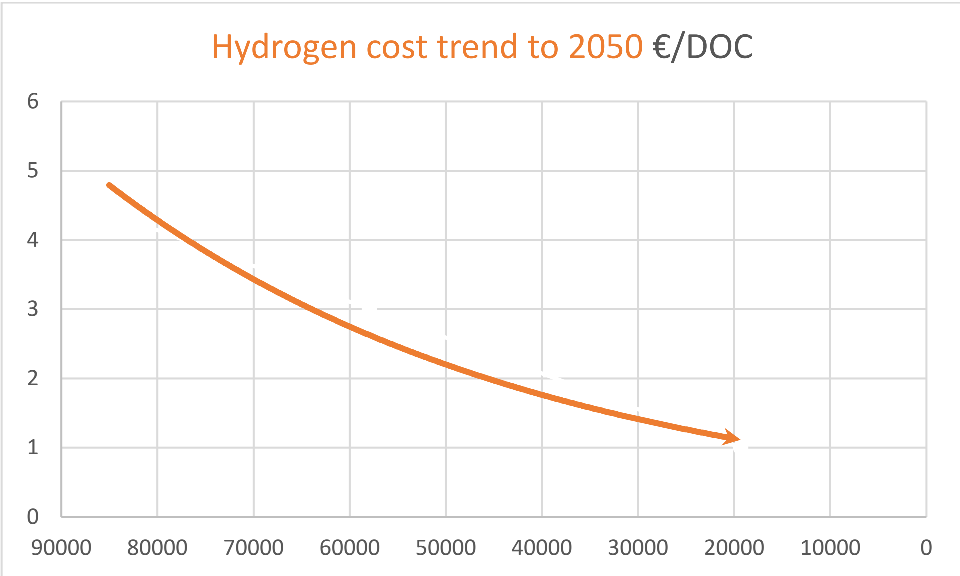

Figure 7-2 – Hydrogen cost trend to 2050

7.2 Subsonic case study

To do a comparison between the ticket price of the supersonic case, we must take in consideration the subsonic case. The aim of this chapter is to consider only the quantity of hydrogen needed from two of the major used airplanes, to underline if also in a medium range flight the conversion of the aircraft could be competitive in fuel costs. The airplanes we are talking about are the same considered before in subsonic case:

- Boeing 737-800
- Airbus A320

Starting from the total costs per block hour of some airline company which operate with the vehicles cited before and doing an average between the fuel utilized from each airplane, we could, throw some simple arrangements, try to re-convert the type of fuel utilized in hydrogen. All these calculations that will be shown after are just to give an idea of how much competitive in costs LH_2 might be.

Now let's focus on the data acquired for each type of aircraft with particular attention to the fuel cost. This cost is related to the kerosene flight operations and throw the right adjustment we will try to redesign it for hydrogen usage.

7.2.1 Airbus A-320

In these table we can find also other operative costs, such as crew salary, aircraft cost, insurance and other related flight costs, that we will not take in consideration, but they are useful for a full treatment of an airline company costs analysis.

Cost Per Block Hour (US$)

Aircraft	Carrier	Crew	Fuel	AC Cost	Mx	Insur.	Other	Total
A320	Alaska	$1,660	$2,942	$1,306	$1,051	$9	$217	$7,186
A320	United	$1,127	$1,726	$184	$1,202	$3	$357	$4,600
A319	Frontier	$636	$1,136	$751	$240	$2	$63	$2,827
A320	American	$944	$1,706	$561	$808	$2	$52	$4,074
A320	JetBlue	$918	$1,764	$517	$956	$3	$128	$4,285
A319	Allegiant	$838	$1,819	$419	$621	$19	$26	$3,743
A320	Delta	$1,220	$1,851	$641	$593	$2	$23	$4,330
A320	Frontier	$684	$1,197	$757	$241	$2	$65	$2,946
A320	Spirit	$733	$1,693	$629	$367	$11	$100	$3,533
A320	Allegiant	$878	$1,901	$444	$652	$20	$28	$3,922

Table 10 – A320 cost per block hour [15]

Taking in account the column related to fuel cost, as can be seen, fuel range is quite wide. Doing an average of that column we can find the midpoint of that cost, that is around:

Equation 29

$$Fuel\ average\ cost\ per\ hour = \mathbf{1844,33}\ \$$$

This cost is related to kerosene aircraft configuration. This value is just to know how much fuel weighs on the direct operative cost. Then through the average of the total costs, that is:

Equation 30

$$Total\ average\ cost\ per\ hour = \mathbf{4291}\ \$$$

By deducting from this average, the fuel cost, we can unbundle, for a separately evaluation, kerosene related cost.

