POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Techno-economic review of hydrogen powered aircraft

Tesi di Laurea Magistrale in
Aeronautical Engineering - Ingegneria Aeronautica

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Academic Year: 2021-22

Invictus by William Ernest Henley

Out of the night that covers me,
Black as the pit from pole to pole,
I thank whatever gods may be
For my unconquerable soul.

In the fell clutch of circumstance
I have not winced nor cried aloud.
Under the bludgeonings of chance
My head is bloody, but unbowed.

Beyond this place of wrath and tears
Looms but the Horror of the shade,
And yet the menace of the years
Finds and shall find me unafraid.

It matters not how strait the gate,
How charged with punishments the scroll,
I am the master of my fate,
I am the captain of my soul.

(William Ernest Henley)

Abstract

The aim of this work is to develop a model to estimate liquid hydrogen aircraft capital invested and operational costs, in order to assess their economic feasibility. Since these should replace existing kerosene aircraft, the model was also applied to conventional aircraft to determine cost differences. The reference aircraft chosen are the ATR72-600, the Airbus A320 and the A350-900. The design data of both aircraft, were obtained with the preliminary sizing tool HYPERION. At the beginning follows an introduction to hydrogen, to explain why the industry is focusing of this new energy source and to give an overview of the new aircraft subsystems layout. Flying hydrogen, also implies changes in the airport system. To evaluate cost at a preliminary stage design, when only few parameters are known, a usual standard is to use DOC models. Among five models, 'TUB' model was chosen because it is used in literature to derive costs for hydrogen powered aircraft. To keep into account the acquisition of additional systems like cryogenic tank, fuel cell, these were included separately to consider their different life cycle. During the operational life of an aircraft, costs relative to fuel represents a huge contributor. Especially on green liquid hydrogen a lot of uncertainties regarding the price at the dispenser aroused, so it was worth investigating the dependency of the aircraft operational expenses on fuel price. To understand its competitiveness with the kerosene powered one, they were compared both on the same mission, representative of their market segment. Afterwards, two different financial target, EBITDA margin and Operational Profit per passenger, were set to evaluate revenues and give an approximate value of a hypothetical ticket price. Since the model outputs differ in a not negligible way, a further market research was done to evaluate how much actually airlines charge for the same mission. Concluding, a market penetration scenario is envisioned: it investigates actual and future passenger demand and the reasons behind its expected growth; possible entry into service and future buyers, with a special attention on the leasing business. Headwinds that airlines need to tackle right now are outlined.

Keywords: hydrogen aircraft, techno-economic, market penetration, airlines

Abstract in lingua italiana

Lo scopo di questo lavoro è sviluppare un modello per stimare i costi operativi di aerei alimentati ad idrogeno, per determinare il loro impatto economico. Siccome quest'ultimi dovrebbero sostituire quelli alimentati a kerosene, il modello è stato applicato anche a loro per determinare le differenze. I veivoli di riferimento sono il regionale ATR72-600, l'Airbus A320 e l'Airbus A350-900. I dati di design sono stati ottenuti tramite il tool HYPERION, sviluppato nel contesto del SIENA project. All'inizio segue una introduzione sull'idrogeno, perché l'industria sta puntando su questa fonte di energia e su come cambierebbe la configurazione dell'aereo. Volare a idrogeno implica anche cambiamenti al sistema aeroportuale. Per stimare i costi in questa fase preliminare di progetto, quando pochi parametri sono conosciuti, si è soliti usare i modelli DOC. Tra i cinque, 'TUB' è stato scelto perché è già usato in letteratura per stimare i costi di aerei a idrogeno. Per considerare l'acquisto di parti aggiuntive, queste sono state aggiunte separatamente per tenere in considerazione il loro differente ciclo di vita operativa. Nella vita operativa di un aereo, una gran parte di spese operative sono dovute al kerosene. Specialmente sul prezzo dell'idrogeno liquido al dispenser ci sono molte incertezze, quindi è sembrato opportuno prevedere differenti scenari di prezzo. I modelli convenzionali e ad idrogeno sono stati comparati sulla stessa missione, rappresentativo del mercato. Successivamente, due obiettivi finanziari, EBITDA margine e Profitto Operativo per pax, sono stati posti per determinare i guadagni necessari e ipotizzare il prezzo del biglietto. Siccome i due metodi differiscono in termini di risultati, è stata fatta una ricerca sul web per capire quanto le compagnie fanno pagare per tratte simili alle missioni scelte. Concludendo, segue una analisi di mercato per capire una possibile entrata in servizio e possibili acquirenti. Sono inoltre menzionati gli ostacoli che affliggono le compagnie aeree.

Parole chiave: aerei a idrogeno, tecno-economico, penetrazione del mercato, compagnie aeree,

Acknowledgements

Here we are, after a long path, at the conclusion of my university career. Some say about a journey that it is not the final destination that matters, but the trip itself. During these years I had the opportunity, and most of all I had the luck, to enrich myself, to grow my knowledge, to expand my views, to create everlasting bonds, to become a better self. Honestly though, it has not been an easy road, and this probably adds on greater satisfaction to the achievement. I cannot deny I had down moments where I questioned myself, if I was honouring the trust my parents had given me. I had moments feeling overwhelmed by the stress, and experienced feelings of discomfort and solitude. But probably as soon as we realize life is not linear at all, from this point on, we almost embrace those feelings, we see them as a potential to turn our weaknesses into strengths, and we learn. We learn, yes, because only through challenging times, you can fully acknowledge your inner self. As I said though, it is not an easy way, and I tried to make the best out of this journey, putting myself onto the line. I am proud of my bravery, I am proud of my efforts and I am proud of the person I became at the end of this journey.

But I could not achieve all this on my own. The support, the stimulus, the confidence transmitted by the people surrounding me has been fundamental. In primis, I would like to say a big GRAZIE to my parents, Nadia and Santo, who are the best parents a son could ever wish. My gratitude will always be tiny compared to what they have done and do for me. A thanks goes to my sister Cinzia, who has been a role model with her kindness and dedication. And how not to mention my "other" family, my special cousin Roberta, my aunt and second mum Pina, my wise uncle Roberto, and my cousin Dario "The Pilgrim". I would not be here without the love and joy you made me grew up with.

As my dad says "surround yourself with better person than you", and this is what I have done in these years. To my closest and oldest friends Beatrice and Alessandro, thank you for all the moments we shared. You showed me the meaning of friendship. To my best karaoke teammate Ciccio, who was there during hard times, and never left, thank you. To Manfredi "il bro", master of "silent study sessions", thank you for all the nights spent studying together. To Carlo, Giò, Massimo and Perri, who have walked me during these years in Milan, thank you for everything, you truly are amazing friends.

Eventually, I own a special thanks to a fantastic woman whom entered my life, Ella. You have always supported me, you have always showed me love, you inspired me to do better, you showed me the world and I will always be grateful for it.

Sergio

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List of Symbols

Variable	Description	SI unit
$\boldsymbol{\eta}_{EM}$	efficiency em	-
$\boldsymbol{\eta}_{PMAD}$	efficiency pmad	-
$\boldsymbol{\mu}$	gravimetric index	-
$\boldsymbol{a}$	annuity rate	€
$\boldsymbol{cc}$	crew complements	-
$\boldsymbol{DP}$	depreciation period	years
$\boldsymbol{f}_{ATC}$	navigational fee	-
$\boldsymbol{f}_{ETS}$	free allocated emission certificates	-
$\boldsymbol{f}_{INS}$	insurance factor	-
$\boldsymbol{f}_{RV}$	residual value factor	-
$\boldsymbol{IR}$	interest rate	-
$\boldsymbol{k}$	spare parts	-
$\boldsymbol{m}_{CO_2}$	mass CO_2	kg
$\boldsymbol{m}_{tank}$	mass tank	kg
$\boldsymbol{n}_{fa}$	number of flight attendants	-
$\boldsymbol{n}_{pil}$	number of pilots	-
$\boldsymbol{p}_{AF}$	price airframe	€/kg
$\boldsymbol{p}_{ENG}$	price engine	€/kg
$\boldsymbol{p}_{EM}$	price electric motor	€/kW
$\boldsymbol{p}_{BAT}$	price battery	€/kWh
$\boldsymbol{p}_{PMAD}$	price power electronics to distribute and manage power	€/kW
$\boldsymbol{p}_{LH_2}$	price liquid hydrogen	€/kg
$\boldsymbol{p}_{el}$	price electrolisys	€/kg

Variable	Description	SI unit
$\boldsymbol{P}_{bat}$	energy battery	kWh
$\boldsymbol{P}_{EM}$	power em	kW
$\boldsymbol{p}_{handling}$	handling fee	€/kg
$\boldsymbol{p}_{landing}$	landing fee	€/kg
$\boldsymbol{p}_{LH_2}$	price refuelling	€/kg
$\boldsymbol{p}_{liq}$	price liquefaction	€/kg
$\boldsymbol{P}_{PMAD}$	power pmad	kW
$\boldsymbol{p}_{st}$	price storage	€/kg
$\boldsymbol{p}_{tr}$	price transportation	€/kg
$\boldsymbol{t}$	total block time	horrs
$\boldsymbol{salary}_{fa}$	flight attendants salary	€/year
$\boldsymbol{salary}_{pil}$	pilots salary	€/year
$\boldsymbol{U}_{ETS}$	environmental fees	€/kg$_{CO_2}$
$\boldsymbol{W}_{AF}$	mass airframe	kg
$\boldsymbol{W}_{ENG}$	mass engine	kg

List of Acronyms

Acronym	Extended name
+1	Plus Interest
AEA	Association of European Airlines
AF	Airframe
AFC	Alkaline Fuel Cell
APU	Auxiliary Power Unit
ASK	Available Seat Kilometers
ATA	Air Transport Association
ATAG	Air Transport Action Group
B	Burden
BWB	Blended Wing and Body
CAPEX	CAPital EXpenditure
CASK	Cost per Available Seat Kilometers
CDG	Charles De Gaulle
CHC	Christchurch
D&A	Depreciation and Ammortization
DOC	Direct Operating Costs
DOH	Doha
EBIT	Earings Before Interest, Taxes
EBITDA	Earings Before Interest, Taxes, Depreciation and Ammortization
EIS	Entry Into Service
EM	Electric Motor
ENG	Engine
EU	European Union
EUR	€
ESG	Enviromental, Social and Governance
ETS	European Trading Scheme

Acronym	Extended name
***F*41**	Form 41 Database
FH	Flight Hours
FMC	Rome Fiumicino
FSNCs	Full-service network carriers
GDP	Gross Domestic Product
GWP	Global Warming Potential
HPC	High-pressure compressor
HPT	High-pressure turbine
HSR	High Speed Rail
HYPERION	HYbrid PERformance SimulatION
IATA	INTERNATIONAL AIR TRANSPORT ASSOCIATION
ICAO	International Civil Aviation Organisation
IOC	Indirect Operating Costs
IPC	Intermediate-pressure compressor
LCC	Low Cost Carrier
LF	Load Factor
LPT	Low-pressure turbine
MAD	Madrid
MCFC	Molten Carbonate Fuel Cell
MTOM	Maximum Take Off Mass
MTOW	Maximum Take Off Weight
NPE	Napier
NZD	New Zealand Dollar
OEM	Operating Empty Mass
OM	Operating Margin
OP	Operating Profit
OPEX	OPerating EXpenditure
OPR	Overall Pressure Ratio
PAFC	Phosphoric Acid Fuel Cell
Pax	Passenger
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PMAD	Power Management And Distribution

Acronym	Extended name
RASK	Revenue per Available Seat Kilometer
ROIC	Return On Invested Capital
RPK	Revenue Passanger Kilometer
SAF	Sustainable Aviation Fuel
SFC	Specific Fuel Consumption
SOFC	Solid-Oxide Fuel Cell
SPT	Sustainability Performance Targets
TMS	Thermal Management System
TOC	Total Operating Cost
TOT	Total
TTBW	Transonic Truss-Braced Wing
TUB	Technical University off Berlin

Introduction

Aviation plays a crucial role for world's society and economy. It allowed to connect countries, exchange goods, boost tourism and especially the economy. Ever since the commercialization of the first aircraft, this has been an always growing business, proving its resilience through hard times, like Covid-19 pandemic. The increasing demand in air travel, though, comes with an increase in CO_2 emissions, since a large amount of kerosene is burn by the turbofan engine of the airplane, and in other pollutants like NO_x, and particles. A lot of effort has been made to improve the fuel efficiency of these means of transport, and still the results would not be satisfying. The need of a different and greener source of energy, is pointing the focus towards the development of electric-powered or hybrid aircraft, and the use of hydrogen either as drop in fuel or to generate electricity via fuel cell. Another option, taken into account to decarbonize aviation, is the so called SAF (Sustainable Aviation Fuel): it would cut emissions by a lower percentage and unlike the other candidates, it does not entail any change in the actual aircraft configuration, since it just substitutes kerosene. A radical change in such a well-established design and expensive product, that is the aircraft, brings techno-economic uncertainties that could limit the profitability of the investment. Hence, the costs effectiveness study of introducing hydrogen powered aircraft will be investigated in this research.

1 | Hydrogen aircraft

In this chapter will be explained the environmental benefits of switching to hydrogen, and also all the additional systems needed to fly this new propellant. Hydrogen can be either used to generate electricity through fuel cells, or directly burn in a gas turbine. In both cases a cryogenic storage has to be installed to keep hydrogen at its liquid state (20 K) at ambient pressure.

1.1. The need to decarbonize

The effects of global warming are becoming more and more visible worldwide, so it is necessary to act as soon as possible, especially in sectors like aviation, highly dependent on fossil fuels. Referring to 2019 - when the number of passengers reached its historical peak with 4.5 billion - CO_2 emissions related to the aviation sector, with 915 million tonnes accounted for 2% of the global human-induced CO_2 emissions and 12% of the transport-related CO_2 [21].

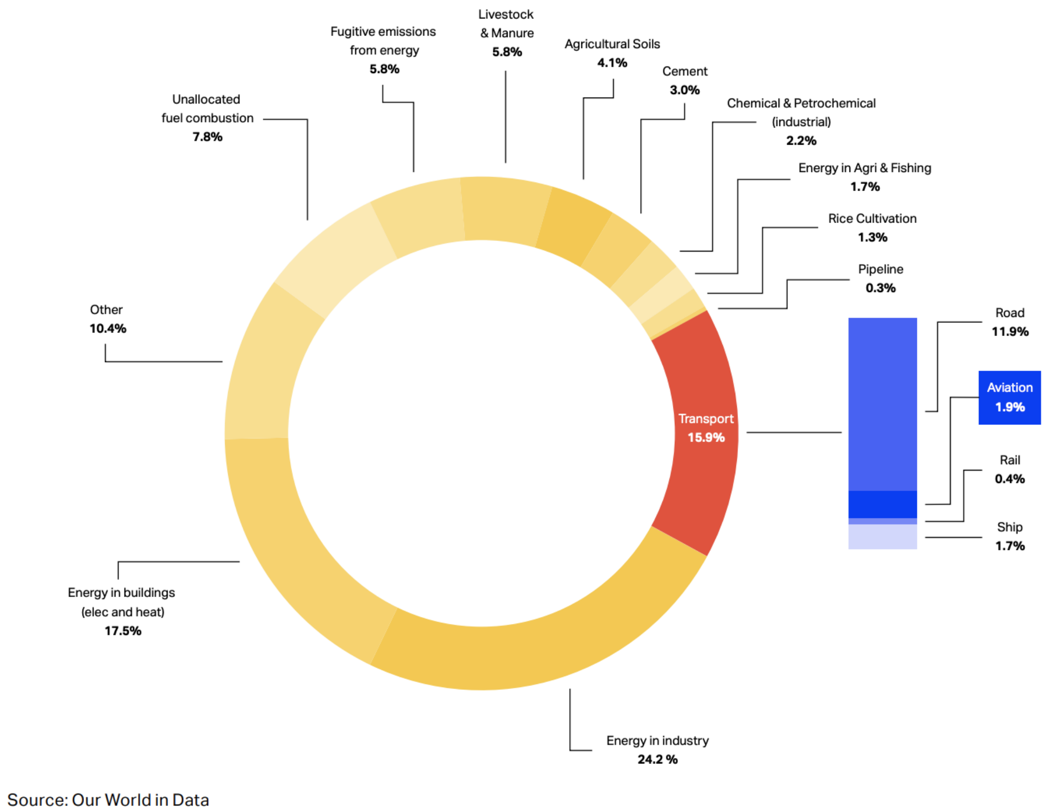


Figure 1.1: Global Greenhouse Gas Emissions by sector [45]

Many stakeholders in the industry hide behind that 2%, but the difficulty to decarbonize aviation is way more relevant with respect to other sectors. In addition to fully address climate impact not only CO_2 and other direct emissions (NO_x and water vapor), but also other contributors such as contrails and cirrus, play an important role as emission-related effects.

CO_2 emissions originate from the combustion of hydrocarbon fuels such as kerosene and SAF. In general, their climate impact is relatively well-known. The climate impact of CO_2 kerosene emissions is used as a benchmark for comparing the impact of other effects: the GWP of CO_2 has a value of 1 or 100 percent .

NO_x emissions arise from chemical reactions at high temperatures in the combustion chamber of jet engines. Therefore, NO_x emissions depend on the design of the engine and a trade-off between fuel-burn efficiency (CO_2 emissions) and NO_x emissions exists. The climate effect of NO_x is less certain than for CO_2 as NO_x influences atmospheric methane and ozone concentrations.

Water vapor is the most abundant greenhouse gas in the atmosphere, both by weight and volume. For H_2 turbines and fuel cells, as they use H_2 as fuel, 2.55 times more water vapor is formed compared to kerosene combustion (for the same energy content).

The properties of contrails and the likelihood of contrail formation depend on the condition of the air the aircraft is flying through. Contrails are formed when hot, humid water vapor mixes with soot particles and aerosols at low-pressure and low-temperature air at high altitudes. At low altitudes (typically less than 30,000 feet) contrails are less likely to form. Therefore, the climate effects of contrails for commuter and regional aircraft are assumed to be negligible. However, for short-range, medium-range and long-range aircraft which fly at altitudes above 30,000 feet, contrails have a significant climate impact. The precise climate impact of contrails is not yet well understood and needs to be clarified by future scientific studies [22].

The absolute GWP values of the four effects and for each technology and fuel can be summarized in the following table:

Emissions pollutans average values

	CO_2	NO_x	Water Vapour	Contrails
Kerosene	100%	100%	10%	100%
H_2 turbine	0%	35%	25%	60%
H_2 fuel cell	0%	0%	25%	30%

Table 1.1: Values benchmarked to kerosene one, assumed as 100% [22]

A common benchmarking metric is CO_2 equivalent (CO_2eq), which includes all the parameters mentioned earlier, and fully relies on the idea of 'global warming potential' (GWP) metric. GWP is a measure of how good an mitted gas traps heat in the atmosphere compared to CO_2. Defined as the time-integrated radiative forcing of an emitted gas or the related effect, relative to the effects created by an equal mass of omitted CO_2, it is assessed over a timeframe of 20 to 100 years.

Over the years aircrafts have improved fuel efficiency at a rate of 1.5% per annum, but still the growth in air travel has led to a 34% rise in CO_2 emissions over the past 5 years. Several targets of reducing emissions have been stated by EU, ICAO, ATAG (Air Transport Action Group) and other stakeholders, highlighting the need to act now.

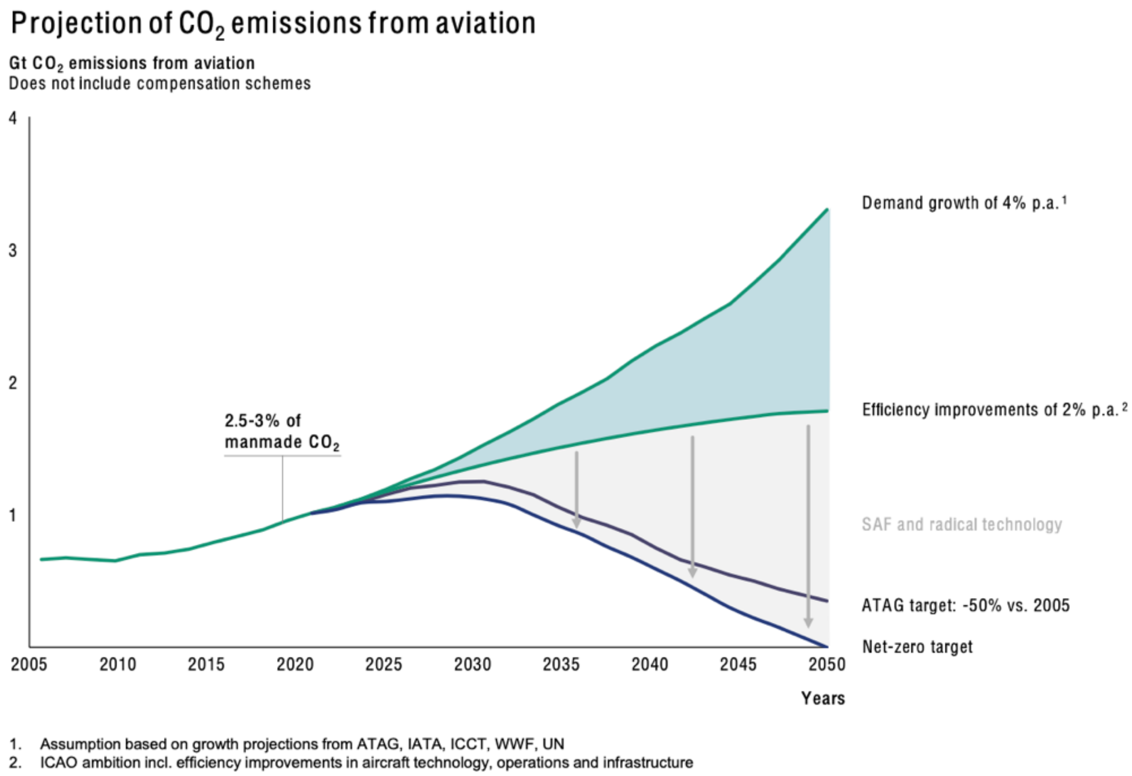


Figure 1.2: Projection of CO_2 emissions from aviation [22]

Due to the high demanding safety standards adopted in aviation, the most feasible option in shorter terms is SAF, while other more disrupting technologies require R&D, certification, flight test, a lot of investments and time.

Sustainable aviation fuels (SAF) include renewable biomass and waste resources with the potential to deliver the performance of petroleum-based jet fuel but with a fraction of its carbon footprint [40].

SAF is a liquid fuel currently used in commercial aviation which reduces CO_2 emissions by up to 80%. It can be produced from a number of sources (feedstock) including waste oil and fats, green and municipal waste and non-food crops. It can also be produced synthetically via a process that captures carbon directly from the air. It is 'sustainable' because the raw feedstock does not compete with food crops or water supplies, or is responsible for forest degradation. Whereas fossil fuels add to the overall level of CO_2 by emitting carbon that had been previously locked away, SAF recycles the CO_2 which has been absorbed by the biomass used in the feedstock during the course of its life. IATA estimate that SAF could contribute around 65% of the reduction in emissions needed by aviation to reach net-zero in 2050 [39].

