Politecnico di Torino

Tesi di laurea magistrale in
Ingegneria Aerospaziale

Conceptual design of a commercial airliner powered by hybrid-hydrogen architecture

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A Giulia Cecchettin,

che la mia corona d'alloro possa
ogni giorno ricordare chi eri.

Che la mia corona d'alloro possa
"darti" quello che ti è stato strappato
ingiustamente in nome dell'amore.

Che questo tuo disegno possa
ricordare tutte quelle donne
che di voce non hanno più.

Che questi fiori possano simboleggiare
la lotta al patriarcato.

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Torino, 10 Aprile 2024

Abstract

The demand for air traffic has been increasing since more people chose air travel to road travel, and as from the pandemic, the impact of human's emissions has become an increasingly obvious and urgent issue. The use of fossil fuel combustion in aircraft at the state of the art, contributes to the escalation of global emissions, the urgent awareness of climate impact is stimulating the search for pioneering solutions for subsonic aviation attempting in *decarbonizing* our skies. Hydrogen's new technology allow to cut the CO2 emissions off, different solutions could be adopted to innovate the air traffic scenario. Primary target of this master's degree thesis project is the development of an algorithm for a conceptual design process for a full hydrogen-powered aircraft with hybrid technology: fuel cell and direct combustion of gaseous hydrogen.
The methodologies employed aim to implement the conceptual design process of a medium-range aircraft whose high-levels characteristics are comparable to the A320 belonging to the Airbus family. The project showed the importance to consider both passenger and cargo configuration as The methodology developed references to Raymer's approach. The traditional approach not mentions the degree of hybridization, consequently the evaluation could not be done by considering the traditional formulae in the literature for hybrid all-electric aircraft such as variation of the empty operative mass due to the presence of hydrogen tanks, introduction of the degree of hybridization due to non-conventional propulsion and the relative fuel cell mass required to produce the energy. Following initial considerations, an approach involving the identification of high power demand phases was considered.
As first step guessing the hybridization degree, then calculating the maximum takeoff mass (MTOW) and sizing the fuel cell in relation to the degree of hybridization degree. The construction of the matching chart is crucial to evaluate the required thrust to sustain and consequently to power the aircraft. Subsequently a preliminary sketch of the aircraft is provided, sizing the hydrogen tanks and the balance of plant, then allocating the fuel cell stack.
Liquid hydrogen is classified as the best hydrogen storage method, this has an impact on the overall structure resulting in heavier tanks compared to traditional kerosene. A trade-off study is then conducted to establish the best degree of hybridization for main propulsion and the power distribution for the secondary systems. The parallel architecture suggested the utilization of the fuel cell (FC) technology in critical phases such as take-off and climb. The FC is aiming at reducing the specific fuel consumption in the aforementioned segments and in gas turbine critical conditions (idle and taxi), establishing the optimal degree of hybridization to reduce the over-all specific fuel consumption referring to the required mission profile. The thesis revealed the potential impact of hydrogen, its operations anyway won't start before 2030.

Chapter 1

Enviromental impact of aviation & current interests

The primary contributors to global CO2 emissions from transportation include road, aviation, shipping, and rail transportation. About 74.5% of these emissions come from road vehicles, with cars and buses accounting for 45.1% and freight for the remaining 29.4%. Aviation, shipping, and rail transportation contribute around 12%, 11%, and 2% of the total CO_2 emissions, respectively. The growth in transportation demand is anticipated to persist globally, propelled by rising populations and the economic advancement of non-developed countries. ([1])

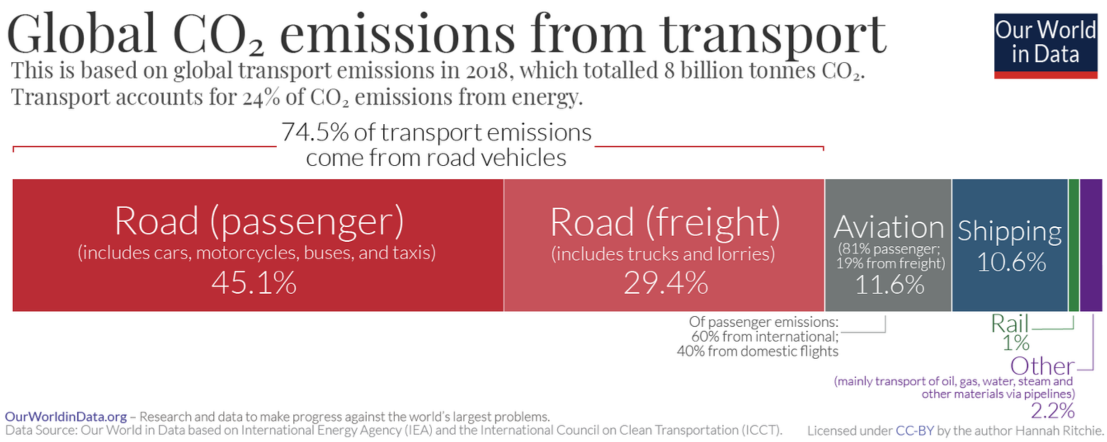


Figure 1.1: Global emissions

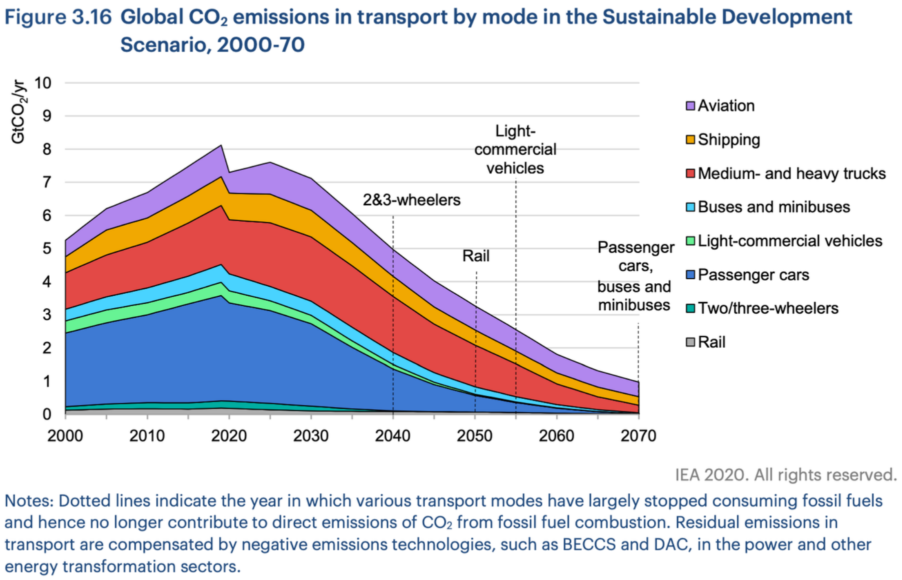


Figure 1.2: CO_2's emissions

1.1 Air quality: pollutants

In subsonic flights some pollutants and greenhouse gases i.e. carbon dioxide (CO_2), unburnt hydrocarbons (HC), soot, sulphur oxides (SO_X), and water vapor (H_2O) are widely known to have be critical with their effects on the environment throughout the duration of a flight, the impact of others remains poorly understood. Aircraft noise and carbon monoxide (CO) are reputedly significant in proximity to the ground, while nitrogen oxides (NO_X) exhibit varying effects at different altitudes. Besides NO_x constitute a threat in the stratosphere to the ozone layer.