Through a simply calculation we can try, knowing the fuel quantity of the aircraft, hydrogen density and the calorific factor between kerosene and hydrogen to create a direct relation between the two different fuel. All these assumption as said before were done just to compare, at net of consumption, how much hydrogen could be competitive in the future. Using that relation, we had the value of hydrogen cost required for the same flight. The cost of the LH_2 considered for this calculation is: $3\frac{€}{kg} = 3.4\frac{\$}{kg}$

Equation 31

$$Hydrogen\ cost\ per\ hour\ of\ flight = \mathbf{2045,8}\ \$$$

7.2.2 Boeing 737-800

The same type of calculation needs to be done for the other aircraft took as refence for this comparison, starting from the same type of table as the previous paragraph.

Cost Per Block Hour (US$)

Aircraft	Carrier	Crew	Fuel	AC Cost	Mx	Insur.	Other	Total
737-800	Alaska	$856	$1,751	$424	$825	$2	$117	$3,975
737-800	Delta	$1,235	$1,811	$666	$619	$2	$24	$4,356
737-800	American	$1,055	$1,701	$627	$904	$3	$53	$4,344
737-800	United	$1,139	$1,787	$299	$816	--	$315	$4,355
737-800	Sun Country	$580	$2,121	$896	$709	$16	$2	$4,324
737-800	Southwest	$1,043	$1,584	$293	$267	$9	$81	$3,276
737-800	Miami Air	$1,813	$2,150	$1,798	$2,272	$83	$135	$8,251

Table 11 – B737-800 cost per block hour [15]

Equation 32

$$\boldsymbol{Fuel\ average\ cost\ per\ hour} = \mathbf{1622,3}\ \$$$

Equation 33

$$Total\ average\ cost\ per\ hour = \mathbf{4697}\ \$$$

Equation 34

$$Hydrogen\ cost\ per\ hour\ of\ flight = \mathbf{1937,5}\ \$$$

The table below show the cost trend of a medium range airplane re-converted to be fuelled by hydrogen. As we can notice, the value that we can appreciate for two airplanes of the same range cover are quite similar.

Aircraft	2022(Actual) $\mathbf{3.4\ \$/kg}$	2030 $\mathbf{1.6\ \$/kg}$	2050 $\mathbf{1.14\ \$/kg}$
A-320	2045,8 $	954,7 $	681,9 $
B737-800	1937,5 $	904,1 $	645,8 $

Table 12 – Hydrogen fuel cost per hour of flight

8 Ticket price

To evaluate the ticket price for each flight we must take in account another cost, as mentioned before, the IOC. Indirect Operating Cost (IOC) means expenditure incurred from items utilized for the support of airline business that vary from one airline to another such as staff salaries, training, ticketing and reservation, sales promotion, vehicles, maintenance, rent, travels, ICT. For the case study that we are evaluating, it will represent the 45% of the TOC (Total operating costs).

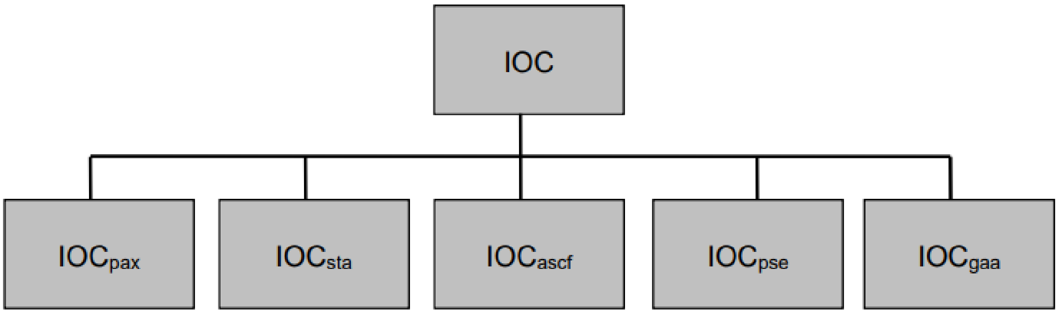

Figure 8-1 – Indirect operative cost partition [17]

where:

