Master Thesis

The Aviation Fuel and the Passenger Aircraft for the Future – Hydrogen

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Abstract

This thesis analyses a new concept of a passenger aircraft using hydrogen as fuel. Due to the future depletion of fossil fuels and growth of aviation within the next years, the aeronautical industry must get ready now for a realistic solution. Many projects were conducted for hydrogen-fueled aircraft designs in the past, however all the effort was focused on an expensive totally new aircraft design. In this work, research is based on the Airbus A320 with a requirement for 1510 NM range at 19.3 t maximum payload. Goal is to redesign the aircraft under the premise of minimum change and minimum costs. Hydrogen as the new energy carrier will be stored at cryogenically temperatures. Still it needs more tank volume. This extra volume is best generated with an aircraft stretch leading to an increase of aircraft length. A minimum change option would be to simply use A320 seating in an A321, using the additional space for the new hydrogen fuel tanks. Unfortunately, the additional volume on its own is not sufficient. Therefore, three different hydrogen-fueled versions are developed. 1.) The A321-HSO stretched beyond the length of the A321. 2.) The A321-HWO with A321 fuselage and additional under-wing podded hydrogen fuel tanks. 3.) A321-H19O with A321 fuselage and A319 cabin. All three versions were designed and optimized in OPerA, the in-house conceptual design and optimization program based on a genetic algorithm. Objective function for the optimization are minimum Direct Operating Costs (DOC). Assumed is a price for hydrogen, energy-equivalent to kerosene and estimated for 2030 to be 1.12 USD/kg. All three versions stayed in feasible dimensions. The weight of the aircraft is decreased between 3.4% (A321-H19O) and 0.7% (A321-HSO). Depending on the version considered, the DOC of the aircraft is increased by 20% to 30%. Hydrogen aircraft do not show CO2 emissions, releasing only water vapor and NOx into the air. However, water emitted at altitude can form cirrus clouds. This effect on global warming is presently not fully understood. The result: If fossil fuels get near to depletion and kerosene gets so scarce that the price of hydrogen matches that of kerosene, passenger air transport remains available with hydrogen-fueled minimum change conversions of existing aircraft types.

DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

The Aviation Fuel and the Passenger Aircraft for the Future – Hydrogen

Task for a *Master Thesis*

Background

Our planet is a finite entity and as such also energy stored on it is finite. Our planet offers carbon-based fossil fuels (coal, oil, and gas) ready to be used. Burning these fuels releases CO2 into the finite atmosphere of our planet which leads to global warming. The question is simply, if taking from one limited reservoir and releasing into another limited reservoir may empty the first reservoir or may overfill the second reservoir within the foreseeable future. Whatever happens first (a reservoir being empty or overfilled) will be the limiting factor for the system. What will happen first? We live in a growing fossil fuel economy where emptying and filling takes place at an increasing rate. At what speed do we want to approach the inevitable. The question is will fossil fuel get too scarce and thus too expensive to be used? Or will CO2 levels reach climate effects (droughts, flooding, severe storms) the earth's growing population cannot cope with? Air transportation is one part of the growing carbon economy and has to carry its share in problem solving. The related research question for aviation is here: What is the best fuel strategy for passenger air transport in a post-fossil fuel era? In a post-fossil fuel era energy will come from renewable energy (wind, solar, bio-mass ...). Most forms of renewable energy (wind, solar ...) will be available primarily as electricity. Electrical energy could be stored in batteries; alternatively, energy could also be converted into a chemical form (gaseous or liquid fuel) to be stored on board. Other forms of renewable energy (like bio mass) could be converted directly to drop-in fuel. The best fuel option for passenger aircraft becomes visible only if aircraft are designed with all iterations and snowball effects for the energy option selected. **Three Master Theses have been set up as a trilogy** to investigate this:

The Aviation Fuel and the Passenger Aircraft for the Future –
a) Batteries, b) Hydrogen, c) Bio Fuel, Synthetic Fuel

a) Batteries: In a post-fossil fuel era (regenerative) energy will exist first of all as electricity. To avoid energy conversions (always going along with energy losses), it

makes sense to try direct storage and use of electricity. But batteries are heavy – a contradiction to the first rule in aircraft design: "Watch the weight!"
b) Hydrogen: Hydrogen production from electricity is simple through electrolysis and today with 70 % already quite efficient. Hydrogen powered aircraft have already been built and have been flown successfully. Hydrogen is a tested technology in aviation that will work. It makes sense to look again at this concept with new ideas to limit investment and to avoid a bulky aircraft.
c) Bio Fuel, Synthetic Fuel: The best fuel is the fuel we have today. Kerosene has a high energy density by weight and by volume. Drop-in fuels are those renewable fuels which can be blended with today's fuel and can be utilized in the current infrastructure and with existing equipment. Drop-in fuels generally have similar parameters and can be blended at various ratios up to 100 %. The challenge here is with availability of bio fuels compared to the huge demand. In a post-fossil fuel era synthetic fuel will come from a power to liquid (PTL) process based on regenerative energy. Will it be possible to scale up the processes fast enough and to deliver at a compatible price? The challenge here is the fuel and not the aircraft.

Among the three options, **hydrogen may be the most promising alternative** as new aviation fuel due to the high content of energy per kilogram and zero emissions of CO2. However, the combustion of the hydrogen still produces water and NOx. Due to the nature of hydrogen, having a lower density and the necessity of storing it at cryogenic temperatures, important changes in aircraft and airport design are necessary that require high investments. The idea is to lower necessary investments by using a minimum change derivative of the Airbus 320 instead of a new clean sheet design. Promising studies have been conducted before, regarding the feasibility of hydrogen as aircraft fuel. The Cryoplane Project was guided by Airbus Deutschland. The Green Freighter Project was led by HAW Hamburg, studying (among others) a new concept of a hydrogen-fueled freighter based on the ATR 72.

Task

Task of this Master Thesis is to study and analyze a hydrogen-fueled concept based on the A320. The hydrogen-fueled aircraft shall have the same requirements as the original kerosene-fueled aircraft. The subtasks are:

- Data collection and comparison: hydrogen and kerosene as aviation fuel.
- Discussion of the main aircraft design differences: hydrogen and kerosene versions.
- Study of various hydrogen tank configurations for the minimum change derivative.
- Analysis and comparison of hydrogen-fueled aircraft with OPerA.
- Use of OpenVSP for the presentation of the aircraft versions.

The report has to be written in English based on German or international standards on report writing.

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List of Symbols

A	Aspect ratio
b	Wing span
C_D	Drag coefficient
C_L	Lift coefficient
D	Drag
e	Oswald factor
E	Glide ratio
g	Gravity acceleration
k_{APP}	Statistical factor for approach phase
k_L	Statistical factor for landing phase
k_{TO}	Statistical factor for take-off phase
l	Length
L	Lift
m	Mass
M	Mach number
m/S_W	Wing loading
n_E	Number of engines
n_{PAX}	Number of passengers
n_{SA}	Number of seat abreast
p	Pressure
P	Power
q	Dynamic pressure
R	Range
s_{LFL}	Landing field length
s_{TOFL}	Take-off field length
S	Surface
T	Thrust
T/mg	Thrust to weight ratio
V	Velocity
W	Weight

Greek Symbols

γ	Climb angle
η_p	Propulsive efficiency
η_m	Motor efficiency
θ	Pitch angle
ρ	Air density
ρ_0	Air density at sea level
λ	Taper ratio
σ	Density ratio
φ	Sweep angle

Indices

$()_0$	Initial
$()_{25}$	25 % of the chord length
$()_{ALUM}$	Aluminium metal
$()_{ATTACH}$	Attachments of the fuel system
$()_{cell}$	Fuel cell
$()_{eff}$	Effective
$()_F$	Fuel, fuselage
$()_{geo}$	Geometrical
$()_{INS}$	Insulation
$()_L$	Landing
$()_{LH_2}$	Referred to liquid hydrogen
$()_{TANK}$	Tank
$()_{TO}$	Take-off
$()_W$	Wing

List of Abbreviations

ACARE	Advisory Council for Aeronautics Research in Europe
AEA	Association of European Airlines
APU	Auxiliary Power Unit
ATAG	Air Transportation Asociacion Group
ATC	Air Traffic Control
ATM	Air Traffic Management
BPR	By-pass ratio
CG	Center of Gravity
CO	Carbon monoxide
CO_2	Carbon Dioxide
DLR	Deutsches Zentrum für Luft-und Raumfahrt
DOC	Direct Operating Cost
GH_2	Gas hydrogen
GWP	Global Warming Potential
H_2O	Water vapour
HAW	Hamburg University of Applied Sciences
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel for Climate Change
LCA	Life-Cycle Assessment
LH_2	Liquid Hydrogen
ML	Maximum Landing Mass
MLI	Multilayer Insulation
MTO	Maximum Take-off Mass
NASA	National Aeronautics and Space Administration
NM	Nautical Mile
NO_x	Nitrogen oxides
OEW	Operational Empty Mass
OPerA	Optimization in Preliminary Aircraft Design
PEM	Proton Exchange Membrane

PEMFC	Proton Exchange Membrane Fuel Cell
PL	Payload
RAT	Ram Air Turbine
RPK	Revenue Passenger Kilometre
SAS	Simple Aircraft Sizing
SFC	Specific Fuel Consumption
SOFC	Solid Oxide Fuel Cell
SP	Seat Pitch
TUB	Technical University of Berlin
UAV	Unmanned Aerial Vehicle
UHC	Unburned Hydrocarbons
VSP	Vehicle Sketch Pad

1 Introduction

1.1 Motivation

The growth of global air traffic in the last years has been one of the most important driving forces for the globalisation. Over the next decades passenger traffic will grow at 4.7% per annum **(Airbus 2014)**. Currently the aviation fuel is almost extracted from the kerosene fraction of the crude oil. During the years between 2000-2013 the price of the crude oil per barrel was multiplied by 4 and this will be the trend of the growth of crude oil.

Current airlines spend more than 30 % of their total costs in jet fuel, that is the reason why all the airlines are trying in different ways to improve the aerodynamic and engine efficiency, investing in new aircraft, increasing the utilisation and the load factor. It is almost impossible to improve the energy efficiency of the future aircraft to compensate the emissions of greenhouse due to the growth of commercial aviation in the next years **(Lee 2010)**. Having said that the forecasted growth in the next years could be reduced because of the higher emissions to the atmosphere.

The selection of the A320 is made because this aircraft is ranked as one of the fastest-selling product lines ever. On the fleet in service nowadays the 78 % correspond to the short-medium haul representing the 60 % of the full distance flown in 2013 according to **Airbus 2014**. Over the 20 next years it is expected even a higher growth in the deliveries of this family.

The solution of all this issues could be the use of new sources of energy for the aircraft propulsion. One of the best alternative fuel, which could alleviate the problem, is the hydrogen. Since many years ago the hydrogen is postulated as one of the best alternative fuel because is a versatile energy carrier of energy and can be produced from a wide range of energy sources, having the possibility of remove the tensions between countries due to the small concentration of fossil sources in the world **(Verstraete 2013)**. Hydrogen production through electrolysis from renewable sources of energy could improve the LCA for this fuel reducing in high amounts the emissions of CO_2 to the atmosphere.

Researches during the project Cryoplane for the hydrogen-fueled aircraft design using a minimal change in the original version showed that the energy consumption increased between 9 %-12 %, **(Westenberger 2003)** due to the fact that although the energy per kilogram is higher than the kerosene, the energy per volume is 4 times lower, so for the same mission requirement the new design needs higher volume for the tanks. This requirement will determine the new design of the aircraft.

1.2 Aim of the Work

The objective of this work is to develop and research a new design of the A320 but for a hydrogen-fueled version, analysing the impact in terms of the Life Cycle Assessment (LCA), the emissions and the viability of operating a new version in the future.

For reaching the main objective an introduction in the aircraft design will be made, because of the cryogenic nature of the LH_2 new systems are necessary to be implemented and also new tanks in the aircraft, so the fuselage weight and length are strongly dependent on the mission requirements and the engine performance of the aircraft will be different. Storing the fuel in the fuselage is a problem for the the wing design, because in this case the bending moment alleviation of the kerosene aircraft is not available.

A feasibility study for operate a hydrogen-fueled aircraft is required in order to analyse if it is possible for the future generation of aircraft to fly using the hydrogen as the main fuel.

The new conceptual design is influenced by all the above issues. Another important objective of this master thesis is to study the impact of the hydrogen emissions in the greenhouse effect and the feasibility of the hydrogen aircraft for being the future fuel aviation.

1.3 Review of Literature

For the future aviation the hydrogen is one of the most important candidate and since many years ago many studies with viable solutions were conducted in order to analyse the potential of the hydrogen as an aviation fuel. Within the next lines the most important works, which this project is based are reviewed:

- "Hydrogen Aircraft Technology" **(Brewer 1991)**: This book is focused on the design of hydrogen aircraft design for civil, military and supersonic purposes. The most important features of the aircraft design are detailed in the book such as fuel systems, tank insulation and engine operation. It is also reviewed the hydrogen production and the airports requirements. The basis for the future designs are setted even if the book is released more than 40 years ago. The book shows many comparisons and design methodology taking care of the issues coming from the hydrogen requirements and it confirms the feasibility of the hydrogen, showing that hydrogen can be a hopeful alternative fuel in the future.

- "Conceptual Design and Investigation of Hydrogen-Fueled Regional Freighter Aircraft" **(Seeckt 2010)**: This Ph.D. has been written during the project The Green Freighter at the University of Applied Science. The work is based on the conversion of the original ATR 72 to a hydrogen-fueled aircraft. Most of the solutions and conclusions developed in this project were adopted for this master thesis. The project presents many possible versions for hydrogen aircraft design, distinguishing between the jet engine and propeller aircraft. It is also reviewed the GWP of the hydrogen as an aviation fuel and one more time the results obtained were positive, proving that the hydrogen is an interesting option for the freighter industry.

- "Cryoplane Final Technical Report" **(Westenberger 2003)**: The Cryoplane Project was an European consortium of 35 partners of the aviation industry and led by Airbus Deutschland. The project considered various range of aircraft, from short till long range. The project was focused on the hydrogen fuel system architecture, the tank design and the environmental effects of this fuel. The results were an increase of the energy consumption between 9% and 14 % and an increase for the *DOC* of 4 %-5 % due to the high surface area required. In terms of safety the hydrogen aircraft will be the same although regulations ground services and some other issues must be adapted.

1.4 Structure of the Thesis

The thesis is divided in five important chapters where the most interesting fields of the study in consideration are analysed:

Chapter 2 In this chapter is reviewed the current situation of the aviation industry and the trend market, comparing the properties of the aviation fuels, specifically the hydrogen and the kerosene, regarding their environmental effect. A brief historical review of the use of hydrogen as an aviation fuel is explained.

Chapter 3 Explains the most important current methods of producing hydrogen and their environmental impact in terms of LCA are analysed. The chapter also deals with the problematic of the liquefied hydrogen, storage and transportation.

Chapter 4 Here the problematic of the tanks is reviewed, being one of the most important issues of the hydrogen aircraft design. The different possible configuration for the tanks and the types of insulation are studied. The most important parts of the fuel system are also detailed.

Chapter 5 The modules used in OPerA are explained along with the different phase conditions for plotting the matching chart.

Chapter 6 This chapter deals with hydrogen-fueled aircraft design. First of all the requirements and mission for the comparisons are setted. Then the different possible solutions and versions are designed and optimized, making the proper comparisons between them and with the original aircraft.

Appendix A This appendix review the use of the fuel cell for aircraft systems and the state of the art of this technology.

Appendix B The most relevant dimensions of the A320 family are collected in this appendix.

2 State of the Art

This chapter reviews the general situation of the aeronautical world nowadays, comparing the current situation with the future trend in aviation, analysing the impact of the commercial aviation in the atmosphere due to the emissions. The problem of the rising prices of the fuel oil and their future extinction is another important issue to consider. The new role of the hydrogen in the world of aviation is also reviewed comparing his benefits with the kerosene in terms of emissions, energy and operation.

2.1 Air Traffic Trend

Air transport is the fastest and safest mode of transport and is impossible to imagine a world without aviation today because it represents the key of globalisation and business worldwide. Aviation is providing more and more benefits for people increasing every day the offered services with more connections and airports. Historically air transportation has exhibited significant growth as can be seen in Figure 2.1.

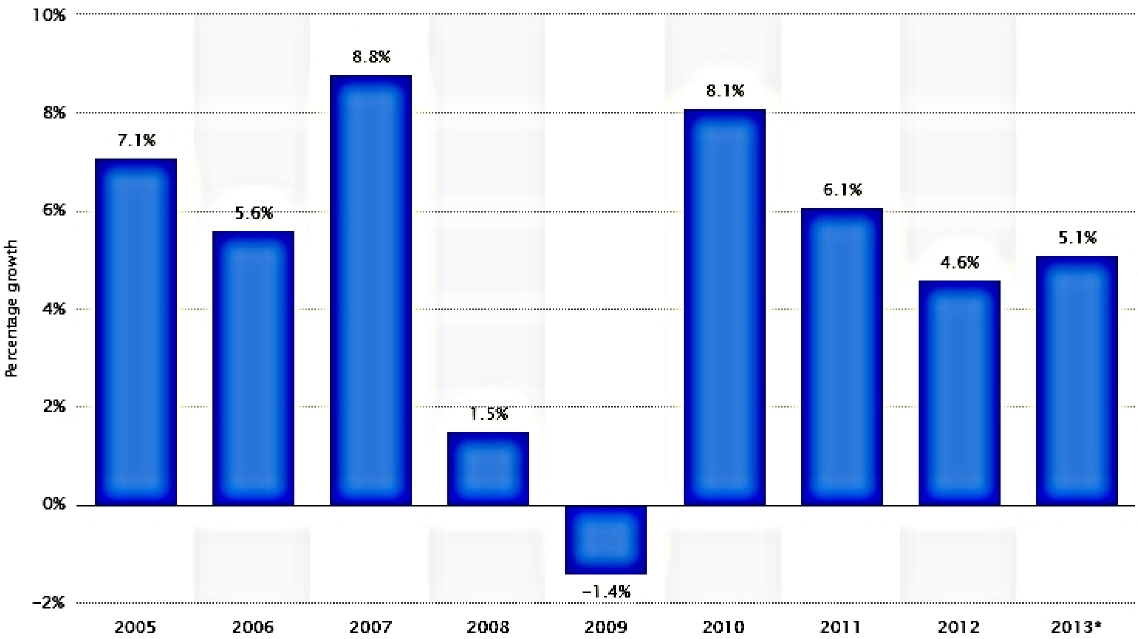

Figure 2.1 Traffic growth **(Statista 2014)**

The forecasted growth of aviation for the future is also very hopeful due to the economic growth prospect in some emergency markets and the high tourism development for the tourists travelling by air in the future. In the next 20 years passenger traffic will grow at 4.7 % annually **(Airbus 2014)**. Aviation creates millions of jobs, not only in aviation industry but also in related fields of the industry and according to the ATAG reports, about 32 million jobs are created worldwide by the aviation industry divided in many fields **(Seeckt et al. 2011)**.

One of the most important number for size up the trend of the air transportation is the RPK which is used for the statistical comparisons in the aviation transport industry for passenger transportation aircraft. In Figure 2.2 is shown the historical predicted growth by Airbus in terms of RPKs.

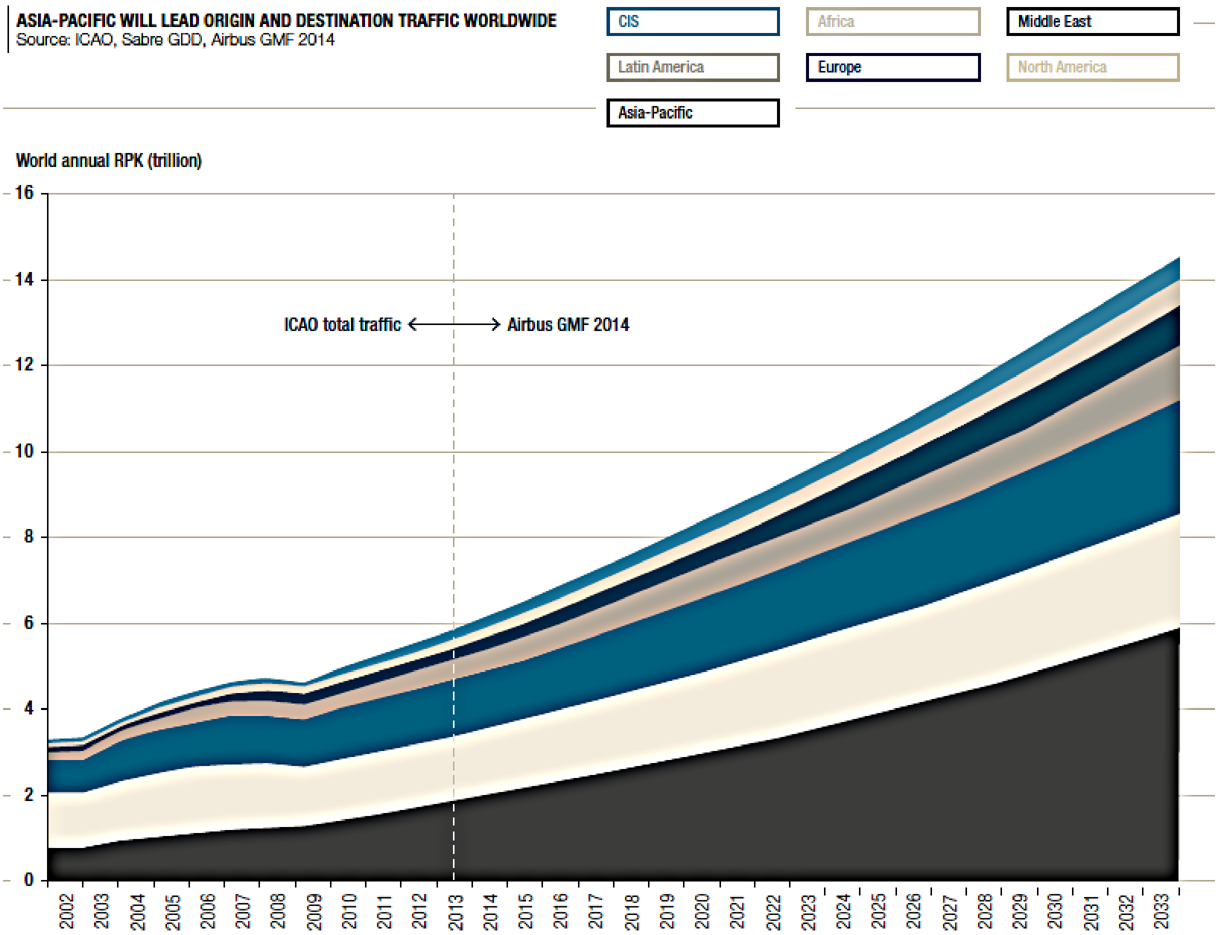

Figure 2.2 Revenue passenger kilometre prediction **(Airbus 2014)**

The forecasted tendency for the RPK is so optimistic because the aviation world strongly depends on the fluctuations of the economy in the world and the market, for example in Asia-Pacific is expected to have a big growth in the future and a lot of new airplanes will be sold there. Another strong increase in the market will be North America and Europe. Other important issue is the replacement of old aircraft in the future **(Nygren et al. 2009)**.

The deliveries of new aircraft for the future according to **Airbus 2014** will maintain the same line of growth and the fleet of aircraft by 2033 is predicted to be increased in 37463 new aircraft including passenger aircraft (with 100 sets or more) and freighter aircraft (with 10 tonnes or greater). This number means that in the next two decades the forecasted fleet will be more than the double fleet in service today. In Figure 2.3 is resumed all the information given in the lines before, concerning the forecasted deliveries of new aircraft.

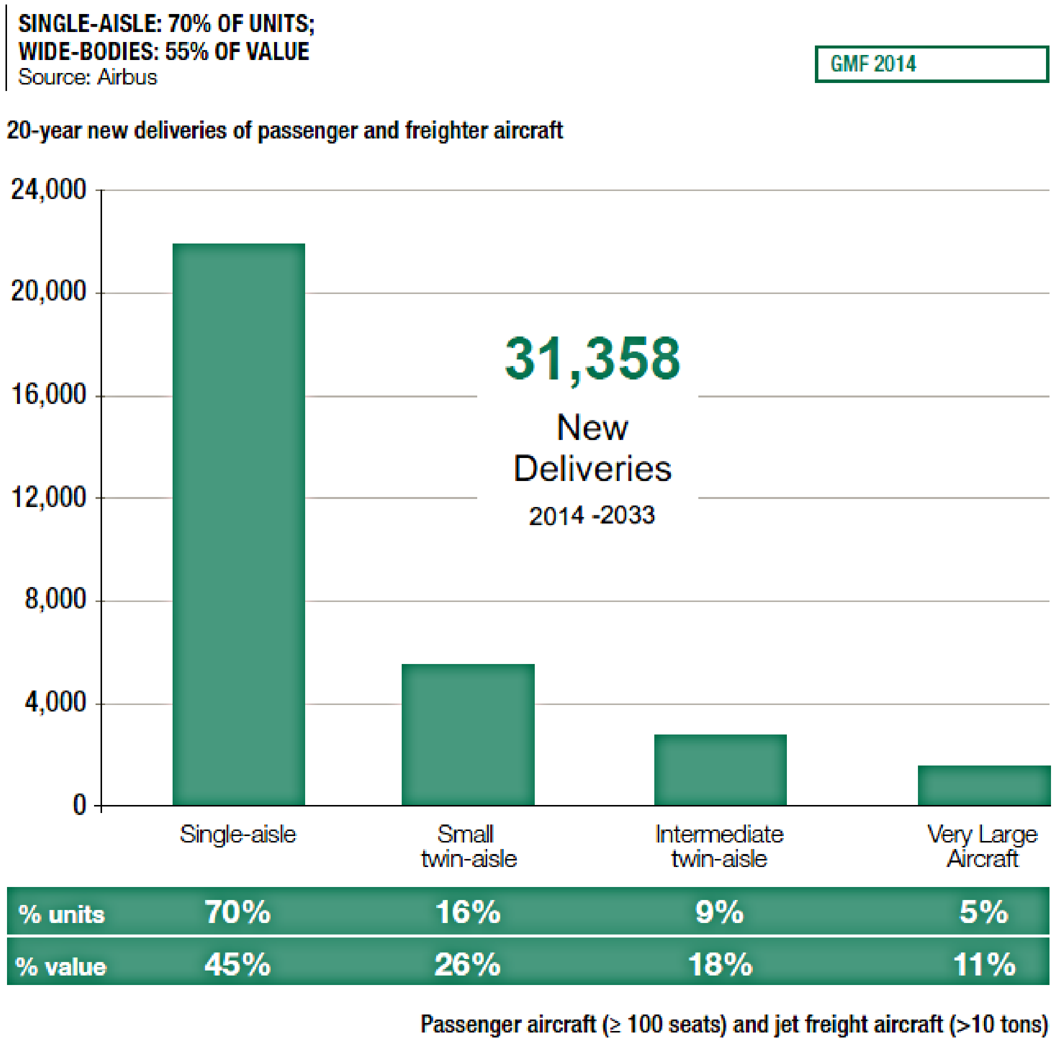

Figure 2.3 Aircraft future deliveries **(Airbus 2014)**

2.2 Aviation Fuels and Environmental Effect

Fuel and emissions are very closed because depending on which kind of fuel is burned in the engines of the aircraft, the type of emissions to the atmosphere will be different. Here it is important to say that not always the traffic growth is correlated with the jet fuel demand because the efficiency of the aircraft and the traffic management are improving very fast in the last years **(Nygren et al. 2009)**. In Europe there is a significant agreement between industries and politicians, to improve the fuel efficiency. In 2001 the Advisory Council for Aeronautical Research in Europe (ACARE) established a few challenges for the new fleet in service by 2020 comparing to the fleet in 2000:

- Reduce fuel consumption and CO_2 emissions to the atmosphere by 50 % per passenger kilometre.
- Reduce NO_x emissions by 80 %.
- Reduce noise by 50 %.

For reaching this aim, is important to increase the efficiency of the airplanes and maintain the same line in the increase of the load factor of the airlines. The load factor will increase due to the high number of passengers forecasted in the next years. This tendency can be seen in Figure 2.4.

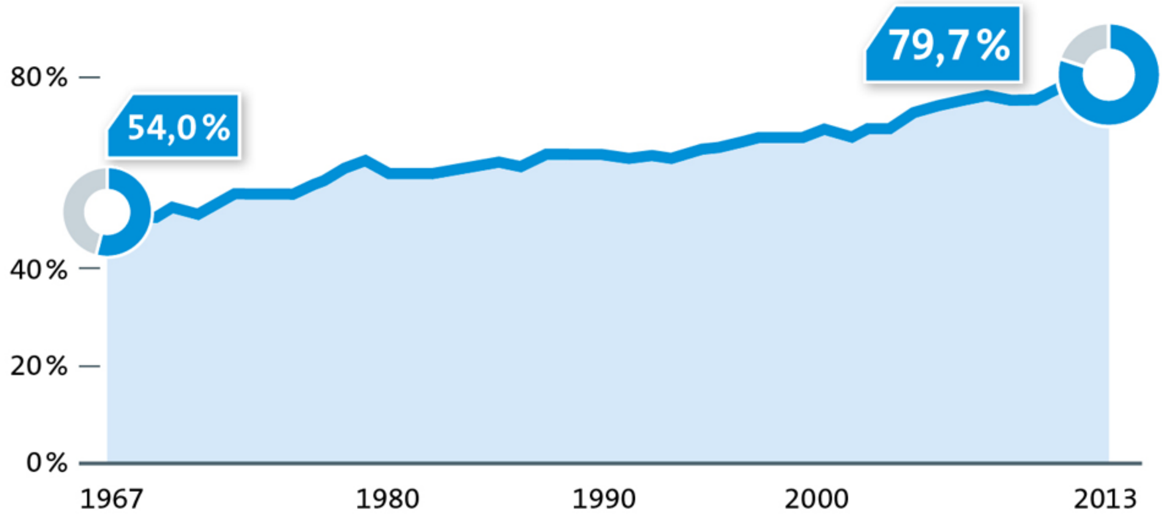

Figure 2.4 Load factor trend for passenger aircraft worldwide **(BDL 2013)**

In spite of all the new improvements in aircraft efficiency such as in Figure 2.10, in the future, will be almost impossible to compensate the emissions of the future aviation because the anticipated growth will be higher than all kind of improvements.

Aviation fuels includes the two types of engines available: jet fuel for turbine engines and aviation gasoline for piston engines however the most used is the jet fuel originated from crude oil. The price of the oil has increased from 2000 to 2013 in 340 %, whereas the passenger air traffic grew 70 % in the same period according to **Airbus 2014**. Worldwide oil demand in the last years has increased as a result of the great development in the worldwide economy.

It is proved that forecasting oil price could be a difficult challenge, in the short and long term because of the high number of external factors which could influence the price of the oil. Lots of institutions are trying to forecast the tendency of the crude oil in the future as it can be seen in Figure 2.5.

In brief, it is clear that the price of the oil will increase in the next years and aviation needs changes for being a profitable industry as it has been until now.

2.2.1 Kerosene

The most used fuel for aviation is the kerosene. For commercial aviation, the common used fuel is Jet A-1 and it is produced using a standard international specification used by the aviation all over the world. Jet A-1 is the normal fuel for gas turbine engines, for military aviation the equivalent fuel is JP-8. In United States is used another variant of kerosene called Jet A and the main difference between them is the freezing point (-40 °C for Jet A and -47 °C for Jet A-1).

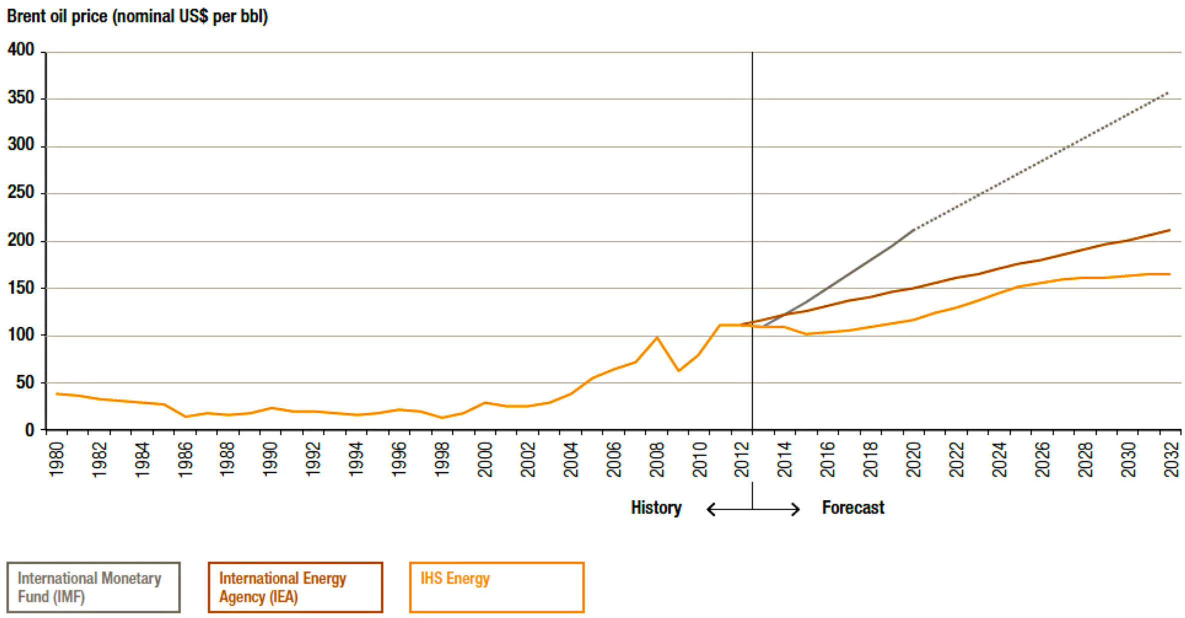

Figure 2.5 Forecasted crude oil price per barrel **(Airbus 2014)**

Jet A-1 has a flash point of 42 °C and an auto-ignition temperature of 210 °C, meaning that it is a safe fuel for handling. The properties of Jet A-1 are shown in table 2.1.