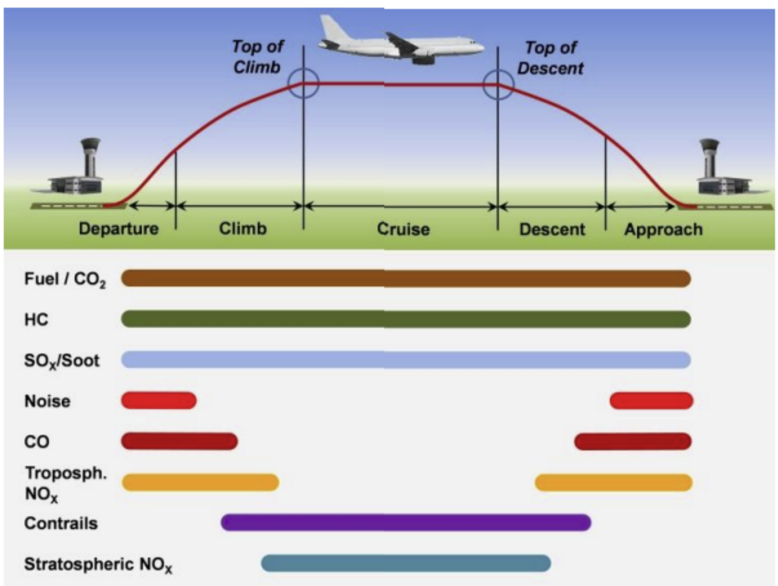


Figure 1.3

The importance of environmental impacts is related to the quality of the air, fuel burned, engine noise. The noise has an important impact around the airports notably during night runway's operations in populated areas. The pollutant could be present as gaseous state and have a significant impact to air quality and human health, photochemical smog evolving in secondary volatile particles. Generally an evaluation of the Air Quality reveals the presence of:

- NOx, family oxides of nitrogen, constituted of nitrogen monoxide and dioxide (NO and NO_2), these elements are produced by the combustion of fossil fuels, at high temperatures in the atmosphere NO oxides into NO_2;
- VOC, volatile organic compounds;
- CO;
- PM, particulate matter includes small solid or liquid particles;
- SO_x, oxides of sulphur

And also the hazardous air pollutants (HAP), known organic gases whose effect could be seen at low concentrations. In June 2020 the EU stated the impact of aviation and pointed out the importance of the carbon neutrality before 2050 introducing hydrogen-powered aircraft starting from 2035. Carbon neutrality's goal could also be achieved with SAF. At the state of the art petroleum-based jet fuels are used to feed the aircraft, the alternative could be the sustainable alternative fuel (SAF) as by 2040, the emissions of CO2 and NOX are expected to increase by 21% and 16% each.

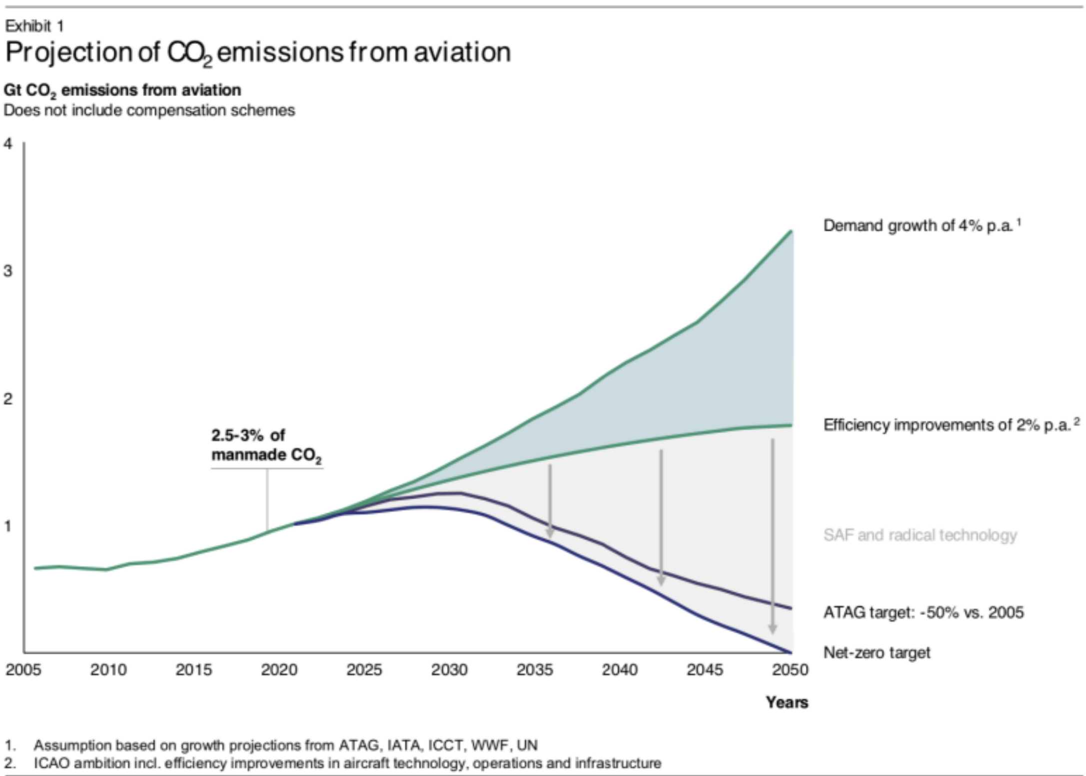


Figure 1.4

Less than 5% of CO_2 are emitted by regional and commuter flights, which edge about 20 percent of today's aircraft, as showed below.