- IOC_{pax} - cost of passengers services
- IOC_{sta} - cost of maintaining and depreciation ground equipment and ground facilities
- IOC_{ascf} - cost of airplane and traffic servicing, control and freight
- IOC_{pse} - cost for promotion, sales and entertainment
- IOC_{gaa} - cost of general administrative expenses

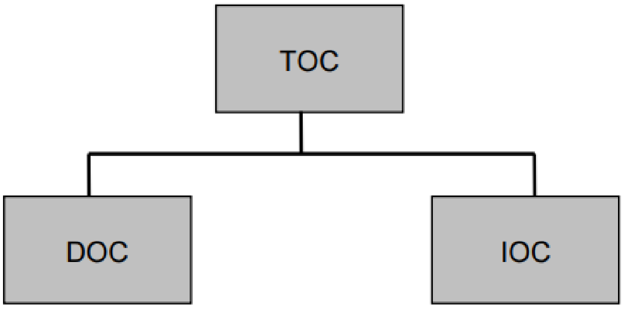

Figure 8-2 – Total operative cost components [17]

TOC result in the sum of the DOC and the IOC valuable with the following relation:

Equation 35

$$TOC\left[\frac{\$}{flight}\right] = DOC + IOC$$

Equation 36

$$TOC\left[\frac{\$}{flight}\right] = DOC + 0{,}45 * TOC$$

For a complete treatment of the case we must compare the result calculate in this section for the LH_2 case, with the initial table from which all data was kept. Table 10 and table 11 as mentioned before represent the case of whole cost by using kerosene as propellant; comparing it with the result in this chapter means to give a critical evaluation of how much better hydrogen could be in terms of costs.

This direct relation could be more clearly explained by means of the ticket price that the passengers must pay to receive this whole service.

Until 1978 ticket price was based on an equal breakdown of the total costs pending on an airline company flight. Nowadays the situation is quite different due to the introduction of algorithms and artificial intelligence technology. The price depends on how much a flight is requested or how much time before the reservation is done.

In this thesis, to ease understand the comparison of ticket price, we will refer to the old one repartition of the price between all the passenger.

In addition to the TOC, the ticket will be increased of a 10%. This addition is due to revenues applied by the airline company to make earnings on each sold ticket.

Equation 37

$$Ticket\ price = \frac{TOC * 1,1}{N° \ pax}$$

8.1 Green Concorde

For the evaluation of the ticket price we have to start from the ticket price in the first version of the Concorde driven by kerosene. The comparison is not so much clear due to the different scenario of application in terms of years, but using the same route for the oldest case and the new one, we could have the right analogy to understand in a much clear way which is the difference in term of price.

For the oldest Concorde a flight of the same route considered for the study case, that is from London to New York was between 8000 and 10000 euros. In the late 90's, that was the period just before the disposal of the Concorde, the conversion between euro and dollar was quite the same as today. So, for a clear understand of the value in which the results are referred: between 8700 and 10700 U.S. dollars.

In the table below, instead, are represented all the cost connected to a flight, but using hydrogen and relative variation because of the expectation cost of the new propellant.

$LH2\ cost\ (\$)$	DOC_{fuel}	DOC	TOC	$Ticket\ Price$
3,4	57968	153930	279872,7	1554,848
1,6	27051	123013	223660	1242,556
1,13	19323	115285	209609,1	1164,495

Table 13 – Green Concorde cost trending

8.2 A320

This chapter is related to the comparison between the cost of the flight done by using kerosene and the liquid hydrogen conversion. The treatment of the subsonic case will be a little bit different from the supersonic case because the amount of available data is much higher. The starting point from which the treatment take place are the data related to the kerosene case:

A320 Kerosene	Cost ($)
DOC_{fuel}	$18443,33$
DOC	42910
TOC	$78018,18$
$Ticket\ price$	$400,09$

Table 14 – A320 kerosene version costs

The data are related to 10 hours operations of the aircraft.

$LH2\ cost$ ($)	DOC_{fuel}	DOC	TOC	$Ticket\ Price$
3.4	20458	44924,67	81681,23	418,87
1.6	9547,07	34013,74	61843,16	317,14
1.13	6819,33	31286	56883,64	291,71

Table 15 – A320 cost trending

8.3 B737-800

For the 737 the calculation to do are exactly the same as the chapter before. As we can notice the data that we are considering are quite similar to the previous case. For this reason, they are considered as competitors in their field of application.