Table 2.1: Typical physical properties for Jet A-1 fuel

Flash point	42 °C
Auto ignition temperature	210 °C
Freezing point	-47 °C
Open air burning temperatures	260-315 °C
Density at 15 °C	.804 kg/L
Specific energy	43.15 MJ/kg
Energy density	34.7 MJ/L

Aircraft emissions are dependent on the type of the fuel used, engine model and engine load. For the kerosene, depending on the supply of oxygen for the combustion process the jet fuel could burn according to the next chemical reactions from **Nojoumi et al. 2009**,

$$C_xH_y + a(O_2 + 3.76N_2) = xCO_2 + \frac{y}{2}H_2O + 3.76aN_2 + other\ products \tag{2.1}$$

$$C_{12}H_{23} + 17.75O_2 + 66.77N_2O_2 = 12CO_2 + 11.5H_2O + 66.77N_2 \tag{2.2}$$

In Figure 2.6 is shown the scheme of the kerosene combustion of an engine:

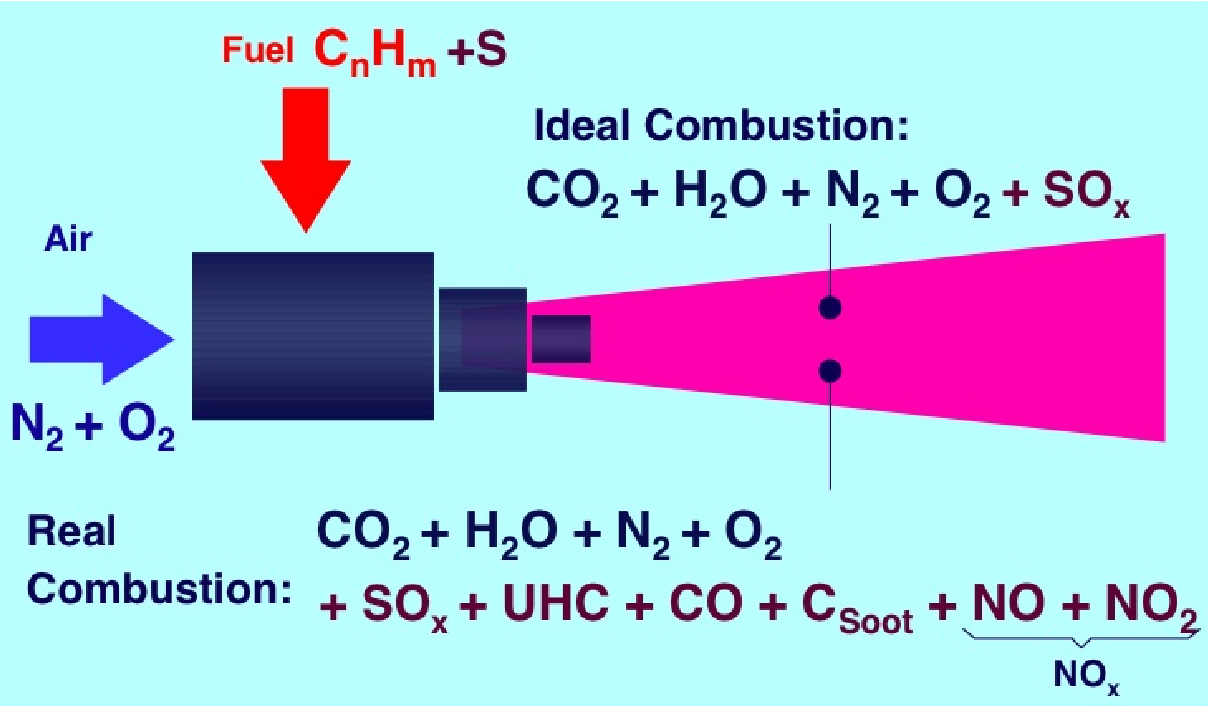

Figure 2.6 Kerosene combustion of an engine

For the complete stoichiometric combustion of 1 kg of kerosene is needed 3.4 kg of oxygen and the products are found in **Seeckt and Scholz 2009**:

- 3.16 kg of CO_2
- 1.24 kg of water vapour
- 14 g of NO_x
- about 3.7 g of CO
- 1.3 g of UHC
- about 1 g of SO_x
- about 0.04 g of Soot

A summary of the emissions released due to the combustion of kerosene is resumed in Figure 2.7, where the red arrows mean the emissions with a warning effect (PM_{25}, O_3, H_2O and CO_2) and the blue arrows have a cooling net effect (SO_x, CH_4).

Aircraft emissions may have influences in the climate change in the next forms **(Lee 2010)**:

1. CO_2 emissions contribute with about 53 % and alter the balance of the radiative energy of the earth contributing to the global warming.

2. Some emissions of the engine such as NO_x with 24 %, could alter or destroy substances that protect the world for the radiative effect modifying the concentration of O_3.

3. The emissions of water vapour with 21 % of contribution, at high altitudes cause the generation of additional clouds and the formation of contrails which could have a harmful influence in the atmosphere. The water vapour is present for 3-4 days at sea level, and

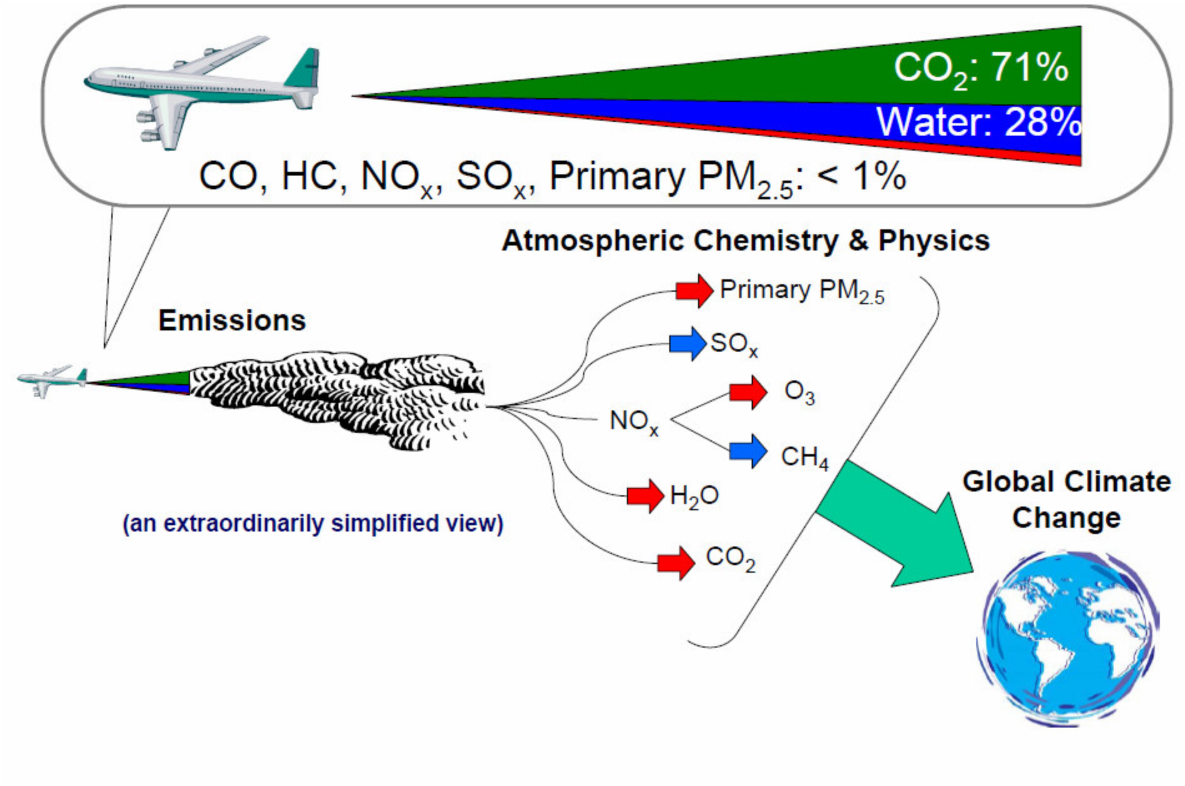

Figure 2.7 Aircraft direct emissions contributing on global climate change **(Jahangir 2009)**

between 6-12 month at the stratosphere **(Khandelwal 2013)**.

The other emissions from the engine (CO, UHC, Soot) contribute with negative results for the atmosphere.

All these emissions may have different results depending on the altitude where they are emitted as it is studied in table 2.2.

Table 2.2: GWP by altitude of some emissions **(Khandelwal 2013)**

Altitude (km)	**GWP (CO_2)**	**GWP (H_2O)**	**GWP (NO_x)**
0	1	0.00	-7.1
1	1	0.00	-7.1
2	1	0.00	-7.1
3	1	0.00	-4.3
4	1	0.00	-1.5
5	1	0.00	6.5
6	1	0.00	14.5
7	1	0.00	37.5
8	1	0.00	60.5
9	1	0.00	64.7
10	1	0.24	68.9
11	1	0.34	57.7
12	1	0.43	46.5
13	1	0.53	25.6
14	1	0.62	4.6
15	1	0.72	0.6

Today the aviation, due to the combustion of kerosene, is a contributor to greenhouse effect (e.g. CO_2, NO_x) and because of the forecasted growth predicted in section 2.1 the emissions will be higher in the future. The contribution of aviation to the global anthropogenic carbon emissions is estimated at about 2 %. In figure 2.8 is shown the contribution to the global emissions of CO_2 compared with other sectors of the industry.

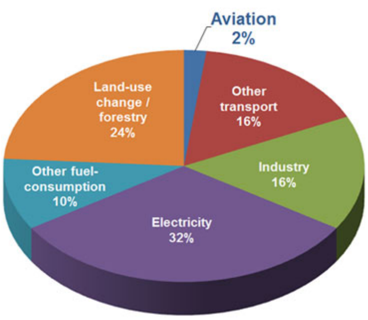

Figure 2.8 Contribution of aviation to CO_2 emissions

This number could increase in the next years due to the possible improvements and emissions reduction from others sectors in the industry **(Sgouridis et al. 2011)**. The Intergovernmental

Panel for Climate Change (IPCC) **(Penner 1999)** suggested an increase till 5 % and by 2050 could reach 15 % of the total contribution to the greenhouse.

The effect of jet engines at higher altitudes could amplify the warming effect of some pollutants and improving the emissions will be even more difficult in the future since the current efficiency of the engines is very high. The emissions of CO_2 to the atmosphere compared to the year 2000 are shown in Figure 2.9.

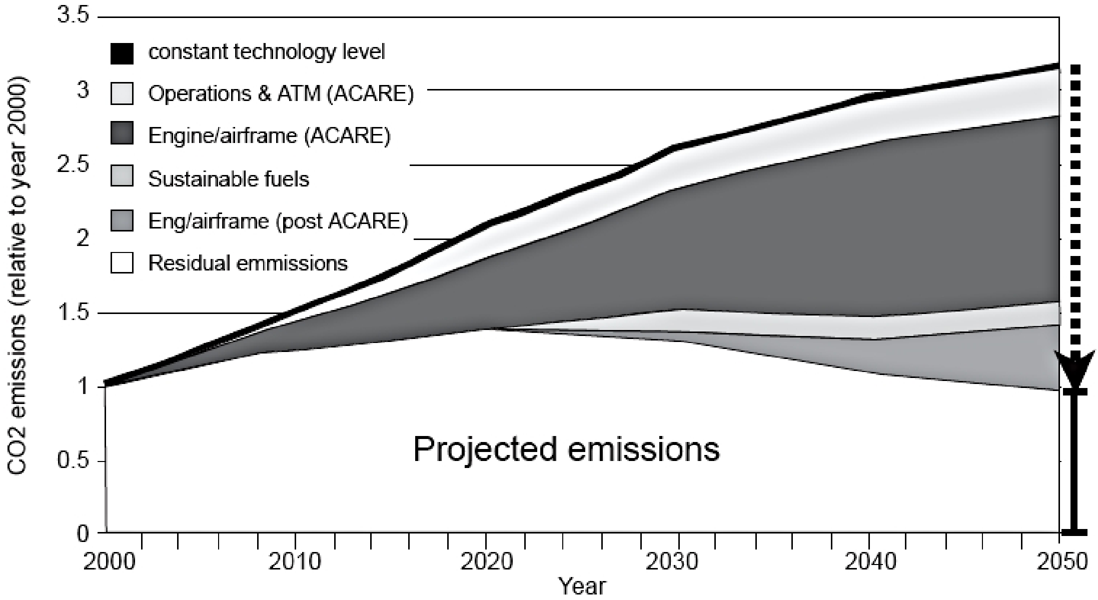

Figure 2.9 Emissions from aviation of CO_2 compared to year 2000

In order to achieve an environmental, political and economic sustainability for the air transportation the reduction of CO_2 emissions should be at a higher rate than the air traffic increase. In order to achieve this challenge some improvements are necessary **(Sgouridis et al. 2011)**:

- Technological efficiency improvements related to the aircraft should be made, such as increasing fuel efficiency or aero-dynamical improvements. Technological changes need about 20 years to penetrate in the whole fleet, so this time is an important issue to be analysed in order to reach the ACARE goals. Some of the new improvements in the efficiency, are shown in Figure 2.10.
- Improvements in ATC operations could reduce the fuel consumption, studying better operations in ground, optimizing the altitude and reducing the delays.
- The use of alternative fuels is one of the best ways to reduce the high level of emissions of CO_2 to the atmosphere.

2.2.2 Hydrogen

The predictions for the growth of aviation, the rising price of fuel oil, the global warning effect and the extinction of fossil fuels lead the world of aviation to research in another kind of fields such as alternative fuels like hydrogen, bio-fuel and batteries.

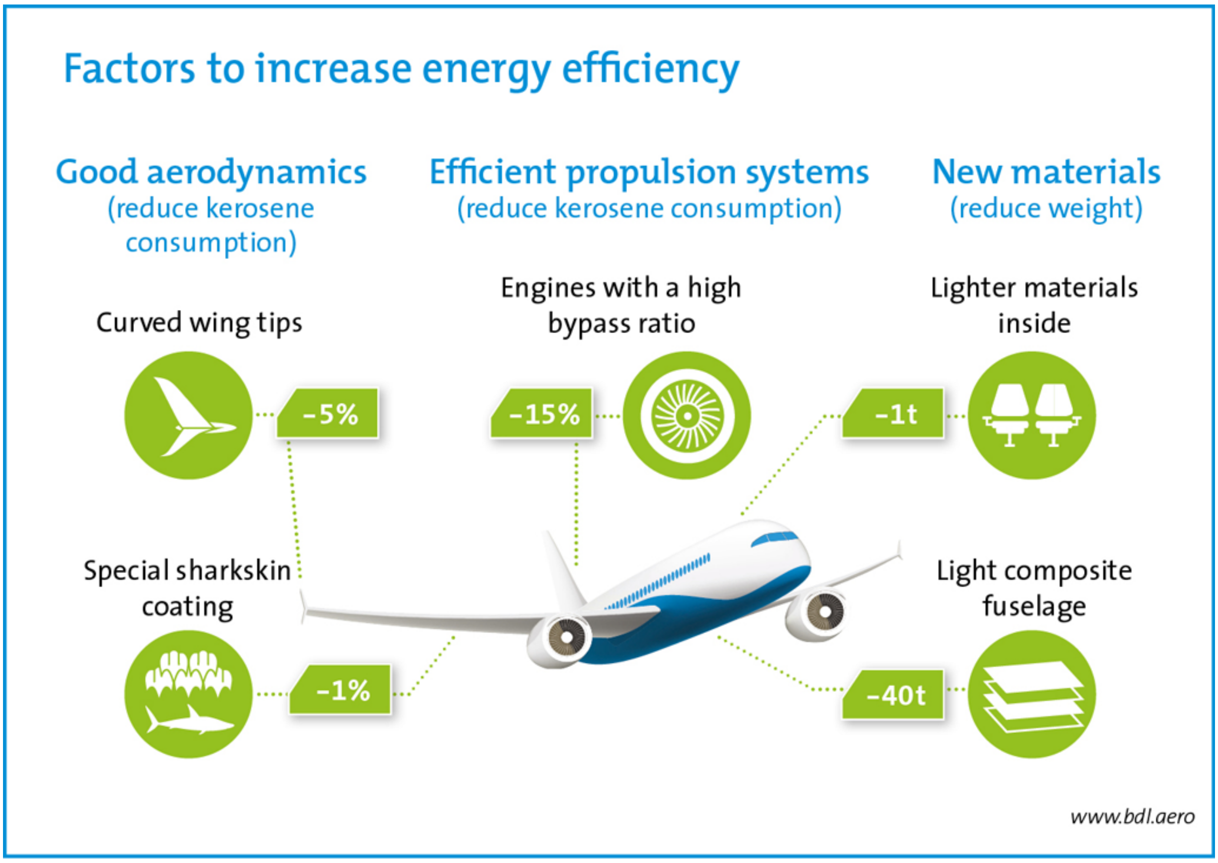

Figure 2.10 Efficiency improvements in aircraft **(BDL 2013)**

Liquid hydrogen is postulated as the one of the best alternative fuels able to be used for aircraft applications and his production can be based on renewable energy, with very low emissions. His use can eliminate the dependency of aviation for crude oil resources and eliminate the contribution of aviation to the greenhouse effect (**Koroneos et al. 2005**).

Hydrogen has been used as a fuel in many researches made by the industry and it is still being used in new projects. This is an important point for the aviation because new developments in other fields could be implemented in aircraft design.

Hydrogen could solve or relieve all the current aviation problems in the future. It is the most abundant element in the universe so the source of this element is guaranteed. Hydrogen is also free of carbon or another kind of impurities found in kerosene. It has been studied since a long time ago and there is a large list of contributors to this studies.

The use of hydrogen as a carrier of energy produced from electrolysis using electricity from renewable energy or nuclear energy could reduce the emissions and the most significant contributors to climate change are the contrails and NO_x emissions **(Verstraete et al. 2010; Yilmaz et al. 2012)** in lower quantities.

Hydrogen combustors could have extremely low emissions of NO_x and near zero emissions of CO_2. For this reasons, the problem concerning climate could be solved.

The combustion of 1 kg of hydrogen uses about 8 kg of oxygen and produces according to**Brewer 1991**:

- 9 kg of water vapour however this number depends on the technology of the engine
- 4.3 g of NO_x

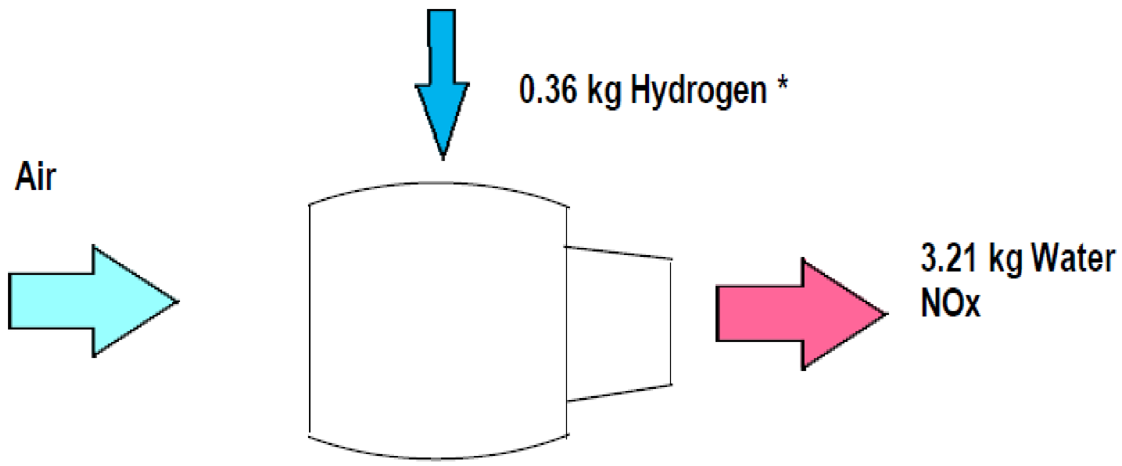

Figure 2.11 Combustion of hydrogen in jet engine

Table 2.3: Comparison of properties between LH_2 and Jet A-1 **(Seeckt 2010)**

Characteristic	Unit	Hydrogen	Jet A-1	Hydrogen/Jet A-1
Density	kg/m3	70.8	775 – 840	0.084 – 0.091
Volumetric energy density	MJ/dm3	8.7	33.2 – 36	0.24 – 0.26
Gravimetric energy density	MJ/kg	122.8	Min. 42.8	Max. 2.87
Freezing point	°C	−259	−47	x
Boiling point	°C	−253	171 – 267	x
Total sulfur content	-	0%	Max. 0.3 %	x

2.3 Hydrogen versus Kerosene

In this section a comparison between the two types of fuel will be made analysing the most important differences between hydrogen and kerosene. In 2.3 are shown the most important differences between the hydrogen an the Jet A-1. One of the first questions to be analysed is the energy. Hydrogen contains nearly 2.8 times more energy per kilogram, however it needs 4 times bigger volume to store the same amount of energy than kerosene figure 2.12.

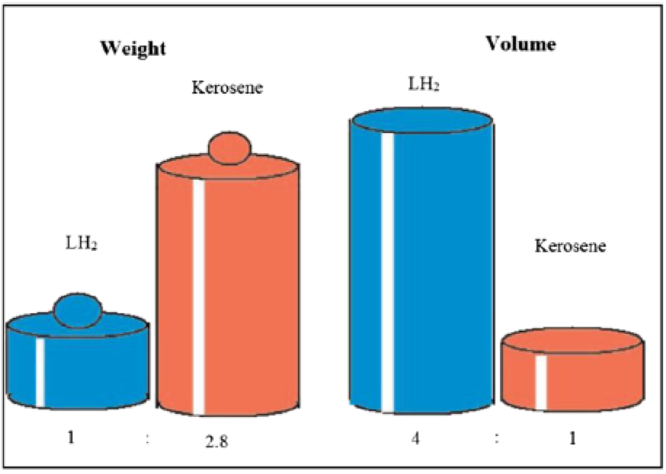

Figure 2.12 Weight-volume comparison between hydrogen and kerosene

This first condition will determine the redesign of the aircraft because for the same trip the volume of the tanks are 4 times bigger and the dimensions of the new aircraft will be different than the original.

For the LH_2, the storage temperature is different than kerosene which do not needs special cooling system for his storage, but in the case LH_2, for it storage a cryogenic temperature is needed till his boiling point of - 253 °C. For this reason special tanks are necessary with good insulation for prevent the effect of boil-off.

In table 2.4 it is shown a comparative between many fuels referenced to gasoline.

Table 2.4: Comparison between different fuels **(Brewer 1991)**

Fuel	**Energy/mass**	**Energy/vol.**	**Temp. (°C)**	**Mass/vol.**
Gasoline	1	1	25	1
JP-5	0.97	1.1	25	1
Methanol	0.44	0.51	25	1.1
Liquid hydrogen	0.61	0.27	−253	0.1
Metal hydride (hydrogen)	0.046	0.36	25	2.5
Methane (3.000 psi)	1.1	0.29	25	0.25
Hydrogen gas (3.000 psi)	2.6	0.06	25	0.02
Liquid propane (125 psi)	1	0.86	25	0.73
Hydrogen (10.000 psi)	2.6	0.2	25	0.08
Methane gas (10.000 psi)	1.1	0.97	25	0.81

Depending on the source of the production of hydrogen the emissions of CO_2 can be very different but when the energy comes from a renewable source this emissions are extremely low as Figure2.13 shows.

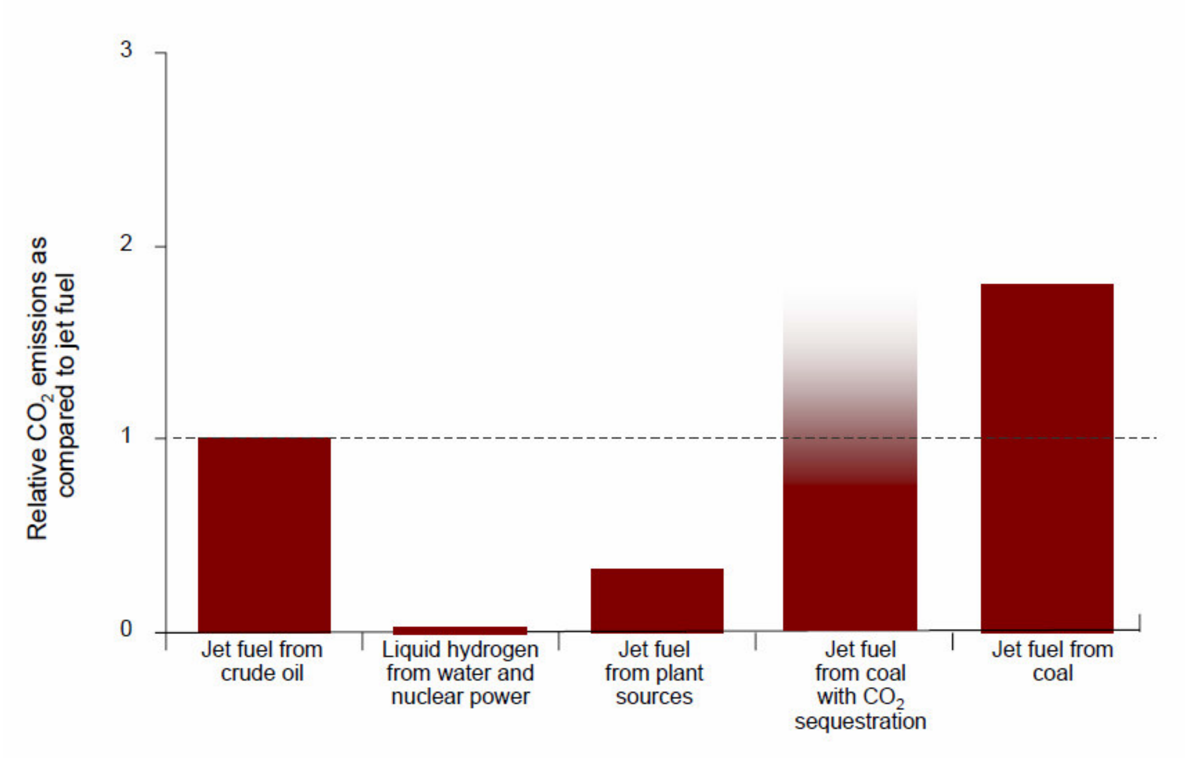

Figure 2.13 Relative CO_2 emissions compared to jet fuel **(Jahangir 2009)**

The emissions of an engine depend on the altitude where the aircraft is flying and there is an important difference between flying at sea level or flying at 11 km as Figure 2.14 shows.

Hydrogen can be stored in gas or liquid state, however storing the hydrogen in gas state could be a really important problem because the volume required for the tanks could be even more than in liquefied state, that is the main reason why GH_2 is not contemplated by aircraft industry. In table 2.5 are shown the differences between the hydrogen gas and liquefied state.

2.4 Historical Review of Hydrogen Aircraft

The first time that the hydrogen was used for flying was for the inflation of balloons, replacing the hot air. The first flight using hydrogen for a gas balloon was made in 1783 by the french physicist Jacques Charles with a balloon of 26 ft of diameter and it carried two passengers **(Brewer 1991)**.

In the beginning of the 20th century the German count Ferdinand von Zeppelin made the first flight with an air vehicle with hydrogen as fuel.

The first aero gas turbine using hydrogen was designed by Von Ohain in 1937 with an experimental engine called (HeS-1). This engine was a turbojet capable to produce a thrust of 250 lb.

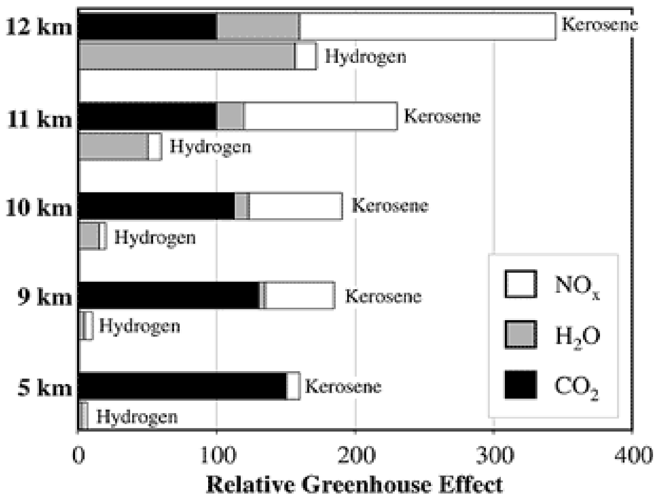

Figure 2.14 Emissions by altitude of kerosene and hydrogen

Two decades later in 1956 Pratt and Whitney made a research for the US Air Force to study the feasibility of hydrogen as fuel. The research was made modifying the injection system of the J57 engine. This work proved that conventional jet engines could be adapted to use LH_2 fuel. In the same year another project from the US Air Force developed a supersonic aircraft called CL-400 by Lockheed able to cruise at Mach 2.5.

The first model flying was the B-57 using liquid hydrogen and pressurized with helium. After this research the US started several programmes for researching liquid hydrogen such as Space Shuttle Program **(Khandelwal 2013)**.

In the 1970 due to the oil crisis new researches of hydrogen started by General Electric and NASA. Later in 1988 the USSR modified the TU-154 aircraft with one engine operating with hydrogen. Then in 1991 the Soviet Union and Germany started a program on hydrogen aircraft similar to the A310. There were two different designs on the basis of this aircraft, the Russian-German programme created a design with the tanks on the top of the fuselage and the other project design powered by NASA-Langley Research Centre used two spherical tanks filled into the fuselage, in order to reduce the surface to volume ratio.

In 2000 the European Commission funded one of the most important projects for the implementation of the hydrogen as an aviation fuel, called CRYOPLANE project. During the realization of the project, different configurations were studied and the feasibility of introducing hydrogen in the world of aircraft was analysed. This programme concluded that LH_2 needs more volume and new systems and tanks must be developed, different than the conventional aircraft. Due to this fact the consumption of energy would increase, as well as the *DOC* between 4 %-5 % according to**Westenberger 2003**.

The first Unmanned Aerial Vehicle (UAV) was developed by AeroVironment in 2005 using hydrogen as fuel. Recently in 2008 Boeing made a civil aircraft with 2 seats capable to fly using a fuel cell powered with hydrogen.

This historical review is briefly resumed in figure 2.15.

Table 2.5: Comparison between GH_2 and LH_2 **(Khandelwal 2013)**

Properties	**Compressed hydrogen gas**	**Liquid hydrogen**
Operating pressure	High	Low
Boil-off	Moderate	High
Cooling capacity	Less	High
Volume	Medium	High
Tank cost	Medium	High
Insulation	Medium	High
Hydrogen permeation	High	Medium
Liquefaction process	Not required	Required
Volumetric capacity	0.030 kg/L	0.070 kg/L

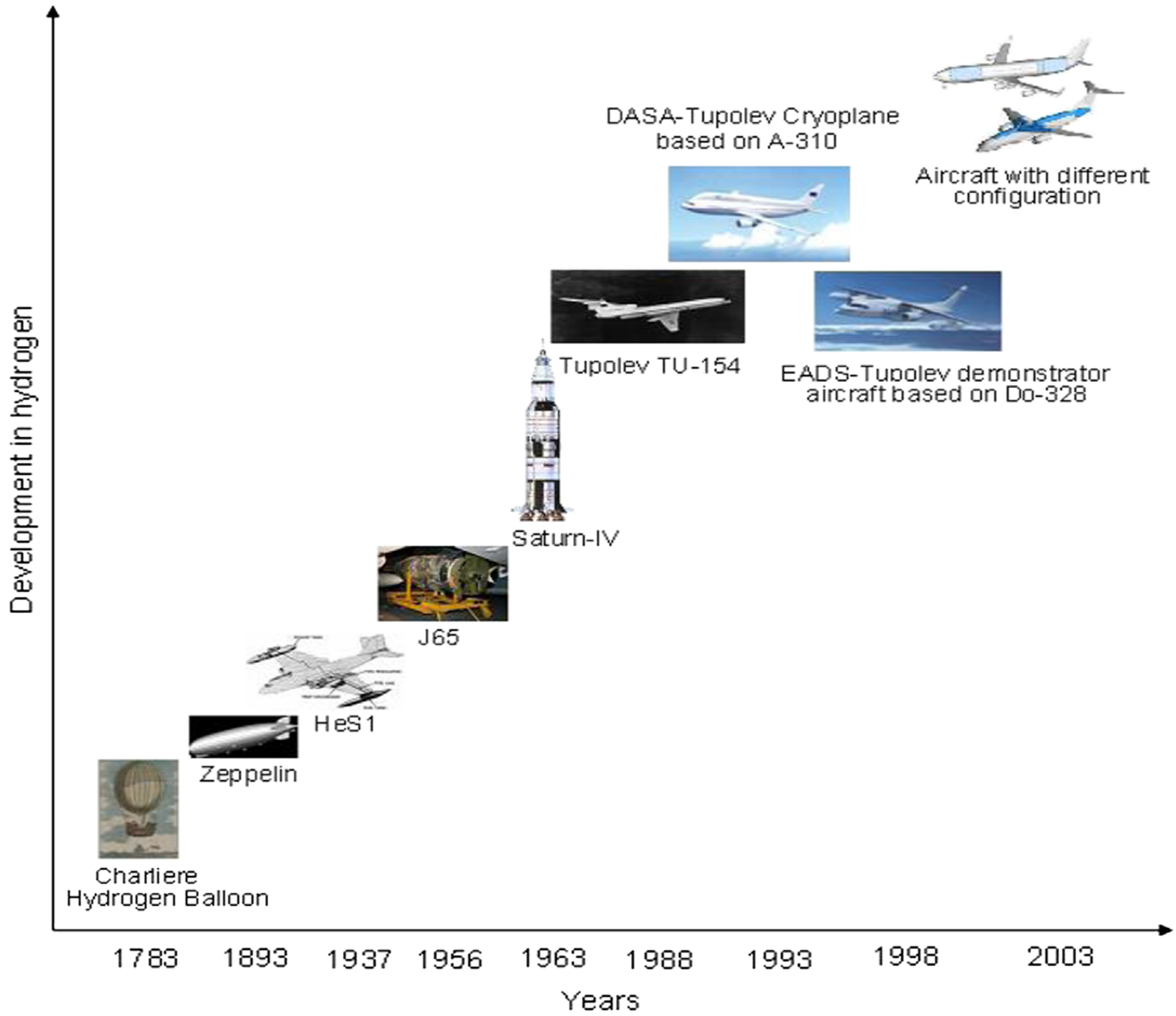

Figure 2.15 Historical review of hydrogen **(Khandelwal 2013)**

3 Hydrogen Production Study

At this point, it is well known that hydrogen is a suitable fuel for aircraft that could be produced from renewable sources of energy and offers many benefits such as extremely low emissions.