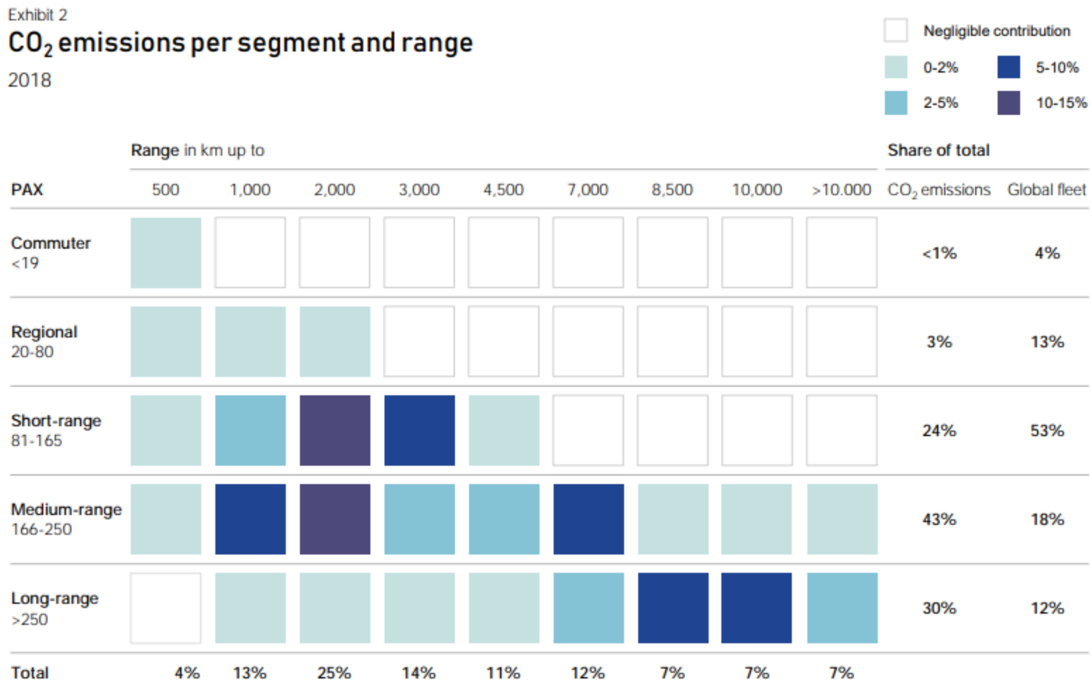


Figure 1.5

As shown in 1.5the main focus should be on short-range segment flying from 1000 to 3000 kilometers , The medium and long-range aircraft show also the same amount of critical emission. The threats involve also the airports and their surroundings, air quality in the vicinity of airports is influenced by ground operations activities.
According to ICAO Annex 16 Volume II there are standards for each aircraft engine emissions for subsonic flights: the characteristic levels of the emissions must not exceed the regulatory levels below $\frac{g}{kN}$:

Emission	Regulatory level	CFM 56 Jet A
Hydrocarbons	$D_p/F_\infty = 19.6$	$D_p/F_\infty = 0.9$
Carbon Monoxide	$D_p/F_\infty = 118$	$D_p/F_\infty = 20.5$
Oxides of nitrogen	$D_p/F_\infty = -9.88 + 2.0\pi_\infty$	$D_p/F_\infty = 69.7$
Smoke number	$SN = 83.6(F_\infty)^{-0.274}$	$SN = 1.5$

Table 1.1: Annex 16, Volume II: Regulatory levels and CFM-56 with $\pi_\infty = 42.0$ and $BPR = 8.3$

Mode	Throttle [%]	Time [min]	Fuel Flow [kg/s]	Emissions Ind. [g/kg]			Smoke N.
				HC	CO	NOx	
Take-off	100	0.7	1.0785	0.05	0.18	64.36	0.9
Climb-out	85	2.2	0.873	0.04	0.15	29.59	0.9
Approach	30	4.0	0.285	0.05	0.99	11.92	1.1
Idle	7	26.0	0.097	0.46	13.77	4.68	0.8

Table 1.2: Measured Data for CFM 56

The **Smoke Number (SN)** refers to the dimensionless term which quantifies smoke emissions measured before and after a known volume flows through a filter paper

sample.
Hydrocarbons (HC): The cumulative sum of hydrocarbon compounds within a gas sample, computed as methane equivalents.
The (NO_x) are the of the amounts of the nitric oxide and nitrogen dioxide.
The mass (in grams) of pollutant (CO, HC, NO_x, nvPM mass or nvPM number) divided by the mass (in kilograms) of fuel provides the emission index **EI**.
The aforementioned Database created by EASA contains information on exhaust gas and it has been used to certificate the specific engine model. The ratio $\frac{D_P}{F_\infty}$ values refers to the mass, in grams (D_P), of any pollutant emitted and are based on Landing/Take-Off (LTO) cycle considering a Jet Fuel A (mixture of 1.9% H/C, 14.7 % Aromatic) International Standard Atmosphere (ISA) conditions:

- Barometer (kPa): $97.7 - 98.8$
- Temperature (K): $279.3 - 290.5$
- Abs Humidity(kg/kg): $0.0009 - 0.0084$

The data-sheet supplies information that will be mentioned in the following chapters, compliance with Annex 16 by ICAO. [2]