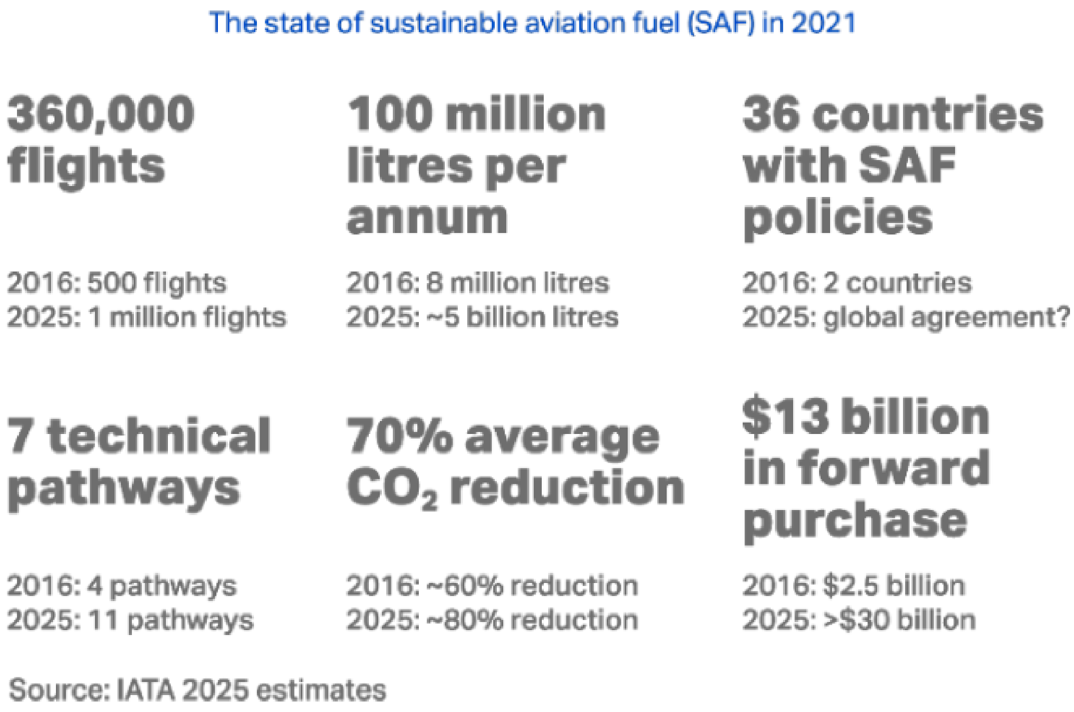


Figure 1.3: Use of SAF in 2021 [39]

While SAF would replace or blended with kerosene, no major changes have to be applied to the engine or the aircraft architecture, independently of the size. Conversely, the application of these new net-zero technologies comes with major changes in the overall architecture and might be suitable for a class of aircraft and not for another: for instance, full-electric battery powered aircraft, given the very low energy densities of battery, are limited to very low range segments. Hence, it is important to understand how emissions are distributed, in order to decide the decarbonisation strategy, meaning where to act first and how to act.

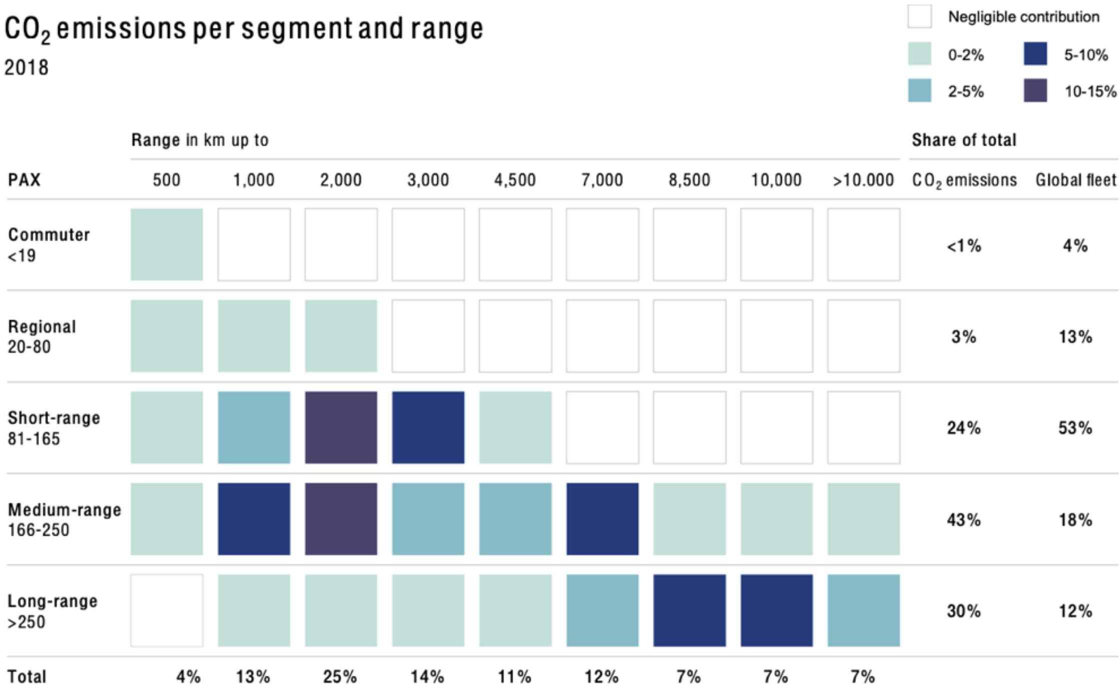


Figure 1.4: CO_2 emissions fragmented per range and segment [22]

From Figure 1.4, it is evident how commuters and regional account for just 4% of total CO_2 emissions, while the most polluting slots are given by short and medium range, accounting for the 67% of total CO_2 emissions and 70% of the global fleet, with a main focus on the 2000-3000 km range as well as on the long-range aircraft. It might seem easy stating to act on the short/medium-range first, but developing the infrastructure to produce, transport and store enough hydrogen to refuel these aircraft is not an easy goal.

Furthermore, Airbus foresees 39000 new deliveries before 2040, so also from an economic perspective a large amount of money has been already handed out by the airline companies for new generation, but still kerosene based, aircraft [44].

The introduction of regional first instead, might lead to a proof of concept in a shorter timeframe with a more affordable amount of money invested in infrastructures, and this could pave the way for the hydrogen ramp-up. Another option considered to help decarbonize this sector, is to actually limit some flights and switching to high-speed railways. The French government has become the first large economy to ban short-haul flights where a train or bus alternative of two and a half hours or less exists–a move which was voted on in 2021 and comes into effect in April 2022 [58].

1.2. Why hydrogen

Hydrogen is one of the most abundant element on the universe, and has the potential to transform the aviation industry into a totally net-zero emission environment. It can be used either burned in gas turbines, or transformed into electricity, via fuel cells, to drive an electric motor. The great advantage of hydrogen lies in its high specific energy of 120 MJ/kg, almost 3 times greater than kerosene; the main drawback is its very low density of 71 kg/m^3 for liquid hydrogen at 20 K and a pressure slightly higher than atmospheric, while 42 kg/m^3 for gaseous hydrogen compressed at 700 bar and at atmospheric temperature. Compared to kerosene (43 MJ/kg and 808 kg/m^3), liquid hydrogen requires almost four times the volume needed to store kerosene on an energy base [23].

It has the highest thermal conductivity among all fuels, and high heat capacity and low dynamic viscosity, which provide superior cooling properties for operation at high speeds and high combustor temperatures [16].

The main hazards according to [2] related to hydrogen are:

- Injuries: these refer to burns or frostbites under contact with cold fluid or burning fluid.
- Pressure hazard: vaporization of liquid hydrogen in the tank or the fuel system, increasing the pressure may lead to leaks.
- Combustion, deflagration, detonation: if leaks occur, the contact of hydrogen with air ignite the fuel, and the damages are limited since hydrogen burns in a vertical buoyant flame. Only for a high ignition energy source, deflagration can turn into detonation.

1.3. How to fly hydrogen

1.3.1. Tank

Since hydrogen has different properties than kerosene, it will be necessary to operate some changes in the design architecture. One of the main challenge is to store hydrogen at 20K (-253 °C), requiring a great deal of attention for the insulation of the tank. Since inleak of heat from the atmosphere are almost inevitable, the liquefied gas will reach its boil-off point and evaporate. Additional systems are also needed for safety considerations, venting, reliability and heat management. A pressurization system is needed in order to operate at the design point to avoid leaks; for overpressurization, a venting system with redundant relief valves and vent line must be installed [19].

For the insulation different solutions ranging from foam to vacuum-jacketed multi-layer can be used, resulting into a nearly zero boil-off for long amount of time (days) or tanks with a boil-off rate below 0.15% per hour in a six hours mission [1].

One of the main parameter describing the tank is the so called gravimetric index:

$$\mu = \frac{m_{LH2}}{m_{LH2} + m_{tank}}$$

The weight of the tank for a reference aircraft is basically nihil, hence a $\mu = 1$ is reached. For LH_2 tanks, according to [2], typical values in literature range from 0.2 to 0.7. As mentioned earlier, LH_2 is 3 times lighter on energy basis than kerosene, so introducing a tank with a weight 66% times higher than the hydrogen stored, the overall weight would still be lighter than the kerosene system. Rather than the weight, the real problem of the tank system is the volume, that would require a large room to be accommodated (see Figure 1.5), with an increase in wetted area and consequently a loss in aerodynamic efficiency [2].

Figure 1.5: A possible tank integration into the airframe (www.airbus.com)

Since the conventional aircraft burns most of the fuel during the mission, another aspect to be further investigated should be how the weight of the tank influences endurance, considering that the amount of fuel LH_2 is inferior compared to reference kerosene. This will impact the mission range, because of its dependence on aircraft's initial and final weight.

1.3.2. Fuel Cell

Fuel cells are basically composed of an anode, a cathode and an electrolyte. Pure gaseous hydrogen is given to the anode where it ionizes, creating mobile H+ and releasing electrons to the electrode; these pass through a proton exchange membrane and react at the cathode with the oxidant, creating water as waste and electricity from the electrons movement.

The great advantage is the efficiency in energy conversion, from chemical to electric, compared to turbine used for the same purpose (in this case from mechanical to electric); and if we compare to batteries, fuel cells are more easily scalable, since power output and energy storage capacity are not dependent each other [6].

In addition, they have higher specific energy [Wh/kg] and energy density [Wh/L] than state of art batteries, and yet a great amount of effort is needed to reach targets of 2000 Wh/kg set by the aviation industry. There are different kind of fuel cells with their specific properties, but now the most promising application for aircraft seems to rely on the Polimer Electrolyte Membrane (PEM) due to the quick start up, use of air as oxidant, and operating temperature range [16].

An overview of the possible fuel cell types is given by [6] in Figure 1.7 with pros and cons

Fuel cell type	Operating temp. [°C]	Fuel compatibility	Power range [kW]	Efficiency [%]
PEMFC	80	H_2, methanol	0.001-1000	40-50
AFC	60-220	H_2	1-100	50
PAFC	200	H_2	50-1000	40
SOFC	600-1000	H_2, CH_4, CO	10-100,000	50-60
MCFC	650	H_2, CH_4	100-100,000	45-55

Figure 1.6: Types of fuel cell [6]

Fuel cells mentioned above are Polymer Electrolyte Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Solid-Oxide Fuel Cell (SOFC), and the Molten Carbonate Fuel Cell (MCFC)

Fuel cell type	Advantages	Disadvantages
PEMFC	high specific power, good efficiency, rapid start-up time	expensive platinum catalyst, expensive compared to conventional technologies
AFC	high efficiency, extremely low cost electrolyte, potential for non-precious metal catalyst	low lifetime, susceptible to CO_2-poisoning (cannot be run with air)
PAFC	mature technology, very good reliability, option for cogeneration application and bottoming cycles	expensive platinum catalyst, corrosive electrolyte, slow start-up time
SOFC	very high efficiency, relatively high specific power, slow start-up time, fuel flexibility, non-precious metal catalyst, high-quality waste heat for cogeneration applications	very high operating temperature, low lifetime, expensive components and fabrication
MCFC	fuel flexibility, non-precious metal catalyst, high-quality waste heat for cogeneration applications	high operating temperature, corrosive electrolyte, low lifetime, slow start-up time

Figure 1.7: Pros and Cons [6]

Fuel cells main characteristics are:

- Low emissions,
- Low noise,
- High reliability (no moving parts),
- Quick recharge possibilities

Aspects that deserve further considerations are:

- Ability to resist shocks during landing and take off,
- Limited transient performance,
- Life cycle,
- Robustness to environmental changes (temperature, pressure, humidity),
- Safety,
- Maintenance required

In order to guarantee the functionality of the fuel cell stack, additional systems like compressors, heat exchangers, etc... must be added, providing more mass to the plant equipment. The value used in this research according to [6], to convert the mass from fuel cell stack to system level is the most optimistic in literature: +50%. Projections for future values at system level are reported in Figure 1.8.

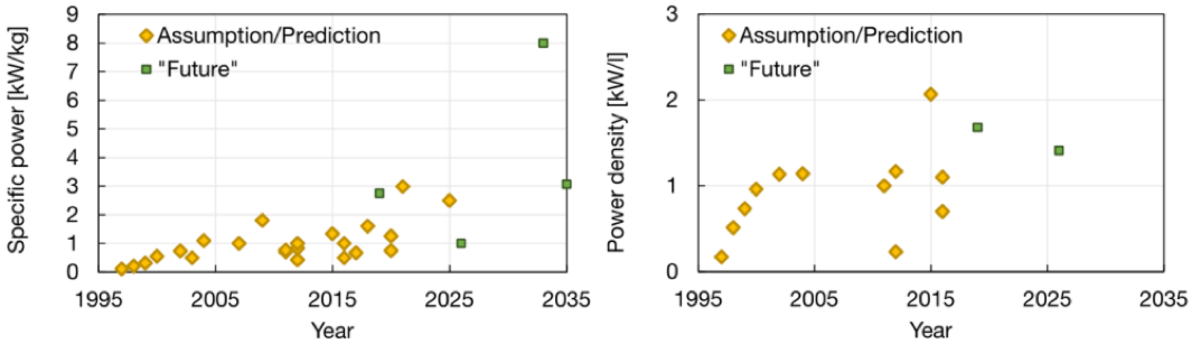


Figure 1.8: Specific quantities projection of Fuel Cell at system level [6]

Fuel cell can be used in aircraft applications to power the electric motor and drive the propeller, to give power at off-design conditions when hydrogen is combusted or substitute the APU (Auxiliary Power Unit), which provides secondary power to aircraft. By secondary power, we define the power needed to activate hydraulic, electric and/or pneumatic systems supporting onboard and flight control systems. Also for ground operation (engine startup), or in case of engine failure, the power is provided by a small turbine served as an APU [19].

In different applications from the aviation's one where the maximum efficiency is required, fuel cells can be reused, granting a high residual value. If this not the case, the materials can be recycled, given their high market value.

1.3.3. Battery, Electric Motor and Powertrain

The importance of batteries for reaching high efficiency during the mission is crucial: their role is to buffer energy for peak shaving and enhance high power capabilities during takeoff and climb [5].

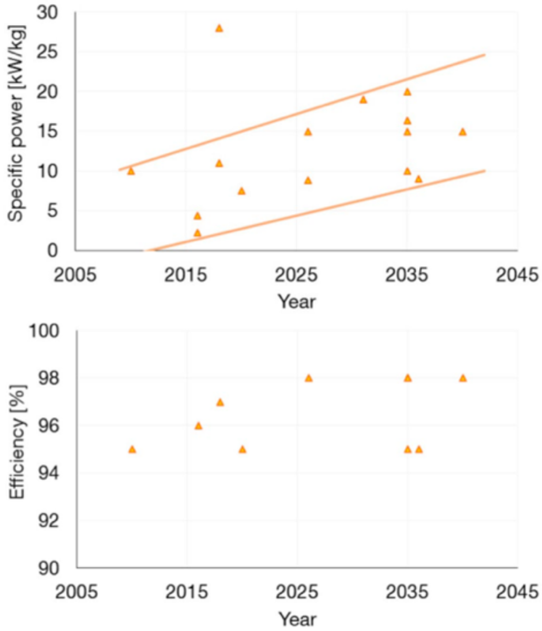
By doing so, the conventional gas turbine can be optimized for one flight condition (cruise), resulting in more efficient and small engine. For instance, a hybrid Airbus A320, for a short mission of 1000 km, obtains a 7.5% savings in fuel burnt, even with the engine scaled to 90%. Estimates based on specific battery energy of 600 Wh/kg. A Boeing 737-800 was retrofitted with a hybrid-electric propulsion system and, with a battery-specific energy of 750 Wh/kg saved 10.4% fuel on a two hours mission. This came with an increase in aircraft weight of 10,000 kg [20].

According to [7], a battery specific energy density of at least 800 Wh/kg is needed to power a single-aisle hybrid electric conventional aircraft. State of art (in 2017) battery specific energy at cell level is around 270 Wh/kg for Li-Ion batteries. The current technology has still too low specific energy, and considering that aviation, among the transport services, is without any doubts the business in which one kg has more influence than others, thinking to operate a narrowbody aircraft only relying on batteries is impossible.

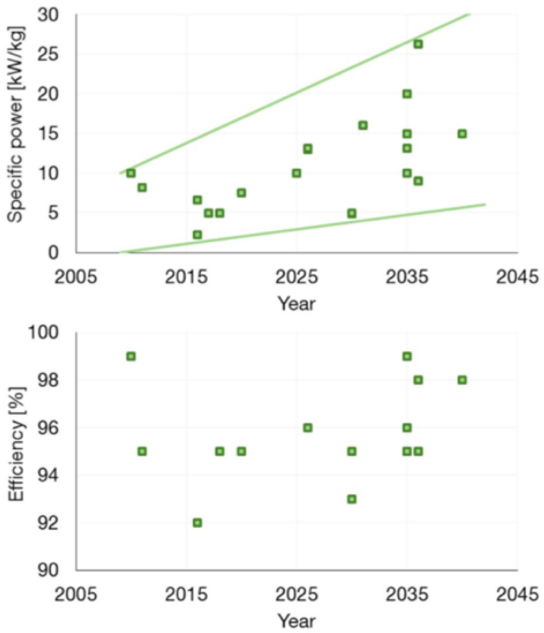
Another important aspect to take into account is batteries life cycle: they range from 1500 to an optimistic 3000 flights cycles, predicted for 2035 [11].

The electric motor is used to transform the power provided by the battery from electric into rotational mechanical power, in order to produce thrust via the propeller. The power is transmitted thanks to the electric powertrain, which is included in the Power Management And Distribution (PMAD), along with power electronics such as converters, inverters, controllers to guarantee the most safe, efficient and reliable power transmission system.

State of art conventional electric motors reach continuous specific power of 5 kW/kg. Projections found in literature of the specific power of electric motor and power electronics are pictured in Figure 1.9.



(a) Assumed specific power and efficiency of power electronics in literature



(b) Assumed specific power and efficiency of electric motors (non superconducting) in literature

Figure 1.9: Power electronics and EM specific power projections

1.3.4. Turbofan and TMS

Changing the characteristics of the fluid entering the engine, the thermodynamic cycle will be different and it is necessary to evidence some differences. In the study conducted by [9], the main outcomes are:

- Reduction of 63.83% in fuel flow: due to the lower heating value of hydrogen, for the same energy rate of fuels, the gas turbine engine will use less fuel;
- Increase in N_2, almost zero CO_2 emitted;
- Energy efficiency and specific thrust of H_2 turbofan are smaller than the counterpart.

Regarding the results obtained by General Electrics on a GE90 turbofan powered by hydrogen, these seem way more comfortable than the previously described. The research outcomes are:

- Increase in thrust,
- More than 50% reduction in thrust specific fuel consumption,
- Increase in thermal efficiency,
- Same propulsion efficiency of kerosene,
- More than 50% reduction in mass flow of fuel,
- NO_x emissions reduced by 68.25%.

By Thermal Management System (TMS), we indicate the procedure of using the engine fluid systems to rack up the heat in excess from different components and systems of the engine, in order to improve improve engine's performance [41]

The resulting heat-management system is therefore integrated in the fuel supply and propulsion systems, where it delivers the hydrogen with at the right pressure and temperature to the combustion chamber, while providing cooling in key engine locations (e.g., compression system, turbine cooling air, and engine exhaust). Being stored at cryogenic temperatures, it can undergo a wide variation on temperature before reaching the combustion chamber. Also considering the very high heat capacity of hydrogen, the quantity of heat which can be taken up is considerable. Without any losses, the theoretical reduction in specific fuel consumption (SFC) can potentially reach 9%; adding heat exchangers in the engine core can maximize engine efficiency, enhancing additional fuel-burn benefits [42].

From [42] mainly 4 configurations for the fuel heat management in the LH_2 eninge's cycle are take into consideration:

- Pre-cooling: The precooler is located between the fan and intermediate-pressure compressor (IPC). It increases the fuel temperature before entering the combustion chamber and decreases the IPC and HPC work by cooling the core flow before compression.
- Intercooling: The intercooler is placed between the IPC and the high-pressure compressor (HPC). It raises the fuel temperature before entering the combustion chamber and reduces the HPC work by cooling the compressed airflow. Intercooling and precooling also enable higher pressure ratios in the compression system and the possibility of reducing the combustor inlet temperature for a given OPR, which will curb NO_x emissions. A challenge with both concepts is the risk of ice formation in the presence of humid air, which could cause a partial or complete blockage of the engine core flow.
- Cooled-cooling air: The main task of the high-pressure turbine (HPT) cooling is to reduce the temperature of the cooling air extracted from the HPC and used to cool the HPT. The potential is to improve the engine efficiency by reducing the amount of secondary air flows for a given turbine metal temperature limit.
- Recuperation: The recuperator is the main source of LH_2 fuel heating before injection into the combustor. Among the other heat exchangers, it has the greatest potential for increasing the fuel temperature.

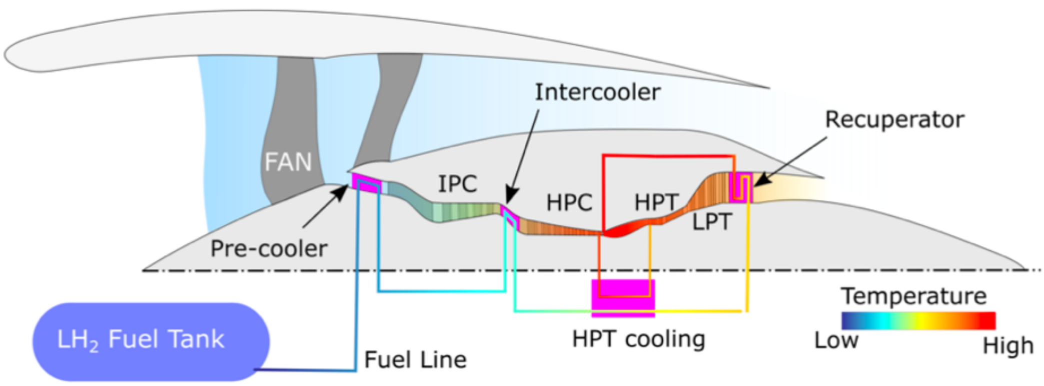


Figure 1.10: Cross-sectional meridional cut of a turbofan engine [42]

In Figure 1.10 it represented a Cross-sectional meridional cut of a turbofan engine, including possible locations for core heat rejection to the hydrogen fuel. The fuel is stored at its boiling point in the cryogenic tank. The temperature of the hydrogen in the fuel line is increased by the different core-installed heat exchangers on its way to the combustion chamber. IPC: Intermediate-pressure compressor; HPC: High-pressure compressor; HPT: High-pressure turbine; LPT: Low-pressure turbine.

1.3.5. Maintenance

A very important aspect during the operational life of the aircraft is the maintenance. Maintenance is fundamental to guarantee the safety of the vehicle, keeping it at its best level of performance and diminishing the downtimes which affect the aircraft utilisation. Also from an economic point view, its shares of costs impact a lot on the airline's expenditure. The understanding of how maintenance costs evolve, results in better management of the cash flow, critical for airlines since they operate on the verge of profitability. Quantifying the impact of maintenance is a hard task, because it requires the collection of consistent and accurate data throughout the life of the aircraft. In our case it is even harder, since there are no data available at all.

Usually, the costs for maintenance in the preliminary model are predicted to be constant per year, which could be defined a "static model". On the other hand, though, a more realistic model should take into account also the "aging effect": routine inspections will unveil more defects with time and non-routine checks will become more frequent, increasing the costs of repair [12]. We can define three categories of aging:

- Technical aging: materials degrade with time;
- Economic aging: it generates events cash flows;
- Financial aging: if the maintenance costs are provisioned, these will be distributed in as many different ways as the different financial policies of the airlines.

From these considerations, it derives an inherent difficulty of retrieving precise data from economic/financial reports of airlines.

In [14] are reported the effect of aging on airframe costs, engine costs and burden.