One of the most important issues regarding the use of hydrogen as a fuel for the aviation is the fundamental question if the hydrogen will be competitive in the economical and environmental aspect in comparison with the kerosene. For answering this question is important to analyse the sources and processes of the production of hydrogen and the main differences with the kerosene production for the future.

3.1 Kerosene Life Cycle

In this section a review of the life cycle of kerosene will be made because today, is the primary fuel in the aviation world. This study includes all the fields of the kerosene production such as the extraction and transportation of crude oil, the refining process, distribution, handling of the aviation fuel and the final combustion in the engines.

Crude oil is a mixture of hydrocarbons. The carbon in crude oil is thought to be originated from the marine organisms that were deposited a long time ago on the bottom of the sea and with a high temperature an pressure were transformed in the actual crude oil.

The extracted crude oil usually contains great quantities of emulsified water as much as 80 %-90 %. This water has to be removed before the transportation of crude oil to the refinery. The petroleum and all his products are transported from their sources to the refinery tankers, trucks, rail roads, pipelines etc.

The aviation fuel contributes with a 6.3 % of the total amount of oil consumed **(Liu et al. 2013)**. The refining process consists on separating the products in the crude oil using a process called atmospheric and vacuum distillation, heating and separating the gases for finally dense back into liquid state. This process is shown in Figure 3.1. In the case of kerosene, a boiling temperature between 205 °C and 260 °C is required. A typical jet composition could be:

- 20 % normal paraffins
- 40 % isoparaffins
- 20 % naphtenes
- 20 % aromatics

For the Jet A the maximum limit for the total aromatic content is limited to 25 %.

The crude oil and refined products are stored in reservoirs and steel tanks which could vary in size, containing several millions of barrels. The distribution line of kerosene from the refinery is complicated. The kerosene may be delivered to big terminals which can re-deliver the kerosene to another distributing centres and finally distributed to the airports.

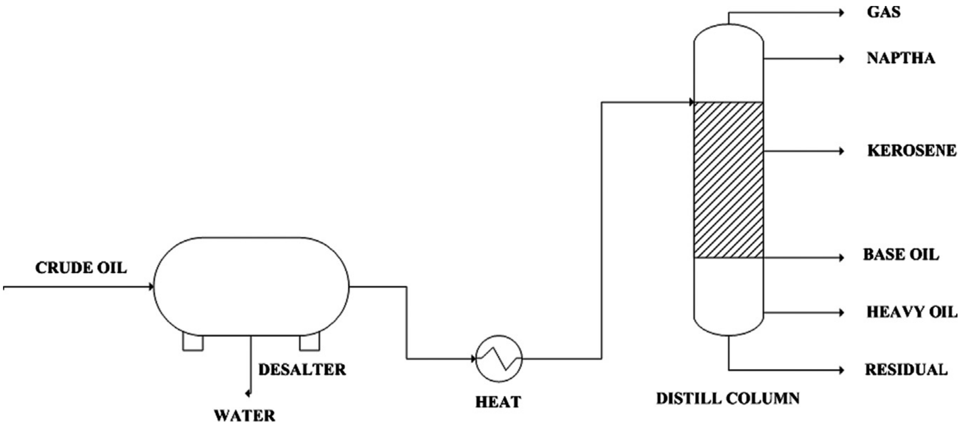

Figure 3.1 Jet fuel process

In Figure 3.2 is shown the life cycle of kerosene.

3.2 Hydrogen Production

Nowadays there are several different processes of hydrogen production depending on the source of the energy for producing the hydrogen: fossil fuel, renewable sources and nuclear power. Today, there are two main important methods for producing hydrogen. The 97 % of the production is based on the natural gas steam reforming method, due to the economic benefit aspect of this method. The other major production is with the electrolysis of water using renewable energy as source.

Another method of producing hydrogen is using direct water dissociation but due to the high temperatures required and the small fraction of hydrogen produced is an impractical way. To overcome this problems a new method is used via water splitting thermo-chemical cycles (WSTC) **(Smitkova et al. 2011)**. In this method the water is decomposed in oxygen and hydrogen via chemical reactions and using another substances in the cycle. This chemical reactions are endothermic and exothermic. The endothermic reactions take place at a temperature between 700 °C and 1200 °C. The most important reactions in this cycle are: the sulphur-iodine cycle, the hybrid cycle and the Westinghouse cycle. This method offers the ability to produce hydrogen without fossil fuels, in a different way.

3.2.1 Hydrogen Production with Natural Gas Steam Reforming

This method is one of the most used processes of producing hydrogen at the moment, due to his economic benefits. For this process the most important benefit is that induces one of the least CO_2 emissions of all the industrial processes at the moment **Koroneos et al. 2005**. Production of hydrogen using fossil fuels reports economical benefits but still the problems of the emissions and the dependency of fossil fuels sources. In a short therm, due to the efficiency and the cost of the method, this process seems to be very attractive for the industry.

In this process hydrocarbons are catalytically splitted in the presence of a steam with a temper-

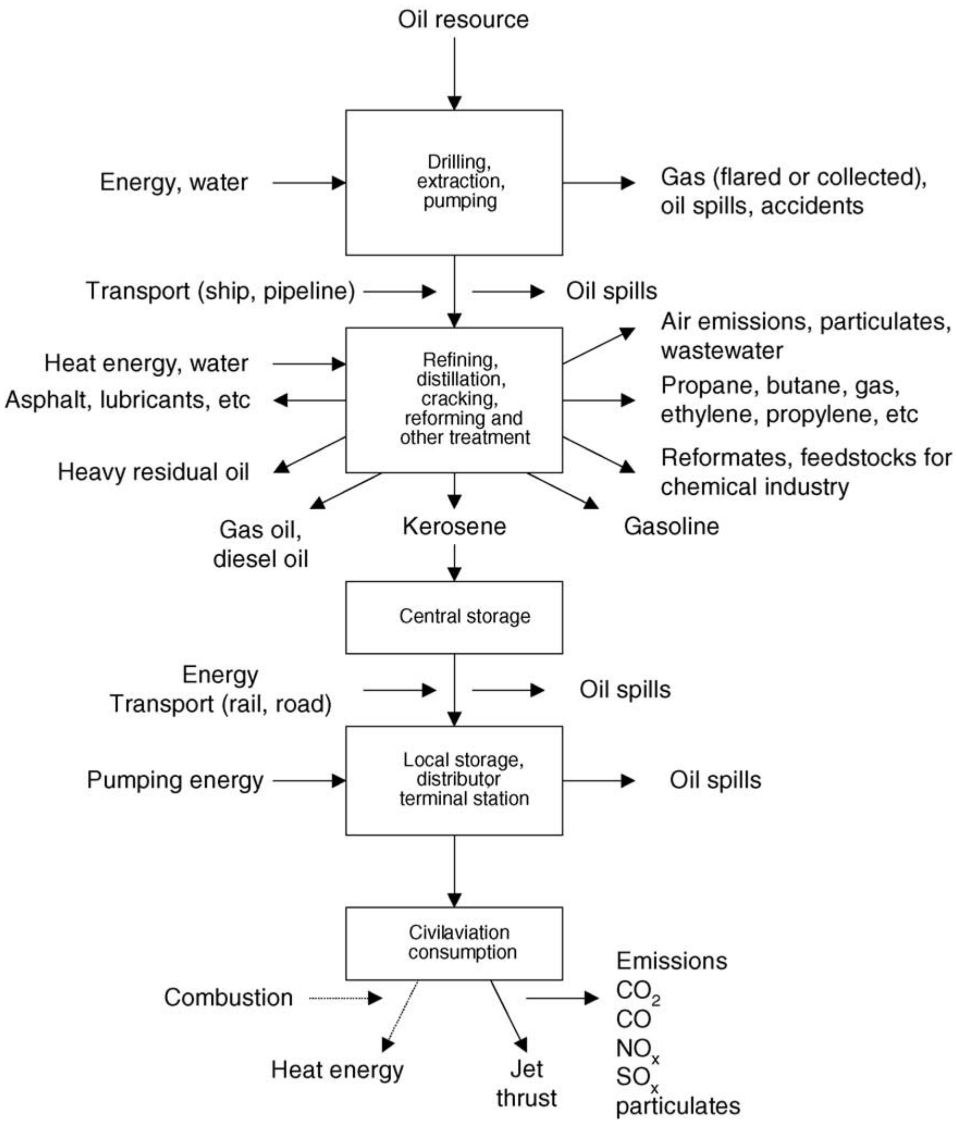

Figure 3.2 Kerosene life cycle **(Koroneos et al. 2005)**

ature near 900 °C. During this split the gas produced (syngas) mainly consists of hydrogen and CO. The representative equation of the process is

$$C_nH_m + nH_2O \rightarrow nCO + (n + \frac{m}{2})H_2 \tag{3.1}$$

Apart of the basic equation others secondary equations take part in the process and the CO_2 is produced from another reactions. In the next equation the CO is transformed from the syngas into

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{3.2}$$

The hydrogen is separated from the product gas and the remaining gas is recirculated and used as fuel for the steam-reforming reactor. After passing several heat exchangers the gas is released to the atmosphere. In table 3.1 are shown the major emissions to the atmosphere for this process. One option which avoid the emissions of CO_2 to the atmosphere is to extract and collect it in tanks.

Table 3.1: Air emissions using steam reforming process

Air emission	**System total (g/kg of H2)**
Benzene (C_6H_6)	1.4
Carbon dioxide (CO_2)	10662.1
Carbon monoxide (CO)	5.9
Methane (CH_4)	146.3
Nitrogen oxides ($NO_x as NO_2$)	12.6
Nitrous oxide (N_2O)	0.04
Non-methane hydrocarbons ($NMHCs$)	26.3
Particulates	2.0
Sulfur oxides ($SO_x as SO_2$)	9.7

3.2.2 Hydrogen Production with Renewable Energy

Hydrogen is considered to be a suitable energy carrier for the environment, but this assertion strongly depends on how it is produced. Today, a great number of innovative processes based on renewable energy are developed for the hydrogen production. Of course the most important benefit of this methods is the extremely low emissions of CO_2 for producing hydrogen, so they can reduce considerably the global warming effect.

The economic analyse in **Westenberger 2003** showed that although these methods could replace the fossil fuels for the production of hydrogen, in economical therms is much more expensive to produce hydrogen using renewable energy than the conventional way with natural gas steam reforming.

Production of hydrogen using the sunlight could offer big environmental benefits only in the case the cost of production could be decreased and the efficiency of the process could be improved **(Khandelwal 2013)**.

Biomass gasification has also a high potential to supply the fossil based process in economical terms, although this process depends on the region of the application of this energy source. According to **Westenberger 2003**, in order to produce 50000 kg/day of hydrogen, 490000 kg of dry biomass is required per day with a total amount of 179 millions of kg per year.

The most important processes based on the renewable energy are:

1. Solar energy using photovoltaics for the conversion.
2. Solar thermal energy.
3. Wind power source.
4. Hydro power source.
5. Biomass energy source.

In Figure 3.3 are shown the total equivalent emissions of CO_2 for the different methods of producing hydrogen based on many energy sources.

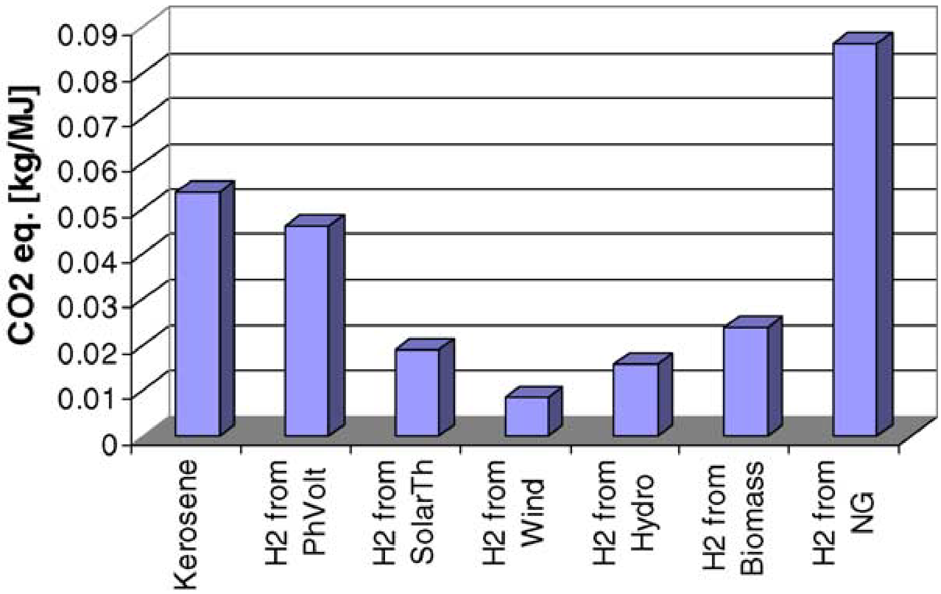

Figure 3.3 CO_2 equivalent emissions from hydrogen production **(Westenberger 2003)**

The process starts always with the extraction of the primary energy, followed by the transportation till the hydrogen production plant, the conversion into hydrogen and finally the liquefaction for the final use. In Figure 3.4 is shown the cycle of the LH_2 production.

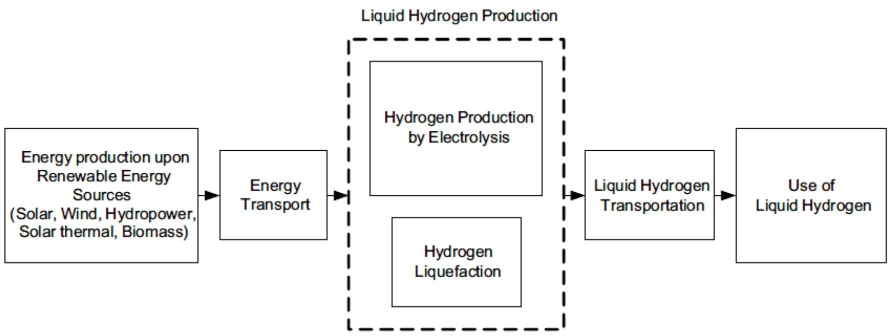

Figure 3.4 Hydrogen liquid production based on renewable sources

3.2.3 Hydrogen Production with Electrolysis

There are various processes for the electrolytic hydrogen production like conventional electrolysis, alkaline electrolysis (with high pressure), membrane electrolysis and steam electrolysis. The high pressure technology could be the most reasonable way of producing hydrogen in the future **(Koroneos et al. 2005)**. The most important advantage is that the hydrogen is provided at high pressure and is favourable for the transportation system.

Hydrogen production based on this method is one of the highest at the moment. The efficiency of this process is established in 77 %. With this process a high purity hydrogen could be obtained and it is possible to produce it at large or small scales.

One of the most important parts of this method is the electrolyzer which consist in a series of cells with a positive and a negative electrode each one. This electrodes are immersed in a mixture of water and alkaline potassium hydrogen (KOH) in order to make the water electrically conductive. The positive electrode (anode) is typically made with nickel and copper and the negative electrode is made with nickel and coated with platinum which increase the rate of hydrogen production.

In order to prevent the mixture between the hydrogen and oxygen molecules a separator such as a diaphragm is needed. The reactions in the cathode are

$$K^+ + e^- \rightarrow K \tag{3.3}$$

$$K + H_2O \rightarrow K^+ + H + OH^- \tag{3.4}$$

$$H + H \rightarrow H_2 \tag{3.5}$$

These equations in the cathode explains the production of the hydrogen, starting with the reduction of the potassium till the production of the the hydrogen molecule as a gas.

The reactions in the cathode are

$$OH^- \rightarrow OH + e^- \tag{3.6}$$

$$OH \rightarrow \frac{1}{2}H_2O + \frac{1}{2}O_2 \tag{3.7}$$

$$O + O \rightarrow O_2 \tag{3.8}$$

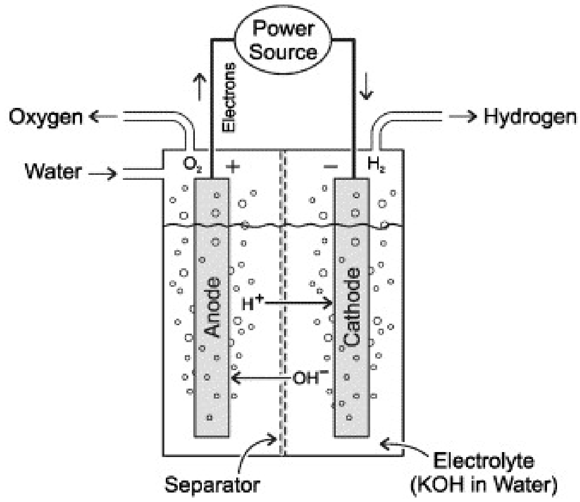

Figure 3.5 Hydrogen production with electrolysis

This reactions start with the oxidation of the hydroxyl ion till the production of the oxygen molecule as a gas. This process can be seen in Figure 3.5.

According to studies made in the Cryoplane project for obtaining 50000 kg/day of hydrogen, 105 MW of electricity and near 28 m^3 of desalted water are required considering an efficiency near 80 %.

The rate of the hydrogen production strongly depends on the current density (current flow divided by the electrolyte area), that is the main reason of using high voltage. The electrolyzers of today have a efficiency between 60 % and 80 %, and can operate at densities of about 2000 A/m^2. Is important to note that the efficiency of the process increases with the temperature and the losses of the thermodynamic process are associated with the heat production **(Koroneos et al. 2005)**.

3.3 Liquefaction of Hydrogen

The gaseous hydrogen is assumed to have a purity of about 96.6 % containing also nitrogen, carbon monoxide, carbon dioxide ant methane as impurities. The gas is introduced into a first stage of hydrogen compressors where it is compressed gas and purified **(Brewer 1991)**. The refrigeration for the liquefaction of the hydrogen is made in a set of cryogenic hydrogen turbines. Another nitrogen refrigerator helps this process.

For liquefying the hydrogen from the gas state is needed a temperature below his boiling point at -253 °C. The best liquefaction process is a combination between the isothermal compression followed by adiabatic expansion, where the gas is cooled due to the Joule-Thompson effect.

For the amount of hydrogen production explained in 3.2.3, the liquefaction process would consume near 25500 kW of electricity for the main electrical power and near 155 kW for the control of the electrical power.

One possible scheme of the liquefaction process could be one like in Figure 3.6.

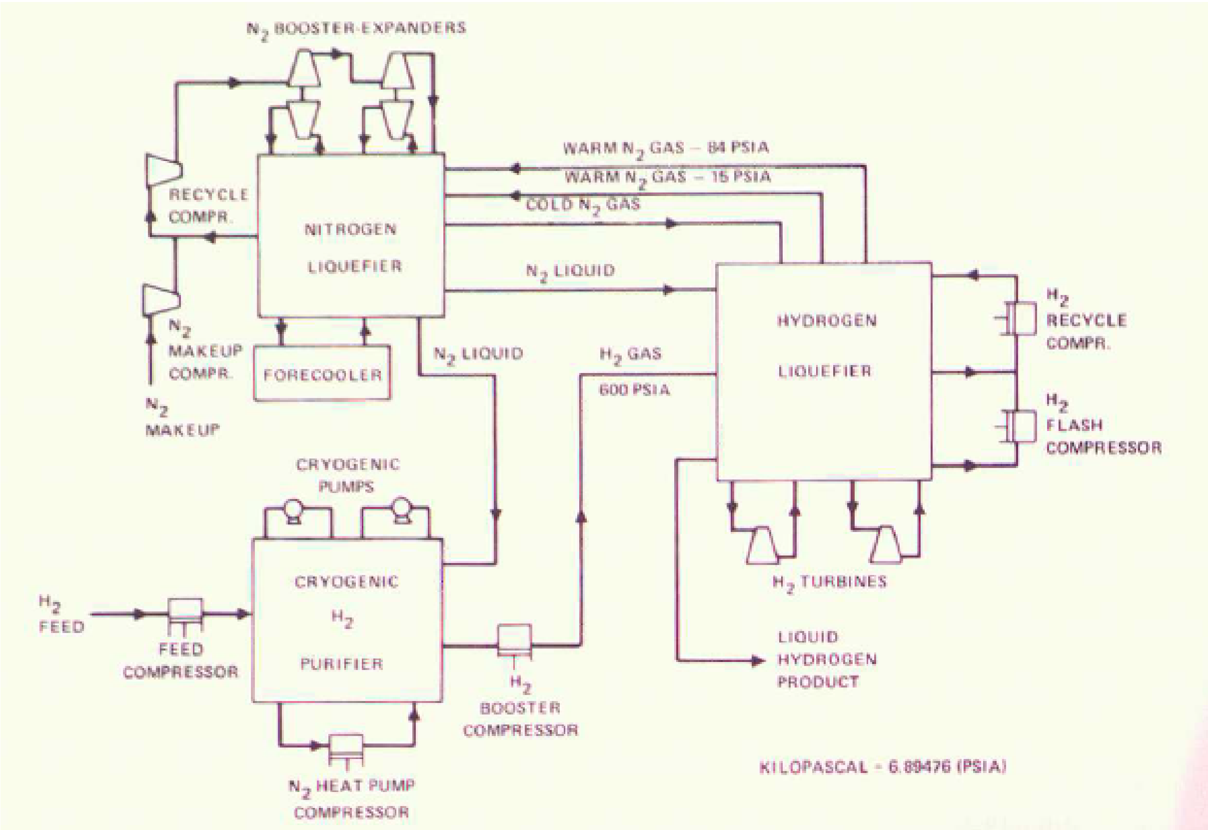

Figure 3.6 Liquefaction process **(Brewer 1991)**

After having the hydrogen in liquid state one important issue is the transport and the facility to be available in the airport. For being an efficient fuel for airline service is important to have all the necessary equipment to liquefy the hydrogen, store it and deliver into aircraft. In order to be efficient the liquefaction plant should be installed in the airport area.

According to **Brewer 1991** there are three methods for the transportation of hydrogen from the liquefaction area to the tanks located in the airport:

- Vacuum-jacketed pipeline.
- Transport using the existing size of truck-trailer from commercial vehicles.
- Transport using rail road for commercial rail cars, which could increase potentially the volume of storage.

3.4 Summary of the Hydrogen Production

Although hydrogen has been proved as a clean fuel for the aviation, it not necessary means that the contribution of aviation to the greenhouse effect will be eradicated. Depending on the process of obtaining hydrogen the emissions may change significantly due to the fact that greenhouse gasses could be released during his production.

In the production of hydrogen using steam reforming of gas natural high emissions of CO_2 and CH_4 are released to the atmosphere due to the nature of the process and the possible losses to the atmosphere which can have a large impact in the environment.

The emissions of the wind, hydro-power and solar thermal energy are very low and could be the most important ways of producing hydrogen with an extremely low impact in the green house effect. Wind and hydro-power methods could also be sustainable even for long distances of transportation. The production with biomass could be very efficient only if the biomass is produced locally, avoiding transportation related emissions (**Westenberger 2003**).

Production using nuclear energy could also be a sustainable method of producing hydrogen with low emissions.

In contradiction with the other methods when producing hydrogen using photovoltaic energy the emissions are very high due to the manufacturing process of the photovoltaic modules. The solution to this issue is to produce the panels in a more efficient way.

The production of hydrogen using renewable energies could alleviate the problem of the environmental effect but is is also necessary to find economical ways for the processes since the economical point of view is could make the difference when deciding to choose the fuel for the aviation.

Summarizing, in the long therm growth, due to all the challenges for low emissions in the future and the necessity to investigate new fuels for the aviation, the use of hydrogen could be achieved with his production based on renewable energy which should be obtained in a clean and economical way for the environment.

4 Cryogenic Tank Design and Fuel System

One of the most important challenges in the technical field of the hydrogen-fueled version in aircraft design terms, is the development and design of the fuel tanks for the storage of the LH_2 in cryogenic state.

Hydrogen could be stored in gaseous state but because of the problems reviewed in table 2.5 and the excessive volume needed, this solution is discarded. The source of the problem is the issue that hydrogen tanks need a bigger volume compared with the kerosene tanks. The material used for the tank must be resistant with a good behaviour for ductility and fracture resistance at cryogenic temperatures. Thus, the weight of the tank will increase which is contradictory with the current tendency of use more and more light weight structures in the airplane. For all this, the process of designing the tanks must take care of special problems, combining the design for lightweight and maintaining structural integrity **(Brewer 1991)**.

The major considerations for the design of a LH_2 tank are:

- It requires an insulation system to reduce the boil-off of the LH_2 and maintain it at cryogenic temperatures.
- The fuel tank must be maintained at a constant pressure usually around 0.145 MPa **(Colozza 2002)** to minimize the boil-off, so this requires a venting system and special equipment.
- The tank must be light.
- The tank should not have a heat leak rate such than the hydrogen will vaporise faster than the engines could burn it in cruise conditions.
- The liquid hydrogen lines for the fuel system must be protected from the atmosphere. If fresh air enters in the tank, it will freeze and the flow lines could be blocked. Helium could be used as a purge gas.
- It should be capable of storing the fuel on the ground for a reasonable amount of time without high losses. Due to the fact that the storage time is limited, the production of the fuel has to be near the airport.

LH_2 has been used in space missions since a long time ago due to his high energy content. Even if in space missions the cryogenic tanks are used, the same tank cannot be used for aircraft application because in space vehicle the tanks have a very short time life with a very high consumption rate and a boil-off about 1.6 % of weight per hour, when an acceptable rate of boil-off for aircraft application is 0.1 % or less according to **Mital et al. 2006**.

At ambient temperature hydrogen will be in gaseous form however at ambient pressure, hydrogen can be stored in liquid state under 20.4 K, however the storage tanks are preferred to be a thin wall pressure vessel with an operating pressure between 0.1-0.35 MPa reducing the mass of the tank.

It is known that hydrogen possesses a tremendous amount of energy but it could be also a perfect cooling liquid. In fact his cooling capacity is 4.9 times of Jet-A.

One the one hand the design of the LH_2 tanks is very dependent on the airframe structure because imposes constraints to the shape and tank dimensions, on the other hand the propulsion system contributes with requirements for a particular mission **(Khandelwal 2013)**.

During the selection of the tank configuration there are some vital points to be analysed in order to make a good selection of the tank as it is seen in Figure 4.1.

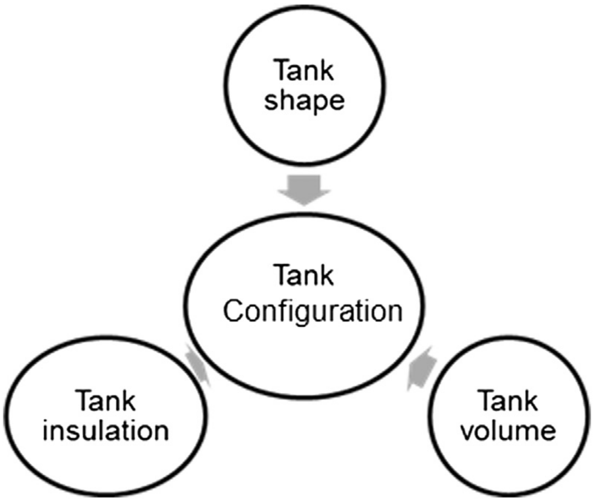

Figure 4.1 Factors for tank configuration **(Khandelwal 2013)**

The main components for storing liquid hydrogen are the materials for the tank and the insulation system.

4.1 Tank Shape and Configuration

Due to the low density of the hydrogen compared to other liquids implies higher volume however the weight required for a particular mission will be less compared to other fuels. An important issue when designing the tank is the question that it should be able to be suitably inspected in accordance to airline standards.

The fuel containment systems are divided in two types: integral and non-integral tanks. Non-integral tanks are designed to resist the loads associated with fuel containment such as pressurization, thermal stresses or dynamic fuel loads and must be mounted in the conventional fuselage, skin and frame structure. The non-integral tanks could be kept outside the fuselage with the consequent problems such as drag increase, stability and the integration issue. One the other hand, integral tanks forms are an integral part of the basic airframe structure. In addition to the loads of the non-integral tanks, this configuration should be able to resist the stresses of the fuselage such as axial, bending, shear from the aircraft loading conditions. In Figure 4.2 are shown the two different types of tanks.

In the case of integral tanks the diameter of the tanks will be imposed by the dimensions of the fuselage. The integral design has a higher volumetric efficiency (volume available for LH_2 divided by volume of fuselage section) leading to a lower drag with weight saving. In addition the integral design is more suitable for inspection and repair. In table 4.1 are shown the differences between a tank of 40000 psi allowable stress in the both configurations.

Figure 4.2 Integral and non-integral tank configuration **(Westenberger 2003)**

Table 4.1: Comparison between integral and non-integral configuration **(Brewer 1991)**

	Non-Integral	**Integral**
Fuel Weight fraction (lb/lb of LH2)		
Tank	0.113	0.196
Thermal Protection	0.079	0.06
Heat shield	0	0.06
Fuselage structure	0.152	0
Total	0.344	0.316
Volumetric Efficiency	0.855	0.927
Accessibility for inspection/repair	Requires removal of tank	Remove heat shield

For all this reasons the integral tank configuration seems to be the most feasible configuration. In the Cryoplane project the tanks were situated over the fuselage and across the wings alleviating the bending moment and increasing the capacity of carrying LH_2 but with a thick and heavy tank wall. For the shapes of the tank, the possible solutions could be spherical or cylindrical tanks in both cases with the diameter of the fuselage. Today the spherical tanks are used in space applications and it is the best solution in terms of the surface area for a given volume. This leads to a lower boil-off rate because the heat flux in the spherical tank is lower. The problem of the spherical tanks is the manufacturing process and the higher frontal area with the consequent drag increase.

The other possible solution is the cylindrical shape of the tank. In this case is easier to manufacture the tank but it has more surface area for a given volume with a high flux heat rate. One of the best point of this design is the possibility of integrate them better in the fuselage section increasing the volumetric efficiency, using the space inside the fuselage in an optimum way. One important problem with the cylindrical shape is that the pressure inside the tank could be not equally distributed and for preventing it the tanks are designed with two semi-spherical caps in the both ends of the cylinder.

In Figure 4.3 are shown the possible configurations for the tank.

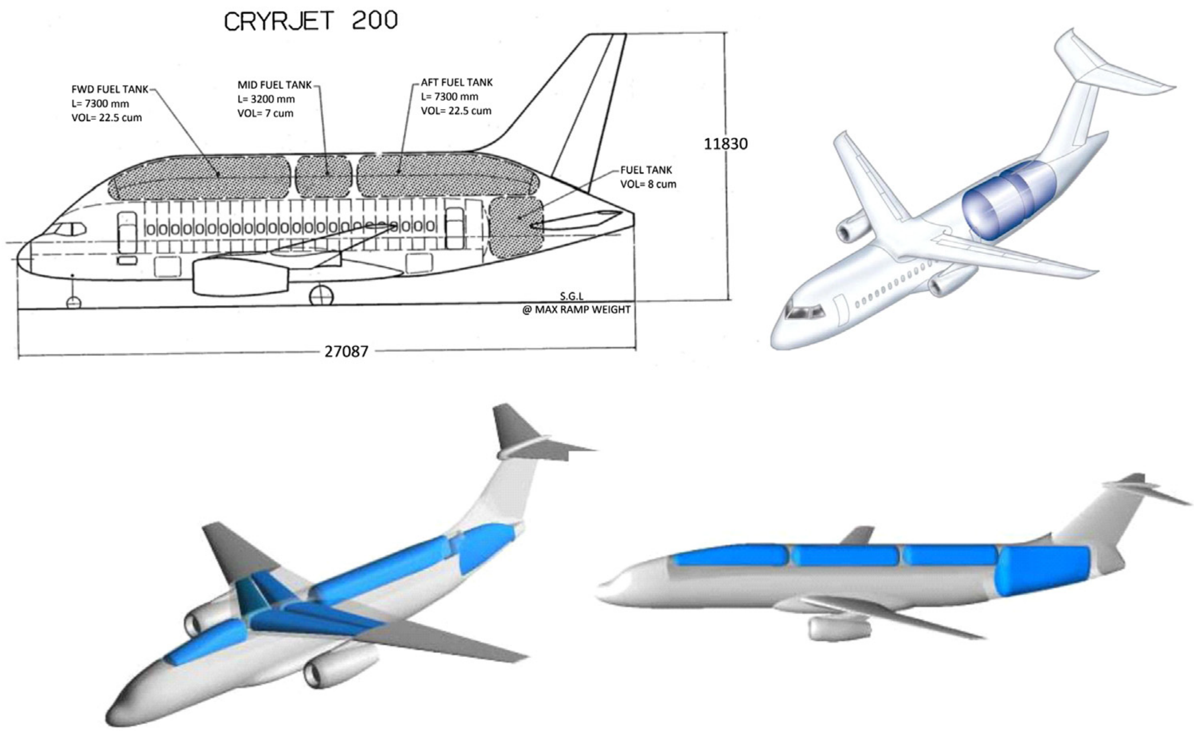

Figure 4.3 Hydrogen aircraft with different tank configuration **(Westenberger 2003)**

Fol all this issues the final configuration for the tank is the integral and if it is necessary combined with external wing tanks using a cylindrical shape.

4.2 Tank Insulation

The other important issue of the tank design is the insulation system. The cryogenic insulation could be applied to the inside or outside tank walls. This question will influence the differential thermal expansion of the structure. In the case of internal insulation the insulation will be exposed to the LH_2 and because of the heat transfer, the hydrogen will change his state to gas which could be a problem if the material used for insulation is permeable to GH_2.

In the external insulation the insulation is applied to the external surface of the tank and it will expand and contract itself. In this case the dimensions of the tank will increase and and the insulation could be easily damaged. Also the insulation must be impervious to air but this requirement is less restrictive than to be impervious to GH_2.

Because of the difficulty to find a material impervious to GH_2 and due to the necessity of being able to inspect the tank the external insulation is adopted.

All atmospheric gases will freeze at cryogenic temperature of LH_2, so the air must be well evacuated from the insulation system.

The design of the insulation system should attend to the main following topics:

1. Reduce the heat rates of the LH_2, minimizing the DOC, because there is a relation between the insulation system and the amount of boil-off permitted.

2. The insulation system must be reliable and safety.

3. Productivity is important, so the tank should be fabricated, assembled and inspected according to aircraft and airline requirements.