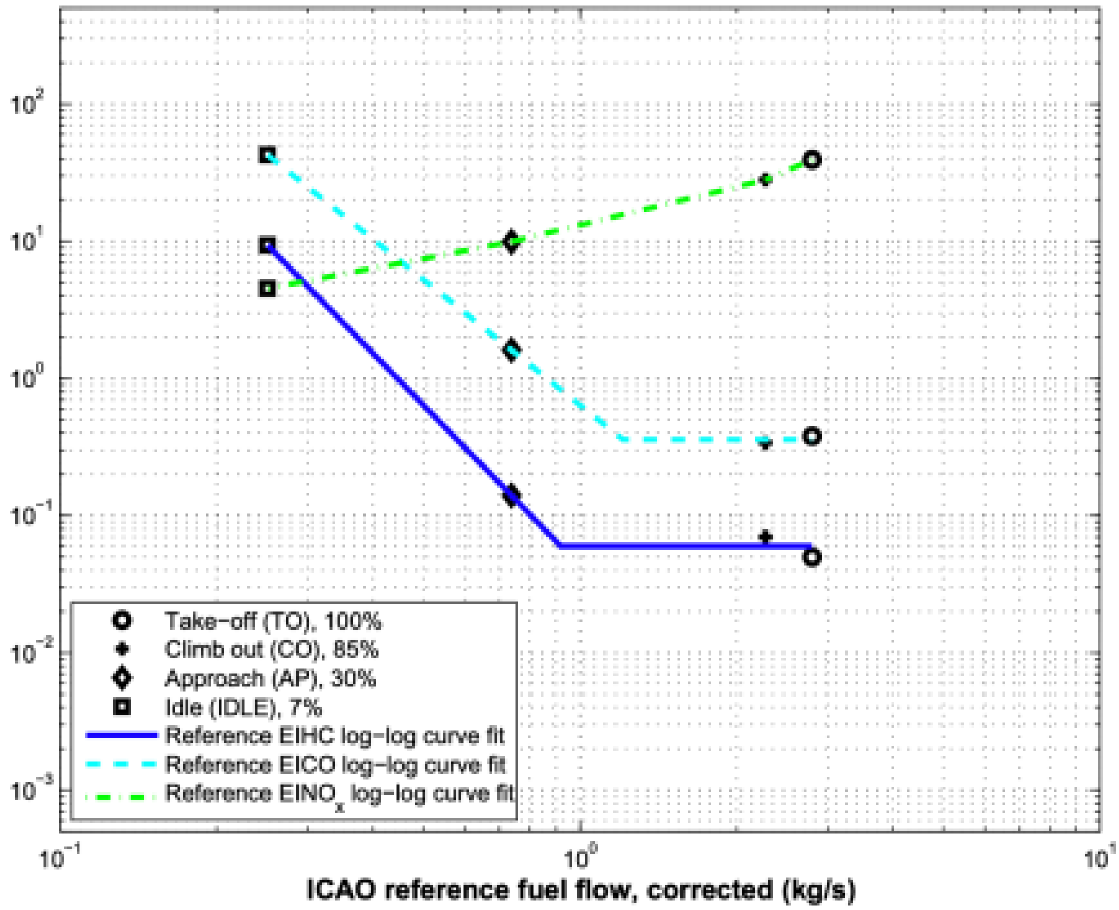


Figure 1.6

As fuel flow increases, $EINO_x$ rises. This correlation derives from the fact that higher throttle inputs require elevate turbine temperatures, consequently increasing the spread of NO_x , as the generation of NO_x is directly linked to combustion temperatures.

Conversely, $EICO$ and $EIHC$ decline as fuel flow increases. This behaviour primarily occurs because unburnt hydrocarbons are less frequently formed when engine efficiency is higher, typically indicated by throttle settings approaching 100%.

1.1.1 Air Quality: brand-new fuels

Exhibit 3

Comparison of new technology and sustainable aviation fuels and new technologies

<table>
<tr><th>Comparison vs. kerosene</th><th>Biofuels</th><th>Synfuels</th><th>Battery-electric</th><th>Hydrogen</th></tr>
<tr><td>Commuter
<19 PAX</td><td rowspan="5">No limitation of range</td><td rowspan="5">No limitation of range</td><td rowspan="3">Maximum ranges up to 500-1,000 km due to lower battery density</td><td rowspan="3">No limitation of range</td></tr>
<tr><td>Regional
20-80 PAX</td></tr>
<tr><td>Short-range
81-165 PAX</td></tr>
<tr><td>Medium-range
166-250 PAX</td><td rowspan="2">Not applicable</td><td rowspan="2">Revolutionary aircraft designs as efficient option for ranges above 10,000 km</td></tr>
<tr><td>Long-range
>250 PAX</td></tr>
<tr><td>Main advantage</td><td>Drop-in fuel – no change to aircraft or infrastructure</td><td>Drop-in fuel – no change to aircraft or infrastructure</td><td>No climate impact in flight</td><td>High reduction potential of climate impact</td></tr>
<tr><td>Main disadvantage</td><td>Limited reduction of non-CO_2 effects</td><td>Limited reduction of non-CO_2 effects</td><td>Change to infrastructure due to fast charging or battery exchange systems</td><td>Change to infrastructure</td></tr>
</table>

Figure 1.7

To achieve *decarbonization* in aviation, there is a requirement for new fuels and propulsion technology. These strategies, in conjunction with enhancements in advanced kerosene propulsion systems and other efficiency measures, serve as complementary solutions:

- Sustainable aviation fuels: the most advanced fuels are derived from biomass or waste sources as for HEPA (e.g., cooking oils and fats). Following these are advanced bio-fuels, synthesized from solid feed stock, biomass such as crops, or algae. Another SAF alternative includes power-to-liquid fuels, categorized here as **synfuels**. Synthesized from hydrogen and CO2 obtained from industrial or biomass these fuels represent an additional path towards sustainability.

- Brand-new technologies: Electrified and hydrogen propulsion, fuel cells and hybrid solutions. This new technologies are different from the state-of-the-art architecture, this inevitable let the conceptual design of an hypothetical project to be refined.

The **Bio-fuels** possess the benefit of being *drop-in fuels* the aircraft does not need to be modified, fuel infrastructure do not need further services and are universally appli-

cable across all aircraft segments. Bio fuels are at the moment commercially accessible and will be .
In contrast to biofuels, the primary source of **synfuels** (power-to-liquid) is electricity. This electricity is utilized initially to generate hydrogen and to capture carbon, the combination is then exploited to produce a kerosene-like fuel. Synfuel could also be utilized in existing aircraft engines and fuel infrastructure, making it suitable for all segments within the aviation industry. However, synthetic fuels could be three times less effective than the newest hydrogen propulsion in reducing aviation's footprint. Given that aircraft employing fuel cell systems exhibit the most substantial potential for reducing climate impact, estimated to achieve a reduction between 75 to 90 percent. Following closely, hydrogen combustion aircraft present the next best alternative, offering reductions of 50 to 75 percent. Synfuels derived from CO_2 obtained through direct air capture yield reductions in the range of 30 to 60 percent as shown in 1.8, while the reduction potential associated with synfuels utilizing CO2 sourced from industrial processes is contingent upon the accounting of CO_2 emissions.
Battery technology has made significant improvements over the past two decades. Nevertheless, for aviation purposes, batteries have low gravimeter energy densities ranging from 0.2 to 0.5 kilowatt-hours per kilogram and limited lifetime cycles. Consequently their utilization is confined primarily to very short flights, such as commuter and regional aircraft. Current studies are carried out in order to enhance energy density, substantial breakthroughs would be necessary to let battery technology available for longer ranges. [3]