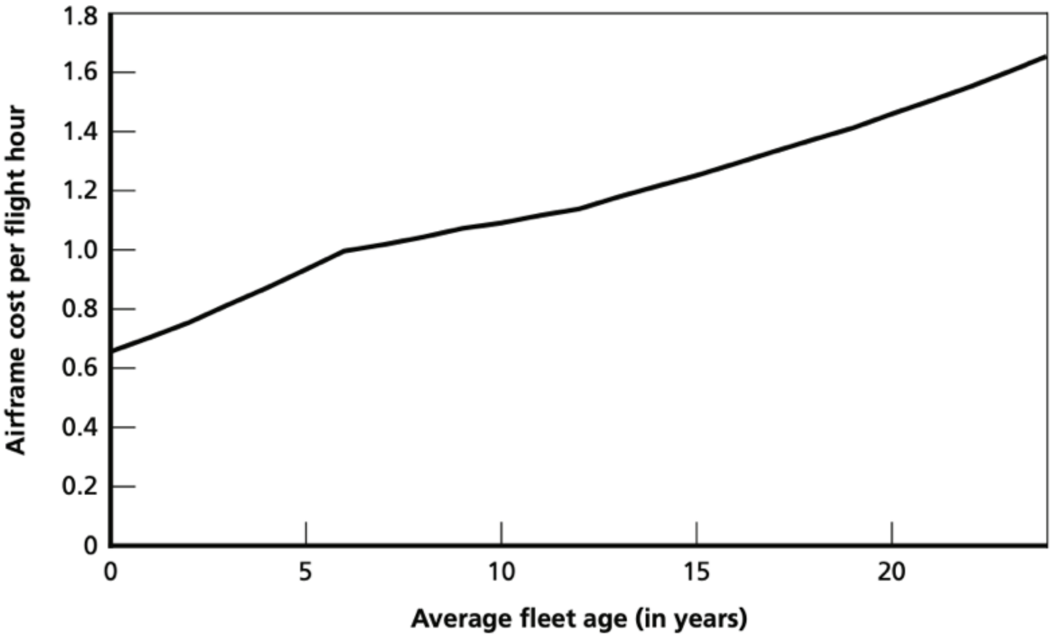


Figure 1.11: Effects of Age on airframe maintenance costs [14]

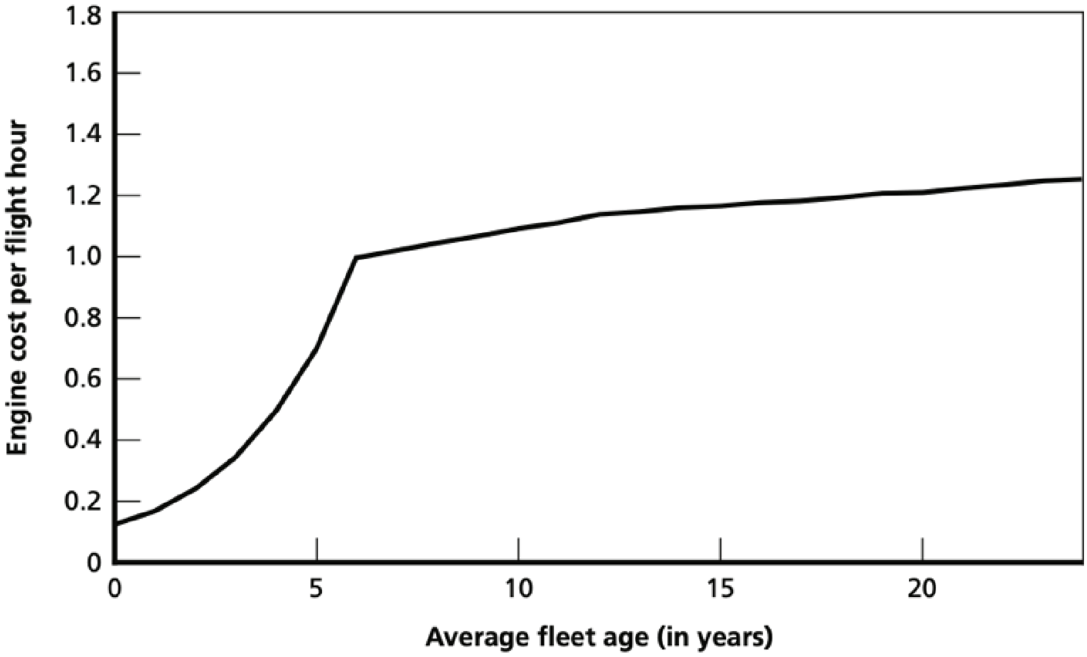


Figure 1.12: Effects of Age on engine maintenance costs [14]

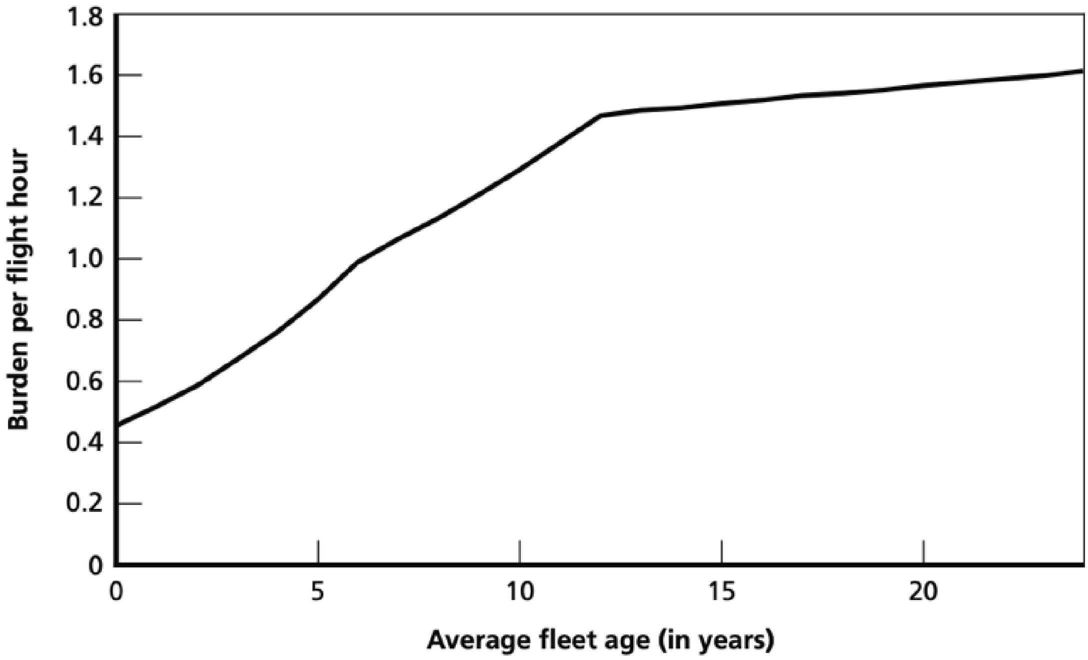


Figure 1.13: Effects of Age on burden maintenance costs [14]

To depict an idea of the aircraft aging effect, the engine costs per flight hour is reported to increase from approximately 0.15 to 1 in almost 6 years. Nevertheless, it is not possible to apply the same results for LH2 aircraft, since the trend was for a cluster of out-to-date vehicles (Form 41). Yet, it is something worth further researches.

Aircraft scheduled maintenance is divided in A-checks, C-checks, D-checks and daily maintenance.

Aircraft scheduled maintenance

	Tasks	Downtime	Occurrence
A-Checks	Checking oil, filter replacement, lubrication, operational tests, inspection	10 hours	Biweekly to monthly
C-Checks	Functional and operational systems checks, cleaning and servicing of aircraft system, minor structural inspections	3 days to 1 week	12 to 20 months
D-Checks	Inspection of airframe structure, wings, landing gear, engines, overhauls	One month	6 to 12 years
Daily Checks	Routine maintenance, inspection, minor repairs, servicing	1 h	Before first flight or when the aircraft is transiting

Table 1.2: Maintenance events divided per tasks, downtime, occurrence [12]

According to [12], the main drivers for maintenance costs are engines (which comprises more or less half of the total maintenance costs), APU and landing gear.

In [15] is given a detailed description of labour and material costs at subsystem level, confirming how the engine represents the highest cost driver alongside the structure.

	DLC		MC	
	[$/FH]	[%]	[$/FH]	[%]
Engines	4.8	16.0	263.7	46.9
Electrical	0.5	1.8	4.8	0.9
Hydraulic	1.0	3.4	4.3	0.8
Flight controls	2.2	7.4	3.9	0.7
Fuel system	1.5	5.1	20.2	3.6
Avionics	3.6	12.0	24.9	4.4
Landing gear	0.5	1.7	8.5	1.5
Pneumatic & Furnishings	5.3	17.8	2.7	0.5
APU	0.6	2.1	24.3	4.3
W&B	2.0	6.6	36.4	6.5
T/R	0.3	0.8	9.8	1.7
Structure	7.5	25.3	158.9	28.3

Figure 1.14: Labour and material costs results at subsystem level

In [13], the collection of pilot reported defects flying Airbus A340-600 from 2014 to 2018 are pictured in a Pareto graph, highlighting that fuel system (Chapter 28), landing gear (Chapter 32), air conditioning (Chapter 21) and communications (Chapter 23) account for 80% of the total.

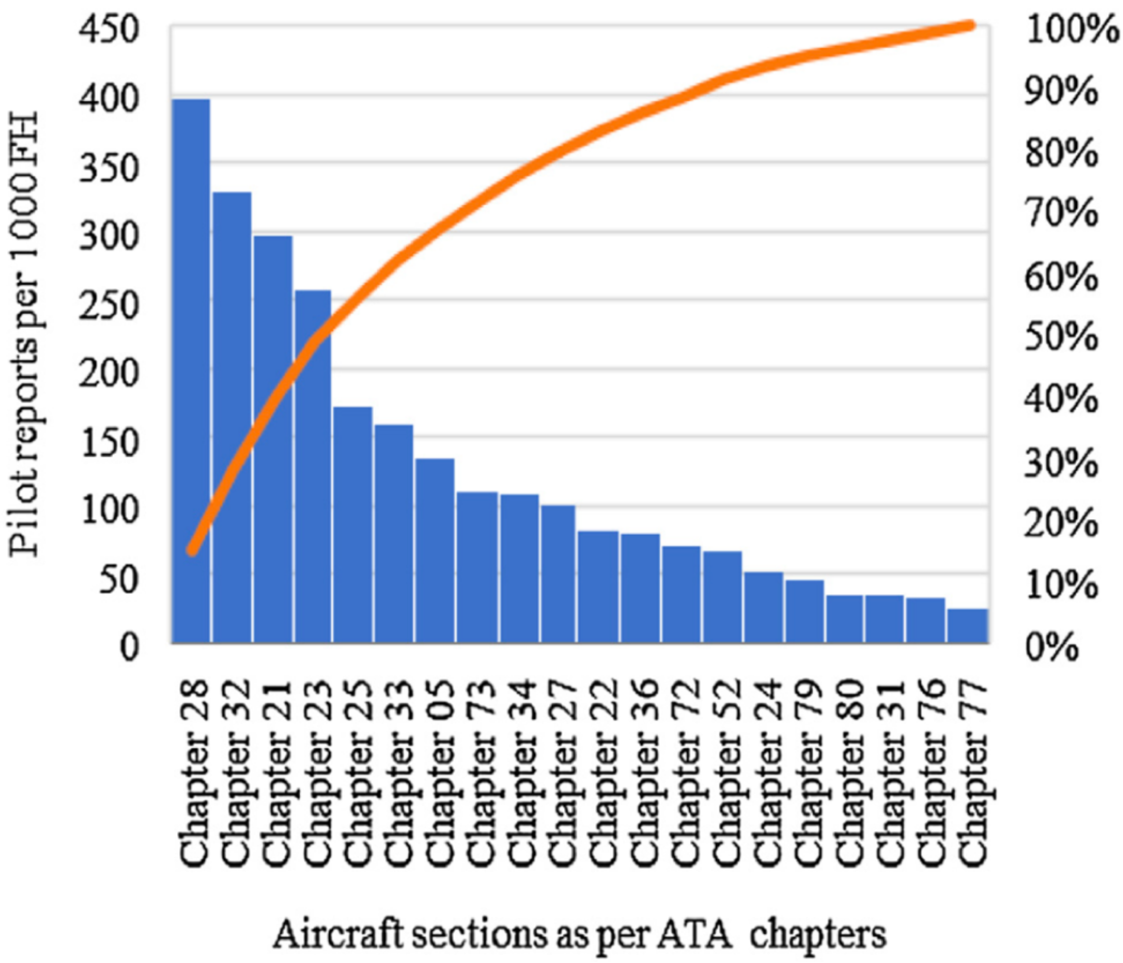


Figure 1.15: Pareto analysis for A340-600 pilot reports from year 2014 to 2018

Uncertainties regarding maintenance of the additional components required to fly LH_2 aircraft arouse, and in literature are tackled with assumptions and/or prediction from different sectors.

In [19], Wehrspohn, et al. assumes that the maintenance effort for the engine is the same no matter which fuel is burn. The necessary tasks for the fuel cell system are based on a maintenance scheduled of a fuel cell bus: intervals are calculated on operating hours, and efforts based on estimates. In addition to the leakage tests envisaged for the bus, further tests are carried out once a year for the entire LH_2 system. Replacement tasks for stacks and subsystems are added and derived by expert estimates.

Regarding the LH2 tank, due to the lack of information, this is treated as a container used for transportation of hazardous materials. The following three standards are also applied to oxygen cylinders in the aircraft:

- Cylinder must undergo periodic requalification every 3 to 5 years. This includes visual inspection and more tests;
- Requalification includes a hydrostatic pressure test in a water jacket;
- The effectiveness of the hydrostatic test is considered unrelated to the level of safety.

The different scenarios comprehend just a visual inspection with an endoscope, or also the case of tank removal. Other two scenarios are considered, whether it is provided a separation point (which would reduce the removal time by 60%) or no separation point [19].

Regarding the other new components, the major assumptions found in literature are summarized:

- Fully electric Powertrain requires about 75% cost of the conventional one [7];
- Fuel system and tank require the same mass expenditure per mass of the aircraft [4];
- Motor maintenance is reduced for the electrified aircraft [18].

1.3.6. Infrastructure

One of the key player in the diffusion of H_2 technology is the airport and its related supply chain. In order to deliver, store hydrogen and refuel the aircraft, changes need to be applied to the infrastructures. Our entire world is 'petrol-based', meaning all the facilities going from pipelines delivering fuel, to the truck refuelling the aircraft before every flight, are designed to operate with kerosene. Different properties of H2 instead, necessitate other requirements including safety and certification ones. According to Holzen, J. [4], the airport system costs, due to these new requirements, will be charged to the hydrogen price at the dispenser.

From a safety perspective, no major changes should arise; even if the safety radius of H2 ground handling can remain the same as the kerosene one, certification are still missing. Refuelling equipment like truck or pipeline – hydrant to dispense LH_2 are needed, since they should be cryogenically cooled.

If H2 production is conceived close by the airport, CAPEX costs for large electrolysis and liquefaction modules are necessary. On the other hand, if the airport increases its demand in H2, a supply pathway with cryogenic pypelines would be fundamental to guarantee sufficient and safe refuelling pace. The cost of cryogenic pipeline systems would impact a lot, but no quantitative assessment is reported. In either way, new storage facilities are needed.

Also uncertainties regarding the refuelling time arise, because in [5] the turnaround is increased causing 5-10% fewer flights; [11] in his study keeps the same turnaround time no matter which fuel is burn, while increases H2 turnaround by 10% in a pessimistic scenario.

1.4. Outlook to the future

1.4.1. SAF

The conversion to either battery-operated or hydrogen- propelled commercial airliners, with no or close to no emissions, is at least 15 years off, based on current progress and regulatory hurdles to overcome. The other option is switching to sustainable aviation fuel (SAF). SAF, which is made from used cooking oil and other bio-based feedstock, is 80% less carbon-intensive than conventional jet fuel. But there is not nearly enough capacity, either existing or planned, to allow the global fleet to switch even 10% of its fuel consumption to SAF. At present, without substantial new investment in production capacity, SAF is both too expensive and in too short supply to be a viable option for global airlines by 2030. In September 2021, around 60 companies operating in the business such as airlines, airports, and oil firms, committed to use at least 10% SAF by 2030. Many aspects limit this voluntary commitment, and different questions arise whether this would drive emissions below an acceptable level. Every carrier should use at least 15% and not 10%, just to keep emissions close to flat against 2019 ones. Being sustainable comes with costs, added to the already significant existing ones. Pledging carbon neutrality could increase the global spending on carbon offsets from $300 million to $100 billion by 2030, according to the Institute for International Finance's Taskforce on Scaling Voluntary Carbon Markets [37].

1.4.2. Hydrogen horizon

On the hydrogen side, ZeroAvia is developing its ZA2000 zero-emission 100% hydrogen-electric engines, to be soon tested on a 19-seat aircraft in order to launch it in the market by 2024. On its roadmap, an agressive development of hydrogen-electric propulsion for bigger aircraft. United Airlines demonstrated its interest in the technology ordering up to 100 ZA2000-RG specimen, since they would be retrofitted to the already existing 50-seat CRJ-550 as early as 2028.

Having a cold source on board such as liquid hydrogen (-253 °C), can be a major breakthrough to enhance super conductivity. The benefit produced in efficiency and electronics power weight could close the gap between conventional and hydrogen technologies. Airbus is working on a demonstrator named "ASCEND" to show that an electric- or hybrid-electric propulsion system complemented by cryogenic and superconducting technologies can be more than 2 to 3 times lighter than a conventional system—through a reduction in cable weight and a limit of 30kW/kg in power electronics—without compromising a 97% powertrain efficiency.

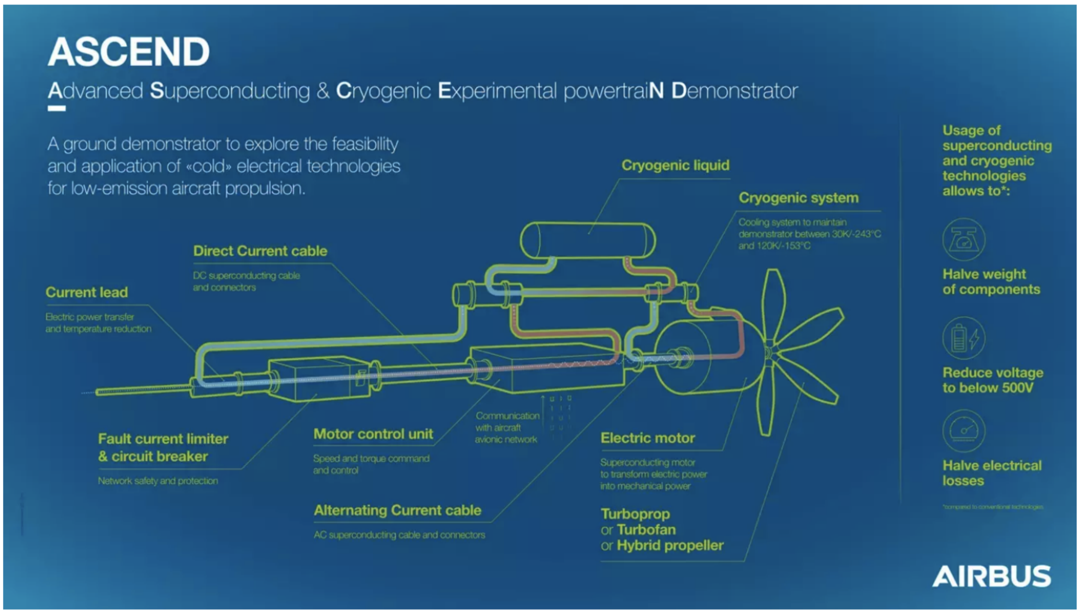


Figure 1.16: ASCEND by Airbus [57]

1.4.3. Revolutionary design

It is worth stressing that the work was based on an evolutionary design of the aircraft, basically meaning the structure of the airplane has the same traditional configuration. More revolutionary concepts are on the rise, that now are gaining more attentions, but still remain far from being used in commercial aviation: Transonic truss-braced wing (TTBW) and Blended Wing and Body (WBW). A TTBW configuration in principle enables the creation of a thin, aerodynamically efficient wing. The main drawback preventing them from being applied commercially has been the reduced velocity at which these aircraft can fly before they enter flutter condition. This design in theory could achieve lift-to-drag ratios approaching 50.

According to [40], main achievements would be:

- Increase in wing aspect ratio, resulting in decreased lift-induced drag;
- Decreased wing root bending moments, efficiently sustained by the brace;
- High-wing engine installation, enabling efficient integration of large diameter high-efficiency propulsors.

The obstacles along the development road consist in a series of analysis, not tipically examined on a cantilevered-low-wing design such as:

- Non-linear structural design
- Non-linear aeroelastic behaviour
- Thin-wing actuation systems
- Others

In fact, NASA is investigating the possibility of a large scale flight demonstrator to accelerate the development of this revolutionary design.

Figure 1.17: NASA Render of a TTBW

The Flying V configuration is a radically new configuration for a long-haul passenger aircraft. The passengers, cargo and fuel are located in the wing.

Figure 1.18: BWB Render

It is estimated to have 20% higher payload- range efficiency than its tube-and-wing counterpart for the same top-level aircraft requirements. This is caused by three factors. First, the absence of a distinct fuselage and tail reduce the wetted area by 5% leading to reduced friction drag. Second, the large winglets increase the effective span of the wing leading to a reduction in lift-induced drag. Finally, the lateral distribution of the payload and fuel reduces the bending moments and thereby the structural weight of the aircraft. These benefits stem directly from the shape of the aircraft and can be further complemented by innovations in the airframe or the propulsion system. While the flight performance during climb, cruise and descent are not notably different from a tube-and-wing aircraft, the take-off and landing characteristics are quite different. Research on the Flying V is still relatively recent, and it is still to be confirmed whether this configuration can meet all the certification requirements, while still achieving the improvement in payload-range efficiency [40].

2 | Airline Economy

The airline service stands as fundamental pillar upon which the economic growth of a country is built. No nation can aspire to cut itself a spot in the global economy without a safe and dependable airline service, and that's why governments continue to promote and encourage its development providing infrastructure, protective regulation and subsidies [35].

According to the International Air Transport Association (IATA), in 2019, the industry contributed $2.7 trillion in GDP and carried more than 4 billion passengers and 60 million cargo tons.

2.1. Aviation resilience

During these recent years, the outspread of Covid-19 pandemic at the beginning of March 2020 and the start of war in Ukraine (2022) had and are still profoundly impacting the aviation business. The pandemic is considered to be the deepest and most prolonged disruption to air travel after the post war era [32].

At the surge of the pandemic crisis in early 2020 and throughout the subquent year, aviation losses ended up exceeding $137bn. According to Bloomberg figures, global airlines raised record numbers of debt since the beginning of the pandemic in early 2020: $250bn in 2020 and more than $340bn in 2021.

During this harsh time, government support has been fundamental to the survival of many airlines. Some have received state-backed loans such while others have been put in payroll support scheme [34]. Governments have moved in many countries to provide support approaching $200 billion in a mix of waived fees, direct cash injections, and loan funds (IATA, 2020).

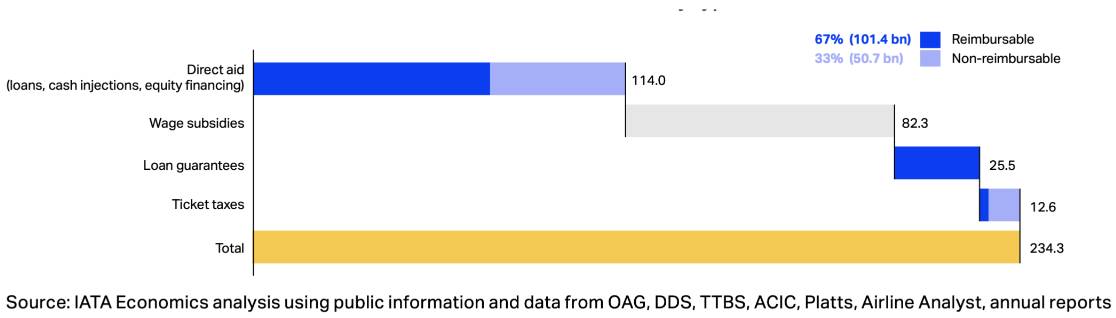


Figure 2.1: Government aid made available to airlines due to COVID-19, by type, USD billion [45]

A surprising factor over 2020 and 2021 has been the sustained flow of capital supporting the industry, which has been undeterred by the restrictions placed on air travel in the search for yield [34].