The keys of the insulation system design are: low thermal conductivity, low emissivity and low density.

According to **Khandelwal 2013** the three most important types of insulation are showed in Figure 4.4.

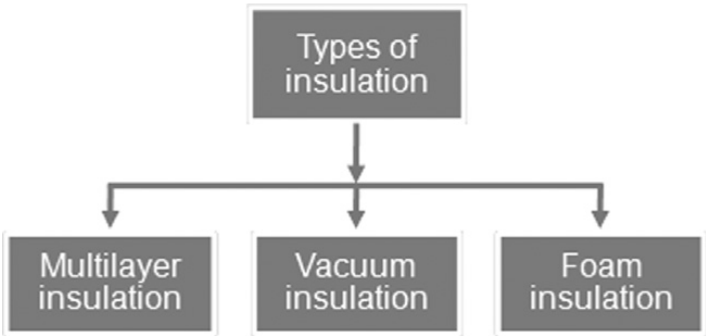

Figure 4.4 Types of insulation **(Khandelwal 2013)**

4.2.1 Multilayer Insulation (MLI)

This method of insulation consists on using thin sheets which acts like thermal radiation shields perpendicular to the direction of the heat flow. This method consist on a reflexive foil able to minimize the radiation flux of heat. The layers are designed with spacer elements with a low heat conductivity built with glass fibre or polyester between the reflecting layers to avoid the metal to metal contact. The optimal number of layers used must be between 60-100 **(Khandelwal 2013)**. If this number increases, the heat transfer due to the heat conduction will increase.

The performance of this method depends on the pressure and the type of residual gas for insulation. High vacuum is required in order to avoid the convection and minimise the heat conduction. The MLI is very sensitive to the fluctuations in pressure.

The materials used for the layers are mostly aluminium mylar films or pure aluminium. The problem of this tank is the high weight obtained although is the best solution for the radiative flux (for space applications) it could be problematic in terms of convection and conduction heat of flux.

In Figure 4.5 is detailed a typical multilayer insulation system with aluminium.

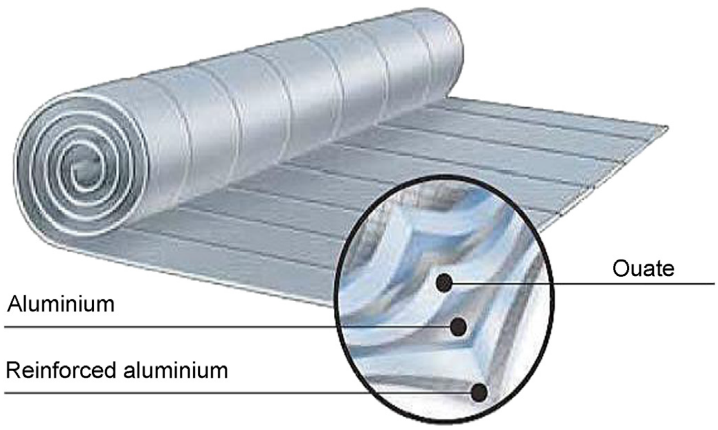

Figure 4.5 MLI typical scheme **(Khandelwal 2013)**

4.2.2 Vacuum Insulation

This kind of insulation could be one of the best solution for minimizing the mass of boil-off. The problem of this method is the difficulty of obtaining vacuum and special equipment is required to suck the air and maintain the pressure of the vacuum chamber. The air has to be separate from the hydrogen in order to avoid the freeze inside the tank system. The wall thickness must be selected consequently because the vacuum jacket is subjected to the external pressure.

This method seems to be important in the future, but in this case the tank will be heavy and stiffeners are required, increasing the weight of the tank. This method will be more expensive because of the special equipment required to maintain the pressure and temperature.

In Figure 4.6 is detailed a vacuum insulated aluminium tank with MLI.

The MLI is located between the inner hydrogen tank and its outer vacuum jacket tank. For measuring the hydrogen mass is used a capacitance fill-level probe. Liquid and vapour piping penetrations are required in order to vent, pressurize, drain and fill the tank **(Millis et al. 2009)**.

In Figure 4.6 is detailed a vacuum insulated aluminium tank with MLI.

4.2.3 Foam Insulation

One of the best points of the materials used for the foam insulation are the low density and thermal conductivity. A simple scheme of this method is shown in Figure 4.8. The rigid foam insulation is applied outside the inner tank wall and a thin metal wall is required to be surrounded around the foam to maintain its structural stability protecting it from external forces.

There are several families of foams suitable for aeronautical use today. The flexible open-cell foams can be an excellent candidate to insulate complex shapes because they can be quickly applied and they have the property of being thermo-formable as it is explained in **Verstraete et al. 2010**, but the cryo-pumping could be a problem with these foams because they have open-cells. Another candidate is polyurethane, although this foam is rigid and is not thermo-

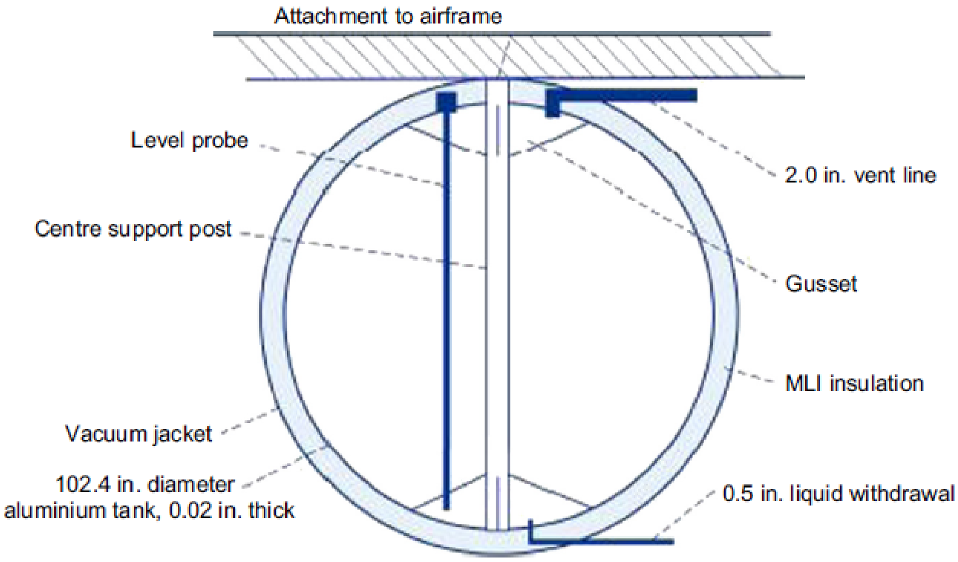

Fig. 12. Vacuum insulation system [43].

Figure 4.6 Aluminium jacketed-insulation tank **(Millis et al. 2009)**

formable. It possesses the good property of having an excellent behaviour with thermal cycles. The last possibility is the Rohacell closed cell with polimethacrylimide which is rigid and thermo-formable.

Figure 4.7 shows the behaviour of the thermal conductivity of the polyurethane foam (32 kg/m^3) and Rohacell foam (51.1 kg/m^3) with the temperature. In this case the Rohacell behaviour with the temperature is better.

The foam insulation concept is more resistant to catastrophic failure than the vacuum-jacketed insulation. The insulation thickness of the tank depends upon the insulation material properties, tank size, allowable boil-off and overall allowable tank weight.

Foam insulation is low cost, easy to implement with a light weight. Vacuum-jacketed and multilayer insulation has been investigated for quite long time and in the case of loss of vacuum it might cause catastrophic failure whereas in foam insulation the chances of catastrophic failure are less.

In order to resume the different types of insulations available at the moment (including two new types such as perlite and aerogel material) in 4.2 are resumed the advantages and disadvantages of all the types.

Table 4.2: Advantages and Disadvantages of Insulation Methods **(Mital et al. 2006)**

Foams (Outside Wall)	
Advantages	Currently in use, well established
	Low cost, easy to implement
	Light weight and low density
Disadvantages	Limited to short duration missions
	Low resistance to thermal radiation
	Potential damage from environmental hazards
Foams (Inside Wall)	
Advantages	Low cost
	Structural wall not exposed to cryogenic conditions
	Reduced CTE mismatch issues of composite constituents
Disadvantages	Necessitates larger structural tank wall increasing mass
	Difficult to seal from cryogenic fluid
	May interfere with fluid management upon failure
Vacuum	
Advantages	Near zero thermal conductivity
	Well established
Disadvantages	Heavier tank walls required
	Costly to implement and maintain
	No resistance to radiation heat transfer
	Near catastrophic failure upon loss of vacuum
MLI	
Advantages	Very low thermal conductivity and radiation heat transfer
	Extremely low density
	Well established
Disadvantages	High vacuum required
	Heavier tank walls required
	Costly to implement and maintain
	Near catastrophic failure upon loss of vacuum

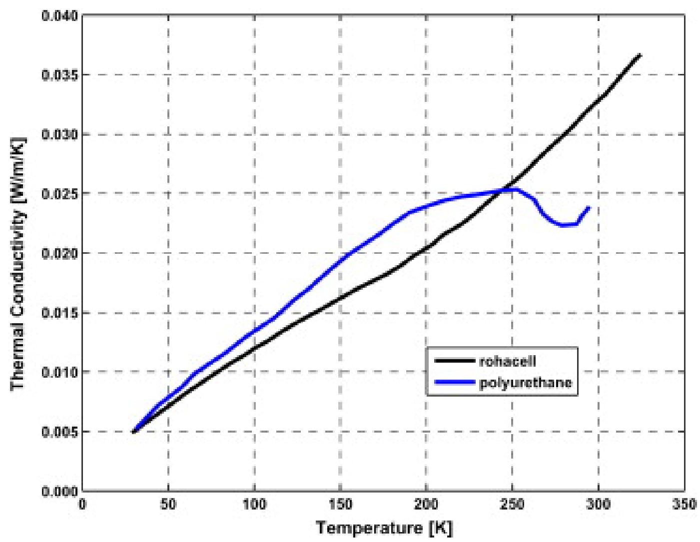

Figure 4.7 Foam thermal conductivity based on **(Brewer 1991)**

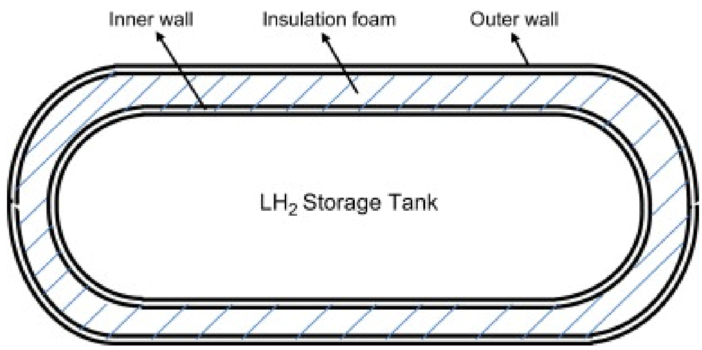

Figure 4.8 Foam insulation **(Khandelwal 2013)**

4.3 Tank Design Considerations

According to **Seeckt 2010** in order to have a reliable information about the materials of the tanks and the insulation, the final selection for the tank is the integral spherical tank with aluminium alloy (2219/2024). The possibility of an external tank is also contemplated. The insulation selected is polyurethane foam, for all the benefits explained, with a thickness wall of 15 cm. An important input for the aircraft design is the mass per squared meter of the both materials,

$$\frac{m_{ALUM}}{S_{TANK}} = 3\ kg/m^2 \tag{4.1}$$

$$\frac{m_{INS}}{S_{TANK}} = 5\ kg/m^2 \tag{4.2}$$

These numbers could considerably increase if the fuel system components of the structure are taken in account. According to **Westenberger 2003** fort a short-medium haul aircraft a reasonable mass for the tank could be

$$\frac{m_{TANK}}{S_{TANK}} = 20\ kg/m^2 \tag{4.3}$$

The tank volume can be calculated once the mass of fuel for the specified mission is known. According to **(Brewer 1991)** the volume of the tank could be calculated using the following approximation

$$V_{TANK} = m_{LH_2}[\frac{1+\frac{allowance}{100}}{\rho_{LH_2}}] \tag{4.4}$$

The value of the allowance is expressed in percent. The allowance contemplates the mass of boil-off, contractions, internal structure and equipment for the tank. The most important values are collected in table 4.3.

Table 4.3: LH_2 Tank sizing allowances **(Brewer 1991)**

	Allowance (%)
Contraction due to cooling and expansion due to pressurization	0.90
Internal structure and equipment	0.60
Trapped an unusable fuel	0.30
Ullage	2.00
Boil-off	
Pressurant gas	1.77
Vented gas	1.63
Total	**7.20**

For the short and medium range aircraft in the Cryoplane project were studied two types of configurations. In the first configuration the tanks were also established across the wing but a lower aero-dynamical efficiency was found due to the fact that the wing was bigger. The alternative configuration was to enlarge the tail cone and incorporate two new tanks over the fuselage, one in front and one in the rear part as Figure 4.9 shows. The same configuration can be seen in Figure 4.10

There are many differences when using the configuration for the tanks over the fuselage or using two tanks one in the rear part an the other on the front part of the fuselage. According to the researches made in the Green Freighter Project in HAW Hamburg, the best configuration for a more efficient aircraft for the tanks is the configuration with the tanks in the rear and front part of the fuselage.

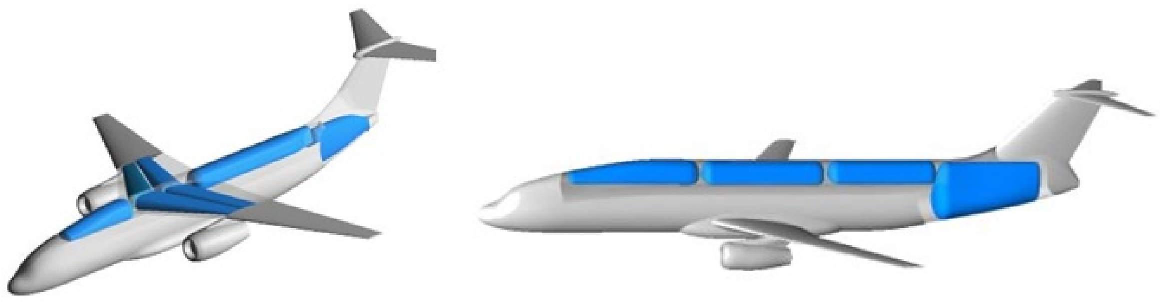

Figure 4.9 Configurations studied during Cryoplane project **(Westenberger 2003)**

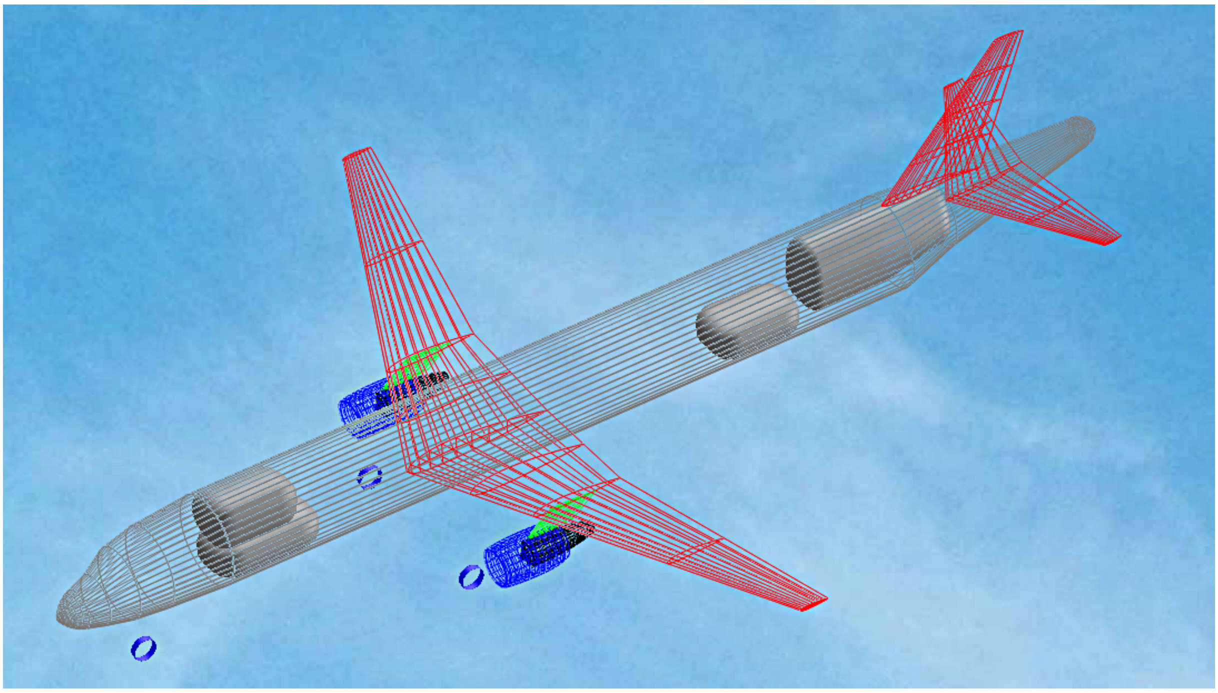

Figure 4.10 Configuration with front and rear tanks

Table 4.4 confirms this results. The configuration with front and rear tanks offers more benefits, being the reason of designing with these type of configuration. The first tank is located between the cockpit and the cabin whereas the second tank is integrated into the tail cone. According to **Roskam 2006** there is not a mandatory regulation where the captain needs to be able to inspect the cabin because this responsibility could either be delegated to the cabin crew or using a camera system. So, in this configuration is not strictly required a passage throw the tank. The other possibility is to create a passageway by making a cutout in the tank such as in Figure 4.11. Because of this adoption, the length of the front tanks will be higher, nevertheless this work adopts the configuration with the passage in order to more functional.

In order to change the less the original configuration of the A320 is better to stretch the fuselage installing a front and a rear tank, because in this way the new configuration of the aircraft will be more closely to the dimensions of the A321 which is an aircraft used in the industry and all the considerations for this plane could be adapted to the new hydrogen-fueled version. If more

Table 4.4: Comparison between the possible tank configurations for medium range

	CONFIGURATION	
FEATURE	**Over the fuselage**	**Front and Rear**
Access for crew and passengers	3†	1
Surface to volume considerations	1	3
Control of C.G.	2	3
Security in case of damage	3	2
Drag Increase	1	3
Weight increase	2	2
Manufacturing process consideration	1	3
TOTAL	**13**	**17**

† 3 is High; 2 is Medium; 1 is Low

length is necessary the solution of using wing tanks is interesting and will be analysed in other sections.

4.4 Hydrogen Fuel System

Aircraft fuel systems include all the systems which connect the fuel containment system with the engines and the basic functions of these systems are the same when comparing with the conventional fueled aircraft. The fuel system consists of two pressurized and and insulated tanks in the front and rear part of the fuselage as it can be seen. The design will be made regarding all the considerations made in 4 with an aero-dynamical shape, proper insulation system, weight considerations and so on. Other systems such as vent system, pumps, pipes, valves are required in order to supply the engines with fuel. According to **(Brewer 1991)** the most important elements of the fuel system are:

Boost Pump : The design of the boost pump must take care of considerations such as reliability, long life and light weight. Three pumps per tank are required in order to not compromise the aircraft safety and justify the aviation regulations.

High Pressure Pump : The most important requirement when designing this pump is to provide fuel during the various operation points of the engines: take-off, climb, cruise, flight idle and landing, in an environment characterized by cryogenic temperature, low viscosity and lubricity. This element, unlike the boost pump, can be isolated from the LH_2 flow. The HPP is located near the engine and is linked to the engine via a mechanical gear.

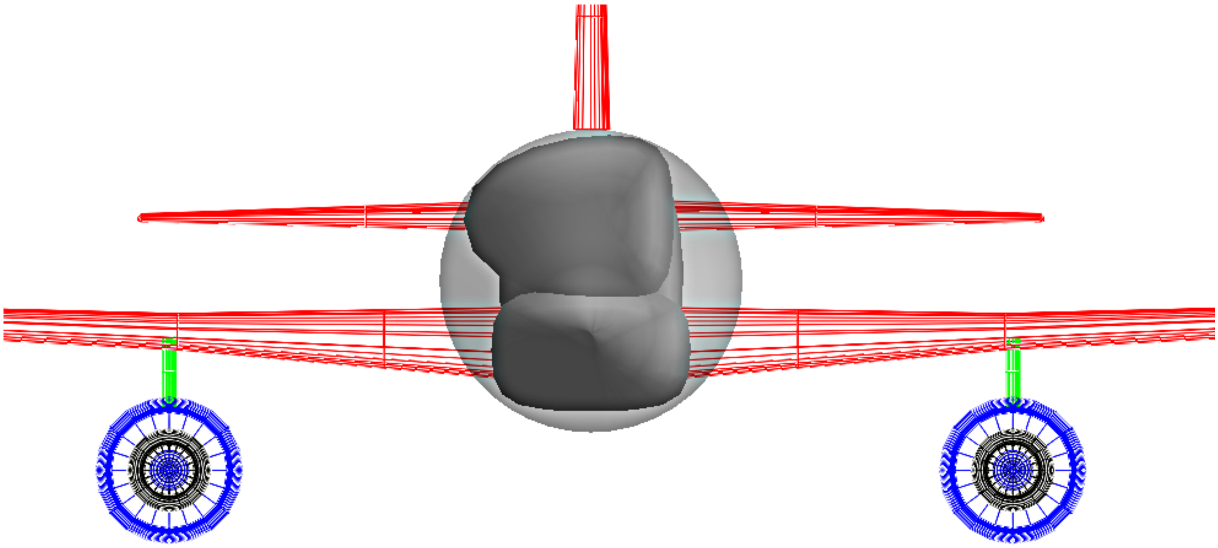

Figure 4.11 Passage in the front tank

Bearing Design : The bearing system of the engine represents one the greatest challenges. The considerations of the bearing system are that it must be able to operate at high rotational speeds ($\sim 50000\ rpm$), with high thrust loads and the most important issue must be compatible with LH_2.

Engine Fuel Delivery Lines : When designing this elements is very important to find a good relation between the diameter-insulation-material of the lines. The design of the cryogenic lines are even more restrictive because the hydrogen could freeze when flowing throw the lines. Also factors such as safety, fabricability and maintainability must be considered.

Engine Fuel Control System : An interface between the fuel delivery and the engine is needed and this system need inputs and outputs involving many engine parameters. It must be monitored with signals and sensors.

Fuelling and Defueling :LH_2 must be supplied by the airport system via valves located in the fuselage of the aircraft throw adapters situated on the fuselage, below the vertical tail. The manifold must be vacuum-insulated. The fuelling adapter is also an important equipment and must take care of safety purposes. A boil-off recovery adapter is needed to permit the recovery of the gaseous hydrogen when refueling. Defueling can be done through the fuelling adapter via the bust pumps.

Tank Vent and Pressurization :Each tank has separate pressurization and vent system but they share a common vent line. When the pressure falls below the nominal value, the boost pumps activate a system which must convert the LH_2 into GH_2 for increase the pressure. This system requires also vent boxes, vent valves etc.

The hydrogen outlet temperature in all regimes range between 15-573 K. Heat exchangers are required for the engine because the fuel must be heated before entering to the combustion chamber and it must be fully vaporized. This elements are used for take away the heat from the hot parts of the engine. The heat exchangers studied in Cryoplane project were: external, internal single and internal dual core. The heat exchangers are represented in Figure 4.12.

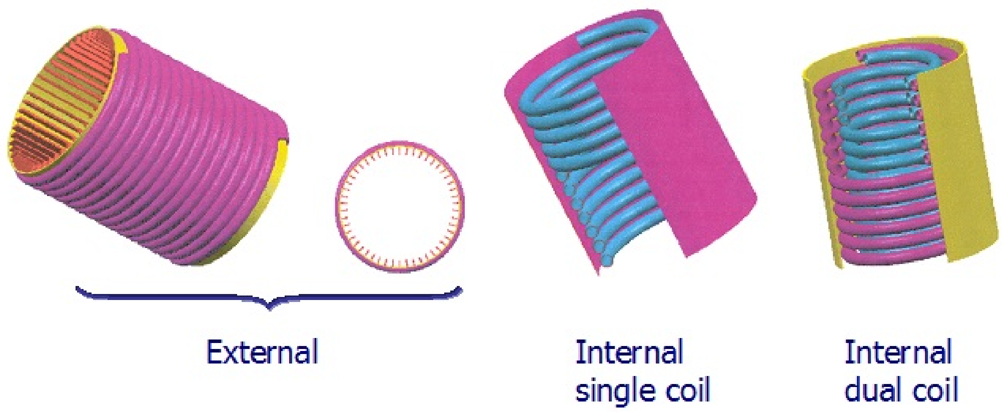

Figure 4.12 Heat Exchangers **(Westenberger 2003)**

The APU can be operated with GH_2 using the common tank vent line. These will reduce the boil-off losses whereas the airplane is on ground and the APU is operating. If the amount of gas is not sufficient the boost pump via a heat exchanger could supply GH_2 to the APU.

In order to predict the mass of these attachments for the tanks according to the researches made by Airbus for the Cryoplane project **(Westenberger 2003)** the number of the mass per volume of tank for the attachments could be

$$\frac{m_{ATTACH}}{V_{TANK}} = 12\ kg/m^3 \tag{4.5}$$

Once the volume and the surface of the tanks are determined for the required mission, an estimation of the mass tank with all the attachments can be made an used for the aircraft design, adding to the OEW of the aircraft. A typical configuration for the fuel system can be found in **Batal 2010** but in this case for an ATR-72 hydrogen-fueled aircraft explained in Figure 4.13. Another design of the fuel system could be seen in Figure 4.14.

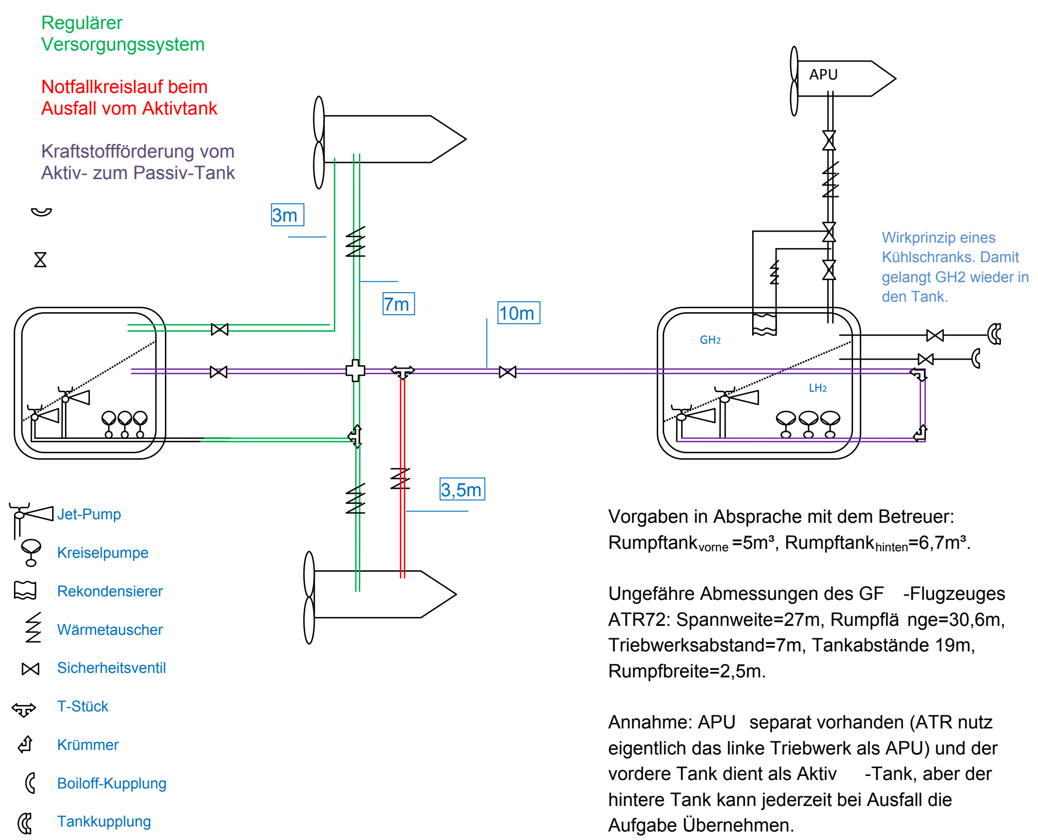

Figure 4.13 Hydrogen fuel system for ATR-72 **(Batal 2010)**

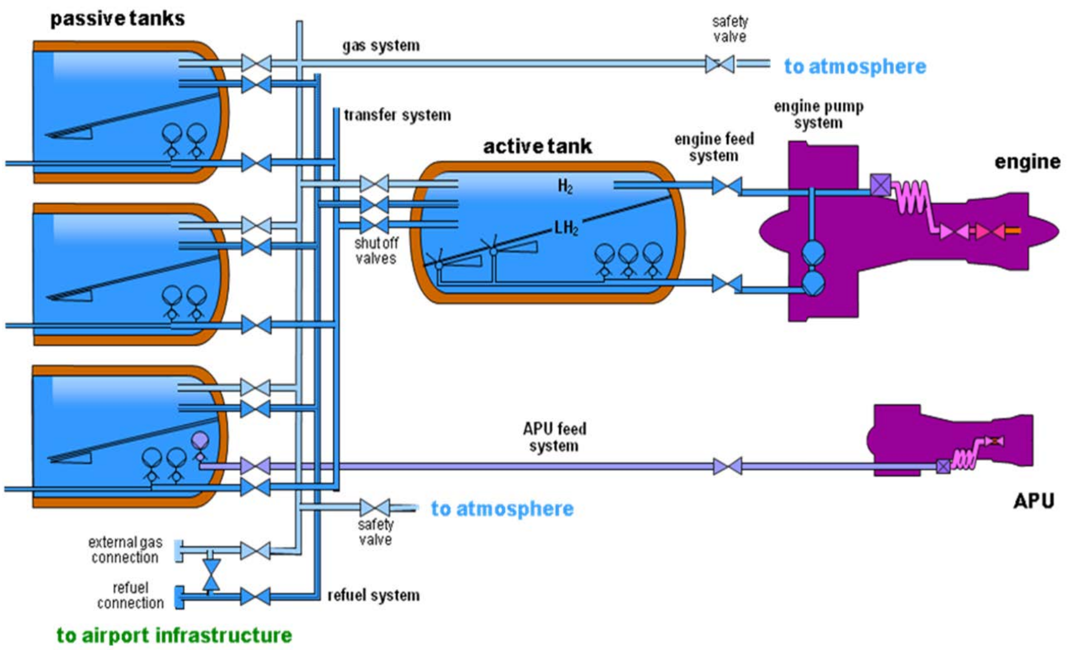

Figure 4.14 Hydrogen fuel system for A310 **(Batal 2010)**

5 Analysis of OPerA

The preliminary aircraft design is one of the most important stages when designing a new aircraft. This process involves the interaction between many multidisciplinary fields which lead the designers to use many interacted studies between different areas. This could be a very hard work if it is followed the traditional way of designing as it is explained in **Torenbeek 1982** or **Roskam 2006**. In order to facilitate this work a tool was developed in HAW Hamburg university, following the methodology developed in **Nita 2012**.

OPerA was built not only for design, but also for optimization purposes. For the optimization, which is one of the most interesting features of the tool, is used the tool called Optimus which is able to find the best combination of parameters in each case of the design. The tool is implemented in Microsoft Excel connected via Visual Basic and it is an easy way of follow, control and understand the equations involved in the preliminary design, confirming the results in form of numbers. OPerA follows the same ideas of the SAS tool, based on the lectures notes of Professor Dieter Scholz in Aircraft Design **(Scholz 2012)**.

When using OPerA it is important to understand how basically it works. First of all the program needs to define the requirements setted by the user and there are also many typical design parameters. When optimizing the aircraft exist the possibility of searching the most suitable combination of the different parameters involved, in order to reach an objective setted before such us minimum DOC, minimum mass of fuel, weight and many others.

In order to be able to generate the Matching Chart there are some different phases with requirements that need to be analysed in the next lines.

5.1 Landing Distance

The analysis of the landing distance starts with the relation found in **Loftin 1980**, which is based on a statistical equation between the landing field and the approach speed

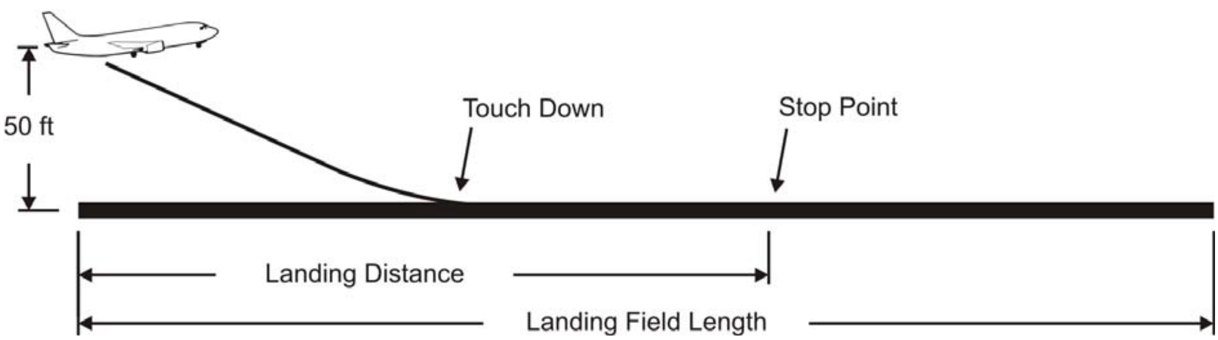

Figure 5.1 Definition of landing field length according to CS-25 **(Scholz 2012)**

$$V_{APP} = k_{APP} \cdot \sqrt{S_{LFL}} \tag{5.1}$$

The factor k_{APP} is setted to the value of 1.86 $\sqrt{m/s^2}$ which is an empirical value and it mostly depends on the break system of the aircraft. Now using the basic relation of weight equal lift, leads to

$$\frac{m_{ML}}{S_W} = \frac{1}{2} \cdot \rho \cdot {V_{APP}}^2 \cdot S_W \cdot C_{L,max,L} \tag{5.2}$$

Using the expression 5.1 and reordering it, follows

$$\frac{m_{ML}}{S_W} = \frac{1}{2g} \cdot \rho_0 \cdot {k_{APP}}^2 \cdot \sigma \cdot S_W \cdot C_{L,max,L} \cdot S_{LFL} \tag{5.3}$$

In this equation there are many constants which can be joined together in one constant called k_L and introducing m_{MTO} for reaching the requirement the value of the wing loading must fulfil

$$\frac{m_{MTO}}{S_W} \leq \frac{k_L \cdot \sigma \cdot C_{L,max,L} \cdot S_{LFL}}{m_{ML}/m_{MTO}} \tag{5.4}$$

Where the value of $k_L = 0.128\ kg/m^3$ is used in OPerA. With relation 5.4 the program will plot the first line of the Matching Chart introducing the values given for m_{ML}/m_{MTO} and $C_{L,max,L}$.