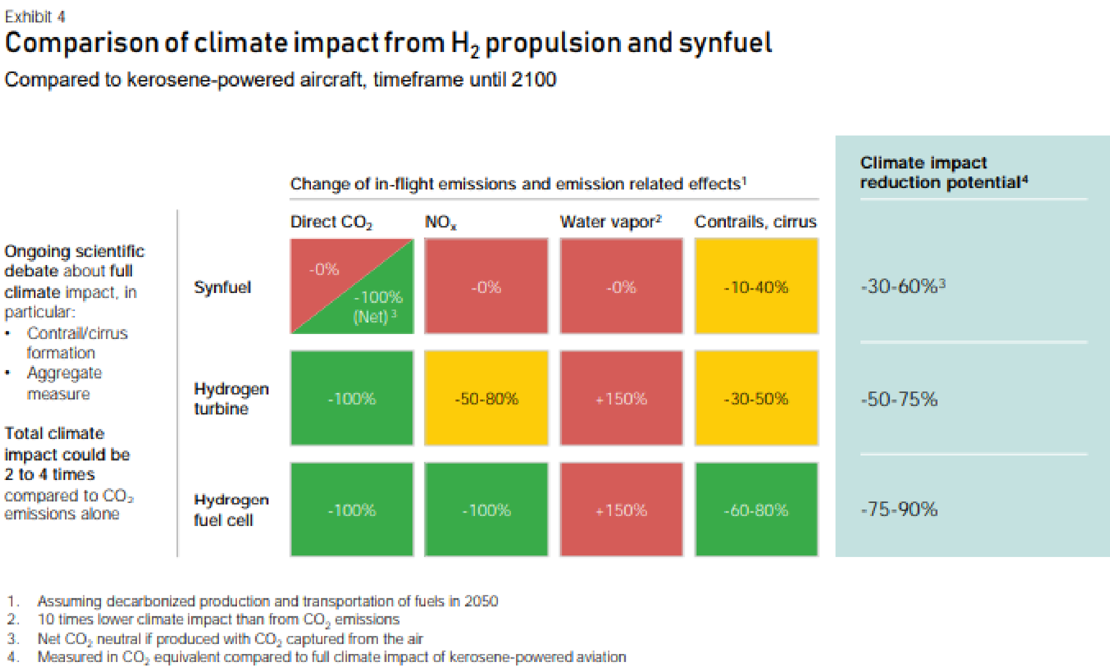


Figure 1.8: Climate impact reduction potential

Hydrogen propulsion holds potential as a fuel source for aircraft, either through combustion in H2-burning engines or via reaction in fuel cells that feed the electric motors. Despite its gravimeter energy density being three times higher than kerosene, hydrogen's volumetric properties necessitate larger onboard tanks and adjusted aircraft designs. The size and weight of hydrogen tanks present significant constraints, particularly for both short range and long range flights with high energy demands, potentially

threatening the economics of long-range aircraft significantly.
Hydrogen fuel solution offers additional advantages: as a fuel does not contain carbon and its combustion does not emit CO_2 during flight. It can be derived directly from renewable energy sources, and synergies with other hydrogen-dependent sectors are feasible. A scaling-up of hydrogen demand across sectors could unlock economies of scale, mitigating at least some of the initial cost disadvantages. Fuel-cell and hydrogen combustion emits almost three times water vapor as by-product.

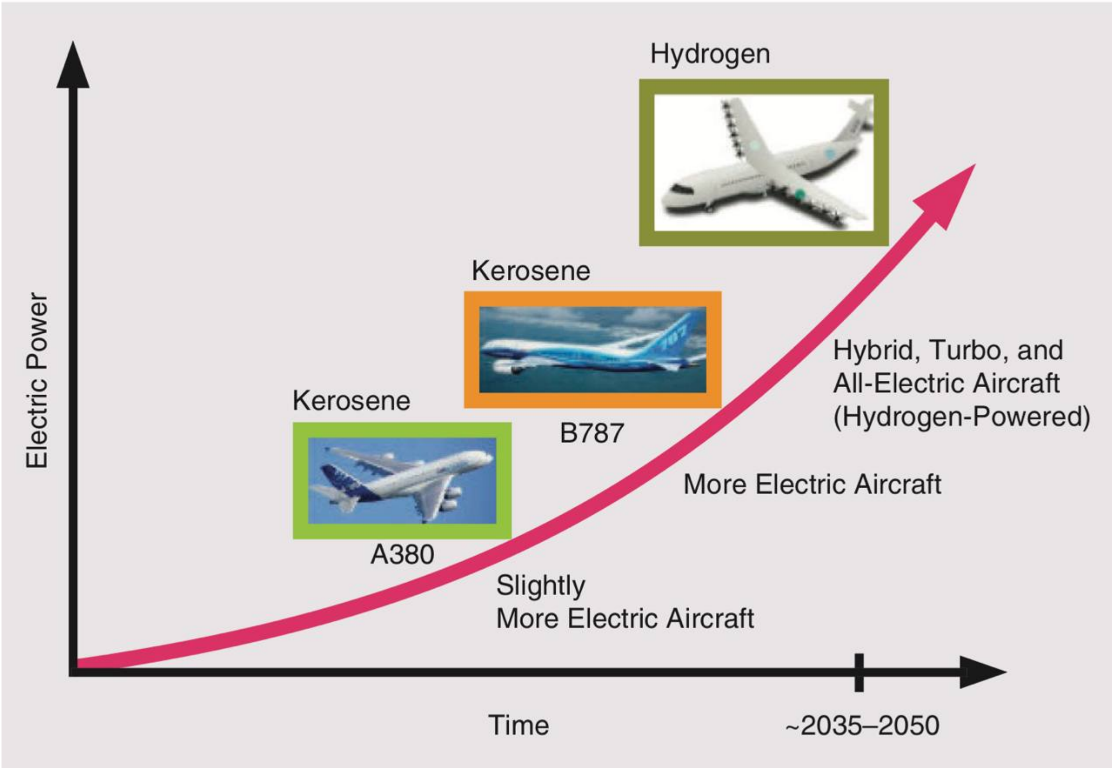


Figure 1.9

As shown in 1.8, the synfuels and bio-fuels for the production of synfuel, carbon origins from the air, the overall result achieved might be net carbon zero.
When transitioning kerosene aircraft to synfuels, it is anticipated that NO_X emissions will remain predominantly unaltered. Conversely, initial studies into H_2-powered aircraft suggest that NO_X emissions could be reduced by 50 to 80% without significant declines in efficiency. Realizing these benefits necessitates further research and development efforts.
Furthermore, in the context of utilizing a fuel-cell propulsion system, the reaction of hydrogen provides no NO_X emissions.