B737 Kerosene	Cost ($)
DOC_{fuel}	$18435,71$
DOC	$46972,86$
TOC	$85405,19$
$Ticket\ price$	$451,87$

Table 16 – B737 kerosen version costs

The data are related to 10 hours operations of the aircraft.

$LH2\ cost$ ($)	DOC_{fuel}	DOC	TOC	$Ticket\ Price$
3.4	19375,04	47912,19	87113,07	460,91
1.6	9041,68	37578,83	68325,14	361,5
1.13	6458,34	34995,49	63628,16	336,65

Table 17 – B737 cost trending

To create a clear relationship between the two case studies, it is necessary to use a format that is "dimensionless" for an intelligible reading of the results. For this reason, let's introduce for each case study the format:

$$\frac{TOC}{pax * km}$$

Aircaft type	$\frac{TOC}{pax * km}$		
	Current Scenario (2020)	Near Future Scenario (2030)	Long-term Future Scenario (2050)
Green Concorde	**0,254485**	**0,203372**	**0,190595**
Airbus A-320	**0,048502**	**0,036722**	**0,033777**
Boeing 737-800	**0,053369**	**0,041859**	**0,038981**

Table 18 – Cases comparison (TOC/km*pax)

In the previous table are shown the result that could be intended such a comparison on how much weigh, flight costs, on each passenger that use supersonic or subsonic case. The values give to us a clear vision on how much a subsonic flight could be more economic, whereas on the other side, through the usage of supersonic case the bill that a passenger have to pay is five times higher than in subsonic, but with a cruise speed that is double.

9 Conclusions

At the end of the whole case treatment, we have to face off now with all the result that after all the calculation came out.

The first point evaluated was about the feasibility and the dimensioning of the solar array infrastructure to produce liquid hydrogen by means of renewable sources, in our case we considered solar energy, for a green production method. After all the assumption about the solar power that the system needs to absorb, to make it eligible to produce sufficient energy for the water electrolysis, was established the dimension in terms of m^2 of the solar cells depending on the study case took in consideration respectively supersonic or subsonic.

So, the answer to our request of power in term of spaces to install a solar array is:

	Hydrogen required	Energy required	Array dimension
Supersonic case	17000[kg]	5,66 [MW]	24926 [m^2]
Subsonic case	23774[kg]	7,92 [MW]	34861 [m^2]

Table 19 - Solar array Overview

As the result shown the terrain dimensions are so much wide. To realize an infrastructure like these, that aim to ensure a flux of continuous energy is a very expensive work to do. Another aspect that could compromise the good success of the entire process is the complete dependence on the sun activity and this is a variable that we cannot control. But despite these negative aspects all the production would be helped by the reduction of the energy required from the electrolysis process, taking it to a higher level of efficiency or by the evolution of the solar cells in order to generate, for the same dimension of array, more electricity than now.

The second crucial point of this treatment was about direct cost evaluation through liquid hydrogen usage. Starting from the hydrogen production cost and creating a trend for the next thirty hear, the aim was to estimate how DOC would change when the supply and demand for LH_2 will grow up and, as said before, the efficiency of the system will raise. To compare the result of supersonic case vehicle, two subsonic type airplanes have been taken in consideration. That two aircrafts have been re-converted to be used with hydrogen as propellant. The final aim was to weight how much the new propellant could be competitive against kerosene. In terms of pollution the result is evident in a zero CO_2 emissions way, but from the values of the calculation done, we can notice that in an actual time scenario, DOC with hydrogen are more than DOC with kerosene. In a future scenario, instead, that is the one from 2030 until 2050 and more, is resulting in a countertrend with costs of the new fuel that encourage LH_2 usage.

As demonstrated also, this situation is reflected in the ticket price, which is much lower for sure in the supersonic case because the data earned was referred to the oldest kerosene configuration of 2000's and for the subsonic case too but in minor change.

Last but not least result took in consideration was about the direct comparison in terms of $\frac{TOC}{pax*km}$. The table show how this format give to us the capability to understand that comparison between subsonic and supersonic case. The value that came out tip decidedly to the side of subsonic case, but on the other hand we must consider that the distance unit covered in the same time from the two type of vehicles is not the same in the unit of time considered because of the different cruise speed owned by the different cases.

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