5.2 Take-off Distance

For analysing the take-off distance it is necessary to consider the regulations found in CS-25. In this case the take-off distance is called the balanced field length (explained in the regulations). Following a similar process like for the landing distance another relation is given for the Matching Chart.

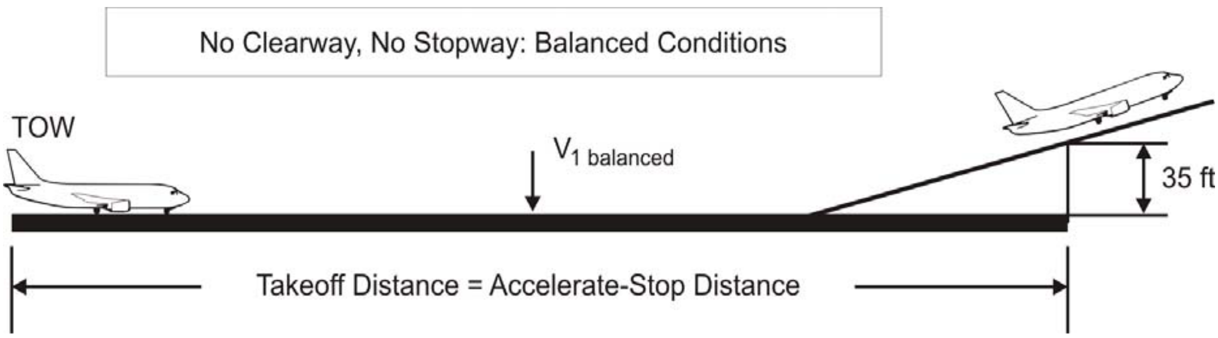

Figure 5.2 Definition of balanced field length according to CS-25 **(Scholz 2012)**

Applying the corresponding equation for the take-off phase

$$m_{TO} \cdot g = \frac{\rho}{2} \cdot {V_{LOF}}^2 \cdot C_{L,LOF} \cdot S_W \tag{5.5}$$

From this equation the V_{LOF} speed is calculated, resulting

$$V_{LOF} = \sqrt{\frac{2g}{\rho} \cdot \frac{m_{TO}}{S_W} \cdot \frac{1}{C_{L,LOF}}} \tag{5.6}$$

The equation of the energy applied for the take off leads to

$$T_{TO} \cdot s_{TOG} = \frac{1}{2} \cdot m_{TO} \cdot {V_{LOF}}^2 \tag{5.7}$$

If the equations 5.6 and 5.7 are combined, the result is another important condition for the Matching Chart

$$\frac{T_{TO}/(m_{TO} \cdot g)}{m_{MTO}/S_W} \geq \frac{k_{TO}}{s_{TOFL} \cdot \rho \cdot C_{L,max,TO}} \tag{5.8}$$

In this equation a new factor has been included: $k_{TO} = 2.3216\, m^3/kg$ and the value of $C_{L,max,TO}$ is related to the value of $C_{L,max,L}$ with the approximation of $C_{L,max,TO} \simeq 0.8 C_{L,max,L}$.

5.3 Climb Rate During Second Segment

During the climb rate, the thrust of the engines must overcome the drag and a part of the weight of the aircraft as it can be seen in the next equation

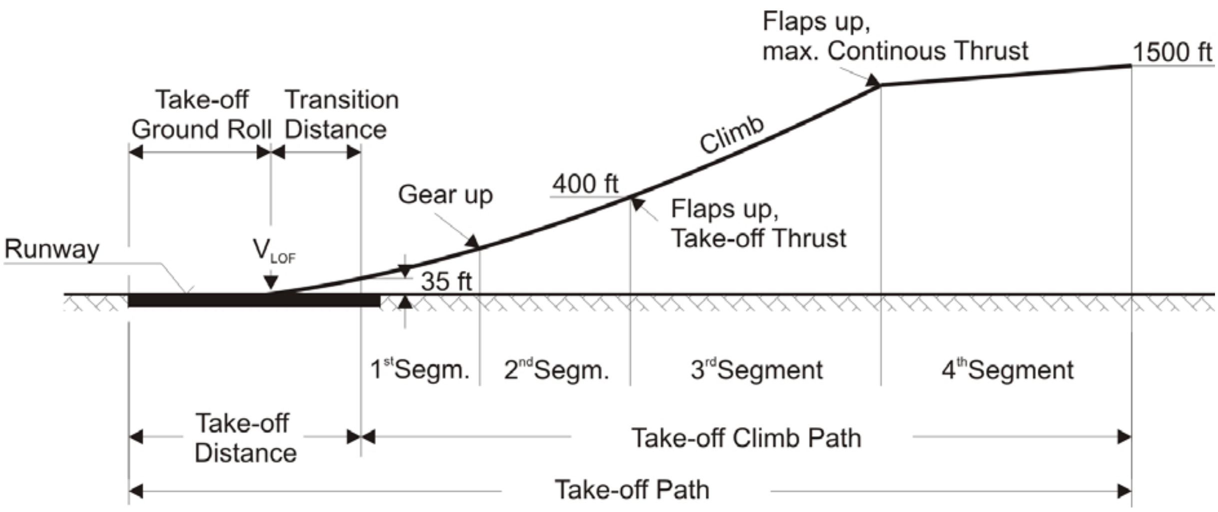

Figure 5.3 Take-off definitions and nomenclature **(Scholz 2012)**

$$T = D + m \cdot g \cdot sin\gamma \tag{5.9}$$

Now making the same balance for the vertical forces a similar relation is shown

$$L = m \cdot g \cdot cos\gamma \simeq m \cdot g \tag{5.10}$$

And now combining both equations the expression leads to

$$\frac{T}{m \cdot g} = \frac{1}{L/D} + sin\gamma \tag{5.11}$$

And adapting it to the condition of engine failure

$$\frac{T_{TO}}{m_{TO} \cdot g} \geq \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_{TO}} + sin\gamma\right) \tag{5.12}$$

In the before equation the value E_{TO} represents the lift-to-drag ratio for the take-off and n_E is the number of engines. The equation 5.12 represents another line of the Matching Chart.

5.4 Cruise Phase

From the cruise phase is determined the cruise Mach number at what the aircraft is designed to fly and it is one of the most important parameters. For this analysis it is necessary to start with the basic equations of the cruise phase

$$T_{CR} = D_{CR} \tag{5.13}$$

$$L = W \tag{5.14}$$

Dividing both equations

$$\frac{T_{CR}}{D_{CR}} = \frac{1}{E} \tag{5.15}$$

Now referring all to the take-off conditions the result is

$$\frac{T_{TO}}{m_{TO} \cdot g} = \frac{1}{(T_{CR}/T_{TO} \cdot E)} \tag{5.16}$$

The relation T_{CR}/T_{TO} is found in **Scholz 2012** which leads to

$$\frac{T_{CR}}{T_{TO}} = (0.013BPR - 0.0397) \cdot \frac{h_{CR}}{km} - 0.0248BPR + 0.7125 \tag{5.17}$$

The equation 5.17 includes the cruise altitude h_{CR} and the BPR. For the wing loading, starting with the basic equation of lift equal weight, leads to

$$\frac{m_{MTO}}{S_W} = \frac{C_L \cdot M_{CR}^2}{g} \cdot \frac{q}{M_{CR}^2} \tag{5.18}$$

And now referring this relation to the altitude:

$$\frac{q}{M_{CR}^2} = \frac{\gamma}{2} \cdot p(h) \tag{5.19}$$

Combining both equations the final result is

$$\frac{m_{MTO}}{S_W} = \frac{c_L \cdot M_{CR}^2}{g} \cdot \frac{\gamma}{2} \cdot p(h) \tag{5.20}$$

In 5.20 $p(h)$ is the pressure as a function of the altitude and γ is the specific heat ratio. With this equations the programme calculates the wing loading and the thrust to weight ratio for the required mission.

5.5 Climb During Missed Approach

In this phase the aircraft is about to land but for some reasons the final decision is to abort the land. In this phase the plane climbs with the landing configuration, so the drag is very high in this case. The requirements for this mission can be found in CS-25 regulations. The process for calculating the line in the Matching Chart is the same as the procedure explained for calculating the equation 5.12.

In this new case it is necessary to refer the variables to the landing conditions as it was said

$$\frac{T_{TO}}{m_{TO} \cdot g} \geq \left(\frac{n_E}{n_E - 1}\right) \cdot \left(\frac{1}{E_L} + sin\gamma\right) \cdot \frac{m_{ML}}{m_{MTO}} \tag{5.21}$$

In this case E_L represents the value of the lift-to-drag ratio in landing configuration.

Once the requisites are explained, with all the phases and parameters that represent the features of the aircraft, the program plots the Matching Chart and the design point for the case. All this parameters can be varied in order to obtain the most suitable combination for reaching the requirement setted before the optimization such as minimum DOC . The list of the parameters used in the tool for the optimization can be seen in table 5.1.

Table 5.1: List of aircraft and cabin variables with the values of the reference aircraft

Parameter	Name	Value A320-200
Landing field length [m]	s_{LFL}	1448
Take-off field length [m]	s_{TOFL}	1768
Max. lift coefficient, landing	$C_{L,max,L}$	3.14
Max. lift coefficient, take-off	$C_{L,max,TO}$	2.82
Mass ratio, max landing to max take-off	m_{ML}/m_{MTO}	0.88
Aspect ratio	A	9.5
Number of engines	n_E	2
Number of passengers	n_{PAX}	180
Number of seats abreast	n_{SA}	6
Wing sweep at 25 % chord [°]	φ_{25}	25
Taper ratio	λ	0.213
Position of the vertical tail in case of cruciform config.	z_H/b_V	0.56
Minimum distance from engine to wing over nacelle diam.	$z_{P,min}/D_N$	0.15
By-Pass ratio	BPR	6
Mach number, cruise	M_{CR}	0.76
Seat pitch [m]	SP	0.74
Aisle width [m]	w_{aisle}	0.51
Seat width [m]	w_{sear}	0.51
Armrest width [m]	$w_{armrest}$	0.051
Sidewall Clearance (at armrest) [m]	$s_{clearence}$	0.015

As has been said, once all the requisites and parameters are setted, OPerA plots the Matching Chart, choosing the optimal point in order to get the lowest thrust-to-weight ratio and the highest wing loading, for the combination selected. A normal Matching Chart is shown in Figure 5.4.

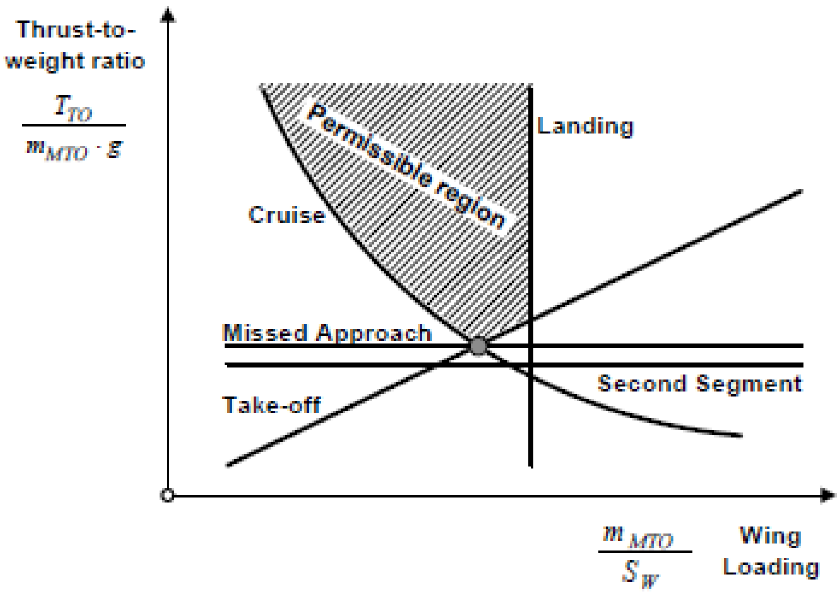

Figure 5.4 Typical Matching Chart with the design point **(Nita 2012)**

5.6 Modules of OPerA

In this section the modules that OPerA uses are explained. First of all it is important to see the list of input parameters that the program needs. This parameters can be divided in two categories: one of them are the user input parameters indicated with bold blue and the others are the experience-based parameters with light blue. The last ones are some parameters based on the experience and data collected from other sources and is better not to change them if other information is not given.

The modules of the program are listed in the next lines:

1. **Preliminary Sizing I**: In this module are calculated basic parameters like in the SAS tool. The most important parameters calculated in this module are the thrust-to-weight ratio T/W and the wing loading m_{MTO}/S_W for the most important phases of the flight: landing, take-off, second segment climb and missed approach. For calculating this ratio the module needs some inputs such as: S_{LFL}, S_{TOFL}, $C_{L,max,L}$, $C_{L,max,TO}$, A, m_{ML}/m_{MTO} and n_E.

2. **Estimation of General Parameters**: In this module are calculated most of the variables that are required by the other modules and most of them are geometric values for the wing, cabin, horizontal and vertical tail, fuselage etc.

3. **Max. Glide Ratio in Cruise**: This module calculates the Oswald factor e and the E_{max}. The user has the possibility of calculating this parameters via many methods which varies in complexity and the results are better approximated in some cases depending on the level of the drag estimation selected.

4. **Wetted Area Estimation**: Here is calculated the wetted area, necessary for calculate the

$C_{D,0}$, the relative wetted area S_{wet}/S_W and also the interference drag. This wetted area is estimated for the most important components of the aircraft.

5. **Interference Factors**: In this section are calculated the interference factors for all the parts of the aircraft. This factors are used to calculate the drag.

6. **Estimation of General Parameters**: This module uses the information from the modules before in order to calculate the zero lift drag $C_{D,0}$. This drag is calculated and corrected using the friction coefficients, form factors, interference factors and wetted areas estimations.

7. **Mass Estimation**: This module contains an estimation of the mass for the most important components of the aircraft for calculating the OEW. The estimations of the masses are based on other methods performed before, found in **Torenbeek 1982** or **Nita 2012** and of course **Scholz 2012**.

8. **Specific Fuel Calculation**: This module calculates the SFC and some others engine parameters using a method developed in TU Berlin by Herrmann which gives a high importance to the bypass-ratio.

9. **Preliminary Sizing II**: This section is similar to the same module developed in SAS but in this new case the results are based on the OEW calculated on the the correspondent module of Mass Estimation. This module checks also if the results are proper, moreover it calculates if the landing mass ratio is enough to accommodate the fuel reserves.

10. **Matching Chard**: This module plots the Matching Chart in 2D and the design point is automatically calculated taking the results from the preliminary sizing sheets.

11. **DOC**: The *DOC* is calculated in this module using two methods and expressed as equivalent-ton-miles cost. One of the methods is developed by the Association of European Airlines in 1989 **AEA** and the other method for calculating the *DOC* is developed by Technical University of Berlin in 2013 **TUB**. Both calculations are shown in the module. Furthermore, a prevision for the future price of the oil is calculated. The Cash Operating Cost *COC* can be also calculated in this sheet.

12. **Added Values**: All the parameters that gives an added value to the airline are considered in this module. Each added value possesses his own weight (a number determined by an expert questioning) and is added to the economics of the aircraft *DOC*. Each added value has a low and a high limit depending if the design is for medium or long range.

13. **Optimization set-up**: This module is one of the most important modules used by OPera. All the optimizations can be made in this module selecting the parameters to be optimized and the boundaries of the most important variables. There are two different forms of optimizations, one of them is called Differential Evolution for multiple parameters variation and the other is called DOE Diagonal for a single parameter variation. All the variables to be optimized are displayed in the sheet with the final results. It is possible to configure the aircraft from this module which connects to the optimization tool Optimus.

14. **Results DE and DOE**: This two modules show the optimization results performed en each case for both algorithms used depending on the iteration.

Once explained how OPerA works and all his modules, the information is resumed in Figure 5.5.

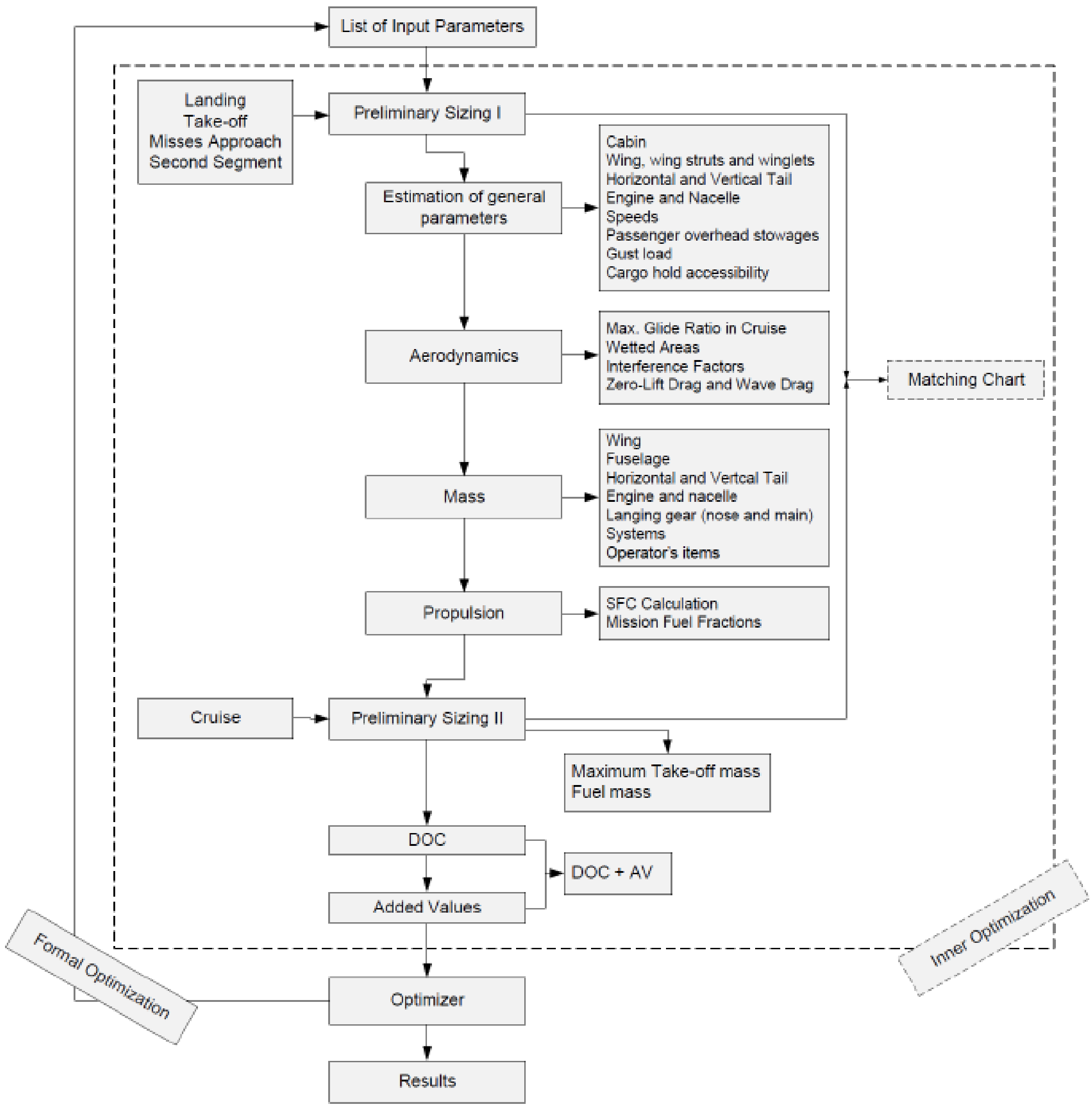

Figure 5.5 How OPerA works **(Nita 2012)**

6 Hydrogen Aircraft Design

6.1 Aircraft Requirements and Comparisons

The reference aircraft for all the comparisons is the A320-200 with all the basic values setted in table 5.1. When designing an aircraft it is important to keep in mind which are the requirements and the reference values in order to be able to make the comparisons with the new redesign. In this case, two of the most important parameters are the m_{PL}, which means how many passengers can fit into the aircraft and another one is the range R, which means the distance that the aircraft is able to carry with the specified payload mass. This two parameters with many others shown in table 6.1 set up all the requirements that the new redesigned versions must achieve in order to make a reliable comparison between all of them.

Table 6.1: Basic requirements

Parameter	Value
m_{MPL} [kg]	19256
R_{MPL} [NM]	1510
M_{CR}	0.76
s_{TOFL} [m]	1767.8
s_{LFL} [m]	1447.8
n_{PAX}	180
m_{PAX} [kg]	93
SP [in]	29

Once that all the basic parameters and the requirements are setted up, is the moment to use them as an input for OPerA in the optimization set-up module. After that the values when for the design point are shown in table 6.2. All the values obtained with OPerA will be the reference results for the A320-200 and this aircraft will be used for the future comparisons with the new redesigned versions for the hydrogen-fueled design. All the values for the reference aircraft obtained, are based on a future scenario where the price of the kerosene increases in linear form within the next years. The current year for the calculations is the beginning of 2014 before the high decrease of the oil price. For the future therm, the calculations are based on the year 2030 where the new versions are supposed to operate.

As it is said OPerA is able to optimize the parameters setted free in order to achieve a goal: in this case the optimization is made for reaching the minimum DOC possible with the best combination of the parameters. The optimization is done respecting all the requirements established before, so it is possible to compare the original version with the optimized. As it can be seen in table 6.2, after the optimization, the aircraft is different and the comparisons can be found in the same table. For the optimization, all the cabin parameters are fixed and maintained as the original values of the aircraft, only the design parameters have been varied in order to maintain the same airport category as the original version. Nowadays the requisites in airports such as the length of the runaways and span limitations are the most important restrictions for the aircraft design and it is necessary to keep them in mind.

After all this considerations, the results of the optimization must be analysed. OPerA makes the optimization for the aircraft in order to reach the objective of minimum *DOC*. For this aim the maximum take-off mass has been reduced in 2.5 %, the fuel mass also is reduced in 12.1 % and the *DOC* experienced a reduction of 3.8 % using the **AEA** method and a 4.1 % of reduction according to **TUB**. The results confirm that OPerA has made what it was expected, reducing the maximum take-off weight and the mass of fuel, also increasing the by-pass ratio and the aspect ratio in order to transform the aircraft in a most efficient version in aerodynamic terms which leads in lower fuel consumption.

Table 6.2: Comparison between the original A320-200 and the optimization

Parameter	Ref. Value	Optimized Value	Variation (%)
m_{MTO} [kg]	72274	70489	-2.5
m_{OE} [kg]	40199	39971	-0.6
m_F [kg]	12819	11262	-12.1
DOC (AEA) [€/NM/t]	1.32	1.27	-3.8
DOC (TUB) [€/NM/t]	1.15	1.10	-4.1
$S_W [m^2]$	120.3	118	-2.0
$b_{W,geo}$ [m]	33.8	35.8	+6.0
$A_{W,eff}$	9.5	12.5	+31.9
φ_{25} [°]	25	13.2	-47.2
λ	0.21	0.16	-25
E_{max}	17.5	20.0	+14.2
T_{TO} [kN]	109.4	88.9	-18.7
BPR	6	9.3	+54.3
SFC [kg/N/s]	1.65E-05	1.58E-05	-4.3
h_{CR} [ft]	38882	33182	-14.7
$m_{MTO}/S_W [kg/m^2]$	600.6	597.6	-0.5

In Figure 6.1 is shown the components for the breakdown of the m_{OE}, *DOC* and the component of the drag.

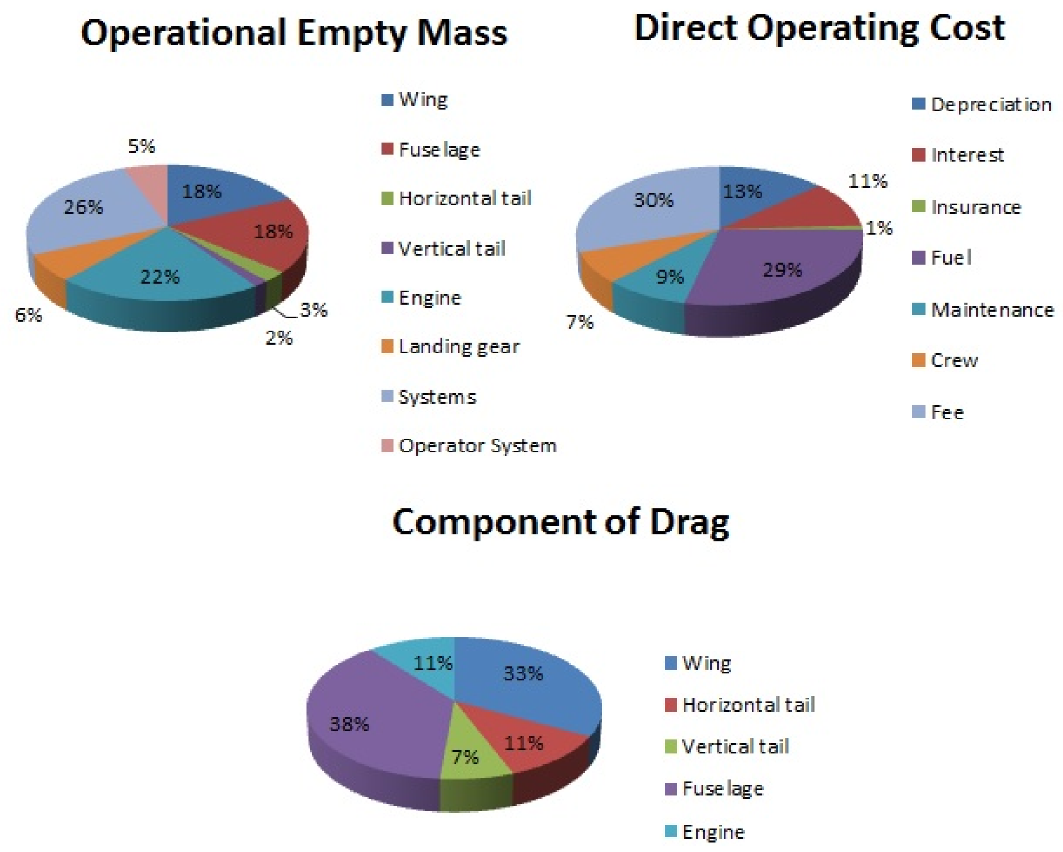

Figure 6.1 Breakdown of the OEW, DOC and Drag Component for the A320-200

6.2 Aircraft Design Considerations for Hydrogen Versions

As it has been explained in other sections of this work, due to the different nature of the hydrogen, the new design will be very different and there are many important differences which make the design of the aircraft in a special way. One of the most important design requirement for the hydrogen versions is the necessity of finding new solutions with minimum changes in the the original aircraft. This requirement means that the original aircraft and his components are used as much as possible in order to design a new version with minimum changes which leads in less price, being more attractive for the industry. Following this necessity one important point of the design is the fuselage length and the tank considerations. The most important issues of the hydrogen-fueled airplanes are:

- Due to the high volume required to fill in the LH_2 into the tanks, it is impossible to use the original tanks on the wing so the first point which is important to comment is that the original tanks of the wings must be replaced with special tanks using the proper materials and form since the hydrogen needs to be stored at a high pressure and at cryogenic temperature. One of the keys for a successfully design with hydrogen is to identify the optimal tank configuration because the design of the aircraft and his performances strongly depend on this configuration. Because of this issue, now the wings do not experience the alleviation in the bending moment like in the case of the kerosene where it is used for this aim. The consequence for the hydrogen versions will be that the wings need to be designed for a higher bending moment which leads into more wing weight.

- The fuselage length for the hydrogen-fueled versions is one of the most important parameter. As it has been explained in other chapters of this thesis the volume required for the hydrogen is higher than in the case of the kerosene and special tanks with proper insulation system and materials are required. The ideal case will be to use the same fuselage provided by the original version, but if the specified requirements such as the n_{PAX} or the m_{PL} for the original mission are mandatory, something has to be done. The studies made for searching the best location for the tanks, reflected that the best option for the new position of the tanks could be into the fuselage and adapting them to the original shape of the fuselage. Another consideration is the necessity to fill in the tanks in a form that the interior design of the fuselage do not change. For this reason it is necessary to stretch the fuselage in order to fill the tanks inside. At this point it is important to say that a new fuselage is required, so it is necessary to use a fuselage with higher length.

- The engine and the fuel systems must be converted for using hydrogen and it is necessary to develop a methodology for adapting the engines in order to be able to burn hydrogen **(Brewer 1991)**. This will particularly affect the fuel lines and the combustion chamber. Because of the high energy per kilogram of the hydrogen the *SFC* will be the reduced by approximately 65 % as it can be seen in studies made by **Corchero 2005**. This lower consumption is very important for the aircraft design and the fuel mass burned in the engines is much lower than in the case of the kerosene. Hydrogen engines are able to run cooler than the normal engines so the life will be higher.

- For the *DOC* calculations it is assumed that the price of the kerosene will rise within the future decades and the price of the hydrogen will go down in the future, for this reason some new efficient production methods are necessary and of course new industries able to use hydrogen must be activated in the future. For general purposes it is assumed that the price of the hydrogen per energy is the same than the price of kerosene per energy, meaning that the price per kilogram of the hydrogen is about three times the price of the kerosene.

- Concerning the drag estimations, because the fuselage will be higher than in the original version, the total surface of the fuselage will be also higher and as it has been said, the wings must be designed for stronger conditions the drag of the new version will be also higher.

- The hydrogen can also be used as a fuel for others applications in the aircraft such as for the APU, fueled by hydrogen as it is explained in appendix A dedicated to the fuel cell. The use of the fuel cell could be very advantageous in terms of efficiency and contamination but it is necessary to take care of the design for a new APU and the use of fuel cells using hydrogen as a fuel. In addition more hydrogen will be required with the necessity of more volume and space leading to more fuselage length and weight.

This new considerations for the hydrogen-fueled versions are implemented in the OPerA version where the mass of the tanks, increment of length for the fuselage and the new *SFC* are corrected according to the new requirements of the hydrogen-fueled design.

6.3 Hydrogen Aircraft Version Overview

In this section will be analysed the different possible designs of the hydrogen-fueled aircraft, all of them based on the original A320-200. As it has been explained due to the nature of the hydrogen and the necessity to fill the tanks into the fuselage it is necessary to stretch the original aircraft in order to be able to reach the requirements of the setted mission. In order to find solutions with minimum changes, attractive for the industry, the first solution is to stretch the original A320-200 to the dimensions of the A321-100 which has a larger fuselage, using the same number of passengers, same mass of payload and the same range. The length above is used to fill the tanks of hydrogen, maintaining the same structure of the fuselage and finding the best configuration for the tanks.

For the specified mission is necessary to stretch above the original A321-100 or use some new configurations for the tank such as wing tanks or use the volume for the cargo for new hydrogen tanks. For this reason there are many possibilities and versions that will be analysed in the next lines:

1. **A320-200**: Reference aircraft A320-200. This is the kerosene original aircraft used for all the comparisons with the new versions.

2. **A320-200-O**: This version is the same that the original RF-A320 but in this new case is optimized with the algorithm used in OPerA and the results are detailed in table 6.2.

3. **A321-HS**: This version is yhe A321-100 stretched the necessary length in order to achieve the requirements of the mission and all the tanks are filled into the fuselage section.

4. **A321-HW**: This version is based on the original A321-100 but in this case not stretched and the necessary fuel above the basic dimensions is filled in two wing tanks, symmetrical installed in each part of the wing.

5. **A321-H19**: For this last version the original A320-200 is changed for the A319-100 with a number of 156 pax in 1 class, maintaining the same payload mass than in the original case and transforming this basic aircraft in the original A321-100 using the length above for all the hydrogen tanks into the fuselage as the other versions.

For the last three versions of the hydrogen-fueled aircraft if the OPerA optimizer is used, a final "O" is added, meaning that the new version is optimised according to the specifications of the tool. For all the versions were designed according to the premise of minimum changes on the original aircraft.

As it is detailed, for the hydrogen aircraft are involved three types of aircraft, starting with the original A320-200, then the A321-100 and finally the A319-100 completing the family of the A320 series available at the moment in service, all designed by Airbus. In Figure 6.3 can be seen the differences between the length of all this family.

The basic version of the A320 and his optimization with OPerA has been explained in the section before. For the hydrogen-fueled version the same analysis and comparison with OPerA is detailed.

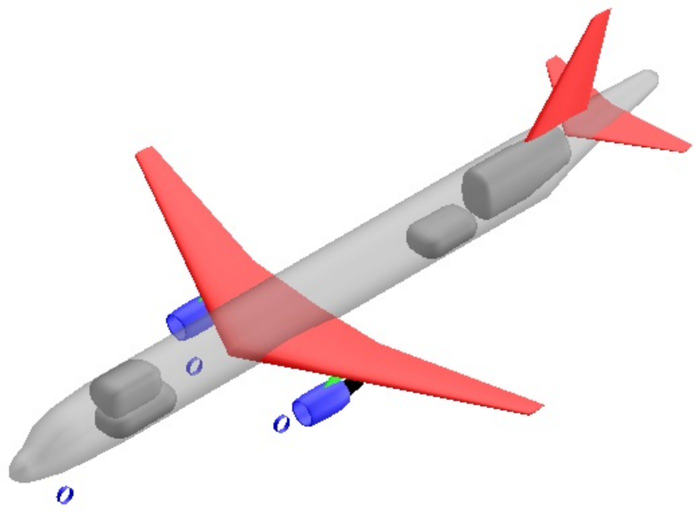

Figure 6.2 Representation in 3D of A321-HS

6.4 A321-HS

This version is the first hydrogen aircraft configuration and it starts with the original A320-200 which is stretched to the original dimensions of the A321-100. However for reaching the original detailed mission the length above is not enough, so the philosophy of the new design starts at this point and the solution adopted in this case is to stretch the necessary length of the fuselage in order to fulfil all the above fuel mass. This version is stretched 4.14 m above the original length of the A321-100 and due this fact the plane will be 11.1 m larger than the original aircraft, increasing the maximum take-off mass and the wetted area. The tanks are adapted to the original fuselage dimensions considering the limitations of the fuselage diameter and the division between the cargo compartment and the usable part for the passengers in the cabin. This tanks are installed in the front and back part of the fuselage using some of the cargo part of the plane as it is shown in Figures 6.4 and 6.2.