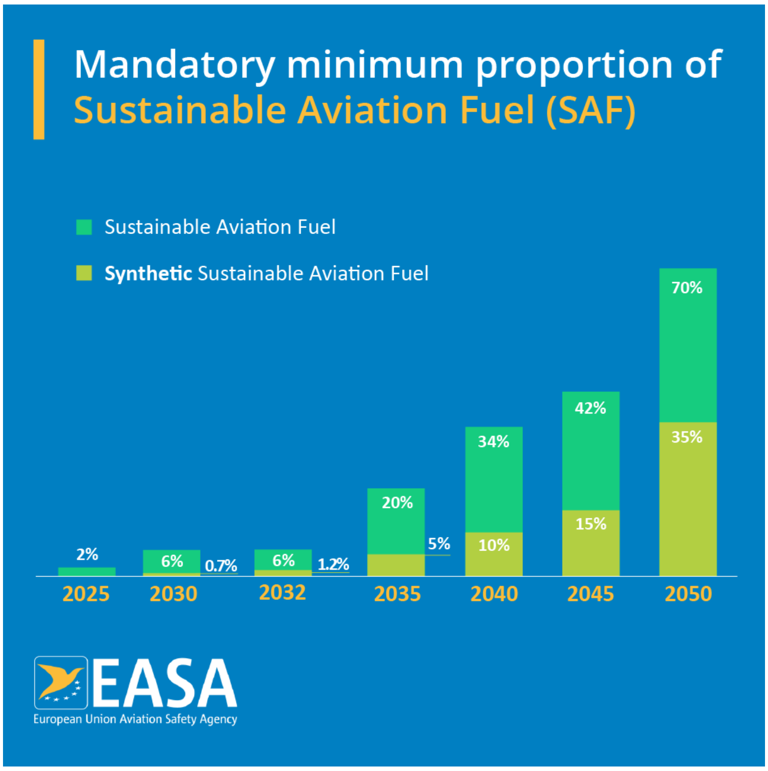


Figure 1.10

Bio-fuels and turbo-electric aircraft could already *decarbonize* the aviation sector in the short-term. In the long term, the *decarbonization* of aviation might use battery-electric as source power for aircraft (very short ranges) and H_2 propulsion (fuel cell or combustion), synfuels, and biofuels which are also suitable for the larger, higher emission aircraft segments.

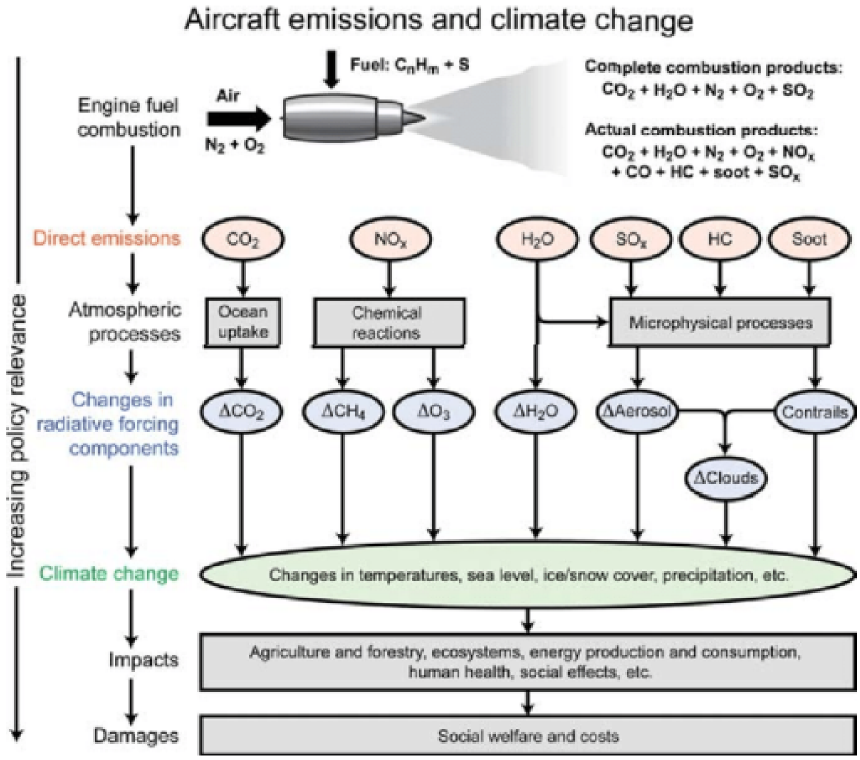


Figure 1.11

Traditional Jet Fuel A affects the Earth's surface temperature with a radiate force:

- Emissions of soot particles that warms the Earth Surface
- Emissions of CO_2
- Emissions of NO_X result in the formation of Ozone in the tropospheric layers and in the reduction of CH_4
- Water vapor that might the Earth Surface
- Sulphate particles emitted arising from sulphur inside the fuel mixture result in a prevalent scattering effect and might be helpful