The nimble recovery of air travel demand from Covid-19 in 2021 and the consequent collapse of the labor market and production capacity to keep up, caused a rise in operating costs afflicting the industry. Aviation's labor shortage is being driven by a variety of factors ranging from health concerns to increasing demand for workplace flexibility to early retirements. The Ukrainian conflict put another burden in airlines' expenses with a surge in interest rate and high inflation in prices for commodities vital to aerospace, such as Jet A-1 and precious metals.

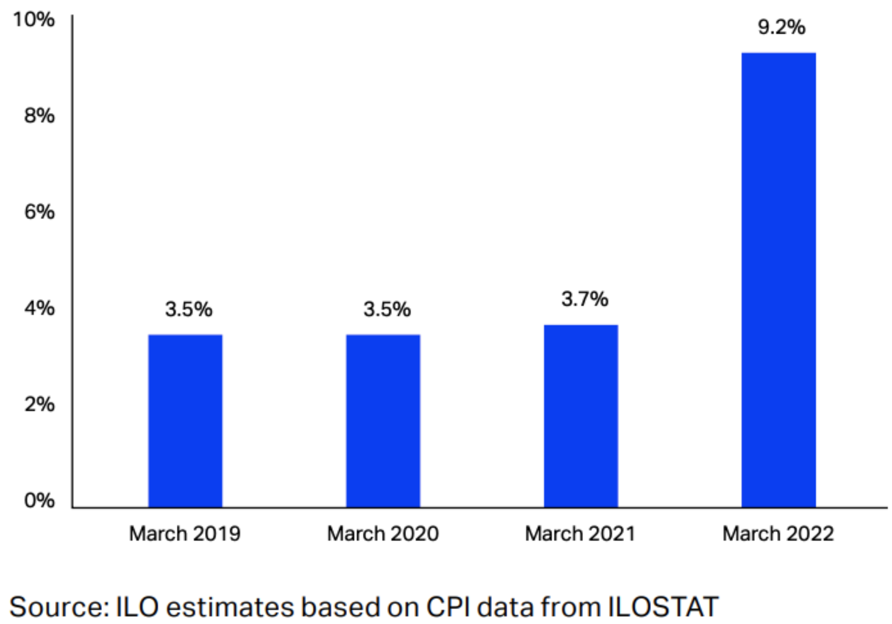


Figure 2.2: Global Inflation Rate (CPI all items), % [45]

Being the industry operating costs highly reliant on fuel prices, accounting from 20 to 50 per cent of total costs, the rise from $78 per barrel to over $140 as of 4 March for Jet-A1 plagued the industry even more [37]. Most airlines to tackle the volatile price of fuel and to reduce the exposure to unexpected changes in price, took refuge in fuel hedging, but the benefit result controversial [29].

A part from the sore in fuel price, this war is causing tighter supplies of some important exports from Russia and Ukraine, and flight restrictions on Russian airspace impacting international flights. Avoiding that huge geographical area means more fuel demand, which in turn could also restrict the amount of payload on board and so curtailing revenues. To avoid this extra cost and inefficiency in the fleet, several airlines suspended routes once flying above Russia [37].

Along the road of recovery, potentially harmful headwinds that airlines will need to deal with are:

- Rising costs of fuel and crucial commodities,
- Rising costs of maintenance since the aircraft were grounded for two years,
- Labour shortages leading to wage inflation,
- Rising interest rates added to the already significant debt burden airlines are facing.

2.2. Factors influencing air travel demand

The supply and demand model clarifies how prices are established in a market-based society. In order to make wise strategic and operational decisions, an airline must comprehend the supply and demand in the market for its own product. The cost of an airline's services, the costs of its rivals, the accessibility of alternative modes of transportation, the frequency and quality of its in-flight services, its safety record, the income and preferences of its customers and macroeconomic conditions, all have an impact on demand [53].

One of the parameter directly linked to the demand is the Gross Domestic Product (GDP). As a matter of fact, the increase in revenue passenger kilometres (RPK) has been growing at a pace of 6.1% per annum during 2009-2019 decade, while GDP at 3.1%. The demand elasticity with respect to income is close to 2. This impacts airlines' decisions on route exit and entry, purchase and leas just to mention few. GDP does not have a steady connection with fares, but due to its strong connection with demand, has to be considered when modelling traffic demand forecasts [54].

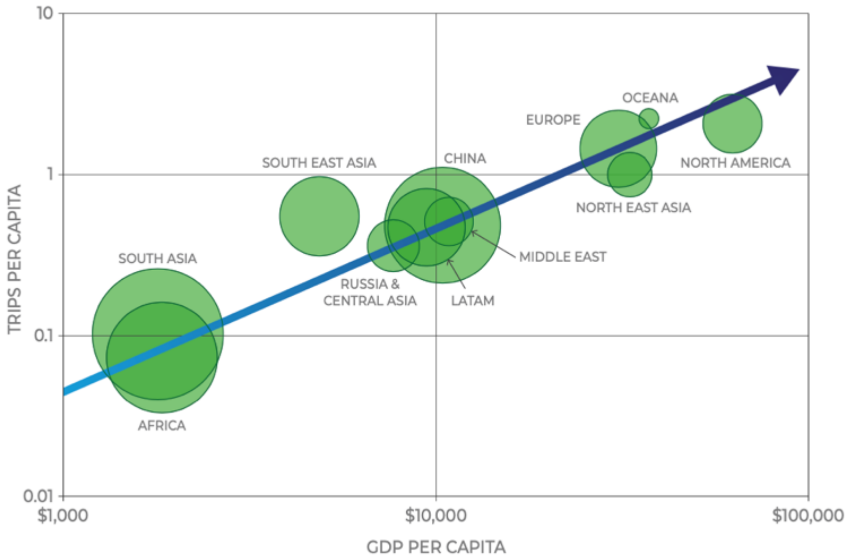


Figure 2.3: Propensity to travel - 2019 [32]

Being the air service a normal good, higher the income per capita, higher will be the willingness for passengers to travel. As more people are entering the 'middle class', more passenger can afford to travel. Nowadays, half of the population is considered to be part of the middle class, while predictions expect a growth to 67% [32]. Furthermore, the average airfares have been declining by more than 50% since

2008 due to:

- Higher seat density,
- Increased passenger load factors,
- Air traffic management improvements,
- High competition among the carriers,
- Investment in new, more fuel efficient aircraft,
- Fleet evolution and optimisation.

The combined effect of rise in GDP and decrease in air fares, boosted the demand for air travel, affecting airlines' growth. Growth in the aviation industry is driven by deregulation, open skies agreements, growth in the economy, and rapid technological change. Airlines have been growing capacity (ASK) through the expansion of both fleet and network. The increase in capacity though, might turn into a financial disaster for two main reasons:

- Over-capacity can obstruct the equilibrium of demand and supply [55];
- Unit profit cannot be increased by means of operating expenses reduction, when the airline size is at the maximum point of unit profit. The decline in total profitability following a substantial growth above this point, is mainly driven by a higher rate of reduction in unit profit than that of an increase in size [56].

2.3. Air Travellers

Air traffic demand has been resilient to crises, and it is destined to increase over the years. As shown in Figure 2.4, Covid-19 pandemic, because of the restrictions put in place to avoid its outspread, only temporarily stopped this upward trend.

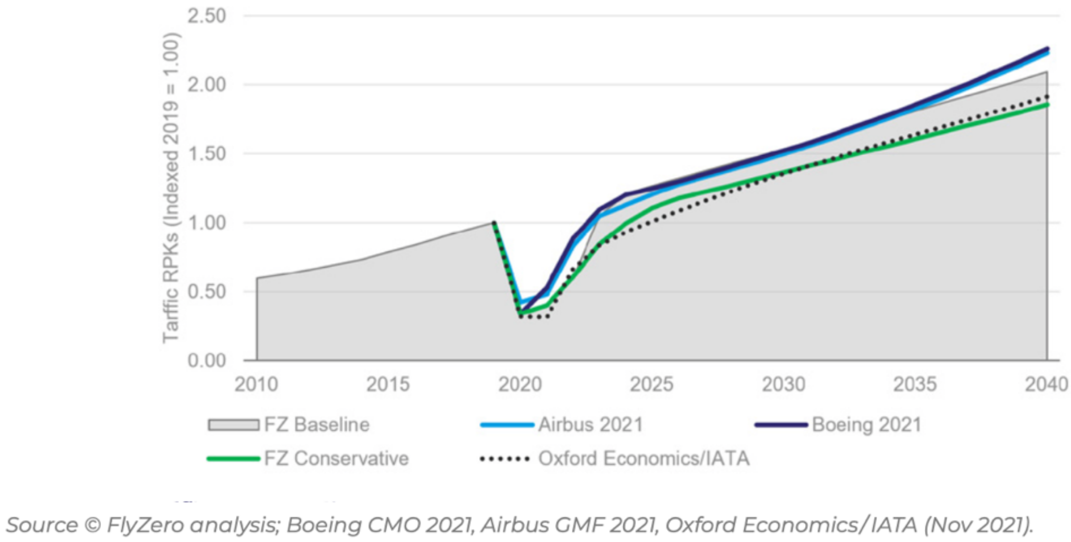


Figure 2.4: Traffic Forecast in RPK [32]

2.3.1. Business vs Leisure

By recognizing that the market is fragmented among various travelers with different demand elasticities, a carrier can tailor its price and the service offered to suit consumers' needs. When price change gives rise to considerable change in consumption, the demand is said to be elastic. On the other hand, if consumers are relatively unresponsive to price change, demand is inelastic [35].

For instance, business travelers are less demand elastic than leisure travelers, because the trip is paid by the company and since there has to be the urge to take the flight, a higher price for the ticket won't stop the company from buying it. They represent a huge source of income for airlines, because of their travelling frequency: 85% of business travelers fly multiple times per year, of which 31% more than monthly. A UK Deparment for Transport survey in 2018 indicates attending meetings being the 58% of the reasons to travel for business. Other reasons are depicted in Figure 2.5:

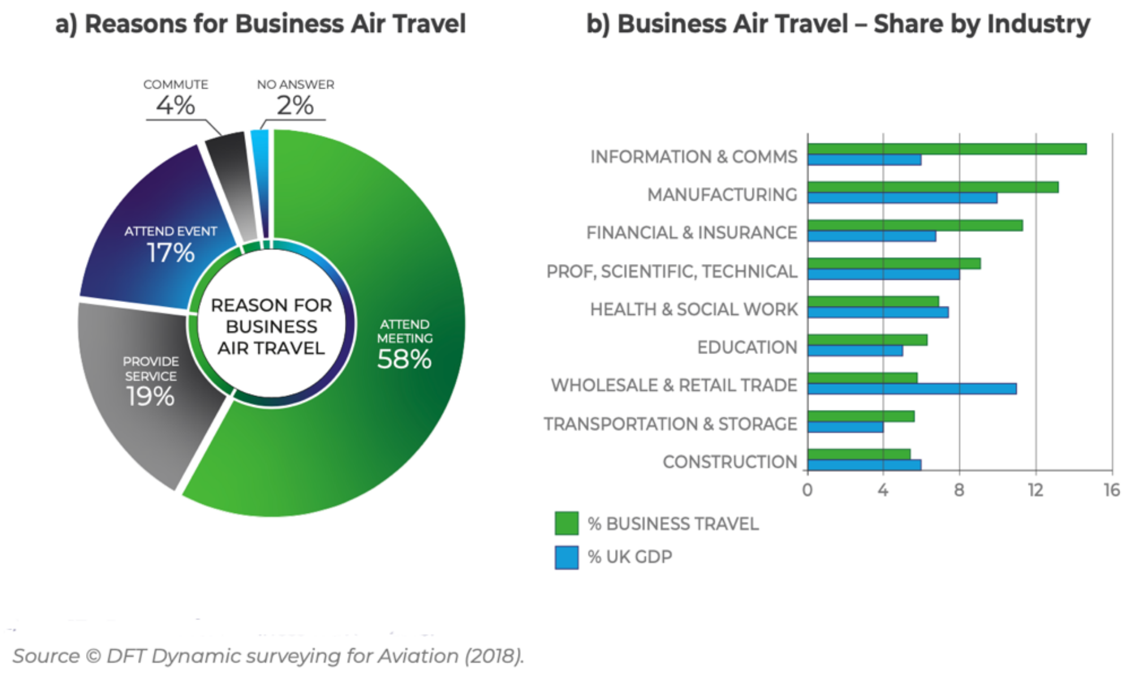


Figure 2.5: Business air travel overview in the UK [32]

Conversely, leisure travelers will likely look for a cheaper option since they pay for themselves and don't have the rush to go on the plane. They represents 80% of total passengers worldwide. The demand for leisure travel is returning to the pre-pandemic level. At the beginning of May, airlines started to register traffic data outperforming the same weeks in 2019. Oppositely, business travelleres perfomed under 31% of traffic compared to 2019, with a gap in recoveries of 34% compared to leisure travellers [37]. A big chunk of business travellers won't probably never return since a lot of companies experimented the easiness of videoconferencing. In addition, many committed to reduce their carbon footprint, and cutting business travels is certainly considered a way. Very often the use of rails represents a better alternative than airtravel. Cost opportunity, along with time savings made this mean of transport preferable. Usually most of the airports are in the outskirt of the city they serve, the access time is way longer due to check-in, security, boarding; on the other hand railway stations are in the city centre and the access time is way shorter, resulting in a more efficient transport system. According to [32], in 2050 HSR (High Speed Rail) could attract more than 300 million passenger, 200 million of which in Europe. This cut in number of passengers though, only stands for 0.8% of global passenger kilometers since only the short segment (300-800) is more impacted.

2.3.2. Pricing strategy

As stated before, price changes affect a lot the leisure travel segment. The price of an airline seat has no correlation to the cost of producing it, but rather reflects the degree and nature of the competition. Competition, or the economic cycle, often dictates the price. The average airfares have decreasing in the last 30 years as a result of it. In a competing market, a carrier with lower costs, or with the need to secure a cash infusion may drive the price down attracting more passengers. In a high-fixed cost industry like aviation, none can bear the loss of several passengers, so it will follow the price leader to conserve market share [35].

Predatory pricing is another common pricing strategic entry barrier in the airline industry. Predatory pricing occurs when a price war is waged by incumbents against new or potential entrants. The incumbent first lowers its price to drive out the rivals and then raises it. By this means, it sacrifices a short- run loss to protect its long-run interest. The recent advance in new technologies of the artificial intelligence, big data, and virtual reality can lead to a revolution in airline pricing and personalization concepts. Dynamic pricing as a result of the capability of analyzing big data allows airlines to predict with a high degree of certainty customer demand and preferences, which makes it possible for the airlines to offer a fare that is closer to the customers' demand [29].

Price discrimination is traditionally seen as one of the sources of price variation, especially in the airline industry and can be split into three degrees: first degree, second degree and third degree. First-degree price discrimination transfers the full consumer surplus to the businesses, which is unlikely to occur in practice as airlines frequently lack the ability to calculate a customer's reservation price. The practice of charging consumers varying rates for consuming various amounts of the same product falls under the category of second-degree price discrimination. Given that the points given to passengers can be used later as a particular kind of discount and that consumers do not have to pay for the points at the time of ticket purchase, a frequent flyer program may likely fall under this category of price discrimination. The charging of various rates to distinct consumer categories, such as men and women, children and adults, is referred to as third-degree price discrimination [34].

With the spread of online booking, this clear transparency of different offers makes undoubtedly the demand for air travel more elastic, hence the need for airlines to find a competitive non-price strategy to engage new clients and retain their market share. Frequent Flying Program might be an example of initiative to keep the customer more loyal, being rewarded with discounts, additional baggage allowance, access to business lounge and others [29].

It is also mandatory to make a distinction between ticket price and revenue. The two terms not always coincide, since most of the earnings derive from ancillaries. In [28] is given a breakdown of the total revenue perceived by Ryanair in 2007 per person (Figures 2.6 and 2.7).

Revenue per passenger (sales)€	**53,3**		
of which:		of which:	
Airfare €	43,7	Operating costs €	42,75
Ancillaries €	9,6	Operating profit per passenger €	10,55

Number of passengers in 2007 – 50.931 thousands

Figure 2.6: Structure of passenger revenue, Ryanair 2007 [28]

Operating profit per passenger	**10,55 €**	**Ancillaries, of wich:**	**9,60 €**
of wich:		Non-flight Scheduled	6,58 €
Profit from air fare	0,95 €	Car Rental	0,50 €
Ancillaries	9,60 €	In-flight Sales	1,44 €
		Internet-related	1,08 €

Figure 2.7: Structure of passenger profit, Ryanair 2007 [28]

Being the operating profit per passenger 10.55 €, the actual margin gained from the air fare is very thin 0.95 €, while ancillaries with 9.60 € account for more than 90% of total revenue.

2.4. Business models

To face the diversity in passengers' needs, airlines operate following mainly two business models, which are representative of the market. Full-service network carriers (FSNCs) are more inclined to base their network on hub and spoke, focusing on an international connectivity, frequency and premium in-flight services. For low cost carriers (LCCs) instead, their core strategy is based on fare price reduction, trying to increase the load factor and earn from ancillaries. The network is usually point-to-point operations in the short-medium range with high utilisation of the aircraft. Offering a 'no frills' service, at an economic price, this business attract more leisure travellers. Conversely, FSNCs offering premium class services for high paying passengers, have to maximize revenues finding an equilibrium between a cheap promotion to fill the seat and business/first passengers willing to pay more [28].

FSNCs have a better stability in number of passengers and show their advantage in generating profits when the overall economy is strong. They earn a lower operating income due to premium service complexity and higher costs related to it. While some FSCs have moved to capture additional fees and charges, the bulk of ancillary revenue for these airlines tends to be derived from financial services rather than service add-ons [31]. Even if less profitable and less efficient than LCC companies, the FSCN carriers can aggregate more revenues thanks to their wider operating scopes and market capitalization [30].

Low cost carriers are more efficient because of their cost structure, making it the perfect business model to operate when the demand is volatile. They are able to decrease prices consistently with high competition and operating on a single stage with a uniform fleet allow them to reduce the effort in routing schedule and maintenance. Operating with thin margins forces these kind of companies to increase their load factor attracting more passenger on board. In India, LCCs carriers accounted for 60% of market share for many years. For lower income consumers, this business model represented the unique opportunity to make aviation more accessible and to develop the local economy by creating work opportunities and boosting tourism. The strong development of this business model put lots of financial pressure on FSNCs, which in turn should try to low their yield to attract more leisure travelers [29].

2.5. Aircraft Market

An aircraft commercialization starts with a concept phase, then development, certification and aircraft handover. Reaching a technological readiness level as soon as possible is necessary to build a functional prototype to show the industry the feasibility of such new technology. During this time frame, it will be crucial to gain certifications to speed up the possible Entry Into Service (EIS). Also because considering the time needed from EIS to a widespread aircraft rollout, we might miss the opportunity to replace a consistent chunk of the global fleet with these new concepts before 2050. Considering conventional aircraft development cycles, which occur every 15-20 years, the next window of opportunity might be around 2030-2035 [22].

Reasons leading companies to purchase a new aircraft can be mainly summarized in

- New markets: the great liberalization of the aviation market, allow companies to enter new routes and seize opportunity to expand their businesses.
- Replacement / Retirement: high fuel cost, increased maintenance, less efficiency are all reason to consider the acquisition of a new aircraft to meet higher performance standards.
- Natural growth: with the increase in passenger demand, also the capacity offered by the airlines has to grow to keep up with the demand.
- Right-Sizing: Demand for a route might change, and it is fundamental for the operator to enhance an efficient solution, in terms of routes/frequency/number of pax, targeted to maximize the operations.

The fast recover in air travel showed once again its strong resilience to crisis. The increasing number of passengers has to be stood back by a numerous fleet. The fleet serving the globe is predicted to grow from a pre-pandemic level of 29990 aircraft to 69090 aircraft by 2050. In the next decade the request of new aircraft to replace retiring ones and to fulfil the increase in demand is announced to be about 2600 models per year, soaring to 3000 in the 2040s [32].

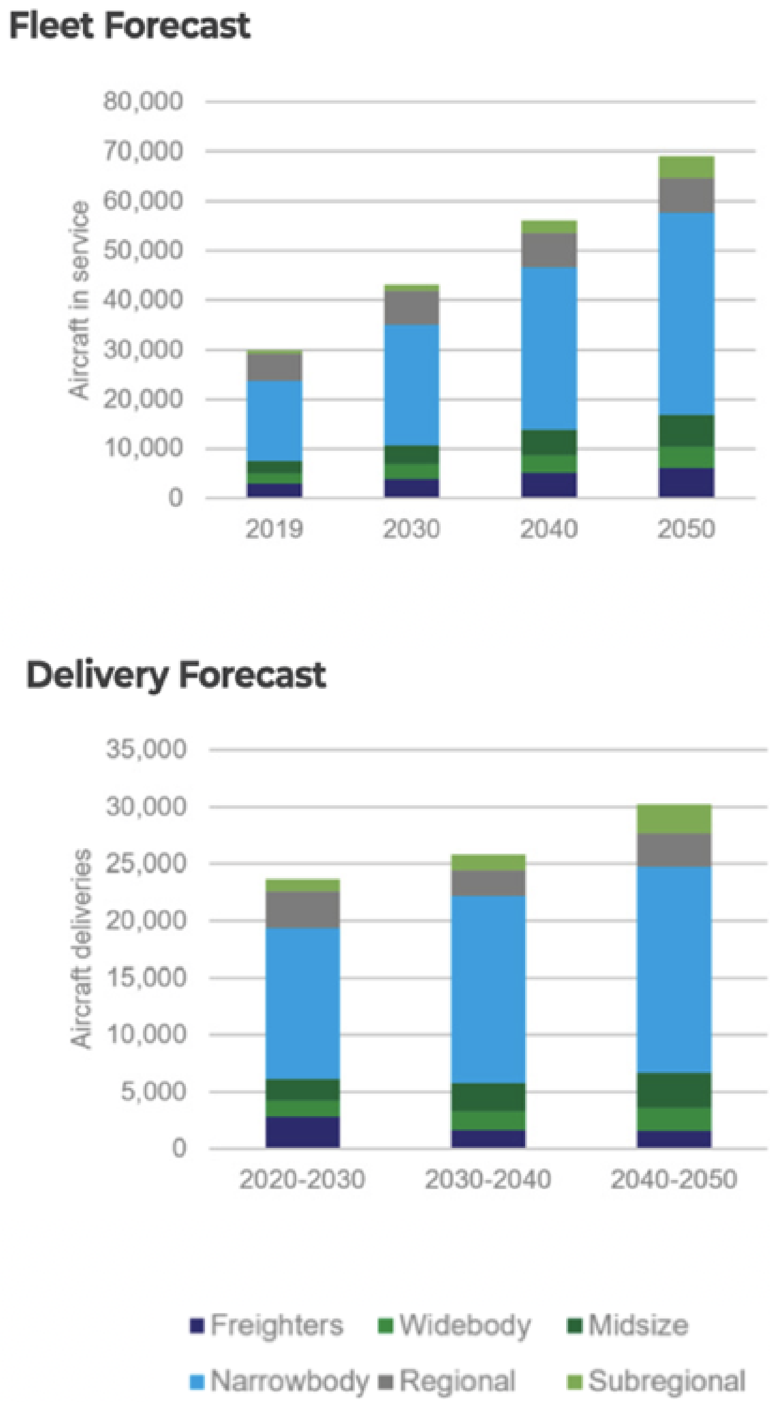


Figure 2.8: Fleet and Delivery 2050 forecast [32]

In 2019, about 13% of the global feet was made up of the latest generation aircraft. standing as the most commercially viable, the narrowbody segment is expected to take a huge market share. The introduction of a narrowbody aircraft powered by LH_2 represents a big chance to drastically reduce CO_2 emissions. At the same time though, it also comes with high risk for airlines and aircraft manufacturers for the amount of money at stake. A failure during the development stage, or a missed ramp-up in hydrogen infrastructure would cause irreparable financial damages.