The design of the forward tank is such that there is a passage in the higher tank in order to connect the cockpit and the cabin of the fuselage, of course with a penalty in the dimensions of the fuselage because about 20 % of the ideal volume is not used which leads into an increase of the total length of the fuselage. Because not always the underfloor containers are completely used, a percentage of them is transformed into volume available for the tanks and it can be seen in the Figure 6.4. The lower tank of the rear part of the fuselage is stretched about 1.1 meter more meaning 260 kg of LH_2. For the backward part, the length above of the original A321-100 dimensions is used for another lower tank with a length of 4.2 m, meaning that is able to carry approximately 970 kg of fuel. With this two tanks and the two higher tanks placed in the upper floor, one on the back which is the larger and the other on the rear, are capable to carry more than 6700 kg of LH_2 which means a total volume of 98 m^3.

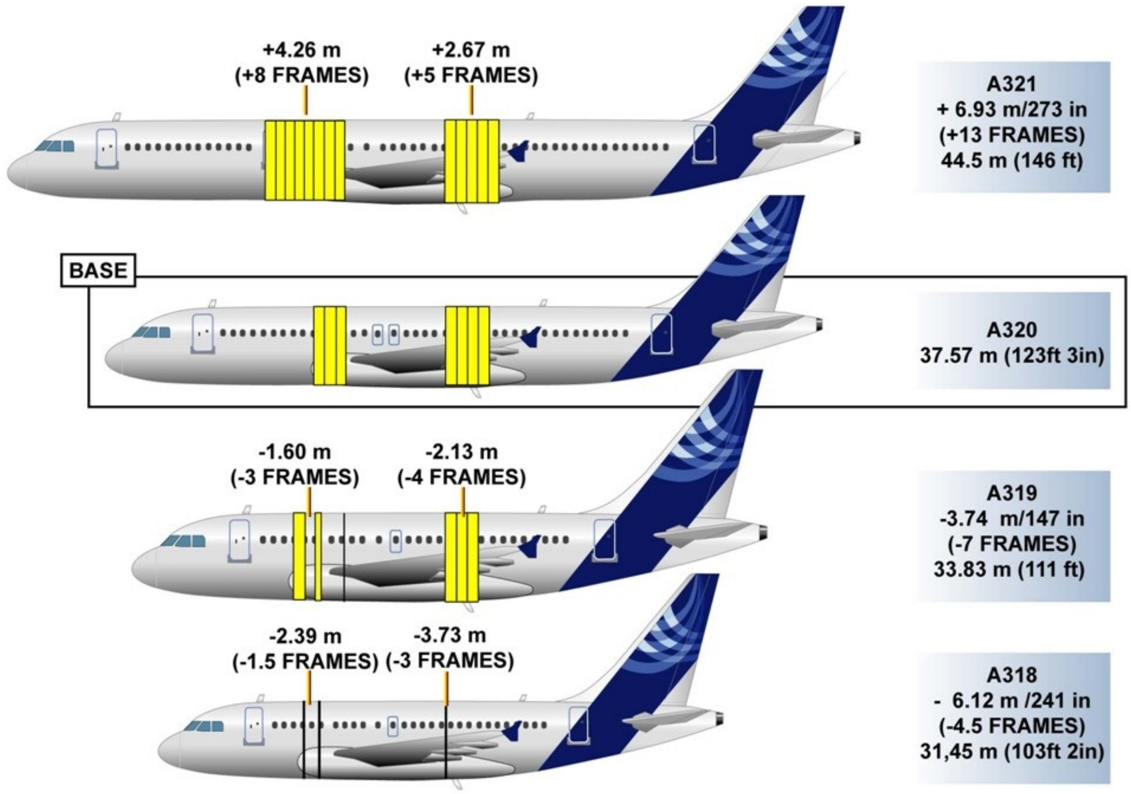

Figure 6.3 Dimensions of the A320 family (Airbus Technical Data)

In table 6.3 is detailed the basic information of the tanks representing the mass of the tanks, mass of fuel and lengths.

Table 6.3: Details of the tanks for the A321-HS

	Length [m]	**Mass of tank [kg]**	**Mass of fuel [kg]**
Rear upper tank	4.14	581.6	1600
Rear lower tank	5.24	315.4	1225
Back upper tank	6.92	1385	2874.4
Back lower tank	4.16	249.3	967.8
	Total [kg]	2531.3	6667.2

Now that the basic statements are setted for the A321-HS version, the results that OPerA tool shows are necessary to be analysed and compared with the original version. There are two possibilities to follow: the original A321-HS without significant changes and the other is the optimised version called in this case A321-HSO with the tools used by OPerA for optimize and find the best configuration of the aircraft for achieving minimum *DOC* in this case.

After introducing the proper changes in the program using the considerations for the hydrogen-fueled aircraft, the results of the two versions, A321-HS and A321-HSO are collected and com-

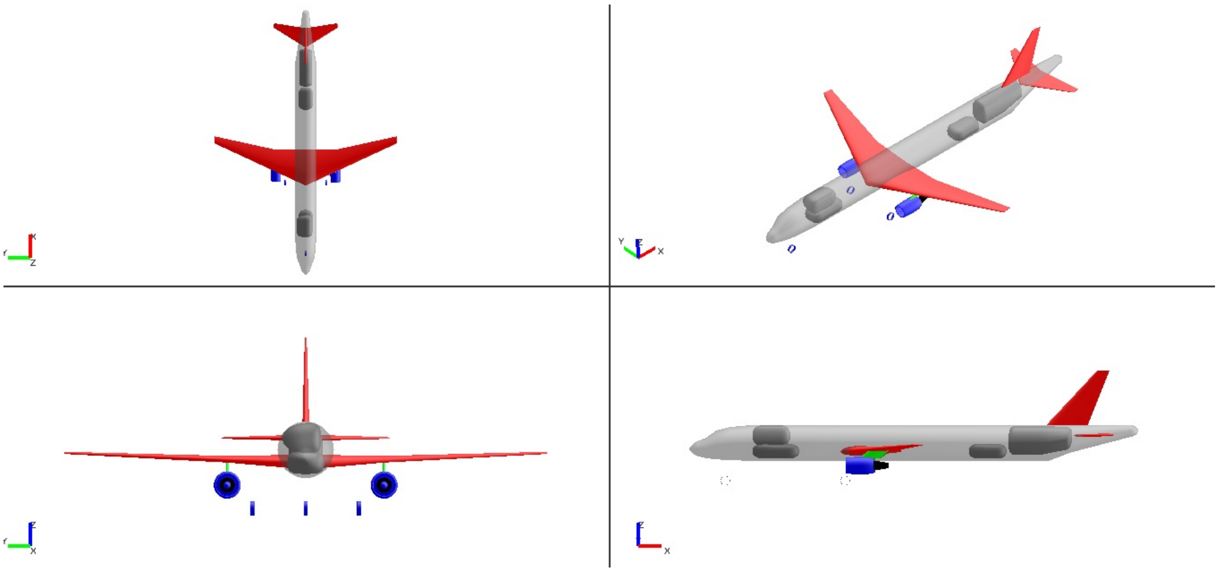

Figure 6.4 Representation in 4D of A321-HS

pared to the original A320-200 in table 6.4.

The results collected in this table show that the hydrogen-fueled aircraft is feasible and even more in optimized version A321-HSO. The most important benefits of using hydrogen as a fuel come from the nature of this fuel. One of the most important facts is the mass of fuel required m_F for the same mission is about half part of the original aircraft. Another important result is the lower *SFC* which is near 65 % lower and more important the thrust required for the engine is lower, about 5 % less in the original A321-HS and 15 % lower when optimizing with OPerA.

The calculations performed by OPerA for the *DOC* can be divided in the two methods explained and the difference between them is considerable because each method gives different ways and importance to the parameters involved in the calculations. For example the method developed by **TUB** gives more importance to the fuel than the **AEA** method. In both cases can be found an increase in the *DOC* having in the best case an increase of 21.9 % for the A321-HSO version.

In reference to the *OEW* is important to note the increase experienced is mainly because of the increase on the fuselage length and the new tanks added for the hydrogen. As it is said the m_F necessary is lower and the *OEW* is higher due to the considerations before, so in general numbers the final result for the m_{MTO} is almost the same being 1.8 % higher for A321-HS and 1 % lower in the case of the A321-HSO. At this point is necessary to make an important reasoning about the advantages gained from using hydrogen and it is important to argue here that the more fuel required for an aircraft to achieve a specified range for its mission, the more opportunity will be to save fuel and gaining much more than in the cases where the fuel mass is not so high because the range of the mission is lower. Naturally the benefits of hydrogen-aircraft is higher for long range designs, and that is the main reason why most of the works done before are focused in long range aircraft design.

The fundamental reason for the improved performance of the hydrogen aircraft design is the favourable increase of L/D when optimizing and its *SFC* in cruise relative to the kerosene design. Relating the wing, a conservative approach has been adopted maintaining the same wing mass that OPerA calculates.

The both designs of the aircraft have been made in the same point, in this case the point selected is the range for maximum payload R_{MPL} of the PL-R diagram.

For the A321-HSO the results are improved when the optimization is performed based on the A321-HS in therms of L/D, DOC, m_{MTO}, m_{OE}, m_F, T_{TO} etc. This version is optimized for the same requirements detailed in table 6.1 and the cabin parameters were maintained in order to have the same references for the comparisons. For the original A321-HS some parameters such as BPR, φ_{25}, λ or the aspect ratio $A_{W,eff}$ were not touched in order to fulfil the minimum changes requirement.

Table 6.4: Results and comparison with A320-200 from OPerA for A321-HS and A321-HSO

Parameter	A321-HS	Variation (A320)	A321-HSO	Variation (A320)
m_{MTO} [kg]	73578	+1.8	71789	-1
m_{OE} [kg]	47658	+18.6	46417	+15.5
m_F [kg]	6664	-48.0	6116	-52.3
DOC (AEA) [€/NM/t]	1.68	+26.7	1.61	+21.9
DOC (TUB) [€/NM/t]	1.49	+29.3	1.43	+24.2
l_F [m]	49.4	+28.8	48.6	+27
$S_W [m^2]$	131.1	+9.0	118	-2.2
$b_{W,geo}$ [m]	35.3	+4.4	36.0	+6.5
$A_{W,eff}$	9.5	0	11.5	+21.4
φ_{25} [°]	25	0	17.30	-30.8
λ	0.21	0	0.16	-24.7
E_{max}	17.6	+0.4	19.1	+8.6
T_{TO} [kN]	103.9	-5.0	93.2	-14.8
BPR	6	0	8.8	+46.3
SFC [kg/N/s]	5.79E-06	-65.0	5.48E-06	-66.9
h_{CR} [ft]	37706	-3.0	33736	-13.2
$m_{MTO}/S_W [kg/m^2]$	560.7	-6.6	610.1	+1.6

6.4.1 Considerations for the A321-HS

In this section some new comparisons for the A321-HS is made in order to have a more detailed point of view for a hydrogen-fueled aircraft. First of all, the details of the new breakdown of the m_{OE}, DOC and component of drag is detailed in Figure 6.5. For the operational empty mass the tank mass has been added and their contribution to the total weight represents is 6 %. The fuselage mass has been increased because now the length of the fuselage is higher and the contribution is increased in 5 % more than the original A320, contributing with a 23 % to the total weight. The weight of the wing is also increased due to the same considerations and the estimated weight of the engines is reduced because the hydrogen-fueled aircraft needs less T_{TO}.

For the *DOC*, the most important difference is the increase in cost of the hydrogen, due to the consideration of equivalent price per energy for both fuels now the price per kilogram is three times higher than the kerosene, but the fuel mass is reduce by 50 %. The total contribution of the fuel is increased from 29 % in the original aircraft till 39 % for the A321-HS.

Analysing the component of the drag, due to the increase of the wetted area of the fuselage and the wing, it is observed an increase of the drag for this components, with a total contribution of 42 % and 34 % respectively. The contribution to the drag of the engines is reduced in 2 % because of the decrease in the thrust and less wetted area for the nacelles.

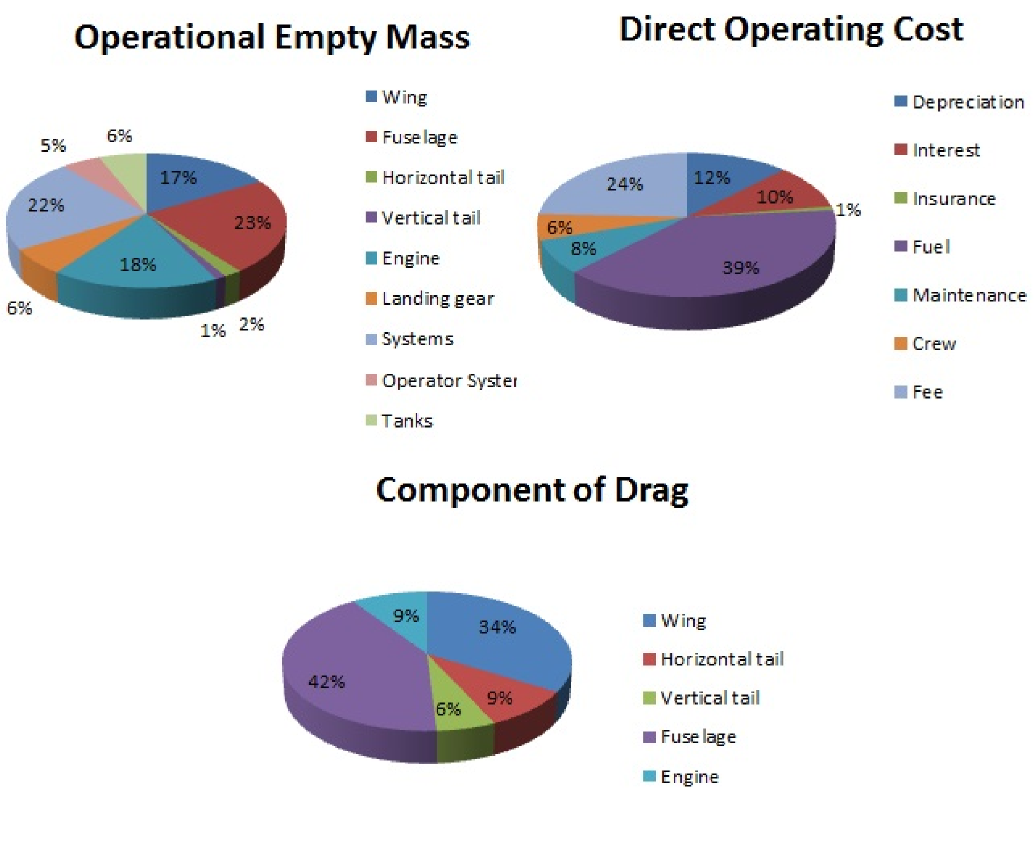

Figure 6.5 Breakdown of the *OEW*, *DOC* and Drag Component for the A321-HS

Because of the highest price of the hydrogen per kilogram the *DOC* of the aircraft is about 27 % higher. With an optimistic future approach, where the price of the hydrogen per kilogram is made in a scenario where the price of the kerosene per kilogram is increasing and the price of the hydrogen is going down, resulting the same price of the hydrogen per kilogram, the results are very different if OPerA is performed for the *DOC* estimations. The results are collected in table 6.5.

After this new price of the hydrogen the results are very different and the most important difference is observed in the *DOC* where according to **AEA** only an increase of 1.1 % is experienced for the A321-HS however when the optimizer is performed the *DOC* is decreased in 2.5 %. For the **TUB** method the decrease is very pronounced in this new case due to the fact that the mass of fuel and his price contribute more to the calculations. Now, because the price of the fuel is three times lower, the *DOC* is 7.6 % lower and -10.6 % for the optimized A321-HSO.

Table 6.5: Results and comparison with A320-200 from OPerA for A321-H and A321-HS for an optimistic price of hydrogen

Parameter	A321-HS	Variation (A320)	A321-HSO	Variation (A320)
m_{MTO} [kg]	73578	+1.8	71493	-1
m_{OE} [kg]	47658	+18.6	46059	+14.6
m_F [kg]	6664	-48.0	6179	-51.8
DOC (AEA) [€/NM/t]	1.34	+1.1	1.29	-2.5
DOC (TUB) [€/NM/t]	1.06	-7.6	1.03	-10.6
l_F [m]	49.4	+28.8	48.7	+27
$S_W [m^2]$	131.1	+9.0	118	-2.3
$b_{W,geo}$ [m]	35.3	+4.4	36.0	+6.5
$A_{W,eff}$	9.5	0	11.5	+21.4
φ_{25} [°]	25	0	16.2	-35.2
λ	0.21	0	0.14	-34.3
E_{max}	17.6	+0.4	19.2	+9.2
T_{TO} [kN]	103.9	-5.0	88.2	-19.4
BPR	6	0	8.5	+41.7
SFC [kg/N/s]	5.79E-06	-65.0	5.59E-06	-66.2
h_{CR} [ft]	37706	-3.0	32198	-17.2
$m_{MTO}/S_W [kg/m^2]$	560.7	-6.6	607.4	+1.1

6.5 A321-HW

The second version of the hydrogen-fueled aircraft is based on the A321-100. The design starts with the original A320-200, maintaining the same basic requirements as the original as well as for the A321-HS. This version emerge from the fact that the A321-HS has bigger length than the original version of the A321, in this case 4.2 m above. Stretching a fuselage means an increase in the cost of the design process and the price of the manufacture will rise also. This fact could be not so attractive for the aeronautical industry, moreover the premise of minimum changes is not achieved very well. A big incentive could be a high pre-order of this type of aircraft in order to start a new production of this version.

For all that, maintaining the original dimensions of the A321-100 may be a good incentive, so the A321-HW will have the same dimensions than the original. The problem is the fact that the length is not enough for the original mission and the requirements detailed in table 6.1 are not achieved. The solution to this problem in this case, is to use wing tanks for the mass of hydrogen above the original A321, installing each of them in the both parts of the wing.

The original A321-100 has the same passengers and cabin length than the A320 but the length above is used for filling the tanks into the fuselage and using the original construction, the tanks are filled in the same way that is done for the A321-HS, dividing them into the rear and the back part of the fuselage. For the rear part, two tanks are installed, one on the upper floor and the other on the space for the cargo. The tank installed on the upper floor of the rear part is designed with a passage for connect the cockpit with the cabin with a penalty of about 20 % of the ideal volume as it said for the version before. For the rear part the same solution as the A321-HS is adopted, using two tanks inserted as before. The lower tank of the backward part of the fuselage has the same dimensions than the correspondent of the rear part with a length of 3.5 m meaning less space for cargo, but usually this space is enough. This new tank is able co carry 805 kg of LH_2.

The total proportion of fuel necessary for both systems, first the tanks with he mass of fuel into the fuselage is about 65 % (5835 kg), and the remaining system of the wing tanks contributes with a 35 % (3225 kg). The Figures 6.7 and 6.8 shows the final configuration of the A321-HS with the wing tanks.

The design of the wing tanks shall be a detailed one, trying to use an aerodynamic shape in order to increase the drag the less possible. Figure 6.6 shows a scheme for the wing configuration with the engines and the wing tanks of LH_2. As it can be seen the best aerodynamic configuration for the wing tanks has been selected and the maximum diameter for the frontal surface is setted to 2.2 m with a length of 6 m able to carry near 2345 kg of necessary fuel. For OPerA this new tanks have almost the same dimensions than an engine and for some calculations the wing tanks can be treated as an engine, for example in terms of wetted area.

The details of the length and mass estimations are collected in table 6.6. As it is said the lower tank for the both parts of the fuselage has the same dimensions, and the length of the two new parts of the fuselage are the same.

For this version another conservative approach is adopted, not changing the mass of the wing and leaving it in the same way that OPerA calculates it. For the fuselage tanks, the total mass

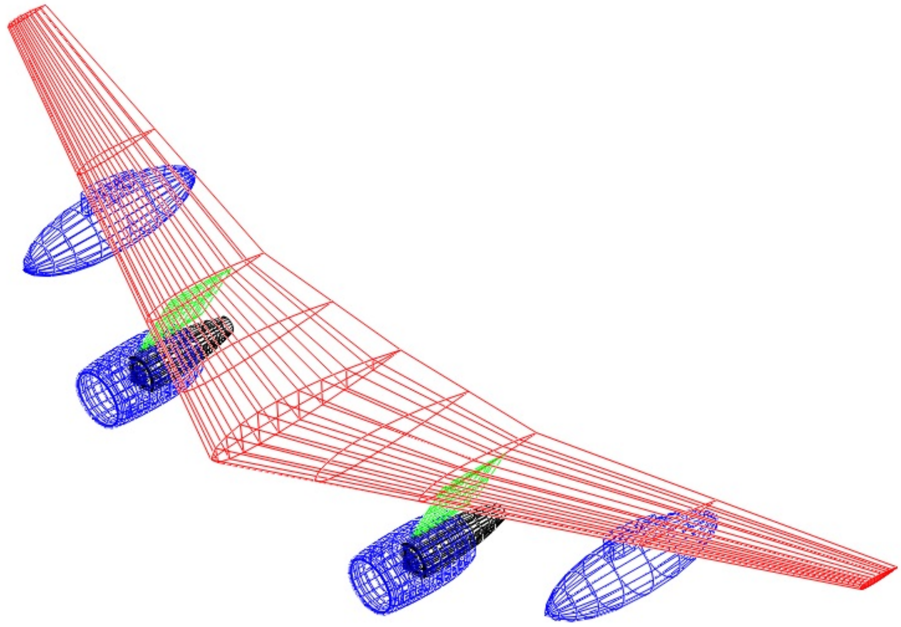

Figure 6.6 Detailed configuration of the wing of A321-HW

of the system, including the weight of the tanks and the LH_2 contained, is distributed half part of the total amount for each part of the fuselage. Because of the wing tanks, a new system of pipes is necessary to design, for the fuel system and connect all the tanks with each other with an intelligent system able to control the amount of fuel in each tank for a good control of the C.G of the aircraft.

The results that OPerA calculates for the A321-HW are detailed in table 6.7 and the philosophy is maintained as it has been done for the both versions before. The basic requirements for the original mission are the same as table 6.1. In reference to the results calculated in OPerA, it is important to comment that first of all the m_{MTO} of the A321-HW is lower, with a percentage about 2.2 % than the original and similar result for A321-HWO. This result is due to the fact that the fuselage is not stretched so much like in the A321-HS, for this reason the m_{OE} is lower compared to version before.

Another important result for this aircraft is the fact that the drag is higher than in the other cases because the tanks increase considerably the factor $C_{D,0}$ which is 9 % higher than the other versions because the two new tanks contributes with higher wetted surface for the drag. This increase in the drag is important because the aerodynamic efficiency L/D 3.9 % lower.

The mass of fuel for the mission when burning hydrogen in the engines is about 50 % less but in this case when computing the decrease of the m_F with the increase of m_{OE}, the final results turns into a a lower m_{MTO}, because of these important result the *DOC* is decreased compared to the A321-HS but is higher compared to the original version as it can be seen in the comparison table 6.7, where the optimized version A321-HWO has better results than the original. The *DOC* is increased between 21.2 % and 23.3 % according to **AEA**.

Table 6.6: Details of the tanks for the A321-HW

	Length [m]	Mass of tank [kg]	Mass of fuel [kg]
Rear upper tank	3.5	484.7	1333.5
Rear lower tank	3.5	207.7	805.3
Back upper tank	3.5	692.4	1300
Back lower tank	3.5	207.7	805.3
Wing tanks	6	880	2345
	Total [kg]	2472.5	6589.1

Table 6.7: Results and comparison with A320-200 from OPerA for A321-HW and A321-HWO

Parameter	A321-HW	Variation (A320)	A321-HWO	Variation (A320)
m_{MTO} [kg]	70716	-2.2	70626	-2.3
m_{OE} [kg]	44871	+11.6	45122	+12.2
m_F [kg]	6588	-48.6	6247	-51.3
DOC (AEA) [€/NM/t]	1.63	+23.3	1.60	+21.2
DOC (TUB) [€/NM/t]	1.45	+25.9	1.42	+23.6
l_F [m]	45.2	+18.0	45.2	+18
$S_W [m^2]$	126.1	+4.8	115	-4.6
$b_{W,geo}$ [m]	34.6	+2.4	35.8	+6
$A_{W,eff}$	9.5	0	11.3	+18.5
φ_{25} [°]	25	0	8.03	-67.9
λ	0.21	0	0.18	-15.5
E_{max}	16.9	-3.9	17.9	+2.2
T_{TO} [kN]	99.8	-8.8	95.6	-12.6
BPR	6	0	9.5	+58.5
SFC [kg/N/s]	5.82E-06	-64.8	5.47E-06	-66.9
h_{CR} [ft]	36720	-5.6	32438	-16.6
$m_{MTO}/S_W [kg/m^2]$	560.7	-6.6	615.3	+2.5

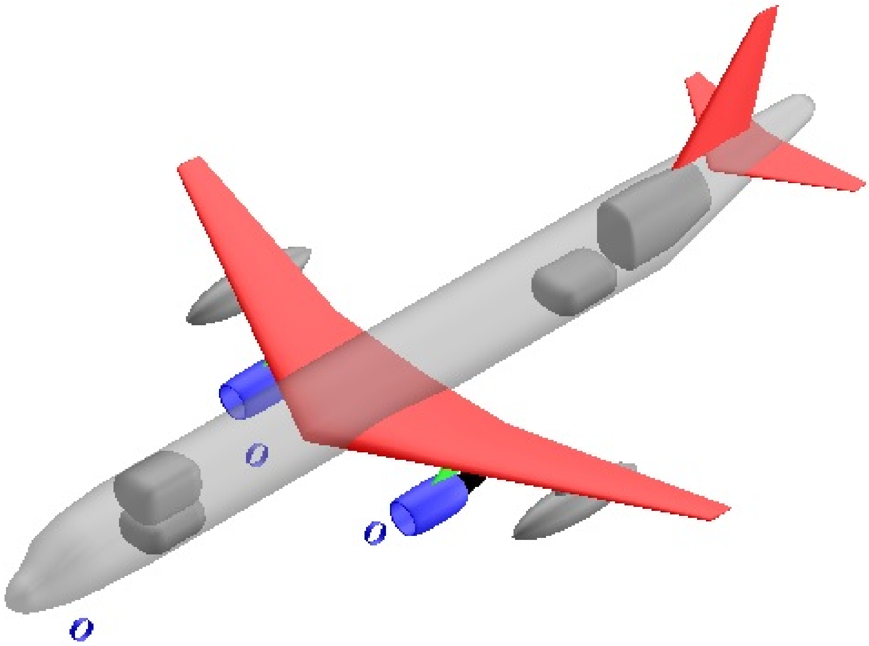

Figure 6.7 Representation in 3D of A321-HW

The integration of the wing tanks for this version has been made respecting the minimum bank angle of clearance of 7 °of the aircraft design. For improving the aerodynamic efficiency of the aircraft and the optimization, the ideal length of the pylon for the engines and the tanks is such that do not interfere with this minimum angle. If the length of the pylon is higher it is better in terms of aerodynamic efficiency for the aircraft and the interference factor are lower for the drag estimations but at the same time more wetter area is added, so the best solution is a compromise between both factors and the design of the tank has to take care of this issue. In Figure 6.9 is detailed this angle and the configuration selected.

Here it is important to make an important analysis for the industry in order to study the best configuration in economic terms for the manufacturing processes. On the one hand, stretching the fuselage is an option adopted for the A321-HS, on the other hand the second solution was to use wing tanks.

One important benefit for stretching the fuselage is the fact that the industry is used to do it with many different sizes and lengths commercially available. The problem of stretching too much the fuselage is that the pitch ground clearance angle θ, may be reduced and the performances during take-off and landing phase could be decreased.

For the case of using new tanks on the wings the processes may change and new important considerations are necessary in order to find out a reasonable way of adapting this wing tanks to the original A321-100 configuration.

In both cases changes are necessary because of all the new hydrogen aircraft design requirements.

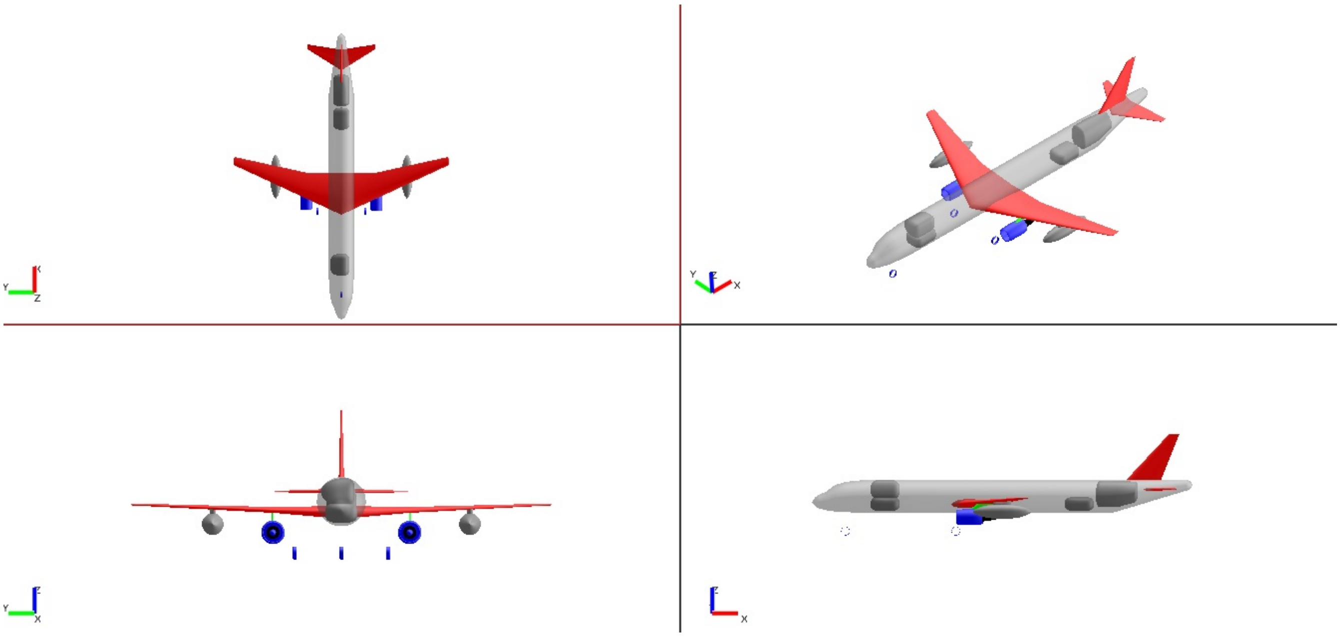

Figure 6.8 Representation in 4D of A321-HW

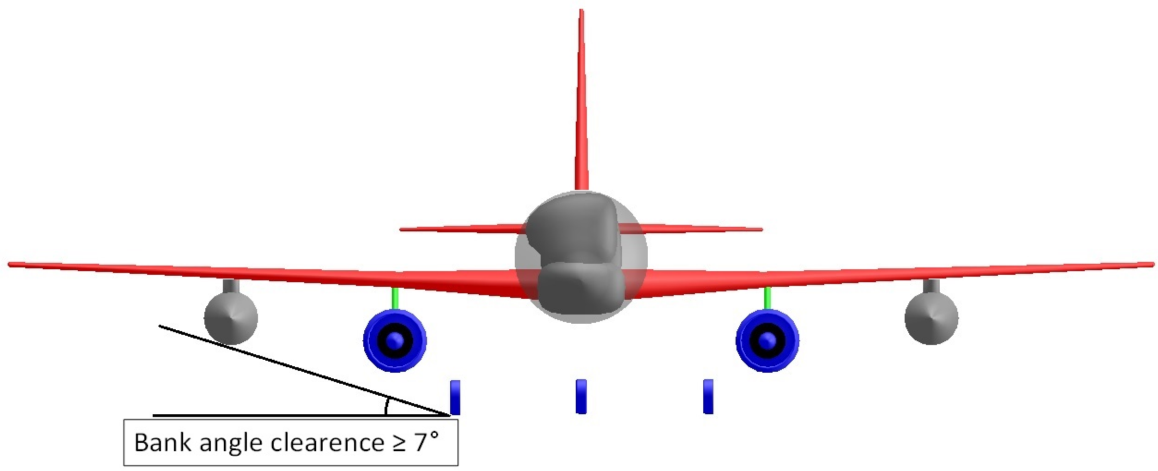

Figure 6.9 Bank angle clearence for the wing tanks of A321-HW

6.6 A321-H19

For this last version of the hydrogen-fueled design is important to argue that the basic requirements stated at the beginning of this chapter, are not fulfilled at all. This fact comes from the necessity of a higher length of the fuselage, so in some cases as it has been seen the length of the A321 is not enough for the mission. In the first case for the A321-HS the solution adopted was to stretch the fuselage more than the original dimensions of the A321, in the second case the version A321-HW, the solution was to maintain the original dimensions of the A321 and use the fuel above for filling two new tanks installed on the wings of the original aircraft.

For this last case the solution of the fuselage length is to maintain the original A321, but the design starts with another version which is the A319-100. This aircraft also belongs to the A320 family of Airbus, but the number of passengers is reduced to 156 in order to use a model available in the market at the moment. For this reason the requirements setted in table 6.1 are not fulfilled at all, because the number of passengers is lower than in the original A320, but for being able to compare with the original version, the total mass of payload, m_{PL} is maintained to his original value of 19.3 t, even if the original number of passengers is reduced, the A319-100 is stretched to the dimensions of the A321-100 which is about 10.7 m larger. The necessary mass of payload above is filled into the cargo volume and will be 2232 kg more for the cargo mass.

The tanks are filled into the fuselage in the same way than the previous two hydrogen-fueled versions, using the length above the original dimensions to insert the new tanks in the two parts of the fuselage. According to **Brewer 1991** for a new design of a hydrogen-fueled aircraft, using the solution of a stretched fuselage, with the tanks filled inside the fuselage, the optimum configuration in terms of C.G control and structural behaviour is to design the aircraft in a way such that the total amount of the increased weight of the system (tank and fuel) is 60 % for the back part and 40 % on the rear part as it is done in the correspondent modified OPerA for this version and for the A321-HS where the tanks are installed as well into the correspondent fuselage section.