1.1.2 Cost impact and comparison between hydrogen and syn-fuel

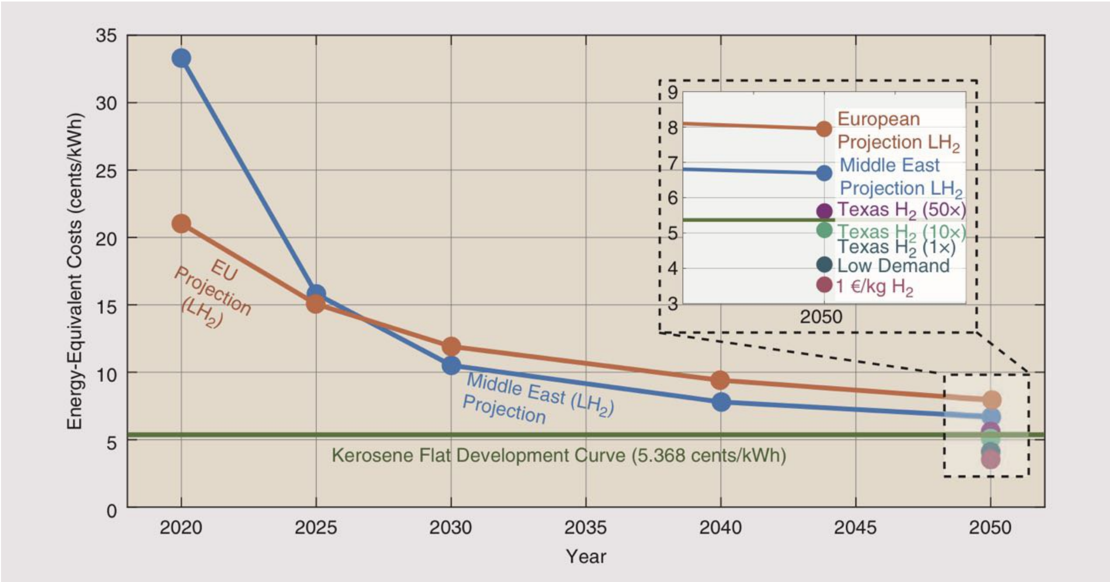


Figure 1.12

Jet fuel is currently four to six times less expensive to produce than hydrogen, the cost is expected to half within 2050, in 1.12 a comparison is made between the jet fuel and liquid hydrogen in terms of cost. As showed, hydrogen could be cheaper when produced in the Middle East than in Europe due to solar renewable energy. [4]
Synthetic and Bio fuels can be introduced for long-haul flights while for segments not exceeding 10000 km range hydrogen option could be considered. The first ever flight using SAF fuel took off in the late November of 2023.

1.2 Very first usage: ballons and airships

The initial application of hydrogen in aeronautics was for inflating balloons. Early balloon experiments at the beginning in France when the Roberts brothers filled a small silk balloon with hydrogen and let it to a height of 3000 ft, traveled 15 mi, despite encountering pouring rain. Later that same year, a larger hydrogen-filled model, measuring 26 ft in diameter, was launched, carrying two passengers covering a distance of 25 mi from Paris in less than 2 hours.
Explorations into gas properties and engineering strides set the stage for creating successful balloons, dirigibles, blimps, and airships. In the mid-1600s, Evangelista Torricelli came up with the barometer to check atmospheric pressure, while Robert Boyle started delving into air weight. Later, in 1789, Frenchman Antoine Lavoisier correctly identified for the first time the element and named it hydrogen. [5]
Early studies of the physics and chemistry of the atmosphere and the stratosphere is re conducted to hydrogen balloons to usage such as reconnaissance and observation. Later on the use of hydrogen in balloons has been excluded and nowadays they are filled by helium because of safety considerations. [6].
The first air fatality occurred during an attempting to cross the English Channel, an

hydrogen-filled balloon had a metal vent valve that produced an electrostatic spark during venting causing the escaping gas to catch fire. Hydrogen valves were made of wood from then on. About 152 years later a similar electrostatic spark would also be the reason behind the known airship disaster of all time, the Hindenburg.

1.3 First development

In the mid of 50's, a report by NACA-Lewis Flight Propulsion Laboratory was released, it included the first studies and the potential of LH_2 as a fuel to feed aircraft was explored. One of the significant improvement was observed in maximizing the theoretically range, the studies carried out toof as example the U.S. Air Force B57 twin-engine medium bomber in a modified version since hydrogen (LH2) was carried in a vessel positioned under the wing tip (left) while hydrogen (GH2) under the right wing tip as a pressurant.

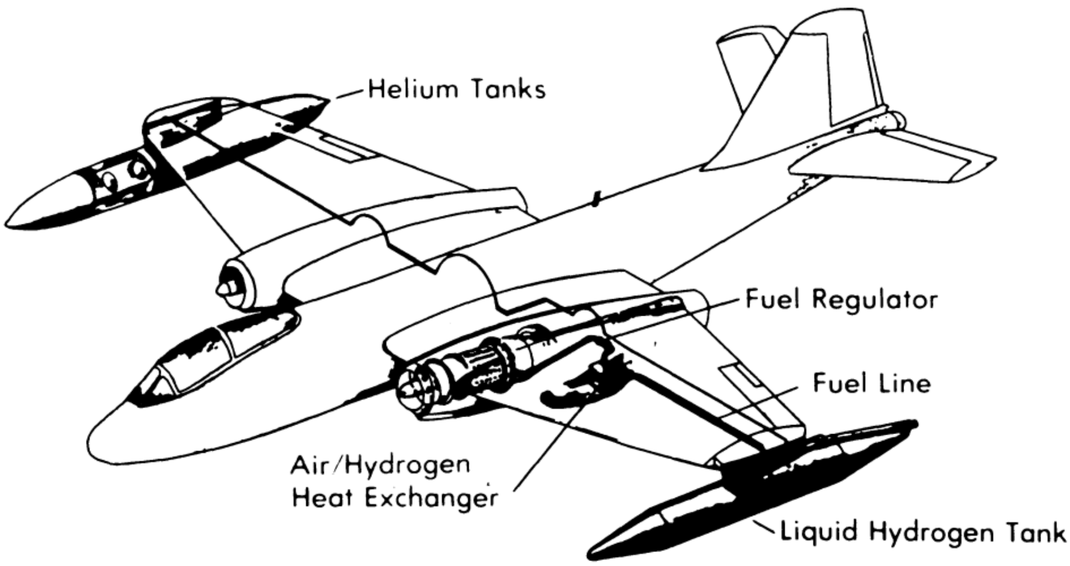


Figure 1.13

The flight test aimed to verify the process of pressurization, the hydrogen tank was pressurized He in a gaseous state in order to let the LH2 flow to a heat exchanger where it was vaporized. The heat exchanger provided the heat sink to convert the LH2 to gaseous state. The mass flow rates were modified to be inversely proportional to the c_p of the two fuels:

$$\frac{LH_2}{Kerosene} = 2.8$$

1.3.1 Adaptability to engines to LH_2

The early studies for adaptability of In early 1956, while the U.S. Air Force was contracting with Lockheed for the development of the $CL-400$ airplane, Pratt & Whitney

Aircraft Division testing a modified J57 engine capable of operating on LH_2. Additionally, it involved the design, construction, and testing of a new engine model, the Model 304.