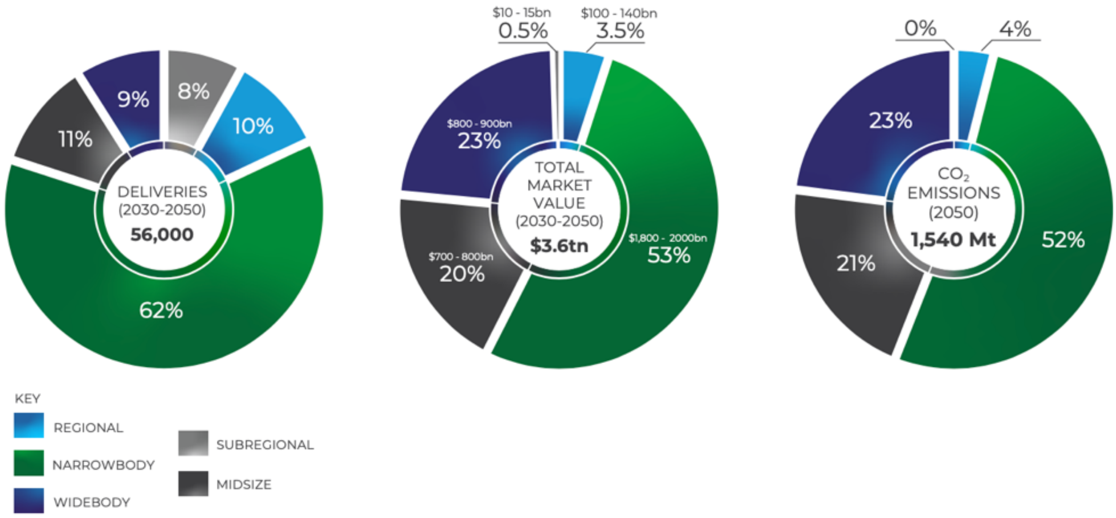


Figure 2.9: Market opportunities - 2030 to 2050 [32]

Consistently with this reasoning, [32] suggests two possible scenarios for these new models to enter the market: midsize first or regional first. The Midsize First strategy aims to commercialize the midsize segment first, since more localized would be the effort to tackle infrastructure challenges during the ramp-up. In addition, considering the combustion turbofan technology to power this segment would also be used for the short haul aircraft, this strategy in a effective way de-risks a narrowbody aircraft development. This strategy for sure would have a way bigger decarbonitazion impact. On the other hand, introducing Regional First, would entail a more decentralized and complex effort to built the necessary infrastucture for LH_2 at small regional hubs, and at the same time it wouldn't de-risks narrowbody aircraft development, being the regional segment constituted of turboprops. At the same time though, the entry into service of these vehicles seems more imminent considering that a lot of commuter demonstrator are starting to emerge. This would be only a stepping stone, but still would create confidence in the industry, paving the way to the introduction of larger aircraft.

According to [32], best previsions for a entry into service per segment are:

- Regional First: regional in 2033, narrowbody in 2037, midsize in 2044 and widebody in 2049.

- Midsize First: regional in 2042, narrowbody in 2037, midsize in 2033, widebody in 2038.

While according to [22], the previsions are: regional time to market of 10 to 15 years, narrowbody within 15 years, midsize within 20 years, and widebody in 20 to 25 years In either way, the road to a widespread of LH_2 propulsion based aircraft still requires a long effort by the industry to overtake the upcoming challenges.

One the major leader in the business, Airbus, set a target to fly with hydrogen by 2035. And yet, Paul Meijers - Commercial Aircraft Leasing, Trading & Financing chez Airbus, commented 'That is extremely ambitious because 2035 in our long cycle space is very challenging and it requires disruptive technologies. We have huge challenges to bring this together, but we have seen a lot of movement over the last year to drive sustainability'. Aviation industry leaders are sceptical of Airbus reaching its goal of developing a hydrogen commercial airliner by 2035, and even if they succeed, the certification process would take years, and it would take several more years ramping up the infrastructure to enable a marketplace launch [34]. It is clear how a lot of uncertainties still pervade the industry, also among the biggest stakeholders, but one thing is sure, the interest to decarbonize this sector is real and it's not a matter of if, but when.

2.6. Airlines Finance

2.6.1. Financial struggles

While demand for air travel and freight has been resilient, the industry's profit margins are very thin because of high fixed costs, overleveraged balance sheet, low entry barriers and fuel price volatility. Plus, airlines' ROIC (Return On Invested Capital) is the lowest among other supply chain sectors in air transportation [31]. ROIC is defined the annual ratio between operating incomes and average invested capital, and it is used to visualize how effectively operating assets are generating operating profitability [30].

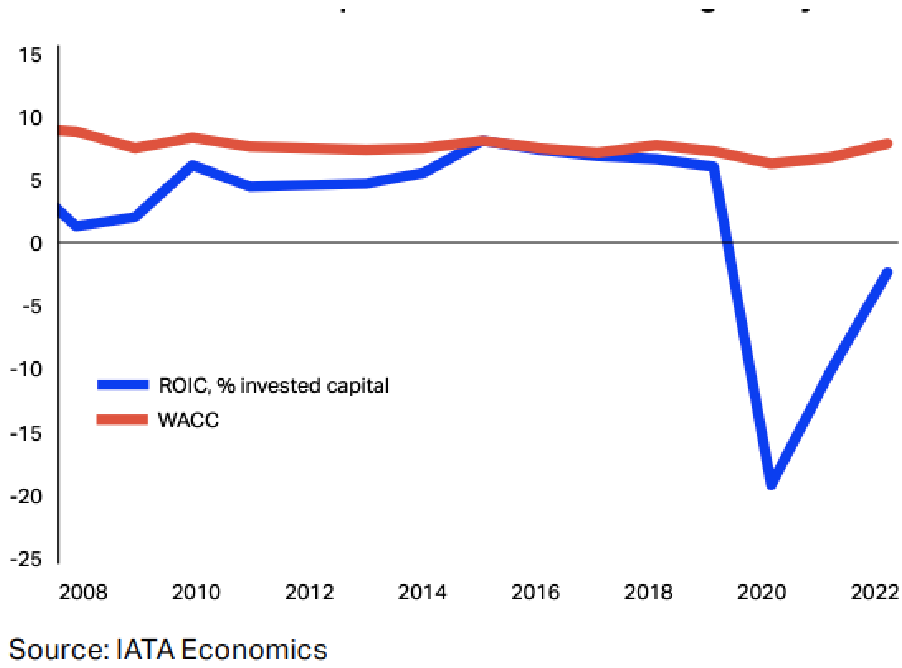


Figure 2.10: Return on capital invested in airlines globally [45]

This emphasises the struggle of the airline sector to sustain financial health: more than 100 airlines have filed for bankruptcy since 1979 (Kumar, 2012).

The sources and degree of diversity in revenue structures, the marginal cost savings of purchasing fuel-efficient aircraft, and the availability of alternative funding channels like secured/unsecured debts or enhanced equipment trust certificates are all factors that can be reviewed by businesses to increase their ability to turn a profit [30].

2.6.2. Leasing opportunity

A significant financial choice is whether to purchase or lease an aircraft. Two popular ways to finance the purchase of an airplane are through an operating lease and a direct purchase with bank financing. Should a carrier buy and keep the aircraft? Should the airline pay in full cash for any purchases or take out a loan to finance them? These choices are based on the state of the market and the financial health of the airline.

In the early 2000s the share of aircraft owned by leasing companies accounted for 20% of the global fleet, while now it is expected to own more than the 60% in the next five years. In 2021 lessors took delivery of 60% of all Boeing and Airbus aircraft orders combined, all placed under some form of lease, be it sale-leaseback, order book, finance lease. In the same year over $32bn have been raised by leasing companies. The quantum raised and the interest rate spreads achieved by each of these investment grade lessors highlight both the confidence the investment community has in the leasing model and also speak to the maturity of aviation as an investable asset class. Even as we move towards a rising interest rate environment, there is a widely-held belief in the lessor community that there will be a continued ability to obtain attractive spreads on unsecured debt for large-scale, well-run leasing platforms. Throughout this recent crisis, leasing businesses have shown that they should not be evaluated using the same credit standards as airlines. Despite the fact that all lessors have some exposure to defaulting airlines and are constrained in their ability to seize and re-lease aircraft to new customers due to the crisis's global scope, they have been successful in negotiating creative solutions to maintain cash flow and raise record amounts of liquidity from a variety of sources, including banks, new alternative lenders, the capital markets, and the private sector. It is clear how this model is gaining much success in the environment [34].

2.6.3. Sustainable finance

Speaking of 'green finance' or sustainable finance from a debt point of view, this can be divided in two different products: use of proceeds instruments, such as green bonds and loans, and sustainability-linked instruments, which can be bonds or loans.

- Green bonds are products where the proceeds raised are demonstrated as being used for green projects, such as renewable energy and energy efficiency projects, which aids decarbonisation.
- Sustainability-linked loans or bonds are not concerned specifically with how the money is being spent, the loan or bond pricing is linked to the overall performance of the company on specific ESG (Environmental, Social and Governance) performance indicators. Sustainability-linked loans or bonds are based on the borrower's sustainability performance, which is measured using predefined sustainability performance targets (SPTs), that are measured by predefined key performance indicators.
- SPTs also need be ambitious, quantitative and measurable on an annual basis, and which are consistent with the issuers' overall sustainability objectives.

If the company meets its targets it can gain a discount on the interest rate for the sustainability-linked loan; likewise, if it does not meet those targets and actually emits more, it is subject to a financial penalty. Helane Becker – Managing director covering airlines, air freight, and aircraft leasing at Cowen (Cowen Inc., is an American multinational independent investment bank and financial services company)- says ”We’re not hearing investors say that they are not investing in the airline industry because of their carbon footprint. I haven’t heard that yet. Maybe that’s coming. Airlines haven’t been stymied in terms of raising capital due to ESG concerns, but potentially it’s coming.” The potential market for sustainability- linked loans and bonds for aviation is certainly there but it is limited. Over the past few years, sustainable finance deals in the aviation sector have been relatively few and far between but they have increased in recent years. In July 2021, British Airways (BA) made history raising $785m with the first enhanced equipment trust certificate (EETC) transaction linked to the airline’s sustainability targets [34].

3 | Airline Business Model

One aircraft is a very expensive product to purchase, to operate and to maintain. Before making a huge investment, it is mandatory to determine how much money are needed to keep it functional throughout its lifetime. Preliminary models are based on few inputs, and allow the designer to start making some economic evaluations. A more detailed model was developed to include the aforementioned additional system requirements, on the same way as [25] included batteries in its 19 seat hybrid-electric aircraft. It follows a description of the different cost items, airlines have to face to operate the aircraft, with a special attention on fuel price which is still very uncertain. Traditional KPIs to evaluate airlines' operational and financial performance are finally commented.

3.1. Direct Operating Costs in literature

We can split the Total Operating Costs (TOC) in Direct Operating Costs (DOC) and Indirect Operating Costs (IOC).

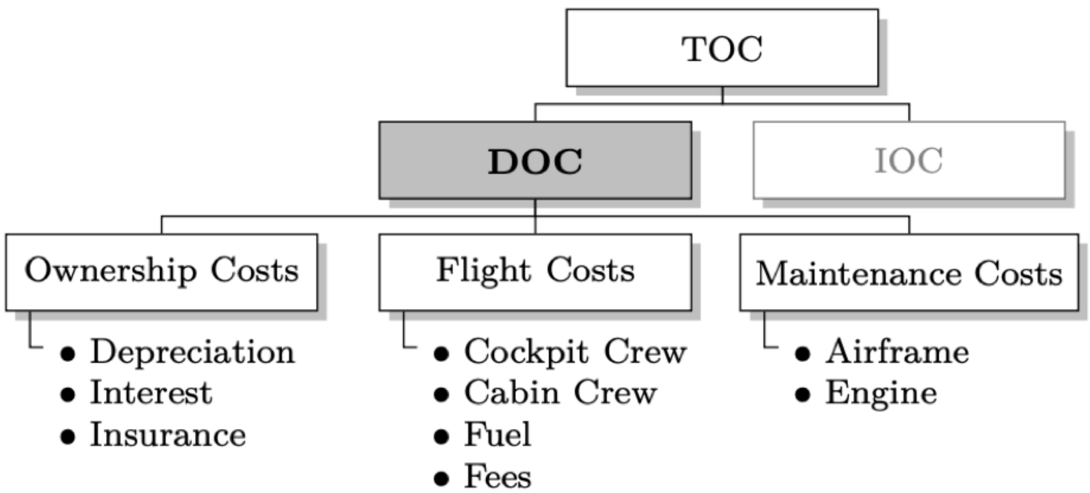


Figure 3.1: Overview of costs to sustain an aircraft

For direct operating costs we include the maintenance costs mainly for the engine and the airframe, which are more costly influential among other components; the ownership costs are due to amortization, insurance of the aircraft with its spare part as well; flight costs are directly related to the mission, while the crew has a fixed salary per year no matter the mission. Fees are divided in landing, groundling, navigation and environmental. Indirect operating costs instead, include sales and costumers service, marketing, administrative and overhead [8].

Especially in the early design stage, when there are still some unknowns regarding the aircraft components breakdown, it is necessary to use a model with a low number of input. DOC models have always been used in aviation, and the resulting relationships are estimated through correlations among existing data and main characteristics of the aircraft. It is true though, that in a cutting-edge and evolving sector like aviation, since the model is based on existing fleet, it should also be updated constantly. While for a completely new technology, like the one we are introducing, the same cost drivers could not be sufficient [19].

Pohya, A. in [24] uses five different DOC model to evaluate the impact of a new technology, summarized in Figure 3.2 with their inputs. The results are rather different in terms of millions of dollars, and the different categories (maintenance, flight, ownership) show different cost shares.

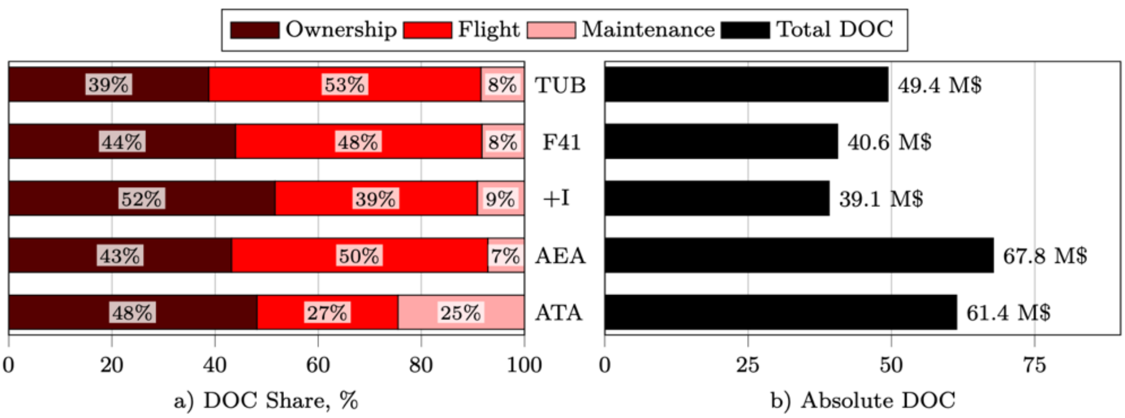


Figure 3.2: Comparison of different DOC models applied to the same aircraft [24]

He concludes emphasising how DOC models are easy and quick to use, but lack in parameters to assess a new technology's impact.

In Figure 3.3 all the different DOC models are divided into their inputs parameters, ranging from a minimum of 11 inputs to a maximum of 18. Main categories includes aircraft's weight breakdown, engine's performance and aircraft's operations related like fuel, flight time.

Required Inputs of selected DOC models						
	Input Parameters	ATA	AEA	+I	F41	TUB
Aircraft	Maximum Takeoff Weight	●	●	●	●	●
	Maximum Landing Weight	○	○	●	●	○
	Operating Empty Weight	●	●	○	●	●
	Manufacturer's Empty Weight	○	○	●	○	○
	No. of Seats	○	●	●	●	●
	Aircraft Model Factor	○	○	○	●	○
	Aircraft Price	●	●	○	●	○
Engine	No. of Engines	●	●	●	●	●
	Weight	○	●	●	●	●
	Thrust	●	●	●	●	●
	Bypass Ratio	○	●	○	○	○
	Overall Pressure Ratio	○	●	○	○	○
	No. of Shafts	○	●	○	○	○
	No. of Compressor Stages	○	●	○	○	○
	Engine Type	●	●	○	●	○
	Engine Price	●	●	○	○	○
Operation/Others	Range	●	●	●	○	●
	Burned Fuel	●	●	●	●	●
	Flight Time	●	●	●	●	●
	Payload	○	●	○	○	●
	Utilization	○	○	○	●	○
	Airline Factor	○	○	○	●	○
	Cost Factor	○	○	○	●	○
	Route Type	●	○	○	●	●
	Airframe Maint. Ratio	○	○	○	●	○
	Engine Maint. Ratio	○	○	○	●	○
	Σ	11	17	10	18	11

Figure 3.3: Input parameters for different DOC models [24]

3.1.1. Modified "TUB" model

Among others, TUB has been chosen to determine direct operating costs of the designed aircraft, because it is the most recent (2010) and it has been used on several study in literature when it comes to hydrogen powered aircraft, even if with some modifications. Since the introduction of a new technology comes with high capital costs, it necessary to include them. CAPEX (CAPital EXpenditure) consists on the depreciation and the insurance rate multiplied by acquisition price of the aircraft. In order to guarantee a much more reliable acquisition price, the aircraft has been subdivided into its main features:

- Airframe
- Gas turbine (if burning hydrogen)
- Electric motor (if hydrogen is used to power a fuel cell)
- Power management and distribution system
- Fuel cell
- Battery
- Tank

On the same way as [25] includes battery as additional capital cost, given that the depreciation rate depends on the life cycle of the item, also fuel cell and tank capital costs will be added separately. The aircraft price for the turboprop is calculated as follow:

$$p_{AC} = p_{AF}W_{AF}(1+k_{AF})+p_{EM}P_{EM}(1+k_{EM})+p_{PMAD}(\frac{P_{EM}}{\eta_{PMAD}\eta_{EM}}+\frac{P_{EM}}{\eta_{PMAD}^2\eta_{EM}})(1+k_{PMAD})$$

where, p_{AF} = price airframe [EUR/kg], W_{AF} = mass airframe [kg], p_{EM} = price electric motor in max continuous power [EUR/kW], P_{EM} = electric motor max continuous power [kW], η_{EM} = EM efficiency, p_{pmad} = price power electronics to distribute and manage power[EUR/kW], η_{PMAD} = efficiency PMAD (inverter/converter*cable), k = with the letter k spare parts are indicated.

The turbofan model was essentially designed retrofitting the kerosene propulsion system with a burning hydrogen one, so only the tank price will be added to the expenditures:

$$p_{AC} = p_{AF}W_{AF}(1+k_{AF}) + p_{ENG}W_{ENG}(1+k_{ENG})$$

where p_{ENG} is the price for gas turbine [EUR/kg] and W_{ENG} is the weight [kg].

To calculate CAPEX we need to find the annuity rate $\boldsymbol{a}$:

$$\boldsymbol{a} = IR\frac{1 - f_{RF}(\frac{1}{1+IR})^{DP}}{1 - (\frac{1}{1+IR})^{DP}}$$

The Interest Rate (IR) is set to 5%; Depreciation Period (DP) is set to 15 years; Residual Value factor (f_{RV}) is set to 10%; The insurance rate is set to 0.5%.

Batteries have a limited life cycle, and the cost for the replacement during aircraft operational life, can be a factor that contributes to upfront investments [18]. The same reasoning can be applied to fuel cells. Their residual value factor though is increased to 40%, because of their high recyclability or reutilisation rate. As mentioned in Subsection 1.3.2 , at the end of their life time, even if not considered suitable for aircraft applications, these technologies might find space in other industry applications.

Value found in literature for an EIS (Entry Into Service) of 2035, predict a life cycle for batteries of 1500, 2000, 3000 flight cycles (pessimistic, base, optimistic) [11]. For fuel cell a service life of 20000 flight hours was found [19], while for the tank predicts a maximum operating life of 12 years, afterwards the tank should be replaced for safety measures. In this study the depreciation period for the tank is set to 15 years.

As well as for the battery and the fuel cell, tank residual value factor is set to 40%.

The price summary is the following in Table 3.1:

Prices scenarios

	Pessimistic	Base	Optimistic
Airframe [€/kg]	1970	1970	1970
Tank [€/kg]	1300	1180	1060
Fuel Cell (cell level) [€/kW]	80	60	50
Flight Hours [hrs]	15000	20000	25000
Battery [€/kWh]	200	120	80
Life cycles	1500	2000	3000
PMAD [€/kW]	60	50	40
EM [€/kg]	120	100	80
LH_2 [€/kg]	8	6	3

Table 3.1: Prices projection component-wise.

For the purpose of this study, a Base scenario price was used to perform the calculations. The price of the tank includes subsystems while EM's price includes cabling

3.2. Maintenance costs

Maintenance centres the category of operation expenses necessary to maintain the aircraft in operation. Three main contributors are the airframe, personnel and the engine:

$$OPEX_{Maint,AF,Material} = \frac{OEM}{1000}(0.21t + 13.7) + 57.5$$

$$OPEX_{Maint,AF,Pers} = LR(1 + B)((0.655 + 0.01\frac{OEM}{1000})t + 0.254 + 0.01\frac{OEM}{1000}$$

where OEM = operational empty mass [kg], t = total block time in hours (actual time of flight plus taxi time), LR = labour rate [€/man hour], B = burden includes airline overhead, the cost of acquiring, maintaining equipment and tools, building, facilities, and other indirect costs [15].

Some though state that the correlation with the operating empty mass, might no be valid anymore due to a different mass distribution for the new aircraft design: the added mass is mainly concentrated on the wing and airframe, not in all components slightly reducing the costs [11]. Considering the tank and its cryogenic system having the same expenditure cost for maintenance as the airframe one, is an optimistic scenario [11].

Since the turboprop and the turbofan engine require different procedures to be maintained, two different formulas are used, respectively:

$$OPEX_{ENG_{fan}} = 7.621 \times 10^{-4} \frac{0.64545 P_{tot,max}}{54.121 \frac{m}{s}} + 30.5t + 10.6$$

$$OPEX_{ENG_{prop}} = n_{ENG}(1.5 T_{SL,Static} + 30.5t + 10.6)$$

The first formula is not dependent on the number of propellers, and only require the total maximum power rate at takeoff and the total block time. The second formula instead requires the static thrust at one engine at sea level, number of engines and total block time.

According to [12] engines requires almost half of the total maintenance costs, and furthermore points out how the APU and landing gear are also very expensive components to maintain routinely. In facts, in [18] it is reported how the higher OEM, due to battery addition for instance, might increase the maintenance required for the landing gear. On the other hand, substituting the conventional APU which is basically made of a gas turbine, with the fuel cell would experience cost savings. Also, the simpler inherent mechanic of electric motors, results in a potential reduction in engine maintenance. For a fully electric powertrain, hence the case of our LH_2 powered turboprops, the maintenance cost is multiplied by 0.9 to account for the fewer maintenance required [25].

Giovingo, D. A. in [15], provides a detailed breakdown at subsystem level of the cost of labour and material for Flight Hour; also in [46] every subsystem has its own maintenance price, but still the impossibility to have a refined breakdown at this early stage of design, forces us to rely on more general input parameters, with all the uncertainties connected.

3.3. Liquid hydrogen price

The most impactful stakeholder in terms of operating expenses it's fuel for sure. To better understand how this aspect can represent an unknown, it's necessary to investigate the production and its supply chain. Hydrogen is recognised as pollutant free fuel, but still the way it is produced might not be that green. It can be either extracted of manufactured, and based on its carbon output it's subdivided in grey, blue or green as depicted in Figure 3.4.

	Grey Hydrogen	Blue Hydrogen	Green Hydrogen
Process/ Technology	Steam methane reforming (SMR) Auto-thermal reforming (ATR)	Carbon capture and storage (CCS)	Electrolysis
Source	Natural gas, gasifier coal, or heavy oil	CO_2-rich stream	Water
Carbon output	8.5–10 kg	0.8–4.4 kg	No carbon emissions

Figure 3.4: Hydrogen production pathways [3]

Since the only carbon free method is to produce Green Hydrogen, in a maximum decarbonisation scenario like the one we are studying, we will assume that the production is based on renewable sources such as wind or solar energy.

Green hydrogen is essentially produced providing electricity to pure water, splitting hydrogen and oxygen.

$$2H_2O + electricity = 2H_2^+ + O_2$$

One of the key challenge is to provide clean electricity: depending on the decarbonisation scenario, from about 500 GW to 1500 GW of electricity would be required to produce LH_2, meaning that 20%-60% of the capacity of renewable sources available today worldwide is needed to produce LH_2 just for aviation. In a 2050 scenario, where 40% of the global fleet is powered by LH_2 and the other 60% by synfuel, it would be necessary to triple or quintuple the renewable energy produced nowadays. It is clear how a huge ramp-up in renewable sources is fundamental [22].