The A321-H19 follows the same philosophy respecting the fuel tanks which are installed in pairs into the two parts of the fuselage. For the lower backward tank a length of 5.5 m is required using a part for the space for the cargo, and carrying almost 1280 kg of LH_2. The details of the lengths and the mass of fuel are collected in table 6.8.

Table 6.8: Details of the tanks for the A321-H19

	Length [m]	**Mass of tank [kg]**	**Mass of fuel [kg]**
Rear upper tank	4.36	612.5	1685.2
Rear lower tank	4.36	262.5	1017.7
Back upper tank	6.54	1312.5	2462.9
Back lower tank	5.47	329.5	1277
	Total [kg]	2517	6442.8

Due to the fact that the mission is the same and mass of fuel required is not so different between the three versions, the total mass of the tanks is almost the same and depending of the version, it will determine more the performance of the aircraft, being an important influence for the total m_{OE}, which in turn influences the m_{MTO}, and the final features of the aircraft.

The final design and configuration for this version is closed to the A321-HS, but in this case the length of the fuselage is lower and the length of the fuel tanks are higher. This difference can be seen in Figure 6.10, where the fuselage and tanks of both versions are quiet different.

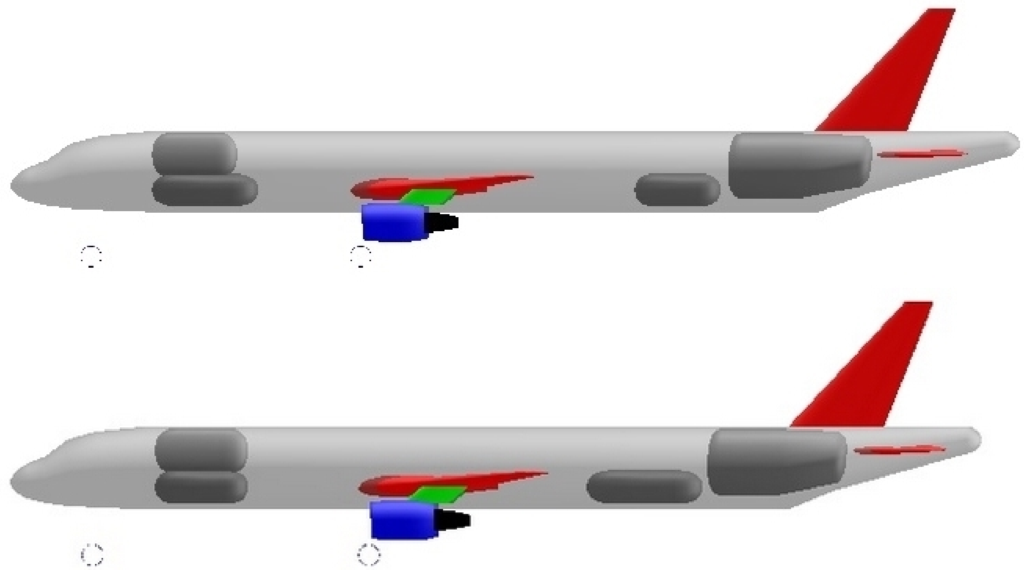

Figure 6.10 Fuselage comparison between A321-HS and A321-H19

Because this version reduced the number of passengers till 156 the *DOC* will rise considerably since it is calculated per passenger and as it is shown in table 6.9 is up to 35 % higher and 31 % for the A321-H19O according tu **AEA**, being even higher the increase according to **TUB**, nevertheless it can be seen better results when the optimizer is performed. On the other hand, the maximum take-off mass of the aircraft has been reduced in this case by almost 2 % because the fuel mass is reduced more than the increase of the operational empty mass which is raised to the value of 12.5 % and 10.5 % for the optimized version.

For the optimization of the A321-H19O, the methodology followed is the same, not touching the cabin parameters even if the number of passengers is lower, the comparisons with the other versions is realistic since the payload mass is the same and the aircraft is designed in the same point of the PL-R diagram at R_{MPL}. The thrust required for the engines is also lower for both versions as well as the *SFC* almost in the same proportions than the other versions.

The results in terms of performance and efficiency are interesting because in this case the original configuration and dimensions of the the A321-100 are almost the same excepting the necessary changes for the fuel system and tanks installation typical of a hydrogen-fueled aircraft design, however the negative point is the fact that the number of passengers is decreased and this can be a negative influence for the industry when deciding to make the final step.

Table 6.9: Results and comparison with A320-200 from OPerA for A321-H19 and A321-H19O

Parameter	**A321-H19**	**Variation (A320)**	**A321-H19O**	**Variation (A320)**
m_{MTO} [kg]	70916	-1.9	69815	-3.4
m_{OE} [kg]	45208	+12.5	44426	+10.5
m_F [kg]	6443	-49.7	6124	-52.2
DOC (AEA) [€/NM/t]	1.78	+34.9	1.73	+31
DOC (TUB) [€/NM/t]	1.61	+39.8	1.56	+36
l_F [m]	46.2	+20.5	46.2	+20.5
$S_W [m^2]$	126.5	+5.1	120	+0.1
$b_{W,geo}$ [m]	34.7	+2.5	36.0	+6.5
$A_{W,eff}$	9.5	0	11.9	+25.3
φ_{25} [°]	25	0	18.84	-24.6
λ	0.21	0	0.14	-34.3
E_{max}	17.6	+0.3	19.6	+11.9
T_{TO} [kN]	100.2	-8.4	87.3	-20.2
BPR	6	0	8.2	+36.8
SFC [kg/N/s]	5.82E-06	-64.8	5.75E-06	-65.2
h_{CR} [ft]	37676	-3.1	31583	-18.8
$m_{MTO}/S_W [kg/m^2]$	560.7	-6.6	579.6	-3.5

6.7 Comparison of Versions

In this section the result that OPerA calculates for all the previous versions explained before are collected and compared, regarding always the basic A320-200 for the comparisons. For all the versions the design point selected is at the original R_{MPL} where the potential benefits for the airlines are the highest, so this point is the same for all the versions. The most important features are collected in tables 6.10 and 6.11 where the first one, shows the results that OPerA calculates for the hydrogen-fueled versions, without using the optimizing tool and the second the same versions but optimized with the algorithm.

Some interesting and important results to analyse, will be commented within the next lines. First of all, it is important to note that the m_{OE} will be higher than the original configuration, because the fuselage is larger and tanks for the hydrogen are required making the operational empty mass higher, varying between 11.6 % with the A320-HW till 18.6 % for the A321-HS, mening more weight than the original configuration. Another important result for the hydrogen-fueled aircraft is the fact that the maximum take-off mass can be reduced in almost all the cases between 0.7 % and 3.4 % less, corresponding the lower value to the A320-HSO. The A321-HS is the only version where the m_{MTO} is raised due to the stretch of the fuselage with a 1.8 % more weight. The higher reduction can be seen in the A321-H19O and the A321-HWO with similar m_{MTO} percentage reduction. Naturally, the m_{ML} is also higher because the value of m_{ML}/m_{MTO} is higher for the hydrogen-fueled new design in order to accomplish the check of weight mass assumptions performed in OPerA. All this information about the relative difference of the certified weights can be seen in Figure 6.11.

The thrust required for the engines is in all the cases lower, alleviating the requirements of the engine and turning in lower temperatures and higher life. The higher reduction in the T_{TO} has been found in the A321-HSO with 20.2 % of reduction and the lowest reduction, with a 5 %, for the A321-HS. Due to the higher content of energy per kilogram of the hydrogen, the SFC is reduced about three times than the kerosene aircraft.

In *DOC* terms, the results of using hydrogen are much higher than the original case and the benefits calculated when optimizing the aircraft with OPerA tool are better. In Figure 6.12 is resumed the calculations of the *DOC* according to both methods and the results according to **TUB** bring out higher *DOC* related to the original version. The *DOC* compared to the original aircraft vary from 21.9 % for the A321-HWO till 34.9 % corresponding to the A321-H19. Nevertheless the *DOC* calculated for the A321-H19 is so high due to the fact that the mass of hydrogen required for the mission is about 50 % lower but the price of the hydrogen with the assumption of same price per energy for both fuels, turns into a price per kilogram of hydrogen three times higher than the kerosene and this mainly makes the *DOC* to increase. The reduction in n_{PAX} makes this growth more accused.

The comparison between the original payload-range diagram and a hydrogen-fueled aircraft such as the A321-HS is detailed in Figure 6.13. The differences with the original kerosene-fueled A320 are quiet significant as it is shown in table 6.12. The design of the new versions has been made in a way that the aircraft is able to cover the original range and performances of the mission setted with 1510 NM.

From the PL-R diagram of a hydrogen-fueled aircraft many important differences are observed:

Table 6.10: Comparison between original versions

	A320-200	**A321-HS**	**A321-HW**	**A321-H19**
l_F [m]	38.4	49.4	45.2	46.2
m_{MTO} [kg]	72274	73578	70716	70916
m_{OE} [kg]	40199	47658	44871	45208
m_{ML} [kg]	63457	69164	66473	66661
m_F [kg]	12819	6664	6588	6443
E_{max}	17.5	17.6	16.9	17.6
T_{TO} [kN]	109.4	103.9	99.8	100.2
BPR	6	6	6	6
SFC [kg/N/s]	1.65E-05	5.79E-06	5.82E-06	5.82E-06
m_T [kg]	-	2531	2473	2517
n_{PAX}	180	180	180	156
DOC [€/NM/t]	1.32	1.68	1.63	1.78
DOC [€/NM/t]	1.15	1.49	1.45	1.61

Table 6.11: Comparison between optimized versions

	A320-200-O	**A321-HSO**	**A321-HWO**	**A321-H19O**
l_F [m]	38.4	48.7	45.2	46.2
m_{MTO} [kg]	70489	71789	70626	69815
m_{OE} [kg]	39971	46417	45122	44426
m_{ML} [kg]	63424	65328	66100	66289
m_F [kg]	11262	6116	6247	6124
E_{max}	20.0	19.1	17.9	19.6
T_{TO} [kN]	88.9	93.2	95.6	87.3
BPR	9.3	8.8	9.5	8.2
SFC [kg/N/s]	1.58E-05	5.48E-06	5.47E-06	8.2
m_T [kg]	-	2323	2345	5.75E-06
n_{PAX}	180	180	180	156
DOC [€/NM/t]	1.27	1.61	1.60	1.73
DOC [€/NM/t]	1.10	1.43	1.42	1.56

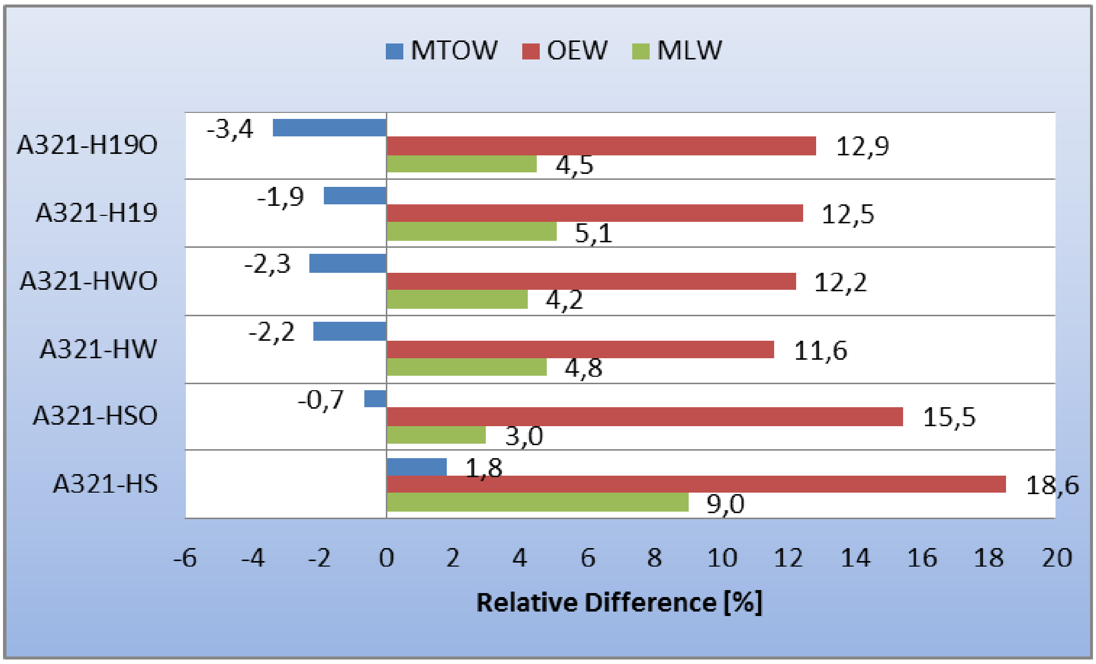

Figure 6.11 Comparison of m_{MTO}, m_{OE}, m_{ML} related to the original A320-200

- The hydrogen version is highly optimized for the range at maximum payload in order to design with the minimum necessary tanks and fuel, leading into lower length for the fuselage.
- The ranges at maximum payload and maximum fuel collapse into a single point because of the optimization selected.
- The flexibility of this aircraft is reduced due to the high optimization for one single point and the new version cannot offer all the possibilities as the original, nevertheless for the normal ranges where most of the time the aircraft will fly this distance is sufficient.

In reference to the length of the fuselage it is important to argue the fact that for the versions A321-HS and A321-H19, even if they are based on the original A321-100 available at the moment, the calculations and estimations performed by OPerA are not totally exactly but both are well approximated to the original length which is in this case 44.51 m meaning 1.5 % more length in the case of the A321-HS and for the A321-H19 3.6 % of deviation.

Table 6.12: Payload-Range diagram for the A320-200 and A321-HS

	A320-200	**A321-HS**	**Variation [%]**
Maximum payload [t]	19.3	19.3	0
Range at maximum payload [NM]	1510	1510	0
Payload at maximum fuel [t]	12.1	19.3	+59.1
Range at maximum fuel [NM]	2840	1510	-46.8
Ferry range [NM]	3530	2265	-35.8

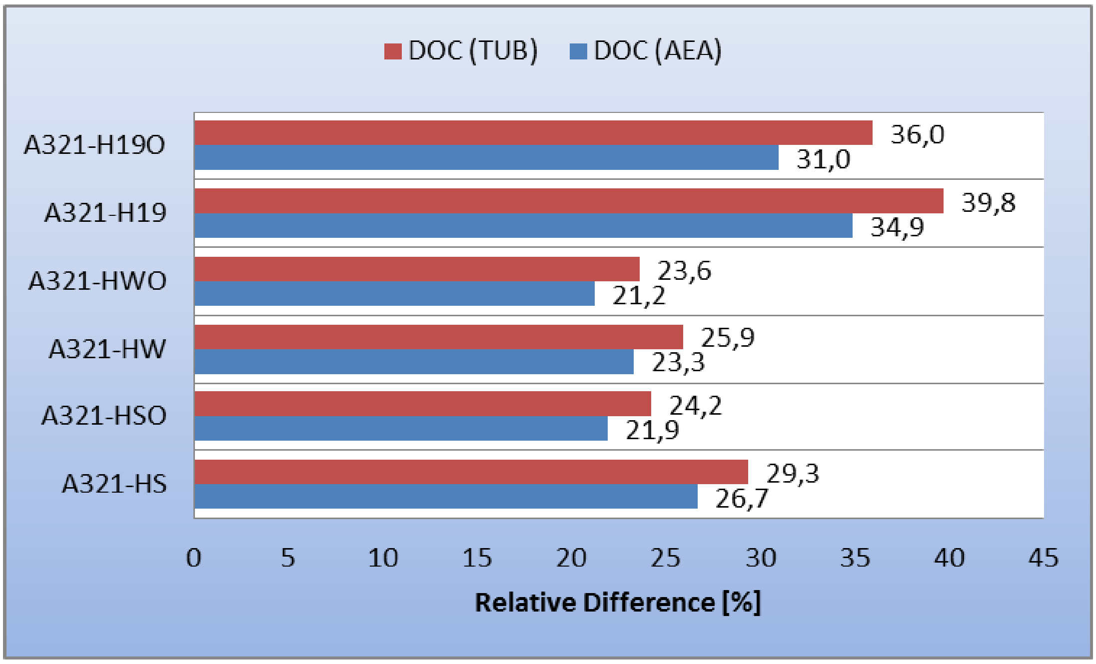

Figure 6.12 Comparison of *DOC* related to the original A320-200

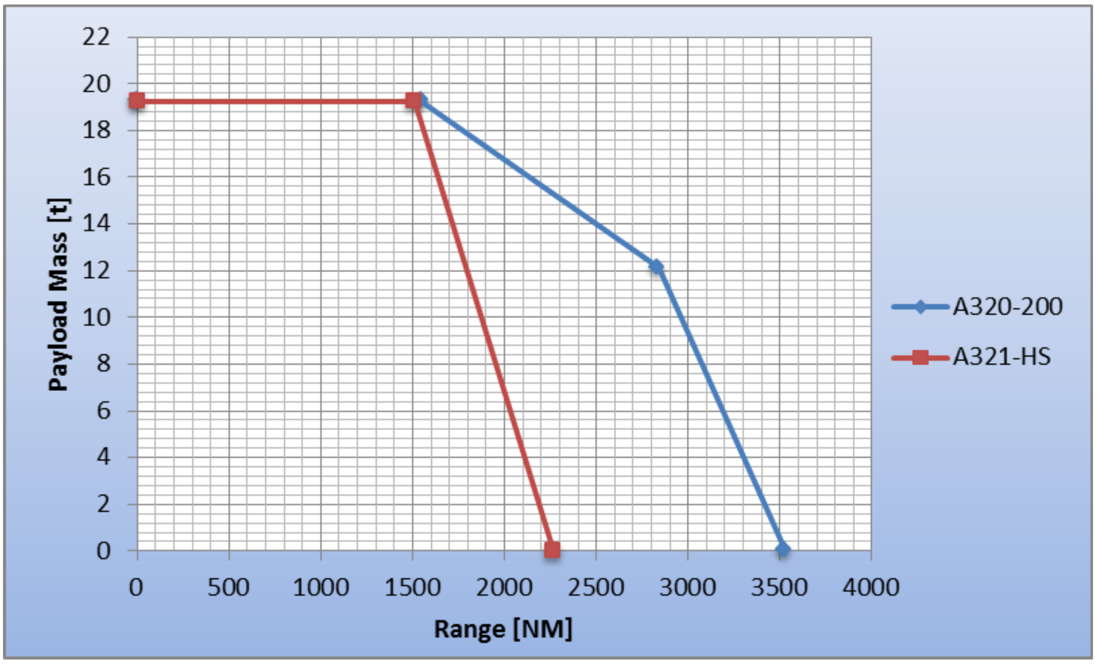

Figure 6.13 Payload-Range diagram comparison between a kerosene and a hydrogen-fueled aircraft

7 Summary and Conclusions

This thesis overviewed the benefits and challenges of introducing the hydrogen as an aviation fuel for commercial purposes. The work is based on a medium-range aircraft, in this case the original A320 kerosene-fueled, for a mission of 1510 NM and 19.3 t of payload, being the most frequently used aircraft.

For facing the problems related to the hydrogen as a carrier of energy and from the technical-point of view, the results indicate that hydrogen-fueled aircraft is feasible. In this thesis the solutions and considerations of the aircraft design were based on the adoption of minimum changes in the original aircraft. As it is studied in the chapters dedicated to the hydrogen aircraft and tank design, for the same mission the new aircraft will need much more volume to perform the same range. Because of the highest volume required, more space is needed for filling the tanks with the consequent increase in the fuselage length.

The redesign is based on the A320 family, stretching the A320 to the dimensions of the A321 in order to still using the fleet available in the market. Thereby, 3 different configurations were studied, all of them based on the mentioned family of aircraft. The result obtained was the feasibility of this conversion with some challenging problems for the conversions such as the design of the tanks and their placement into the aircraft. Regarding the infrastructure, safety considerations and airport requirements, necessary changes must be done for the special features of the LH_2.

The design was optimized for the point of the maximum range with maximum payload because is the point where the potential benefits reported can be higher. All the versions are able to reach the specified mission, but due to the high optimization made for this point, the flexibility of the aircraft is lower than the original case.

The hydrogen-fueled aircraft will be closer to the features of the A321 meaning higher dimensions. The results in terms of weight were an increase in the OEW of the aircraft from 11 % to 19 % more weight, because of the new tanks and larger fuselage. The MOW of the aircraft is reduced from 0.7 % to 3.4 % depending on the version mainly because the decrease of fuel mass which is 50 % less than the kerosene-fueled aircraft for the same mission.

The DOC under the consideration of same price per energy is increased in this case. due to the fact that the price of the hydrogen is three times higher and the mass of the fuel is just the half. Another interesting result obtained is the fact that the more fuel required for a specified mission, the more opportunity will be for the hydrogen to obtain more benefits with the decrease in the mass of fuel, however a new design is required for a long-range aircraft, being a hard work to base the redesign on an available kerosene-aircraft.

Summarizing, this thesis has demonstrated the possibility of converting a medium-range commercial aircraft to hydrogen, with some challenging changes and the possibility of still flying in the future with an available and clean fuel. The zero emissions of CO_2 and only the release to the atmosphere of little proportions of NO_x and H_2O make this fuel to be an attractive an interesting alternative for the aviation industry.

8 Recommendations

For reaching the aim of this work, the hypothesis listed for the aircraft design were in some cases as simple as possible and without loss of generality. All the studies conduced before for the implantation of the hydrogen as the new fuel for the aviation, showed very good results and the possible benefits of using hydrogen will be even higher within the next decades. However this change will be a hard work because this transition will involve many other fields, not only from the aircraft design point of view which has been proved feasible, but also more technological and political support is necessary.

The application of hydrogen for commercial purposes, requires a deeply study of the infrastructures issues with the consequent changes of the current airports for operating with hydrogen, taking care of the cryogenic nature of this fuel and a more detailed study of the problems appeared due to the boil-off, fuelling and the new hydrogen systems. For being a really clean fuel, the production of hydrogen must be based on renewable energy because the hydrogen production plays a significant role in the environmental impacts. Other industries are necessary to be activated in order to start the production of hydrogen to a massive scale.

The engine performance parameters are better in the case of the LH_2 and the efficiency of the engines will be higher, maintaining the current trend of engine improvements. A more detailed study of the consequences when burning hydrogen into an engine is necessary, specifically the impact of the water vapour on the climate at high altitudes.

From the aircraft design point of view is relevant to clarify that simple solutions were implemented in OPerA in order to get the most first relevant results. Some improvements in the tool could be:

- A more detailed study of the volume available when converting the aircraft to the A321, and the optimization of the hydrogen tanks dimensions. A study of structural analysis and a new airframe mass estimation will improve the approximations.
- For the *DOC* estimations, the hypothesis was the equivalence of the price per energy between both fuels and it will be useful to review the method for the hydrogen, focusing the study on the maintenance, fuel cost, aircraft price, ground handling fees, etc.
- For the engine is necessary to design a proper fuel system and the model of the *SFC* may be reviewed and take care of other important parameters not only the volumetric energy of the hydrogen.
- The design was performed to the point of the payload-range diagram of maximum range with maximum payload. Another possible design can be analysed, focusing the optimization to another point, less or more challenging, depending on the mission established to fulfil.

An interesting future work can be the design of a long range hydrogen-fueled aircraft where the savings of hydrogen fuel mass are even higher and compare the results in terms of *DOC* and aircraft performance with a medium-range aircraft. The new long range aircraft must be completely redesigned and suitable requirements are necessary to be setted.

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Appendix A Fuel Cell with Hydrogen

A.1 Introduction

Nowadays the aviation industry including the biggest aircraft companies in the world such as Airbus and Boeing are trying at all costs to be more an more efficient an minimize the impact of the aviation in the climate change, reducing the emissions of the harmful gasses to the atmosphere in order to achieve the important goals for the ACARE 2020, as it has been said in other chapters of this work. Other factors such as the reduction of the noise and *DOC*, with a high reliability. In these sense, aircraft systems are strongly influenced by the source of energy they are powered.

In the last years the tendency of substituting the pneumatically and hydraulic systems with electrical systems of the aircraft has increased as it can be seen in the new aircraft generation (A320 NEO, B737 MAX, A380, B787, A350XWB) due to the fact that this new systems, powered by electrical sources offer more benefits to the aviation, such as lightweight structures, flexibility and more reliability. Fuel cells are a hopeful promise in order to achieve all this aims for ground and cruise operations **(Renouard et al. 2012)**.

Aircraft consume electrical energy from a lot of sources during operations in the ground and flight as it is shown in table A.1, for the electrical systems of long range aircraft.

Table A.1: Main electrical consumers for a long range aircraft

Main Electrical Consumers	Conventional System		All Electrical System		System Power [kW]
	Non-Active in Flight	Active in Flight	Non-Active in Flight	Active in Flight	
Auxiliary Hydraulic Pumps		(X)[a]		(X)	(60)
Fuel Pumps		X		X	10
Ice & Rain Protection		X		X	10
Lighting		X		X	15
Commercial Loads		X		X	25
Avionics		X		X	10
Galleys		X		X	75
Cargo Doors			X		15
Flight Control				X	80
Landing Gear				X	25
Engine Starter			X		350
Wing Anti Ice				X	200
ECS				X	400
Total Demand [kW]	145 (205)		1215 (1275)		
In-Flight Demand [kW]	145 (205)		850 (910)		

[a] () means emergency cases and values in the table are a combination between the A330 and B777

In most of the airplanes, the electrical energy is obtained by generators connected to the main shaft of the engines. This source of energy could be thought that is an efficient way of obtaining electricity but this is not true at all. In order to increase the number of systems of the aircraft using electrical energy, higher generators are required charging more and more the engines with the consequently decrease of the propulsive efficiency, contrarily with the improvements expected **(Eelman et al. 2004)**. The thermodynamic efficiency of the engines and the generators are limited to a maximum. Nowadays the thermodynamic efficiencies of the engines is about 50 % and in the case of the production of electrical energy from the main engines is about 40 % according to **Keim et al. 2013**.

In order to solve all this problems another sources for the electrical energy production on the aircraft are required and the fuel cell could alleviate all this problems, providing the energy with a higher efficiency.

The use of hydrogen as a fuel for the aviation and his benefits are well known, however not only the use of this fuel for burning it in a jet fuel engine is possible, but also it can be used for a fuel cell system.

A.2 Hydrogen Fuel Cell Principles and Types

The basic principles of the fuel cell are very simple. It is known that water can be separated in hydrogen and oxygen by passing an electric current through it (electrolysis). This process could be reversed and the hydrogen and oxygen can be recombined producing electric current. The hydrogen fuel is combusted in the reaction found in **(Larminie et al. 2003)**

$$2H_2 + O_2 \rightarrow H_2O \tag{A.1}$$

In this equation the heat energy is being liberated and electrical energy is produced. However the amount of electricity produced in this method is not so big and improvements in the electrolytes are required. To understand the production of the electrical energy is necessary to go inside each electrode and analyse the chemical reactions in each one, however this equations change with the different types of fuel cell. In Figure B.6 is shown the process for a simple fuel cell.

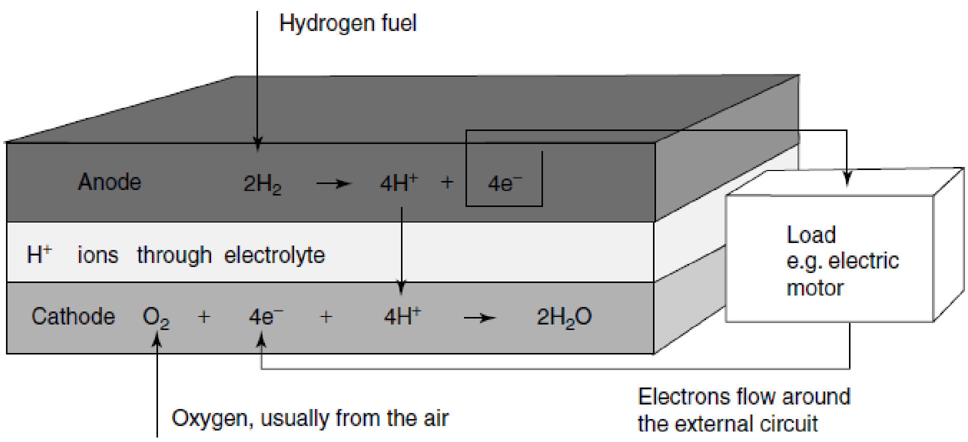

Figure A.1 Hydrogen acid electrolyte fuel cell **(Larminie et al. 2003)**

This method for obtaining electrical energy possesses a higher efficiency when comparing to the standard way, where mechanical energy is being transformed into electrical energy as it is shown in the comparison detailed in Figure A.2 for the feasibility study of the fuel cell, where the efficiency of this process is about 83 %, higher than the conventional way.

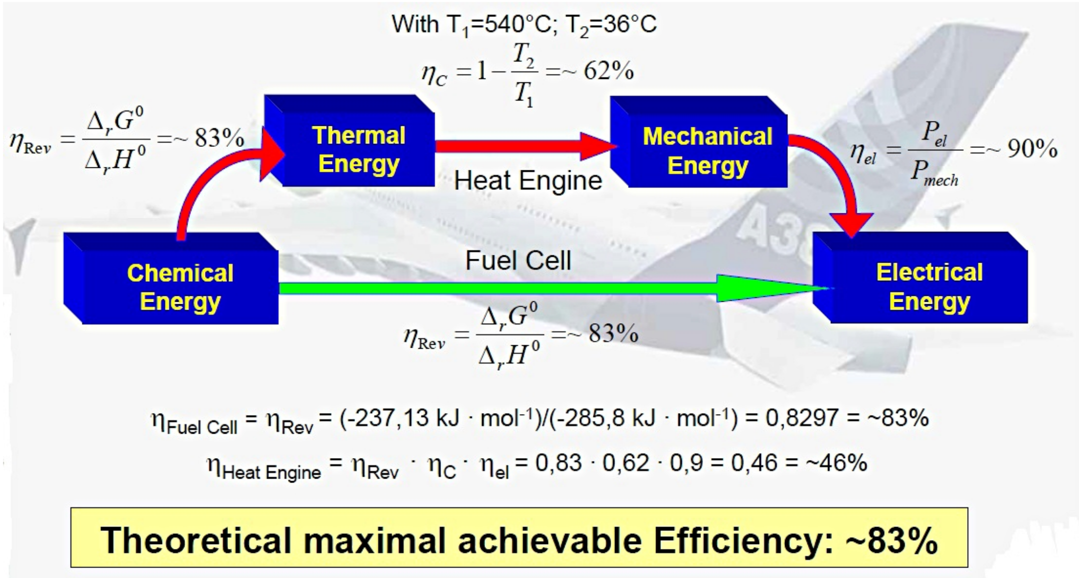

Figure A.2 Heat engine versus fuel cell **(Volker 2006)**

For aircraft applications there are two main types of fuel cell considered: PEM and SOFC **(Romeo et al. 2012)**, each of these systems have different benefits and ways of working for aircraft use.

PEM : In this cell the electrolyte is a solid polymer, where protons are mobile. The most attractive features of this cell are the high power density, high efficiency and fast start-up. A lot of improvements have been made in the last years due to the researches made in the automotive industry. The most important problems of these cells are the water and heat management, low tolerance to impurities and the high cost. These problems could be solved with the high temperature PEM fuel cell which can be operated in the range of 100 °C and 200 °C, however the normal temperature of use the fuel cell is about 120 °C **(Romeo et al. 2012)**. The PEM fuel cell is shown in Figure A.3.

SOFC : In this cell the electrolyte is made by a solid oxide material, typically Zirconium and Cerium and operates in a temperature range between 600 °C and 1000 °C. The most important advantages of this cells are the cost, the long term durability, robust behaviour and large flexibility. The most important differences and characteristics of the two types of cells are shown in Figure A.4.

A.3 State of the Art of Fuel Cell

Today many institutions are researching on this kind of fuel cell and as it has been said the most important aircraft manufacturers are trying to demonstrate the feasibility of these cells for some aircraft systems. In order to reduce the noise and exhaust emissions in ground operations and

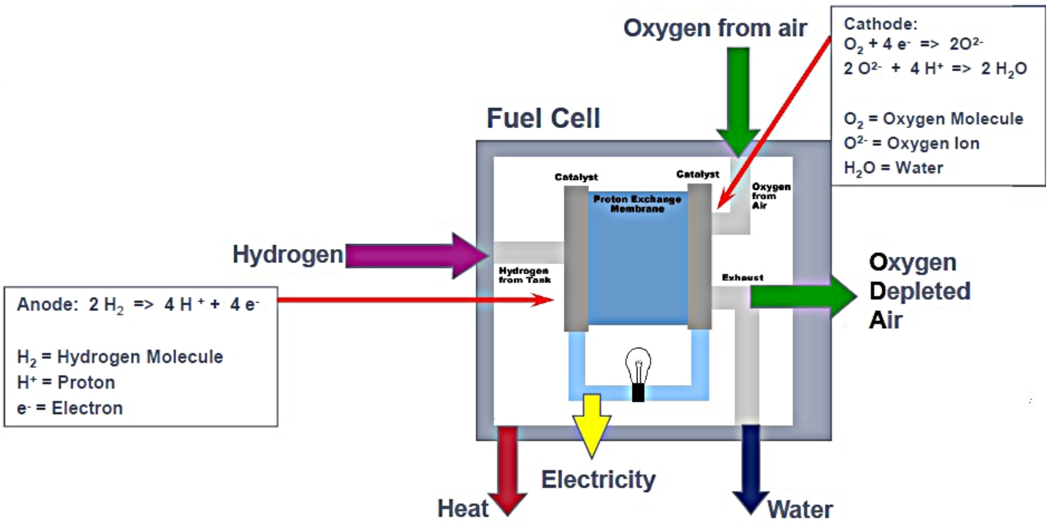

Figure A.3 PEM fuel cell scheme **(Volker 2006)**

	Proton Exchange Membrane Fuel Cell (PEMFC) Fuel Cell with polymer (sulfonic acid polymer → Nafion) as electrolyte.	**Solid Oxide Fuel Cell (SOFC)** Fuel Cell with ceramic (Y_2O_3-stabilized ZrO_2 → Yttria-stabilized zirconia) as electrolyte.
Advantages	- High development status (>100 kW_{el}) - Many thermal cycles possible - Water generation at cathode side	- High working temperature (~800°C) - Simple Cooling System - Insensitive against Gas Impurities - Simple Fuel Processing - Highest efficiencies - No humidification needed
Challenges	- Low working temperature (~80°C) - Complex cooling system - Sensitive against CO - Complex Fuel Processing - Humidification needed	- Only few thermal cycles possible - Low development status for mobile application (20 kW_{el}) - Water generation at anode side

Figure A.4 PEMFC versus SOFC **(Volker 2006)**

because of the low efficiency of the APU, near 20 %, is being studied the possibility of replacing it by fuel cells. According to the studies made by DLR, the APU contributes with near 18.5 % to the NO_x handling emissions. The efficiency of the fuel cell working as a replacement system could reach a percentage of 40 %. Another benefit when using on flight the fuel cell is the possibility of producing water on board, instead of filing the water tank on ground with the possibility of weight reductions.