Alongside the production, storages are necessary to cover fluctuations in LH_2 demand, either at the airport and along the supply chain. Depending on the way hydrogen it is carried, gaseous pressure tanks or cryo cooled tanks for LH_2 will impact in CAPEX costs. While the easiest way to produce hydrogen, would be in the vicinity of the airport, this would imply access to low cost renewable energy sources. Scenarios with imported hydrogen have to be taken into account, since it could be cheaper and/or necessary to fulfil the high demand at the airport. Hydrogen can be transported via ships, trucks, pipelines either gaseous, liquid, or chemically bounded to another atom to increase its poor volumetric density. Bounding it chemically would require a conversion/reconversion unit in order to have pure hydrogen at the filling station. The different carriers are summarized in Figure 3.5.

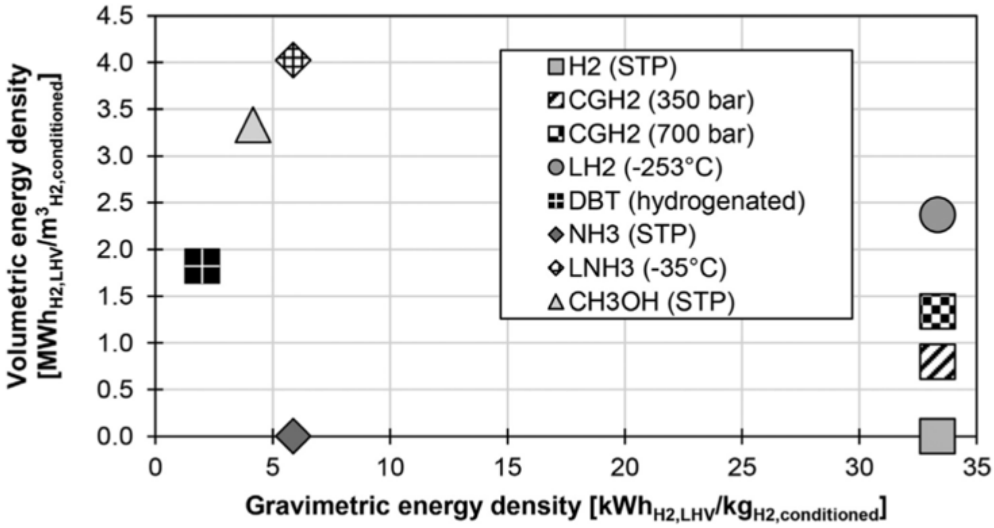


Figure 3.5: Hydrogen carriers [26]

In Figure 3.5 CGH2 = compressed gaseous hydrogen; CH3OH = methanol; DBT (LOHC) = Dibenzyltoluene; GH2 = gaseous hydrogen; NH3 = gaseous ammonia; LH2 = liquid hydrogen; LNH3 = liquid ammonia; STP = standard temperature and pressure.

The final cost of H_2 at the filling station will be given by the contribution of each element in the supply chain:

$$p_{LH2} = p_{electrolisys} + p_{liquefaction} + p_{transport} + p_{storage} + p_{refuelling}$$

Depending on the production site and the pathway chosen, costs of hydrogen at the dispenser will differ. Sens et al. in [26] makes a detailed analysis of the costs necessary to supply heavy duty-vehicles in Germany. Hydrogen production is assumed by water electrolysis on a large scale system. Since a water supply is necessary, also a reverse osmose desalination and pipeline to provide water are considered. All the costs include auxiliaries, installation, etc. The case study is based on 4 different production sites, from local to national to international, considering the different carriers, storage and transportation options. The main assumption regarding the carrier, is that once the hydrogen has been converted into a different carrier at the production site, it will be reconverted in GH_2 or LH_2 only at the filling station. A simplified overview of the pathways is given in Figure 3.6

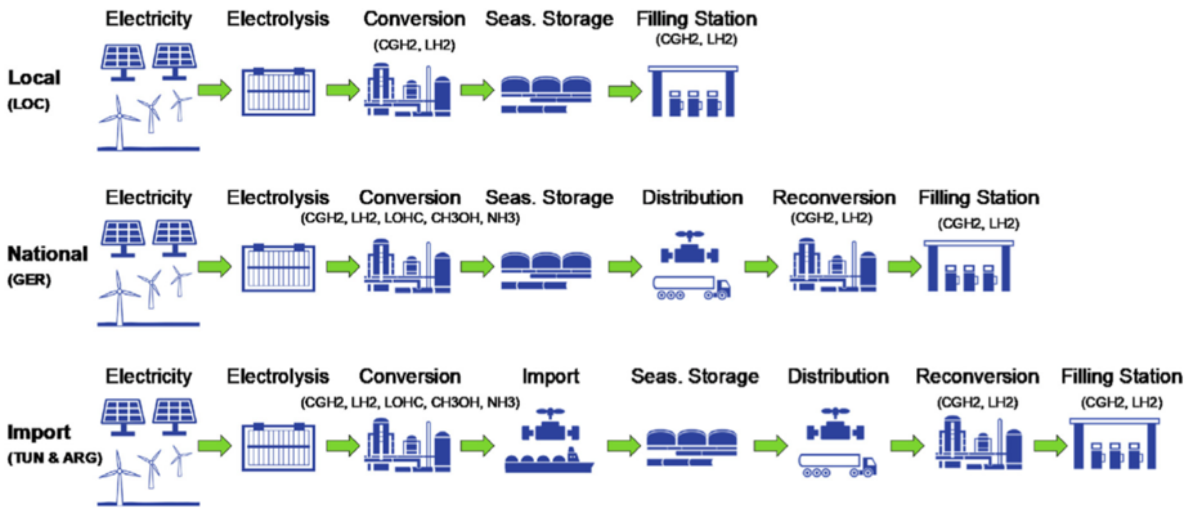


Figure 3.6: Hydrogen possible supply chains [26]

The main findings of this studio are:

- GH_2 filling: for the most favourable supply chain for gaseous filling, a price of 5 €/kg in 2030 is expected (bandwidth around 4-8 €/kg). In 2050 prices drop at 4 €/kg (3-7 €/kg)
- LH_2 filling: in 2030 the price is expected to be 7 €/kg (bandwidth 5-12 €/kg), while for 2050 a price below 6 €/kg is expected (4-8 €/kg)

In both cases it is more advantageous to transport hydrogen in its final form, avoiding any reconversion process. Even though several options for condition, transportation and storage were analysed, the most expensive process along the different supply chains is the production one.

In line with what has been just said, Holzen, J. in [4] compare different studies investigating the cost of H_2, either from studies specific for aviation or for others sectors, assessing how production and its dependence on low cost RES has the biggest impact. From the different results found in literature, he sets three scenarios for LH_2 cost delivered at the filling station.

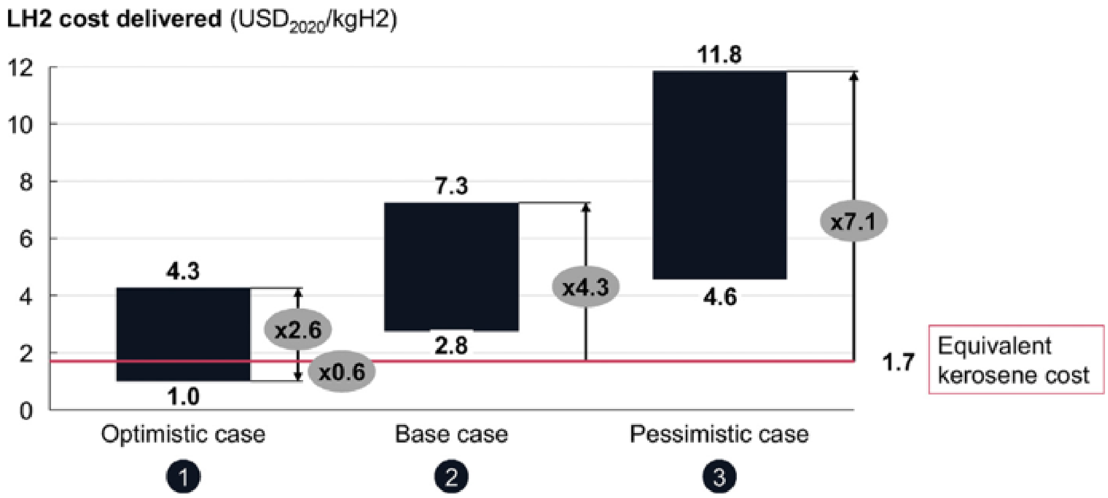


Figure 3.7: Hydrogen costs at the dispenser [4]

In Figure 3.7 are pictured cost ranges for liquid hydrogen at the dispenser derived from literature review and cost assessments depending on the H_2 cost scenario (from optimistic to pessimistic); comparison to kerosene costs translated into LH_2-equivalent costs based on LHV (Lower Heating Value) of kerosene and LH_2.

In a more recent study [27] Hoelzen, J. provides a more detailed overview of the refuelling system, in order to understand which refilling option suits better the airport depending on its size. Although this information is not much relevant in terms of added costs to fuel price (from 3% to 4% of total LH_2 costs), it certainly represents a major enabler in the H_2 technologies deployment. The choice of LH_2 pipelines and hydrants, compared to trucks, is still uncertain on economic bases. For airports with large demand of LH_2 (above 100 ktLH_2) and low space on the apron, the main drivers should be safety and efficiency guaranteed using pipelines. For smaller airports (demand below 20ktLH2/annum) a more practical and economic approach is feasible with refuelling trucks. A cost projection of 2.60 \$2020/kgLH_2 at larger airport and 3.50 at smaller airport for 2050 is envisioned.

3.4. Fees and crews

Model of fees applied is the same as for conventional aircraft. Their high dependence with MTOM, is due to the correlation of MTOM with profitability. The introduction of new fees or modification to the reference ones, which is likely to happen [25], are not considered.

$$OPEX_{handling} = p_{handling} payload$$
$$OPEX_{landing} = p_{landing} MTOM$$
$$OPEX_{ATC} = f_{ATC} R \sqrt{\frac{MTOM}{50000}}$$

According to [4] fees are divided in:

- Handling includes costs for the turnaround process and pax handling, with $p_{handling}$=0.1 €/kg;
- Landing, with $p_{landing}$=0.01 €/kg;
- Navigation fees depend on the range in [NM], with f_{ATC}=0.5

Also environmental fees represent a share of costs affecting conventional aircrafts: in Europe, commercial aviation belongs to the Europe Trading Scheme (ETS), hence they have to buy from the market CO2 allowances, depending on much emissions are emitted minus the amount of free allocated emission certificates (f_{ETS}) [7].

$$C_{ETS} = U_{ETS} mCO_2, flight(1 - f_{ETS})$$

Another operating cost is represented by the crew, which this time is independent on the fuel used, but only on how many seats are flown. Generally speaking, every 50 PAX, companies have to hire one flight attendant. To fly the same aircraft during the year, different crews (Crew Complements) alternate.

$$OPEX_{crew} = cc(n_{pil} salary_{pil} + n_{fa} salary_{fa})$$

The average salary for flight attendant is 80,000 \$2020/year, while for a pilot is 180,000 \$2020/year [25].

3.5. Key Performance Indicators

In every business, in order to control the desired project output, it is fundamental to control the main sub-processes leading to the optimum result. In this scenario, Key Performance Indicators (KPIs) are customizable business measure, directly linked to business operation/strategy, used to visualize and hence control, processes, status and possible trends. A good KPI can be defined as such, when it is measurable and supports the company goals in an effective way [47].

Traditionally airlines consider their business driven by high costs and their machines driven by kilometres. Most of the KPIs in fact are standardized by ASK (Available Seat Kilometres), that is a measure of airline's capacity. Since the additional cost to fly an extra passenger can be considered marginal, and if not occupied, the empty seat flown won't produce revenue, it makes sense to maximize revenues and load factor [29].

According to Doganis, for an airline to be profitable, managers need to find a good combination among unit costs, unit revenues or yield, and achieved load factors. The right interplay among these parameters will determine if the airline's revenue and financial ambitions can be met. Unit costs are measured with CASK, while unit revenues are calculated with RASK. Load factor is instead a metric to indicate capacity utilization, that is how many kilometres are generated by the occupied seats with respect to available seat kilometres. The former is also known as Revenue Passenger Kilometres (RPK). RPK it is an important measure, because not only load factor is embedded, but also parameters such as average haul length and aircrafts number. Yield, or passenger average fare, it is used to indicate revenues obtained per unit of output sold. Yield hence assumes a crucial role and requires a system to manage it, in order to avoid high yield or low yield spills. Charging too much (high yield) for the ticket might dissuade clients to buy, while charging too little (low yield) would result in little revenues [31].

Revenue or yield management, referring to McGill and Van Ryzin (1999), is a Practice of combining price and inventory controls (meaning seats and different booking options), to maximize revenue. A trivial example could be how cheaper is the ticket bought months in advance the departure, compared to the day before. As Sabre's Ben Vinod put it, 'yield management is, selling the right seat, to the right customer, at the right price, at the right time to maximize system revenues and profitability' [35].

Increasing yield might be an opportunity to raise revenues, but alongside with that an airline can and should concentrate also on the other parameters: operating costs (CASK) and demand (ASK). Some basic strategies are outlined in Figure 3.8, showing risks and possibilities.

	Intended Benefit	**Strategy Pitfalls**
Cutting Fares/ Yields	Stimulate Demand	The price cut must generate a disproportional increase in total demand, "elastic demand"
Increasing Fares/ Yields	Increase Revenue	The price increase can be revenue positive if demand is "inelastic"
Increase Flights (ASM)	Stimulate Demand	Increases Operational Costs
Decrease Flights (ASM)	Reduce Operational Costs	Lower Frequencies made lead to market share losses and lost demand
Improve Passenger Service Quality	Stimulate Demand	Increases Operational Costs
Reduce Passenger Service Quality	Reduce Operational Costs	Excessive cuts can reduce market share and demand

Figure 3.8: KPIs interplay strategies [36]

Increasing fares (consequently yields for the same flight) can be profitable only if the demand is inelastic, meaning that consumer is unresponsive to price change. On the other hand, cutting fares can be stimulating for the demand, since it would attract more elastic travellers. A lower fare can be most favourably consumed by leisure passengers for instance. A surge in capacity might be risky, since flying a larger fleet or flying more kilometers comes with high fixed costs and these must be matched with a surge in demand. Lastly, the quality aspect is always twofold: on one side cutting shorts on quality might be badly perceived by the client and resulting in a fewer shares of passengers; on the opposite side, ensuring a certain quality comes with increase in operational expenses.

The operational expenses (OPEX) are the sum of fuel, fees, maintenance and crew costs, necessary to operate the aircraft. The aforementioned KPIs that will be calculated during this thesis are here summarized:

- Available Seat Kilometers (ASK) = KM*Seats
- Revenue Passenger Kilometers (RPK) = KM*Pax
- Load Factor (LF) = $\frac{RPK}{ASK}$

- Revenue = Fare average*Pax
- Yield = $\frac{Revenue}{RPK}$
- Cost per ASK (CASK) = $\frac{OPEX}{ASK}$
- Revenue per ASK (RASK) = $\frac{Revenue}{ASK}$

If we had to be more precise, revenue it does not perfectly match the description above: some airlines can afford to lower the fare, because most of the revenue come from ancillaries. For a better understanding of how all the KPIs relates, the reader is invited to look at Figure 3.9.

Figure 3.9: A more detailed KPIs overview

When it comes to profitability, other KPIs such as EBIT, EBITDA can be utilized to drive financial performances. Earnings Before Interest Taxes Depreciation Amortization (EBITDA), is used to determine the earning potential of company. It can be calculated as the sum of operating income (operating revenues minus costs) and depreciation and amortization (D&A) expenses [48]:

$$EBITDA = operatingprofit + D\&A = Revenue - OPEX + D\&A$$

- Operating Income: This is the revenue from operations minus operating expenses, including the cost of goods sold, overhead, depreciation, and amortization. Importantly, operating income excludes tax expense and interest on debt.
- Depreciation: An accounting method to allocate the costs of physical (tangible) assets over its life expectancy. You cannot expense the purchase or construction costs of a long-term asset all at once. Instead, you subtract a portion of the expense each year over the asset's useful life. Depreciation measures the utilization of an asset's value by tying cost to the benefit gained over the asset's lifetime. The cash flow for the asset's acquisition occurs in the first year. Since depreciation occurs over the asset's lifetime, it represents a deductible non-cash expense.
- Amortization: This is an expense similar to depreciation, except it refers to intangible assets. It's a way to expense the cost of patents, trademarks, copyrights, goodwill, and other intangible assets over their lifetimes. Like depreciation, amortization is a non-cash expense.
- Total Revenue: This is the total receipts from sales, adjusted for discounts and returns. We also call it gross income.

Earnigs Before Interest Taxes (EBIT), or "operating income", measures the profitability of a company in a specific period, with all core operating costs.

In this work, an EBIDTA margin of 5, 10 and 20% was set. From this target, knowing the operational costs and D&A, revenues for different scenarios were calculated.

The analysis was carried out trying to focus on specific market segments, as divided in [32]. The main market segments can be summarized as:

Category	Description	Typical Examples
Subregional	9 - 19 seat turboprops	Cessna Caravan, Beach 1900, DeHavilland Twin Otter, Dornier 228
Regional	20 - 120 seat turboprops or regional jets	ATR, Dash 8, CRJ, E170/190
Narrowbody	120 - 220 seat narrowbody aircraft, up to 2,400 nmi sector distance	A220, A320, B737
Midsize	Narrowbody aircraft over 2,400 nmi sector; 200-300 seat widebody aircraft, less than 5,250 nmi sector distance	A321XLR, B757, B767, A330
Widebody	Over 300 seats or over 5,250 nmi sector distance	A350, B787, B777

Figure 3.10: Market segments [32]

For every category a reference aircraft has been chosen, and its relative hydrogen counterpart has been designed to replace it, guaranteeing almost the same performances in terms of capacity and speed. Regional aircraft segment is composed of turboprop and regional jets types. This segment is in direct competition with different surface mode of transports, and in the upper end is frightened by the narrowbody market. The reference aircraft picked is the ATR-72. The shorthaul market (narrowbody) is the one fulfilling more share of demand, with this fleet the global aviation was able to operate 64% of flights in 2019. One of the most representative aircraft for this group is the Airbus A320. For the widebody category, covering long rage stages, the Airbus A350 was chosen.

The conventional model and the hydrogen counterpart were benchmarked on the same mission, allowing a thoroughly comparison. The mission was retrieved from [32] data sheet, containing, for each segment, the average sector per day (frequency and length), average block time and other information used to tune some parameters such as flight cycles per year.

The aim of the comparison can be stated as the follow: considering the same financial target, same operational conditions (same city-pairs), how much should the airline charge for the ticket? Is it expensive to switch, and if so, how much?

3.6. Quality of Key Performance Indicators

Generally, certain industries, such as asset-heavy ones, will have relatively high EMs (EBITDA Margins). Specifically, asset-heavy companies have larger depreciation expenses. Since you add depreciation to revenues when figuring EM, the value you calculate will be higher [52].

Cost per available seat kilometres in principle represent a metric giving insights about the overall efficiency of flying the airplane, because with increased efficiency less expenses are due to fuel. Still though (CASK) has its limits: aggregating results does not help discerning the reasons for changing costs. Seat configurations are another key and variable driver of CASK's denominator: the same exact airplane might be configured with less seats but more spacious because are flying business. CASK includes the costs incurred by non passenger divisions, such as cargo or maintenance. Comparisons are almost impossible between carriers that aggregate freight or third-party maintenance operations in their financial reports. CASK neither gives companies deep insight into their costs nor identifies concrete levers to reduce them. The only real way for airlines to learn how cost differentials add up is to build a bottom-up view of the unit costs, volumes, and productivity of their cost buckets. Tracking, measuring, and benchmarking costs is most useful when it inspires action, and that is exactly what driver-based benchmarking helps carriers do. As airlines continue to face cost pressures, a driver-based comparison provides the fact base they need for discussing the trade-offs required to find and implement appropriate savings [38].

For instance, labor costs represent the second largest operating cost item: short terms high fixed costs with common inefficiencies in the labor force, thwart airline's chances to increase its performances. As [30] suggests, measuring revenue generated per employee, becomes a crucial parameter which carriers should take into account. Considering that the first aim of a company is to maximize its shareholders' wealth, it becomes imperative to evaluate financial metrics in airline performance. Improving operating efficiencies does not necessarily mean improved financial efficiency: if a higher load factor implies a better utilisation, we cannot state the same for profitability. It is also important to underline that improving operations stage is limited among airlines, a more meaningful effort should be done to attention the profitability stage, where resource allocation becomes crucial.

4 | Results

4.1. Siena Project

The estimated designs considered were obtained through HYPERION sizing tool, in the context of SIENA project.

HYPERION (HYbrid PERformance SimulatION) is the tool developed by Politecnico di Milano on MatLab, used to preliminary size the aircraft with innovative propulsive systems. HYPERION is a two step sizing process: a convergence on the MTOW of the aircraft gives initial estimations of the mass of the components and power quantities. Subsequently, a time marching algorithm computes the relevant parameters as the mission evolves, allowing to consider the dynamics of the propulsive system. This leads to a correction of the previously estimated quantities, that constitute the final design. The sizing mission is divided into take off, climb, cruise descent, loiter, approach with go around, climb, diversion cruise, descent, approach and landing [43].

SIENA, Scalability Investigation of hybrid Electric concepts for Next-generation Aircraft, is a project born with the ambition to accelerate the development of hybrid electric A/C technologies in larger vehicles through the identification of scalable technologies that are reusable across vehicle classes. Economic, operational and regulatory aspects, will be considered in the project beyond the technical considerations. Those include key elements such as impact on infras- tructure, vehicle safety, operational reliability and industrial competitiveness, will ensure that the technologies proposed are not only technically feasible but viable for the industry as a whole.

4.2. ATR 72

The ATR72-600 is a latest version design this well-popular twin turboprop. During the years more than 1000 frames were built of the ATR72 series, showing a great interest in this machine. It is mostly used for hub feeding, but it also operated in point to point missions. Some of the key features are listed below.

ATR72

	LH_2	**Kerosene**
MTOM [kg]	23766	23766
Payload [kg]	7880	7900
Seats	70	70
Average sector regional	4.6 sector/day 660 km (356 NM)	4.6 sector/day 660 km (356 NM)
Block hour	1.5	1.5
Flight hour	1.36	1.36
Flight cycles	1679	1679
Fuel burn [kg]	305	1300
Fuel price [€/kg]	6	1.15

Table 4.1: Main features of the two ATR72 designed models

The LH_2 version is still a twin turboprop with propellers driven by electric motors, powered by fuel cell. The resulting weight breakdown sized in HYPERION is listed below in Table 4.3

ATR72 LH_2 Weight breakdown

	Values in [kg]
MTOM	23766
OEM	15421
Payload	7880
Electric Motors	461
Battery Cells	1152
Fuel Cell	683
Tank	253
Systems	2436

Table 4.2: Main components weight of the hydrogen ATR72 designed model

Other important data such as specific power and specific energy of the components used for the design are listed below:

Specific quantities of electronic components

	Values in [kg]	Unit
Battery Specific Power	2.28	[kW/kg]
Battery Specific Energy	0.35	[Wh/kg]
Electric Motor Specific Power	11.10	[kW/kg]
Fuel Cell Specif Power	4.80	[kW/kg]

Table 4.3: Specific quantities chosen in the design

The following inputs were used to generate the yearly expenses to operate these aircrafts a on single mission. The cost breakdown is divided in OPEX and in CAPEX. Operational expenditures are generated by

- Fees,
- Crew,
- Maintenance,

- Fuel

Depreciation and amortization is derived by the price of acquisition of the aircraft, made up component-wise also considering spare parts:

- Airframe,
- Tank,
- Battery,
- Fuel Cell
- Electric Motors
- PMAD

The hydrogen ATR72 flying 660km, 1679 times per year, generates the following operating expenses

Hydrogen ATR72 Expenses and Shares

	Values in Million €/annum	Shares
CAPEX	2.95	26.49%
OPEX Fuel	3.07	27.57%
OPEX Fees	1.93	17.33%
OPEX Crew	2.18	19.53%
OPEX Maintenance	1.44	9.13%
OPEX tot	8.19	73.51%
DOC tot	11.7	100%

Table 4.4: DOC, ATR72 LH_2

Kerosene ATR72 Expenses and Shares

	Values in Million €/annum	Shares
CAPEX	3.14	29.09%
OPEX Fuel	2.50	23.16%
OPEX Fees	2.02	18.71%
OPEX Crew	2.18	20.15%
OPEX Maintenance	0.97	8.95%
OPEX tot	7.66	70.91%
DOC tot	10.8	100%

Table 4.5: DOC, ATR72 Conventional

If we compare CAPEX, for the LH_2 version, even though we had to add shares related to fuel cell, battery and hydrogen tank, the price for the conventional engine is way higher than a propulsion system with electric motors. Fees for the conventional increase due to carbon taxes deriving from burning Jet A-1 fuel. This fee was not sustained by the hydrogen counterpart, being responsible for zero CO_2 emissions. Maintenance opex increase for the ATR 72 LH_2, due to a heavier OEM. Crew opex remain the same for both aircraft. The increase in total OPEX for the LH_2 aircraft is about 6.9% if benchmarked with its conventional peer.