DLR : For several years the DLR worked for the development of fuel cell systems for aircraft applications, in cooperation with Airbus (**Kallo et al. 2010**). In July 2009 with the motor-glider $ANTARES-DLR-H_2$, which achieved to take-off only with fuel cell power. The fuel cell delivers up to 25 kW of electrical power, and can maintain the level flight with about 10 kW. It used high temperature PEMFC. The total efficiency from tank to propeller was about 44 % (twice that of a conventional piston engine) (**Romeo et al. 2012**). The main purpose of this flight was to demonstrate the reliability of flying with a fuel cell and using the system as a replacement of some components such as the APU.

Airbus : Airbus was working on the project CELINA (Fuel Cell Application In New Config-

Geometry	
Wing Span	20 m / 65.6 ft
Wing Area	12.6 m² / 135 ft²
Aspect Ratio	31.7
Fuselage Length	7.40 m / 24.3 ft
Fuselage Height	1.64 m / 5.4 ft
Weight	
Empty Weight	460 kg / 1014 lb
Maximum Weight	660 kg / 1455 lb
Waterballast	100 l / 26.4 USgal
Min. Wing Loading *	42 kg/m² / 8.6 lb/ft²
Max. Wing Loading	52.4 kg/m² / 10.7 lb/ft²
Glide Performance	
Best Glide Ratio	56
Min. Sink Rate at weight	0.49 m/s / 96 ft/min | 530 kg / 1168 lb
Stall Speed at weight	73 km/h / 39.4 kt | 530 kg / 1146 lb

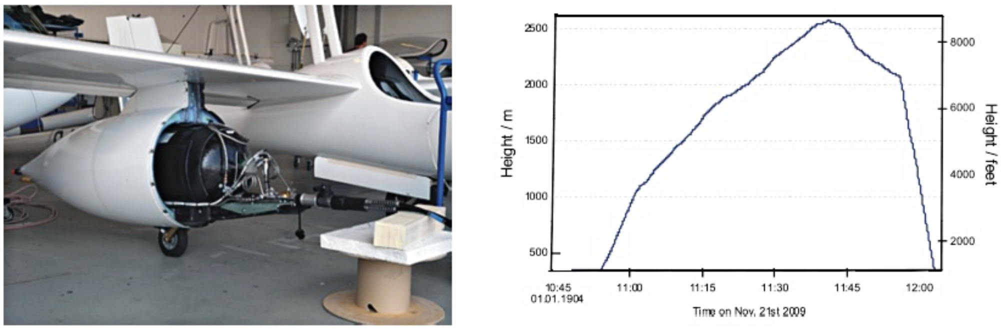

Figure A.5 $ANTARES-DLR-H_2$ features **(Kallo et al. 2010)**

ured Aircraft) which had several purposes (**Romeo et al. 2012**):

- Define the requirements for a fuel cell power system in order to accomplish the certification rules and achieve a safety system with the proper maintenance and installation design.
- Design an appropriate fuel cell system and all the related subsystems.
- Evaluate the fuel cell performances in various operating points.
- Integrate the fuel cell with the current systems.

In order to justify the effort of the fuel cell, Airbus created the multifunctional fuel cell system in which many systems of the aircraft are powered and replaced by the fuel cell. According to the final results of this project the major benefits when using fuel cells are the reduction of weight, emissions and *DOC*. In Figure A.6 can be seen the most important possible replacements of the multifunctional fuel cell system.

Airbus and DLR presented the first commercial aircraft powered by fuel cell at the ILA Berlin Air Show in 2008.

Boeing : The company is also currently developing and researching systems for fuel cell technologies in order to reduce the noise and emissions for the APU and another sub-systems of the aircraft. In April 2008 Boeing Research and Technology Europe achieved in Madrid

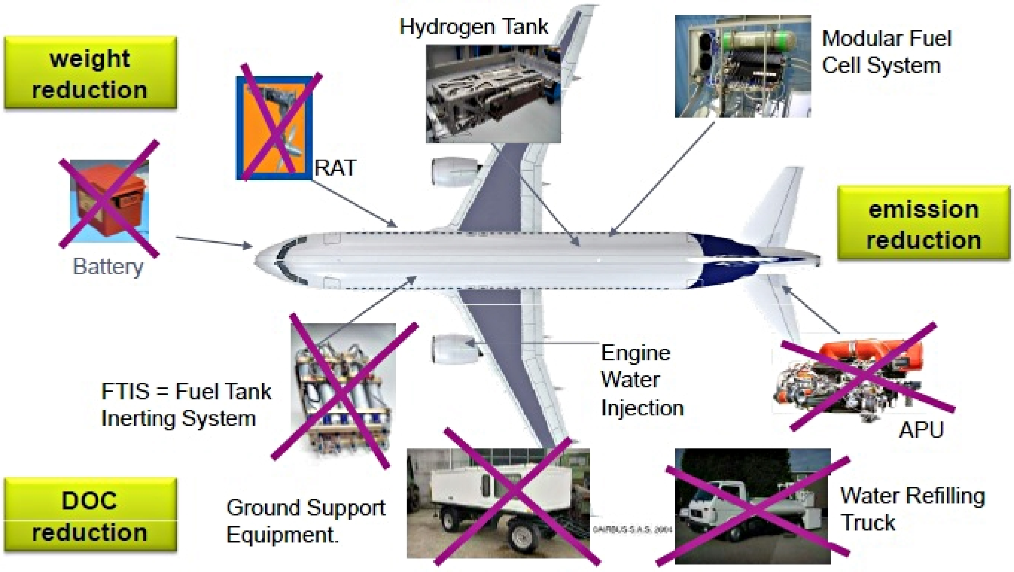

Figure A.6 Benefits of the multifunctional fuel cell **(Volker 2006)**

(Spain), to fly with the first electrical powered two-seats fuel cell motor-glider. In this project a two seats Super Dimona was modified in order to include a PEM fuel cell, to power a 40 kW electric motor coupled to the propeller. The flight was successful and the aircraft climbed to a 1000 m and flew with a velocity of 100 km/h in cruise for about 25 minutes.

A.4 Fly with Hydrogen Jet Engine or Fuel Cell?

Today the viability of flying with the hydrogen jet engine is becoming more and more realistic and there are many studies in this field proving this feasibility. The modifications required for the kerosene jet engine are not so big and as it is said, the most important problem is to deal with the highest volume required for the storage of the LH_2. On the other hand, the possible entry of the fuel cell in the market with more and more efficiency and increase of performances require them to be deeply analysed and make a good difference between the fields where this kind of technology could be implemented. Currently, the best option for using the fuel cell is when the APU is replaced by a fuel cell system, with all the benefits explained. This is not the only possibility and the next step is to use the multifunctional fuel cell since this system could support all the electrical systems of the aircraft with the elimination of the RAT, APU and battery weight reduction. The potential of water production on-board is also an interesting point to consider, according to **Renouard et al. 2012** a fuel cell with a power of 100 kW could produce an amount of 50 l of water per hour which can be used for toilets and air conditioning. The fuel cell could be very advantageous considering the weight reduction, emissions and improvements in the specified mission.

In order to make some first estimations and calculate some numbers for the hydrogen jet engine a theoretical and first estimation of some interesting parameters are analysed.

In this work, 3 different types of hydrogen-fueled aircraft with jet engine have been designed with different performance and features. The mission setted for the design of the aircraft at the beginning of this work, detailed in table 6.1 with a range of 1510 NM and a payload mass of 19.3 t is maintained the same. For the comparisons the A321-HS is selected and some interesting results in terms of weight and fuel mass estimations for the comparisons are collected in table A.2.

Table A.2: Details of the A321-HS

Parameter	A321-HS	A320	Variation
m_{MTO} [kg]	73578	72274	+1.8
m_{OE} [kg]	47658	40199	+18.6
m_F [kg]	6664	12819	-48.0

This results performed using OPerA show an increase 1.8 % in the m_{MTO}, 18.6 % in m_{OE} and a reduction of 48 % for m_F.

Once the estimations for the jet engines are made another considerations when flying with fuel cells are made for comparing the two types. When flying with fuel cells one of the most important parameters is the power required for flying and it is well known that the power required in cruise for flying is

$$P_{flight} = TV_0 \tag{A.2}$$

Where P means is power, T is the thrust and V_0 is velocity of flight. When flying in cruise it is known that $T = D$ and $L = W$ and for the aerodynamic efficiency $E = L/D = W/T$. So the required thrust for flying is $T = W/E$.

For the power is necessary to consider the efficiency for the electrical motor and the propulsive efficiency of the flight.

$$P_{cell} = \frac{P_{flight}}{\eta_m \eta_p} \tag{A.3}$$

η_m is the efficiency of the electrical motor and η_p is the propulsive efficiency which according to **(Torenbeek 1982)** can be estimated as

$$\eta_p = \frac{2}{\frac{V_s}{V_0} + 1} \tag{A.4}$$

Where V_s means the exit velocity of the flow. And now the final equation for the required power for the fuel cell in cruise turns into

$$P_{cell} = \frac{WV_0}{E\eta_m\eta_p} \tag{A.5}$$

The current electrical motors have a high efficiency, near $\eta_m = 0.95$ and $\eta_p = 0.8$. With the same values for the weight and velocity of flight, the value of $P_{cell} = 12\,MW$ which is the power required for the aircraft when flying with fuel cell technology. According to **(Volker 2006)** the mass-specific power for an actual PEM fuel cell is about 1 kg/kW and the volume-specific power is 1.5 l/kW. Using the total P_{cell} required for the flight the total weight and volume of the potential PEM fuel cell is

$$W_{cell} = 12000\,kg;\; V_{cell} = 18000\,l \tag{A.6}$$

One of the first and biggest differences when flying with a fuel cell is the high weight of them in this case is near 12 t. Only the weight of the fuel cells will contributes with 30 % more for the OEW of the aircraft. Also the hydrogen has to be filled in the fuselage or wings meaning more weight due to the tanks and the mass of fuel needing more volume. The engines will be radically different in this case and the performance of the aircraft will be changed. The life of the cells is limited and it is established in a certain number of cycles before changing them.

With the current technology of the fuel cell the range able to reach is really small compared to the hydrogen jet aircraft. Due to the highest weight and volume required for the fuel cell it necessary to make a new redesign of the aircraft with a big increase in the volume which will make the aircraft not being feasible, since almost all the aircraft volume will be used for the cell and LH_2. The jet engine in this case is much more efficient from all points of view, that is the reason why the power generation from the fuel cell should be only made for smallest systems such as the APU and others parts of the aircraft powered by electrical energy. Only in this way the use of the fuel cell could be more advantageous.

Appendix B A320 Familly Dimensions

In this appendix the most important dimensions of the A320-200, A321-100 and A319-100 are collected from the Airbus data.

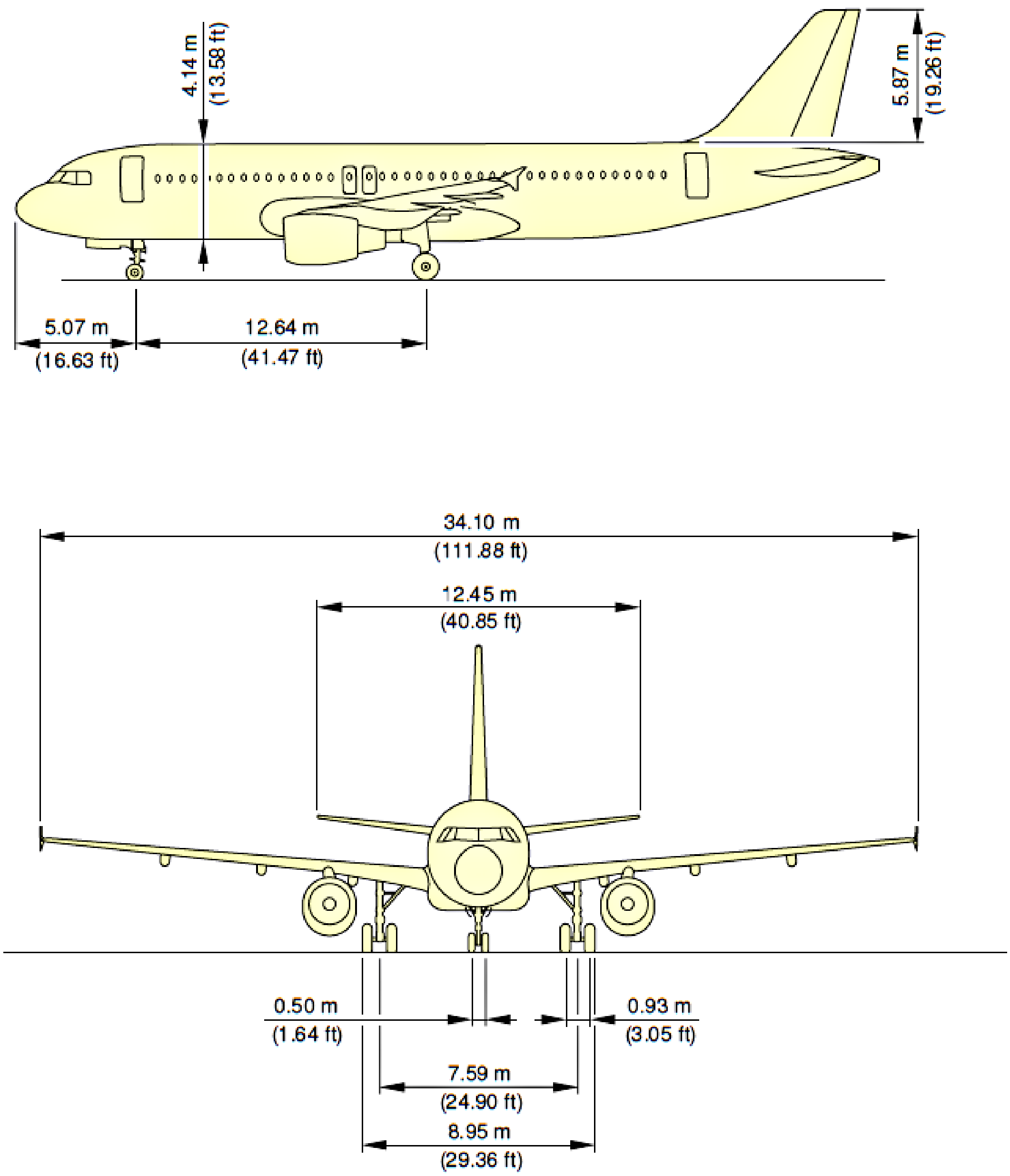

Figure B.1 Side and front view of the A320-200 **(A320 2014)**

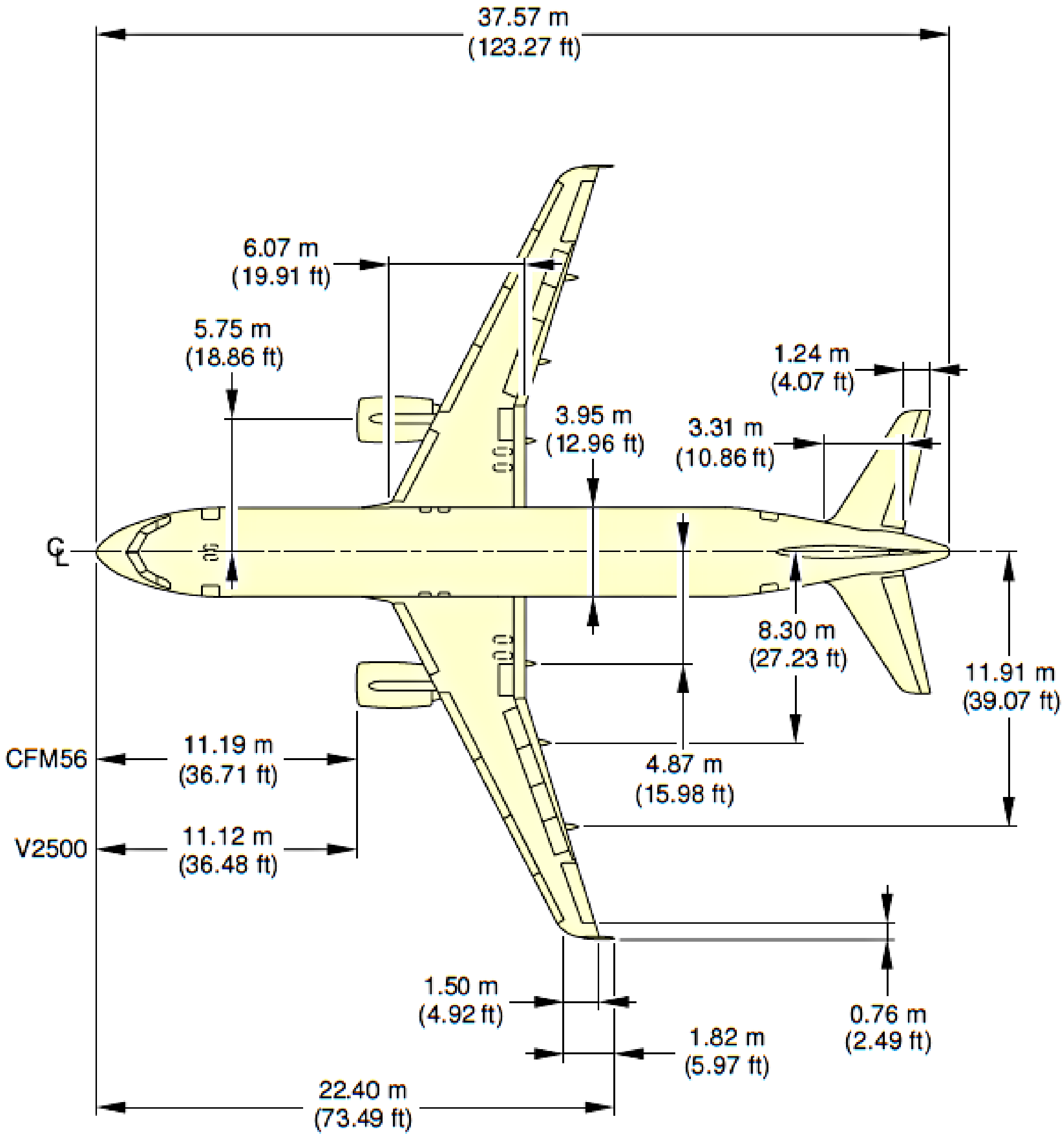

Figure B.2 Top view of the A320-200 **(A320 2014)**

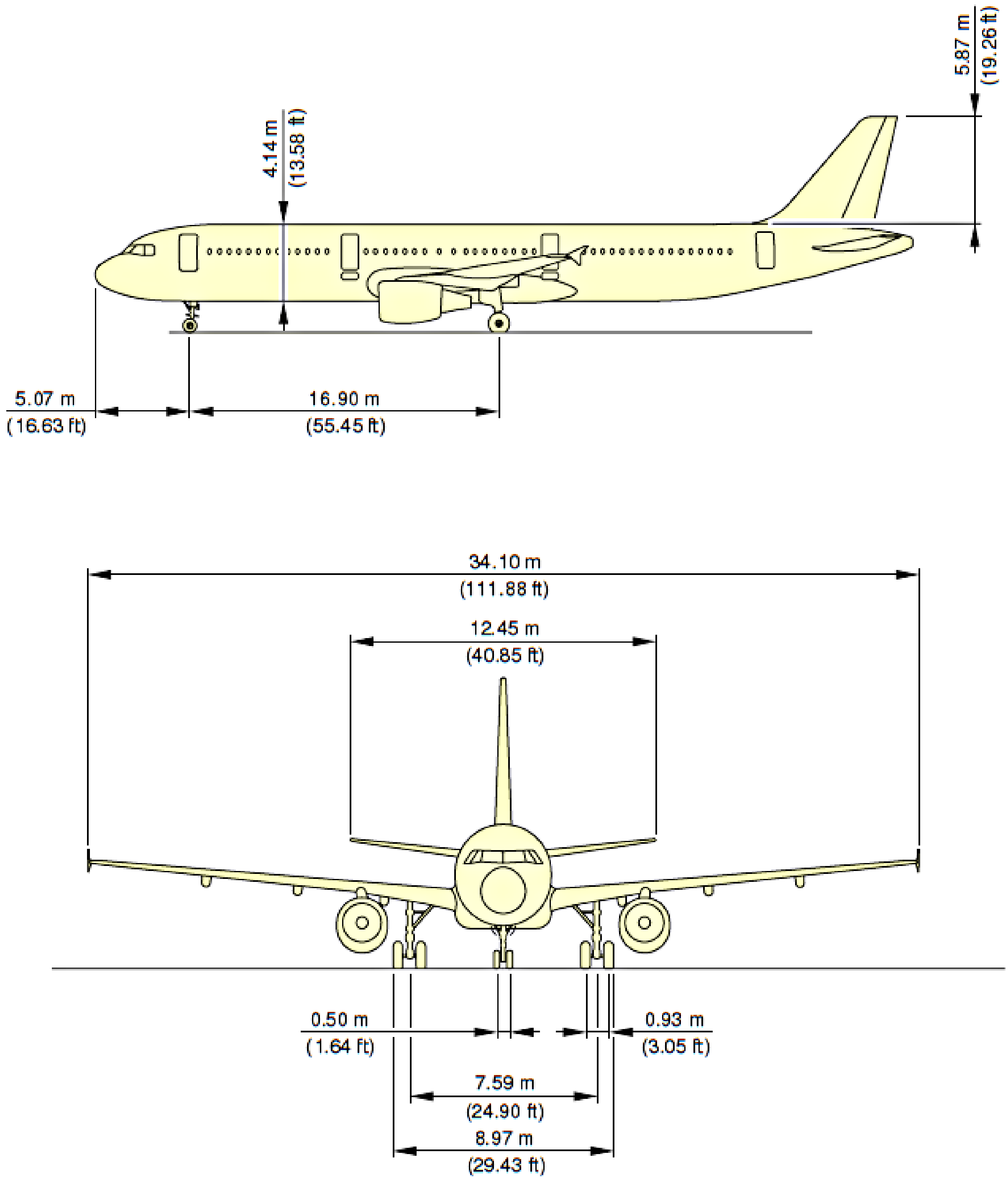

Figure B.3 Side and front view of the A321-100 **(A321 2014)**

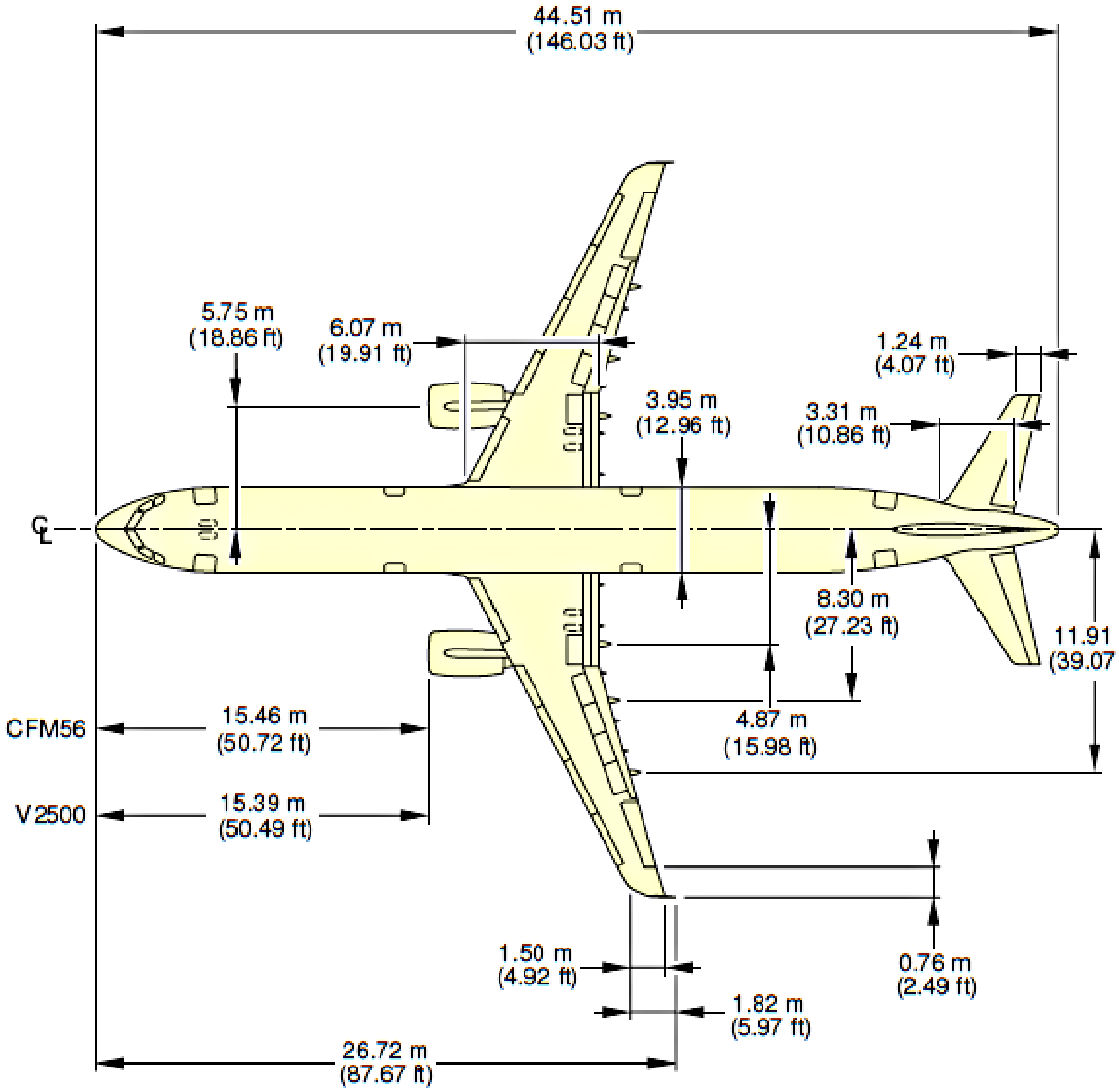

Figure B.4 Top view of the A321-100 **(A321 2014)**

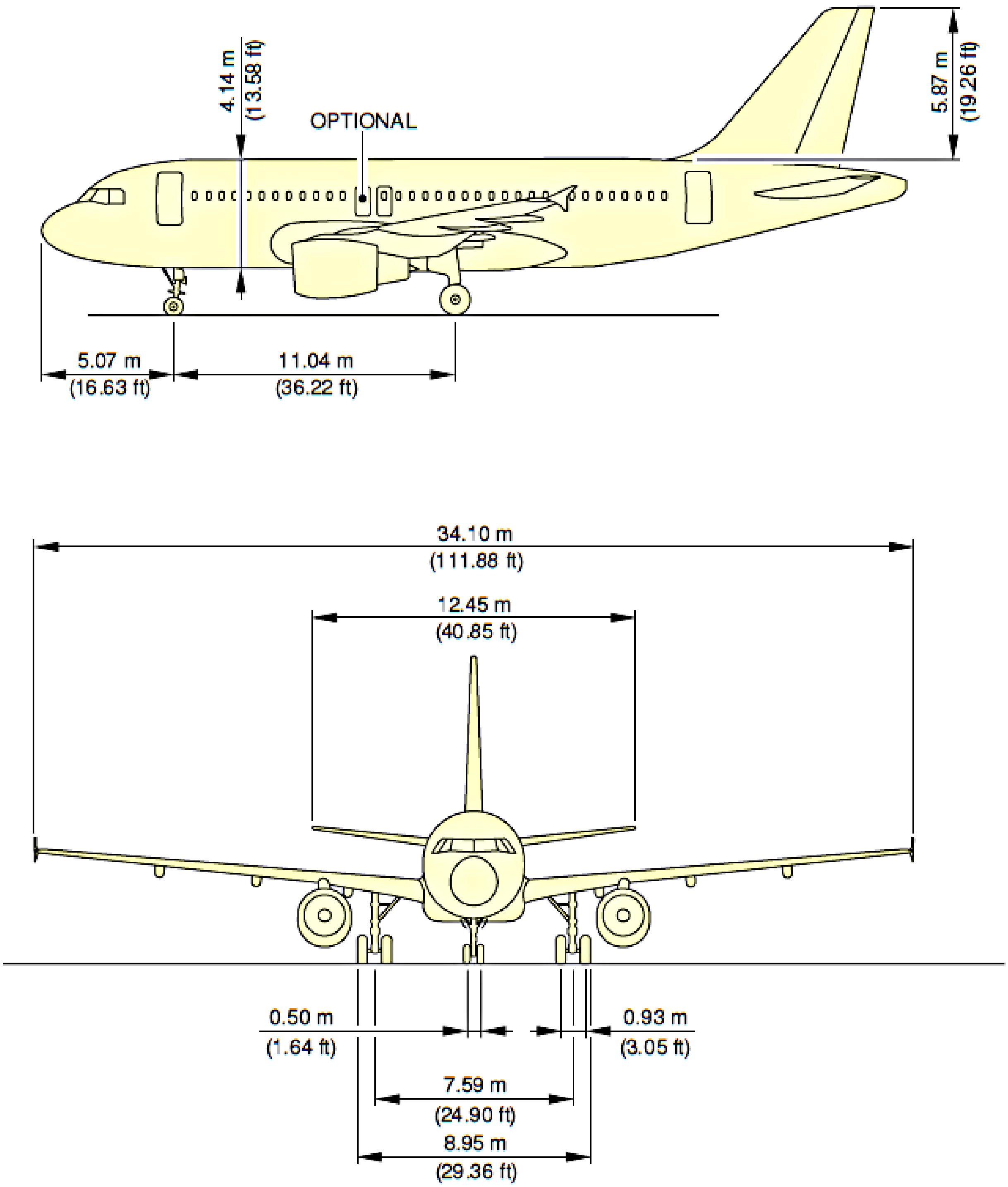

Figure B.5 Side and front view of the A319-100 **(A319 2014)**

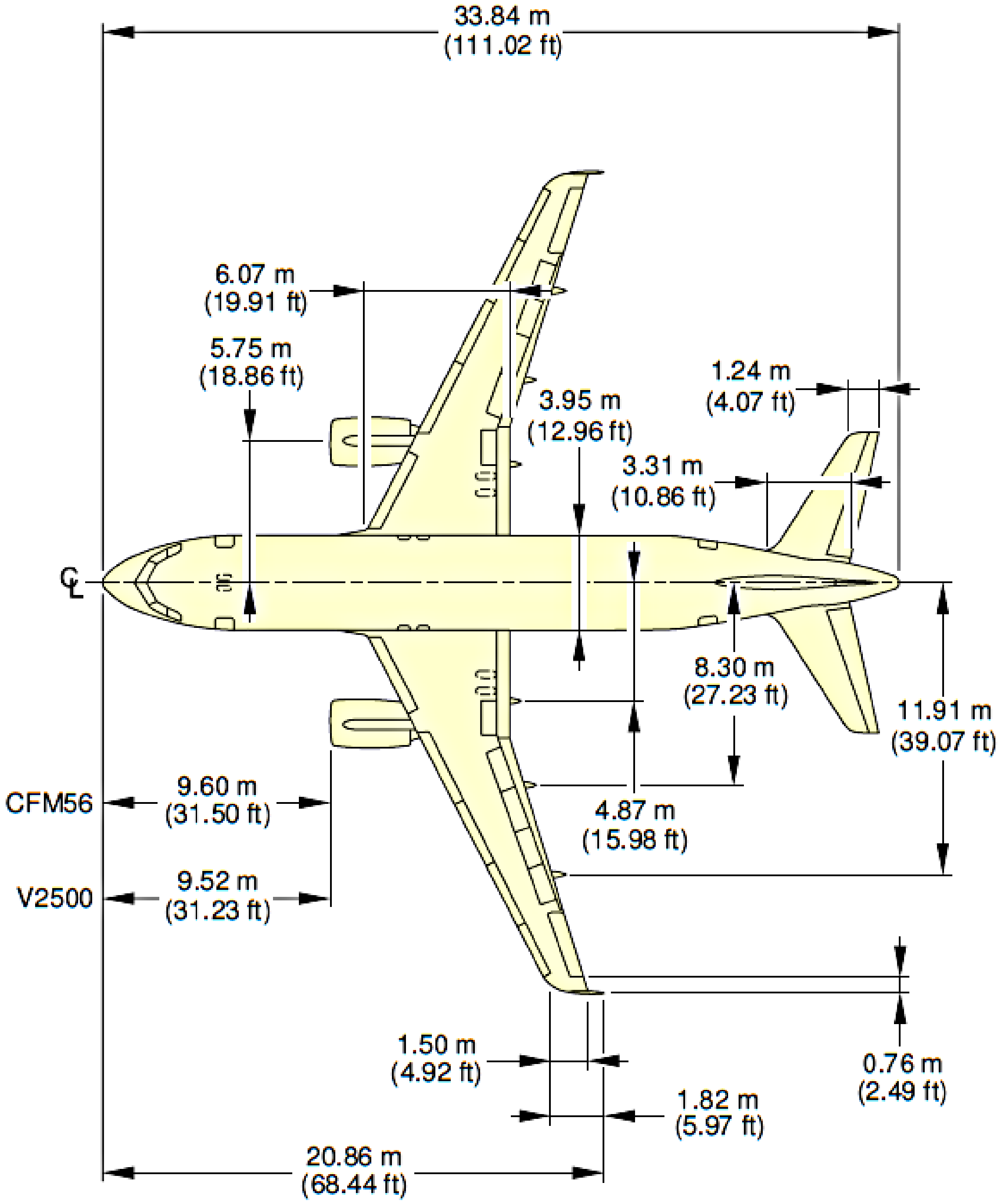

Figure B.6 Top view of the A319-100 **(A319 2014)**