Once known the operational expenses and D&A values, setting an EBITDA margin of 5, 10 and 20%, it was possible to calculate the necessary revenue to reach the target. Different Load Factor scenarios are set to simulate a change in demand. When the different demands are known, the calculation of yield and fare average came pretty straightforward.

In Table 4.6 below it is shown the calculation with EBIDTA margin of 10%. The other results obtained for the LH_2 models putting different EBITDA margins are shown in the Appendix A .

KPIs ATR72 models

	LH_2	Conventional
ASK in million	77.5	77.5
Revenue in € million	5.82	5.02
CASK in € cents	10.57	9.89
RASK in € cents	7.52	6.48

Table 4.6: KPIs obtained setting an EBITDA Margin of 10%, ATR72 Conventional and LH_2

Mission KPIs LH_2

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	38.7	46.5	54.2	62.0	69.7
Yield in € cents	15.03	12.53	10.73	9.40	8.35
Fare Average in €	99	83	71	62	55

Table 4.7: Setting different demand scenarios, the average fare was calculated, ATR72 Conventional

Mission KPIs Conventional

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	38.7	46.5	54.2	62.0	69.7
Yield in € cents	12.96	10.80	9.26	8.10	7.20
Fare Average in €	85	71	61	53	47

Table 4.8: Setting different demand scenarios, the average fare was calculated, ATR72 LH_2

The increase in CASK for the LH_2 aircraft, due to higher maintenance cost and expensive price of fuel, is matched by an increase in RASK. Probably the most intuitive parameter to compare is the fare average price. Increasing the revenue has to be stepped back with an increase in ticket price; as mentioned before though, revenue and ticket price not always are equivalents, but this will be investigated later on. The average fare increase from conventional to LH_2 is about 16%. Since fuel costs represent a good share of operational expenses, and still there is a lot of uncertainty regarding hydrogen price at the refueling station, other two scenarios will be discussed too. The hydrogen price was set to 4.5 €/kg and a very optimistic price of 3 €/kg. It is interesting to note how for the first scenario, prices match almost exactly the ones a conventional airline should charge. In the more unfeasible scenario of 3 €/kgLH2, prices drop by -17%.

Fare Average for different LH_2 price sCenarios

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
Conventional	85	71	61	53	47
LH_2 6 €/kg	99	83	71	62	55
LH_2 4.5 €/kg	85	71	60	53	47
LH_2 3 €/kg	70	58	50	44	39

Table 4.9: Fares obtained simulating a change in LH_2 price, compared to conventional, ATR72

4.3. Airbus A320

The Airbus A320 Neo family is a development of the A320 family of narrow- body airliners produced by Airbus. In 2010 the year of commercialization, already 2000 orders were placed, making it the highest-selling airliner. Powered by a Pratt & Whitney's PurePower PW1100G-JM geared turbofan, Airbus says 'the A320neo delivers 20% fuel savings and CO_2 reduction compared to previous-generation Airbus aircraft' [49].

Assessing the innovative propulsive configuration proposed for the Airbus A320 the two jet fuel-burning engines have been replaced by hydrogen-burning engines. Therefore, the energy comes from hydrogen, which is stored as a liquid in an insulated tank. Later in the project, a hybrid assist for the fan will also be implemented: the electricity will come from a fuel cell, which will also power the on-board systems. For the sake of this study, only the effects generated by changing the propellant will be investigated.

The major structural differences among the two players consist in an increase of the airframe length to accommodate the tank for liquid hydrogen storage. As far as the regional airplane is concerned, the influence of the tank volume is not much relevant, considering the little quantity of hydrogen stored. When it comes to short-hauls segment, the increase in range and passengers implies higher fuel consumption, which necessarily lead to an increase in airframe weight of 15% for the LH_2 version, to make room for a larger tank. For a conventional aircraft the tank weight is considered close to zero when compared to the kg of fuel stores.

The two versions were benchmarked on a mission of 1317 km, being the average range for this market. With this mission range, in 2021 according to [50], almost all the world's 20 busiest air routes would have been covered.

A320 Models

	LH_2	**Kerosene**
MTOM	74794 kg	78425 kg
Payload	19700 kg	20100 kg
Seats	179	179
Average sector narrow-body	4.1 sector/day 1317 km (711 NM)	4.1 sector/day 1317 km (711 NM)
Block hour	2.4	2.4
Flight hour	2.24	2.24
Flight cycles	1497	1497
Fuel burn	1600 [kg]	3820 [kg]
Fuel price	6 €/kg_{LH2}	1.15 [€/kg] Jet A-1

Table 4.10: Main features of the two A320 designed models

Since the main characteristics relative to the hydrogen concept here developed, can be summarized in an increase in OEM, expensive cryogenic tank add-on, while the engines are almost the same in terms of weight. These factors will incur in a costlier acquisition price, reflected by an increase in CAPEX.

Hydrogen A320 Expenses and Shares

	Values in Million €/annum	Shares
CAPEX	11.7	32.49%
OPEX Fuel	14.4	40.15%
OPEX Fees	4.7	13.13%
OPEX Crew	2.9	7.99%
OPEX Maintenance	2.3	6.35%
OPEX tot	24.3	67.51%
DOC tot	36.0	100%

Table 4.11: DOC, A320 LH_2

Conventional A320 Expenses and Shares

	Values in Million €/annum	Shares
CAPEX	10.5	38.71%
OPEX Fuel	6.6	24.33%
OPEX Fees	5.1	18.73%
OPEX Crew	2.9	10.58%
OPEX Maintenance	2.1	7.65%
OPEX tot	16.6	61.39%
DOC tot	27.1	100%

Table 4.12: DOC, A320 Conventional

A huge impact is once again determined by fuel OPEX: flying a single aircraft on the same route will increase fuel expenses by more than 100%. Once again it is clear how much fuel expenses burden the industry, and the necessity to reach and go below a threshold in LH_2 price becomes a key enabler for this new technology. The great advantage of higher energy provided by 1kg of hydrogen, which is roughly equivalent to 3kg of Jet A1, is lost in economic terms, considering that the LH_2 price of 6 €/kg is almost six times the one for Jet A1. It becomes necessary more than before, to investigate the sensitivity to fuel prices. Also here, the same two scenarios for the LH_2 price are considered. The overall increase in direct operating costs is calculated to be around 33%. To keep up with higher OPEX, average fares will necessarily have to grow.

KPIs A320 models

	LH_2	Conventional
ASK in million	353	353
Revenue in € million	14.0	6.81
CASK in € cents	6.88	4.70
RASK in € cents	4.00	1.90

Table 4.13: KPIs obtained setting an EBITDA Margin of 10%, A320 Conventional and LH_2

Mission KPIs LH_2

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	176	212	247	282	318
Yield in € cents	7.93	6.61	5.67	4.96	4.41
Fare Average in €	105	87	75	65	58

Table 4.14: Setting different demand scenarios, the average fare was calculated, A320 LH_2

Mission KPIs Conventional

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	176	212	247	282	318
Yield in € cents	3.86	3.32	2.76	2.41	2.14
Fare Average in €	51	42	36	32	28

Table 4.15: Setting different demand scenarios, the average fare was calculated, A320 Conventional

It becomes evident from these results how deeply fuel price affects an airline, when it comes to ticketing strategy. Halving LH_2 price from 6 to 3 €/kg, would make the LH_2 A320 a cheaper option than its conventional counterpart.

Fare Average for different LH_2 price senarios

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
Conventional	51	42	36	32	28
LH_2 6 €/kg	105	87	75	65	58
LH_2 4.5 €/kg	74	62	53	47	41
LH_2 3 €/kg	45	38	32	28	25

Table 4.16: Fares obtained simulating a change in LH_2 price, compared to conventional, A320

4.4. Airbus A350-900

The Airbus A350 is a long-range, wide-body jet airliner developed by Airbus. The first A350 design proposed by Airbus in 2004, in response to the Boeing 787 Dreamliner, would have been a development of the A330 with composite wings and new engines. As market support was inadequate, in 2006, Airbus switched to a clean-sheet "XWB" (eXtra Wide Body) design, powered by Rolls-Royce Trent XWB turbofan engines. The longest operated sector was Qatar Airways' Adelaide–Doha at 13.8 hours for 6,120 NM (11,334 km). 45% of flights were under 3,000 NM (5,556 km), 16% over 5,000 NM (9,260 km), and 39% in between [51].

The hydrogen version is a retrofitted conventional one, burning hydrogen stored liquid. The considerations made for the structural design of the A320 here don't apply: the design here had the objective to maintain the same size for the aircraft, while modifying the payload. The A350 brings up to 332 passengers, while the hydrogen version can bring up to 266 passengers.

A350-900

	LH_2	Kerosene
MTOM	193815 kg	281668 kg
Payload	26631 kg	53800 kg
Seats	266	332
Average sector widebody	2 sector/day 5197 km (2806 NM)	2 sector/day 5197 km (2806 NM)
Block hour	7.0	7.0
Flight hour	6.77	6.73
Flight cycles	730	730
Fuel burn	15500 [kg]	40429 [kg]
Fuel price	6 €/kg_{LH2}	1.15 [€/kg] Jet A-1

Table 4.17: Main features of the two A350 designed models

MTOM is way bigger for the conventional one (282 ton versus 194 ton), due to payload and fuel. Also the weight of the engines is higher for the kerosene version (44% increase) since it has to sustain almost 90 tonnes more.

Hydrogen A350-900 Expenses and Shares

	Values in Million €/annum	Shares
CAPEX	32.6	28.68%
OPEX Fuel	67.9	59.75%
OPEX Fees	5.38	4.73%
OPEX Crew	3.9	3.44%
OPEX Maintenance	3.87	3.41%
OPEX tot	81.1	71.32%
DOC tot	114	100%

Table 4.18: DOC, A350 LH_2

Conventional A350-900 Expenses and Shares

	Values in Million €/annum	Shares
CAPEX	34.1	39.87%
OPEX Fuel	34.0	39.75%
OPEX Fees	9.4	11.26%
OPEX Crew	3.9	4.58%
OPEX Maintenance	3.88	4.54%
OPEX tot	51.4	60.13%
DOC tot	85.5	100%

Table 4.19: DOC, A350 Conventional

All the expenses are comparable between the two models, except when it comes to fuel related expenses. This shows once again how a price of 6 €/kg for liquid hydrogen at the dispenser results in a major barrier for airliners to operate the new technology.

KPIs A350-900 models

	LH_2	Conventional
ASK in billion	1.01	1.26
Revenue in € million	53.9	19.3
CASK in € cents	8.03	4.08
RASK in € cents	5.06	1.53

Table 4.20: KPIs obtained setting an EBITDA Margin of 10%, A350 Conventional and LH_2

Difference in revenues account for almost 34.4 millions €, which is almost three times the revenues necessary to obtain an EBITDA Margin of 10% for the conventional. Also the cost per available seat kilometers jumps from 4.08 € cents to 8.03 € cents. These details shows how much fuel expenses affect this market segment.

Mission KPIs Hydrogen

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	505	605	706	807	908
Yield in € cents	10.67	8.90	7.62	6.67	5.93
Fare Average in €	555	462	396	347	308

Table 4.21: Setting different demand scenarios, the average fare was calculated, A350 LH_2

Mission KPIs Conventional

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	630	756	882	1010	1130
Yield in € cents	3.06	2.55	2.18	1.91	1.70
Fare Average in €	159	132	113	99	89

Table 4.22: Setting different demand scenarios, the average fare was calculated, A350 Conventional

Fare Average for different LH_2 price senarios

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
Conventional	159	132	113	99	89
LH_2 6 €/kg	555	462	396	347	308
LH_2 4.5 €/kg	360	300	257	225	200
LH_2 3 €/kg	166	138	119	104	92

Table 4.23: Fares obtained simulating a change in LH_2 price, compared to conventional, A350

Lowering the price of hydrogen at 3 €/kg results crucial to achieve similar economic performance of the kerosene based aircraft, which still remains more economic under every aspect.

4.5. Operating Profit

In 1997 Cleland suggested a performance management system, called CBA (Contribution Based Activity), which focuses on the output in terms of the fundamental activity to reach that output. Complementing financial (profit = revenue − costs) with operational metrics (units of output), hence working with key profit-driving indicators, can lead to a better and more thoroughly management overview.

In line with this approach, Demydyuk, G. [28] proposes to concentrate on profit instead of revenue per seats, and not ASK or RPK. In literature in fact, the unit profit is usually considered per ASK, as it grasps the supply of airtravel capacity [31].

In her research, [28] she demonstrated that airlines which tried to achieve gradual increase in yields, RPKs and load factors, hence focusing on 'traditional' KPIs, belonged to the class of financial low performers. On the other hand, high performers were companies which tried to increase their operating profit per passenger. Operating profit per passenger is considered the most significant variable predicting airline profitability, while the approach based on revenue, unit cost and load factor can be misleading. This KPI (Operating Profit per Seat sold) can be defined as:

$$OP = \frac{Revenue - Costs}{SeatsSold}$$

This method implies considering the airline business as driven by passengers and not kilometres. From this approach, also results easier to set more meaningful and immediate targets to be implemented by the staff. Targeting a profit margin of 1 EUR per passengers is more straightforward than trying to achieve one cent of operating profit per RPK. The effect of earning that extra euro per passenger, but at the same time possibly lose that extra euro if not considering the aforementioned indicator, multiplied by millions of passengers per year, can turn into a financial success or disaster.

Another parameter that is used to monitor financial health of a company is the operating margin [31], [**?**]. The operating margin (OM) is defined as the percentage of profit made for 1 EUR of revenue:

$$OM = \frac{Revenue - Costs}{Revenue}$$

Setting different operating profit per passenger of 10, 5 and 1 €, permitted to calculate the revenues necessary to sustain such profit. Simulating different demand, so modifying the load factor, operating costs per passenger carried and the average fare were calculated. Also for the case where LH_2 has a price of 3 €/kg, the average fares were reported. Operating margin was subsequently obtained. Following this approach, the results among the two carriers are not so exacerbated. The operating margin increases accordingly to a reduction in average fare: since the net profit was kept constant, the airline which is able to minimize its ticket price, obtains a higher margin. The two parameters OP and OM are profoundly correlated.

4.5.1. ATR72 Fare average

Considering the LH_2 ATR72, the difference in average fare compared to the conventional is +7 € for the baseline scenario, while -13 € for the most optimistic scenario. Since this segment is used on very short routes, the influence of fuel price does not a play a major lever to operational costs.

Revenue in € Millions for different OP, Conventional ATR72

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OP=10€	8.24	8.36	8.48	8.59	8.71
OP=5€	7.95	8.00	8.08	8.12	8.18
OP=1€	7.71	7.72	7.74	7.75	7.76
OM, OP=10€	7.13%	8.44%	9.71%	10.94%	12.14%
OM, OP=5€	3.70%	4.40%	5.10%	5.79%	6.46%
OM, OP=1€	0.76%	0.91%	1.06%	1.21%	1.36%

Table 4.24: Revenue and OM, ATR72 Conventional

Average Fare for different OP, Conventional ATR72

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OPEX per pax in €	130	109	93	81	72
Average Fare, OP=10€	140	119	103	91	82
Average Fare, OP=5€	135	114	98	66	77
Average Fare, OP=1€	131	110	194	82	73

Table 4.25: Fares obtained for different scenarios, ATR72 Conventional

Revenue in € for different OP, ATR72 LH_2 6€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OP=10€	8.78€	8.90	9.01	9.13	9.25
OP=5€	8.49	8.54	8.60	8.66	8.72
OP=1€	8.25	8.26	8.27	8.29	8.30
OM, OP=10€	6.69%	7.93%	9.13%	10.30%	11.44%
OM, OP=5€	3.46%	4.13%	4.78%	5.30%	11.44%
OM, OP=1€	6.69%	7.93%	9.13%	10.30%	11.44%

Table 4.26: Revenue and OM, ATR72 LH_2 6€/kg

Average Fare for different OP, ATR72 LH_2 6€/kg,

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OPEX per pax in €	139	116	100	87	77
Average Fare, OP=10€	149	126	110	97	87
Average Fare, OP=5€	144	121	105	92	82
Average Fare, OP=1€	140	117	101	88	78

Table 4.27: Fares obtained for different scenarios, ATR72 LH_2 6€/kg

Revenue in € Million for different OP ATR72 LH_2 3€/kg,

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OP=10€	7.25€	7.36	7.48	7.60	7.72
OP=5€	6.95	7.00	7.07	7.13	7.19
OP=1€	6.72	6.73	6.74	6.75	6.77
OM, OP=10€	8.11%	9.58%	11.00%	12.37%	13.71%
OM, OP=5€	4.23%	5.03%	5.82%	6.59%	7.36%
OM, OP=1€	0.87%	1.05%	1.22%	1.39%	1.56%

Table 4.28: Revenue and OM, ATR72 LH_2 3€/kg

Average Fares for different OP, ATR72 LH_2 3€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OPEX per pax in €	113	94	81	71	63
Average Fare, OP=10€	123	104	91	81	73
Average Fare, OP=5€	118	99	86	76	68
Average Fare, OP=1€	114	95	82	72	64

Table 4.29: Fares obtained for different scenarios, ATR72 LH_2 3€/kg

4.5.2. A320 Fare average

The A320 starts to show fuel price dependency: from 102 € for the conventional version, the hydrogen powered counterpart's fare average surge by a 44% to 147 € for the baseline, while only a 2,9% increase is attributed to the most optimistic scenario. In both cases, the conventional version demonstrates to be the more economic choice. If liquid hydrogen price is scaled down to 3 €/kg, then the adoption of the more eco-friendly aircraft won't be economically disrupting for airlines.

Revenue in € Millions for different OP, Conventional A320

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OP=10€	17.96€	18.22	18.49	18.76	19.03
OP=5€	17.29	17.42	17.55	17.69	17.82
OP=1€	16.75	16.78	16.80	16.83	16.86
OM, OP=10€	7.46%	8.82%	10.14%	11.42%	12.67%
OM, OP=5€	3.87%	4.61%	5.34%	6.06%	6.76%
OM, OP=1€	0.80%	0.96%	1.12%	1.27%	1.43%

Table 4.30: Revenue and OM, A320 Conventional

Average Fares for different OP, Conventional A320

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OPEX per pax in €	124	103	89	78	69
Average Fare, OP=10€	134	113	99	88	79
Average Fare, OP=5€	129	108	94	83	74
Average Fare, OP=1€	125	104	90	79	70

Table 4.31: Fares obtained for different scenario, A320 Conventional

Revenue in € Millions for different OP, A320 LH_2 6€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OP=10€	25.61	25.88	26.15	26.42	26.68
OP=5€	24.94	25.08	25.21	25.34	25.48
OP=1€	24.41	24.43	24.46	24.49	24.51
OM, OP=10€	5.23%	6.21%	7.17%	8.11%	9.03%
OM, OP=5€	2.68%	3.20%	3.72%	4.23%	4.73%
OM, OP=1€	0.55%	0.66%	0.77%	0.88%	0.98%

Table 4.32: Revenue and OM, A320 LH_2 6€/kg

Average Fares for different OP, A320 LH_2 6€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OPEX per pax in €	181	151	129	113	101
Average Fare, OP=10€	191	161	139	123	121
Average Fare, OP=5€	186	156	134	118	106
Average Fare, OP=1€	182	152	130	114	102

Table 4.33: Fares obtained for different scenarios, A320 LH_2 6€/kg

Revenue in € Millions for different OP, A320 LH_2 3€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OP=10€	18.40	18.66	18.93	19.20	19.47
OP=5€	17.73	17.86	17.99	18.13	18.26
OP=1€	17.19	17.22	17.24	17.27	17.30
OM, OP=10€	7.28%	8.61%	9.90%	11.16%	12.38%
OM, OP=5€	3.78%	4.50%	5.21%	5.91%	6.60%
OM, OP=1€	0.78%	0.93%	1.09%	1.24%	1.39%

Table 4.34: Revenue and OM, A320 LH_2 3€/kg

Average Fares for different OP, A320 LH_2 3€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OPEX per pax in €	127	106	91	80	71
Average Fare, OP=10€	137	116	101	90	81
Average Fare, OP=5€	132	111	96	85	76
Average Fare, OP=1€	128	107	92	81	72

Table 4.35: Fares obtained for different scenario, A320 LH_2 3€/kg

4.5.3. A350 Fare average

Considering the long haul version, it becomes imperative a reduction in fuel price to even consider the replacement of the kerosene version from an economic perspective: the average fare passes from 336 € to 655 €, with an increase of 98%. In the other scenario, the average fare rises to 378 €, with an increase of 'just' 13%. It is worth reminding that the LH_2 has 266 seats vs 332 of the conventional counterpart, so more revenues have to be collected on a single passenger.

Revenue in € Millions for different OP, A350 Conventional

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OP=10€	52.64	52.88	53.12	53.36	53.61
OP=5€	52.03	52.15	52.27	52.39	52.52
OP=1€	51.55	51.57	51.59	51.62	51.64
OM, OP=10€	2.33%	2.83%	3.19%	3.63%	4.07%
OM, OP=5€	1.16%	1.39%	1.62%	1.85%	2.08%
OM, OP=1€	0.24%	0.28%	0.33%	0.38%	0.42%

Table 4.36: Revenue an OM, A350 Conventional

Average fare for different OP, Conventional A350

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OPEX per pax in €	424	354	303	265	236
Average Fare, OP=10€	434	364	313	275	246
Average Fare, OP=5€	429	359	308	270	241
Average Fare, OP=1€	425	355	304	266	237

Table 4.37: Fares obtained for different scenarios, A350 Conventional

Revenue in € Millions for different OP, A350 LH_2 6€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OP=10€	82.04	82.23	82.43	82.62	82.81
OP=5€	81.55	81.65	81.75	81.84	81.94
OP=1€	81.16	81.18	81.20	81.22	81.24
OM, OP=10€	1.19%	1.44%	1.65%	1.88%	2.11%
OM, OP=5€	0.60%	0.71%	0.83%	0.95%	1.07%
OM, OP=1€	0.12%	0.14%	0.17%	0.19%	0.22%

Table 4.38: Revenue an OM, A350 LH_2 6€/kg

Avearge Fare for different OP, A350 LH_2 6€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OPEX per pax in €	835	696	596	522	464
Average Fare, OP=10€	845	706	606	532	474
Average Fare, OP=5€	840	701	601	527	469
Average Fare, OP=1€	836	697	597	523	465

Table 4.39: Fares obtained for different scenarios, A350 LH_2 6€/kg

Revenue in € Millions for different OP, A350 LH_2 3€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OP=10€	48.08	48.28	48.47	48.67	48.60
OP=5€	47.60	47.69	47.79	47.89	47.99
OP=1€	47.21	47.23	47.5	47.27	47.29
OM, OP=10€	2.04%	2.47%	2.80%	3.19%	3.58%
OM, OP=5€	1.02%	1.22%	1.42%	1.62%	1.82%
OM, OP=1€	0.21%	0.25%	0.29%	0.33%	0.37%

Table 4.40: Revenue an OM, A350 LH_2 3€/kg

Fare Average for different OP, A350 LH_2 3€/kg

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
OPEX per pax in €	485	404	347	303	270
Average Fare, OP = 10€	495	414	357	313	280
Average Fare, OP = 5€	490	409	352	308	275
Average Fare, OP = 1€	486	405	348	304	271

Table 4.41: Fares obtained for different scenarios, A350 LH_2 3€/kg

4.6. Differences in model output

When comparing the average fares resulted from the different approaches, the latest approach gave higher results, which seemed more adherent to reality. In the following figures, the highest and lowest mean fare average are on display, taking into account different fuel price, classes and approaches.

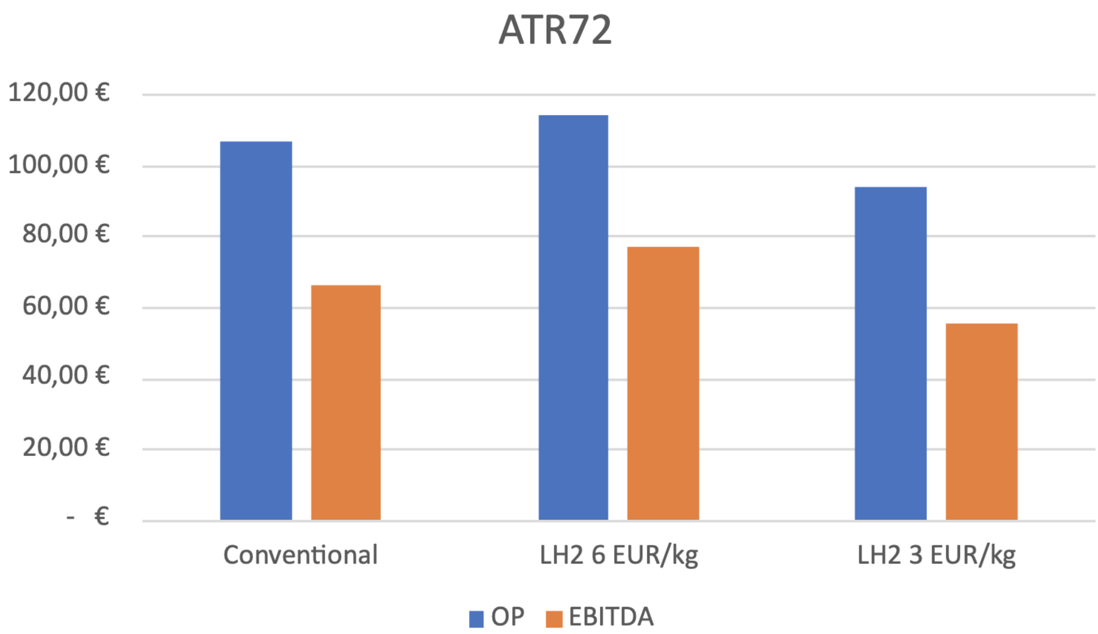


Figure 4.1: ATR72 mean ticket price from the two approaches

The results obtained for the ATR72 show a neat increase in mean ticket price when using Operating Profit as financial target. The airliner using the ATR72 hydrogen version could charge around 114 € with LH_2 at 6 €/kg, while 94 €/kg in the more optimistic scenario of 3 €/kg. This would result in a cheaper ticket than the conventional one, being around 107 €.

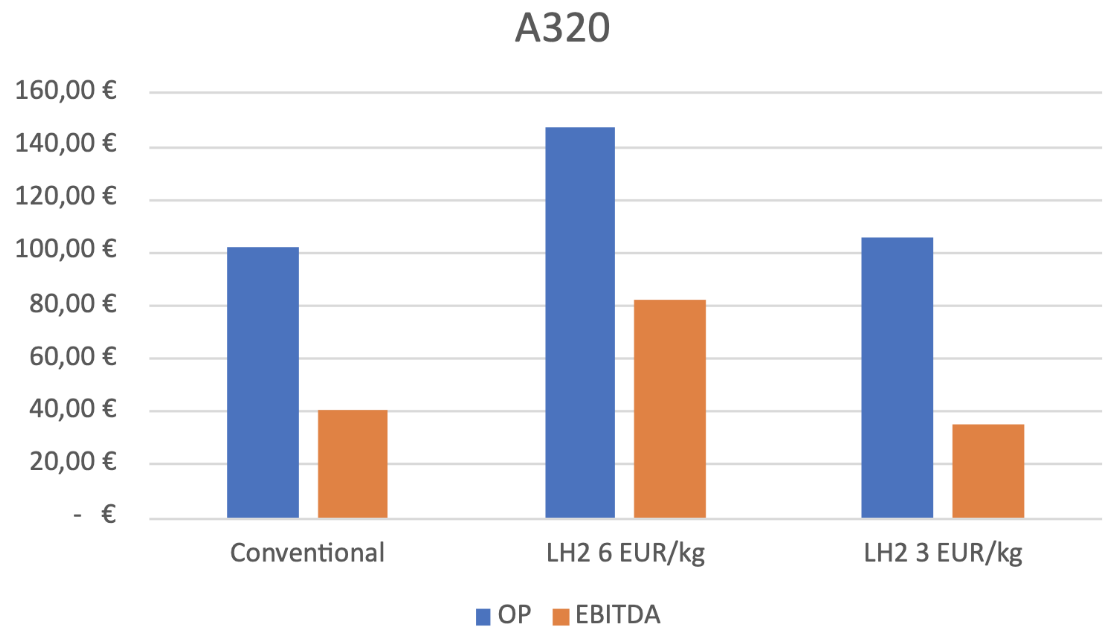


Figure 4.2: A320 mean ticket price from the two approaches

The results obtained here instead show a lot more of difference between the model outputs, probably due to the higher stake of D&A that adds on as a non cashback injection to revenues when using EBITDA Margin. The conventional A320 in fact, sees an increase in ticket price of more than 100%; in the same way when LH_2 is at 3 €/kg, the price spikes from 35 € to 105€.

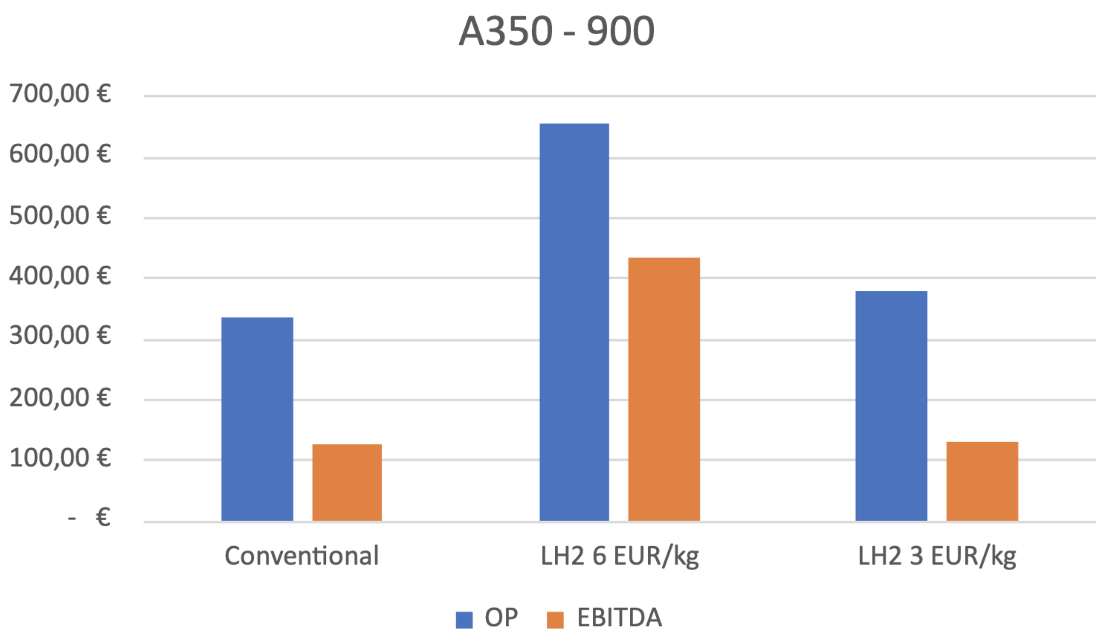


Figure 4.3: A350-900 mean ticket price from the two approaches

The A350-900 results confirms this trend in fare average increase from a model to another. Prices almost triple, going from 124 € to 336 € for the conventional while from 129 € to 378€ for the optimistic hydrogen price. When targeting Operating Profit, the conventional version not only carries more people (332 vs 266) but still results more economic than its hydrogen counterpart.

4.7. Airlines booking

To have a direct comparison with the actual market price, a research across the website to book a ticket was carried on. Even tough the ticket price strategy differs among airlines and their actual cost model leading to a ticket price is way more complex than the one used in this study, this comparison for sure will help to realize which of the two model is more in line with reality.

4.7.1. NPE-CHC

For the ATR72, the flight operated by Air NewZealand from Napier (NPE) to Christchurch (CHC) on the 10/10/22 was chosen because of its stage length (573 km), similar to the one chosen in this study. In New Zeland due to its geographical configuration, preventing the devlopment of sostitutive mean of transport such as

High-Speed Railways (HRS), and due to its low population, the regional turboprop represents a great opportunity to move across the country. Air NewZeland is operating 29 ATR72 and 23 Q300, that is a smaller turboprop with 50 seats. The different price options are in Figure 4.4

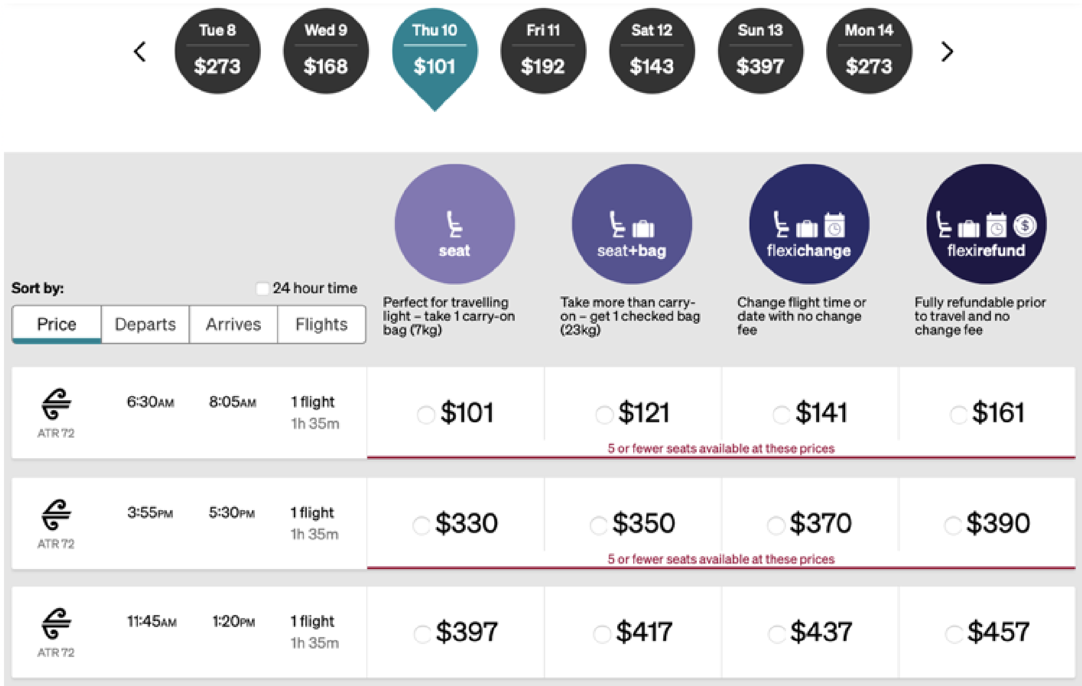


Figure 4.4: ATR72 operated by Air NewZealand, ticket price

Considering an exchange rate NZD/EUR of 0.59, fares range from a minimum of 60€ to a maximum of 234€ with a fare average of 147€, so more or less similar to the price found considering net profit as the target.

4.7.2. FMC-MAD

For the A320, Ryanair company was chosen since it represents one of the most famous airline in Europe, and operates mainly short-hauls that fit the sample. To be fair, Ryanair operates the A320 market rival, the Boeing B737. Airbus A320 and Boeing B737 are the world's best-selling aircraft of all time that changed the game in the aviation industry. They both have set the standard on the single-aisle market through their introduction and improvement continuously. In terms of order and deliveries are neck-to-neck, meaning both aircraft have a throat-cut global competition. In terms of performance are perfectly comparable, so it deemed a perfect substitute. Specifically, a flight from Rome (FMC) to Madrid (MAD) for its stage length of 1334 km was considered, while the reference mission considered in the study is 1317 km.

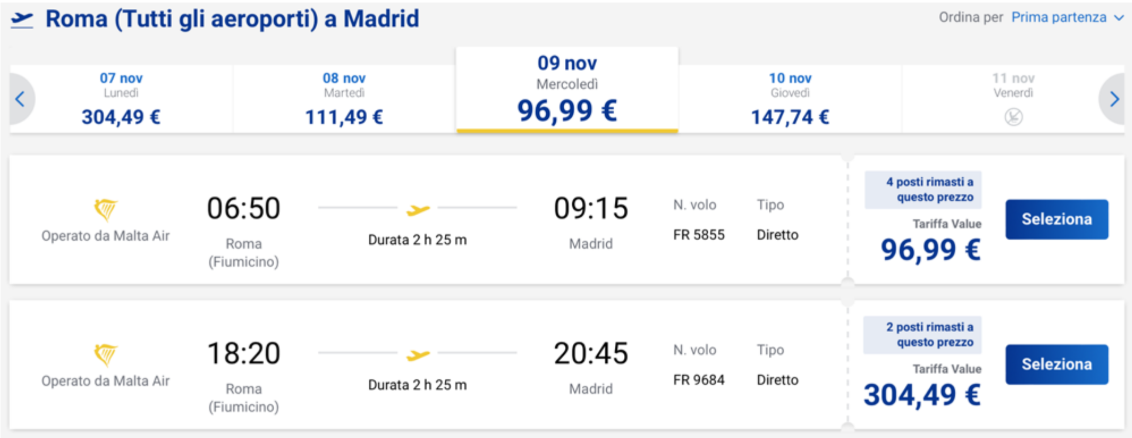


Figure 4.5: A320 operated by Ryanair, ticket price

The european market is well known for its high competitiveness, so carriers have to set lower prices to attract passengeres, and yet the cheapest mean ticket price is around 200 €, being higher than the average fare found using both methods. Still though, the net profit approach seems to predict more accurately the price.

4.7.3. DOH-CDG

Regarding the A359, a flight operated on 10 november 2022 by QatarAirways from Doha (DOH) to Paris Charles de Gaulle (CDG) with stage length of 4993 kilometres (reference mission of 5197 kilometers) was taken into account. QatarAiways in 2019 was crowned by Skytrax as the best airline in the world, therefore it represents the best benchmark possible.

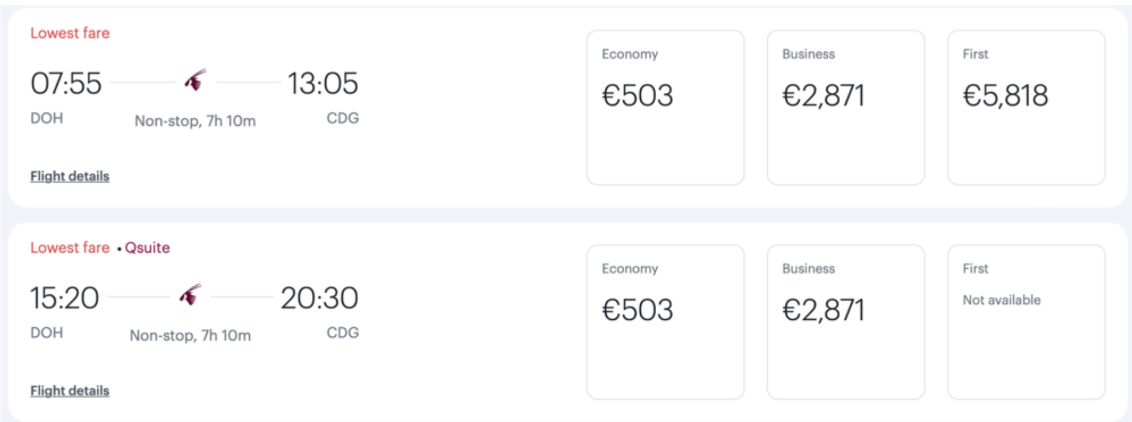


Figure 4.6: A350-900 operated by QatarAirways, ticket price

QatarAirways adopts a fixed price policy, since the ticket has the same price no matter the time of the day or the day of the week. The price of 503€ is way higher than the two found in this study, but the price achieved targeting net profit is way more realistic than the one found targeting EBITDA margin (334€ vs 114€).

Conclusions and future developments

As shown in this work, hydrogen represents a good mean to reach zero or near zero emissions in aviation. The increase in passenger demand will inevitably increase flight-related emissions, so a lot of pressure has been put to the aviation community to decarbonise the industry as soon as possible. The first window of opportunity to introduce a commercial narrowbody will be around 2035, but this comes with major challenges either technological and economical that have to be overcome by the industry players.

- Research and Investment: to enable the compatibility of hydrogen as a fuel, several changes to the conventional aircraft architecture are needed. Fuel Cell state of the art specific power has to reach higher values to be implemented in commercial short and medium-hauls aircraft. Cryogenic pumps, compressors, valves will be necessary to handle liquid hydrogen at -253 °C, as well as a cryogenic tank with a great deal of insulation. Research efforts should be pointed towards a volume reduction of the tank, in order to decrease the room to accomodate it.

- Maintenance: the application of these new technology not only impact the design, but also the required maintenance to keep them functional. Since no data from existing aircraft are available, a clear maintenance schedule is yet unknown, but only based on maintenance schedule for different vehicles. More downtime translates into less aircraft utilisation and more expenses, so this adds uncertainties on the model.

- Infrastructure: Airports will have to face investments to serve hydrogen aircraft: new cryogenic refuelling systems, whether truck or pipelines and new storage facilities to handle liquid hydrogen. Also safety concerns that could influence the turnaround time, deserve further studies.

- Fuel Price: The production of hydrogen it is still a niche market, hence the price is very high. Furthermore, to produce green hydrogen through electrolisys, a huge scale-up in renewable energies is critical. Along the supply chain, production of hydrogen with electricity represents the most expensive procedure. In addition, new delivery systems are required to keep up with a soar in LH_2 demand at the airport. The final cost at the dispenser is influenced by many factors, but certainly remains one of the main enabler in the diffusion of hydrogen powered aircraft.

The model used to estimate operational and purchase price, it's a preliminary tool to make economic considerations at an early design stage. Prices are predicted in order to keep up with the economic scalability of the technology until 2035. If the application of this model allows to obtain quick economic insights, this does not take into account the aging effect or the demand seasonality and for the new technology the maintenance effort is based on assumptions. After a broad explanation of the main KPIs used by the industry to monitor economic and operational performance of airlines, targeting Operating Profit per passenger and not EBITDA, results in better financial results. Obtaining as output of the two model, an average ticket price, allowed to make a direct comparison between the model output and the actual market ask, which is more in line with the OP target. In all three classes analyzed, the economic superiority of the conventional aircraft is only threatened by the hydrogen counterpart when the price of liquid hydrogen drops to 3 €/kg, showing a lot of sensitivities to fuel price.

Many investments are required to actually permit hydrogen powered aircraft to become a valid alternative to kerosene based aircraft. Many stakeholders are involved, going from manufacturers to airports, to institutions and the community in general. Right now airlines are still struggling to find financial stability, still trying to recover from the financial burden caused during Covid-19 pandemic and now tackling rises in primary goods prices due to inflation. With this being said, probably the lease business, recently rising billions through investments, will become one of the first key player to introduce hydrogen aircraft in their fleet. There's a long road before hydrogen aircraft will entirely replace kerosene based ones, but the entire industry is focused to shift towards carbon neutrality as soon as possible, so it is not matter of if, but when.

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A | Appendix A

Hydrogen ATR72 Expenses and Shares

	Values in Million €/annum	Shares
CAPEX	2.95	30.72%
OPEX Fuel	1.54	16.01%
OPEX Fees	1.93	20.10%
OPEX Crew	2.18	22.65%
OPEX Maintenance	1.44	10.59%
OPEX tot	6.66	69.28%
DOC tot	9.60	100%

Table A.1: DOC, ATR72 LH_2 3€/kg

Hydrogen A320 Expenses and Shares

	Values in Million €/annum	Shares
CAPEX	11.7	39.67%
OPEX Fuel	7.2	25.00%
OPEX Fees	4.7	16.42%
OPEX Crew	2.9	9.99%
OPEX Maintenance	2.3	7.94%
OPEX tot	17.1	59.35%
DOC tot	28.7	100%

Table A.2: DOC, A320 LH_2 3€/kg

Hydrogen A350-900 Expenses and Shares

	Values in Million €/annum	Shares
CAPEX	32.6	40.89%
OPEX Fuel	33.9	42.60%
OPEX Fees	5.38	6.75%
OPEX Crew	3.9	4.91%
OPEX Maintenance	3.87	4.86%
OPEX tot	47.1	59.12%
DOC tot	79.7	100%

Table A.3: DOC, A350 LH_2

KPIs ATR72 models

	LH_2
ASK in million	77.5
Revenue in € million	5.5
CASK in € cents	10.57
RASK in € cents	7.12

Table A.4: KPIs obtained setting an EBITDA Margin of 5%, ATR72 LH_2

Mission KPIs Hydrogen

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	39	47	54	62	100
Yield in € cents	14.24	11.87	10.17	8.90	7.91
Fare Average in €	99	88	71	62	55

Table A.5: Setting different demand scenarios, the average fare was calculated, ATR72 LH_2

KPIs ATR72 models

	LH_2
ASK in million	77.5
Revenue in € million	7.1
CASK in € cents	10.57
RASK in € cents	8.46

Table A.6: KPIs obtained setting an EBITDA Margin of 20%, ATR72 LH_2

Mission KPIs Hydrogen

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	39	47	54	62	100
Yield in € cents	16.91	14.09	12.08	10.57	9.40
Fare Average in €	111	93	80	70	62

Table A.7: Setting different demand scenarios, the average fare was calculated, ATR72 LH_2

KPIs A320 models

	LH_2
ASK in million	353
Revenue in € million	11.3
CASK in € cents	6.88
RASK in € cents	3.80

Table A.8: KPIs obtained setting an EBITDA Margin of 5%, A320 LH_2

Mission KPIs Hydrogen

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	176	212	247	282	318
Yield in € cents	7.51	6.26	5.37	4.70	4.17
Fare Average in €	99	88	71	62	55

Table A.9: Setting different demand scenarios, the average fare was calculated, A320 LH_2

KPIs A320 models

	LH_2
ASK in million	353
Revenue in € million	15.7
CASK in € cents	6.88
RASK in € cents	4.46

Table A.10: KPIs obtained setting an EBITDA Margin of 20%, A320 LH_2

Mission KPIs Hydrogen

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	176	212	247	282	318
Yield in € cents	8.92	7.44	6.37	5.58	4.96
Fare Average in €	118	98	84	74	65

Table A.11: Setting different demand scenarios, the average fare was calculated, A320 LH_2

KPIs A350-900 models

	LH_2
ASK in billion	1.01
Revenue in € million	52.0
CASK in € cents	8.03
RASK in € cents	5.06

Table A.12: KPIs obtained setting an EBITDA Margin of 5%, A350 LH_2

Mission KPIs Hydrogen

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	505	605	706	807	908
Yield in € cents	10.11	8.43	7.22	6.62	5.62
Fare Average in €	526	438	375	328	292

Table A.13: Setting different demand scenarios, the average fare was calculated, A350 LH_2

KPIs A350-900 models

	LH_2
ASK in billion	1.01
Revenue in € million	55.7
CASK in € cents	8.03
RASK in € cents	4.13

Table A.14: KPIs obtained setting an EBITDA Margin of 20%, A350 LH_2

Mission KPIs Hydrogen

	LF = 0.5	LF = 0.6	LF = 0.7	LF = 0.8	LF = 0.9
RPK in million	505	605	706	807	908
Yield in € cents	12.01	10.01	8.58	7.51	6.67
Fare Average in €	624	520	446	390	347

Table A.15: Setting different demand scenarios, the average fare was calculated, A350 LH_2