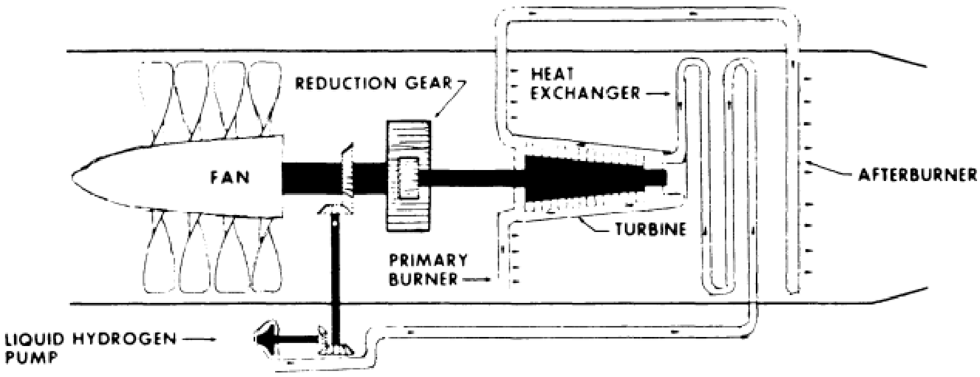


Figure 1.14: Model 304 engine

The conversion of the J57 engine to run on LH_2 was completed within a remarkably short span of five months, with initial tests conducted in the fall of 1956. LH_2 was delivered to the engine through a single-stage, engine-driven centrifugal pump, which maintained a slight net positive suction head to prevent cavitation. Before entering the combustion chamber, the LH_2 underwent warming in a counter flow heat exchanger, utilizing air bled from the compressor discharge. An axial, tube-type injection system was adopted following early tests, demonstrating acceptable burner-can discharge temperature profiles and efficient combustion with combustor cans considerably shorter than those required for conventional hydrocarbon fuels.

Space case

Indeed the largest user of hydrogen in aeronautics has been conducting by rocket engines in space vehicle propelled by a liquid hydrogen/liquid oxygen rocket engine since 1963.

1.4 Current interests

Figure 1.15: Virgin Atlantic

Virgin Atlantic's Flight100 demonstrated that Sustainable Aviation Fuel (SAF) is a safe and effective replacement for fossil-derived jet fuel. This flight, operated on a Boeing 787 with Rolls-Royce Trent 1000 engines, marked a great world-first achievement for 100% SAF use on a commercial airline flying across the Atlantic.
This project has been a collaboration among Virgin Atlantic, Boeing, Rolls-Royce, Imperial College London and many more. This historic flight underscores its crucial role in decarbonizing long-haul flights.
The SAF used in Flight100 is a mixture of 88% HEFA (Hydroprocessed Esters and Fatty Acids) supplied by AirBP and 12% SAK (Synthetic Aromatic Kerosene). This blend is needed achieve the necessary aromatics for normal engine function.
Virgin Atlantic is committed to sustainable aviation and will continue to lead in this area and can achieve aviation's 10% SAF by 2030.

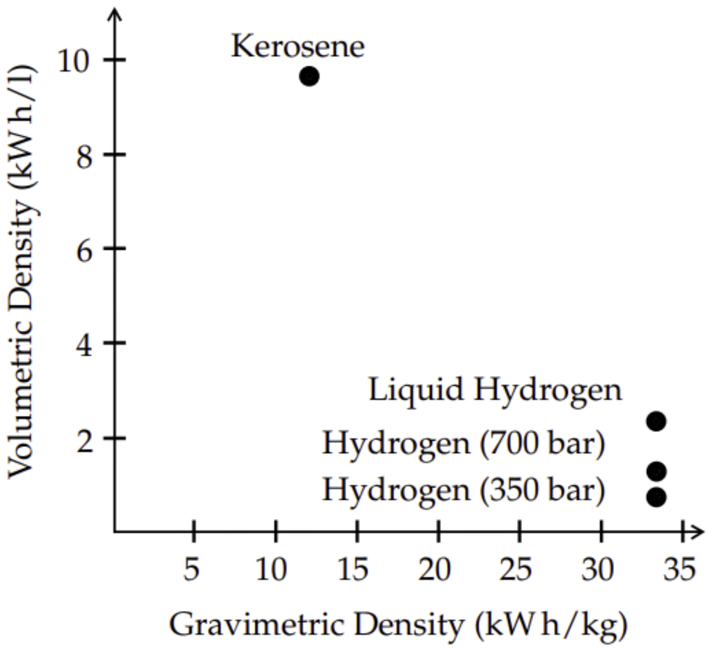
Chapter 2

Hydrogen technologies

In order to cut off the emissions from aviation sector new technologies are developed, replacing the classical fuel combustion with a hydrogen combustion. In this paper both direct combustion and fuel cell have been considered.
There are two methodologies of using hydrogen as an energy source: it can be burned directly inside gas turbines, like tradional Jet-A1. In this way it is possible to make only minor modifications to aircraft turbines of the turbofan , but it demands the development of a new fuel system. Since no carbon participates in the combustion process, the emission of the greenhouse gas CO2 is entirely avoided, and there's a notable reduction in nitrogen oxides NO_x. Additionally, hydrogen boasts a higher gravimetric density. There are two concepts of using hydrogen as a direct combustion:

- Direct conversion into thrust with a combustor
- Conversion into electrical energy for electric motors

The fuel cell system is an alternative to direct combustion, with less emissions than the other options due to the fact that its only by-product is water. Besides, it represents a greener way to travel if the hydrogen is produced by a carbon-free source as for hydrolysis, which implies no CO2 emissions.



Hydrogen has a higher gravimetric density than kerosene. Anyway the climate impact of hydrogen combustion in aircraft remains significant, because of the high production of H_2O vapor which results in contrails formations in the atmosphere. Besides, hydrogen's volumetric density in the liquid state is not favorable compared to kerosene, as illustrated above. This is only partially compensated by the higher gravimetric density, resulting in some considerations about the tanks. Larger tanks are required than kerosene-powered aircraft tanks, creating tank integration and configuration challenges. These problems are accentuated by efficiency issues relating to boil-off phenomena and heat losses.
Hydrogen can be stored either in gaseous form or in liquid state, providing the same amount of energy the liquid state requires less volume but chilled at 20 K. Whereas the gaseous state would need an higher pressure tank to keep the pressure controlled.[4]
Currently electric airplanes have a power-to-weight (PTW) ratio of 16 $\frac{kW}{kg}$ for a 100-seater aircraft, is important the synergy with LH_2 can be used as both the fuel source and the coolant because of the efficiency as a cryogenic cooling medium. In fact, the LH_2 must be evaporated in a boiler before it is burned in either a hydrogen combustor or in a fuel cell. Four different architectures are available:

- **Fuel cell propulsion system (FCPS)**
- Fuel cell combined with electric propulsion system
- Pure hydrogen combustion propulsion
- Hydrogen-fueled turbo electric propulsion

An approach to achieve complete electric propulsion at a 100% rate involves the utilization of a **fuel cell propulsion system**. Within this FCPsystem, electricity is produced to operate one or more electric propulsors, each comprising an electric motor and a propeller. Additionally, integration of a battery within the system facilitates rapid load adaptation and optimizes the peak performance of the propulsor, a trade-off study must be performed to avoid over-weight issues.

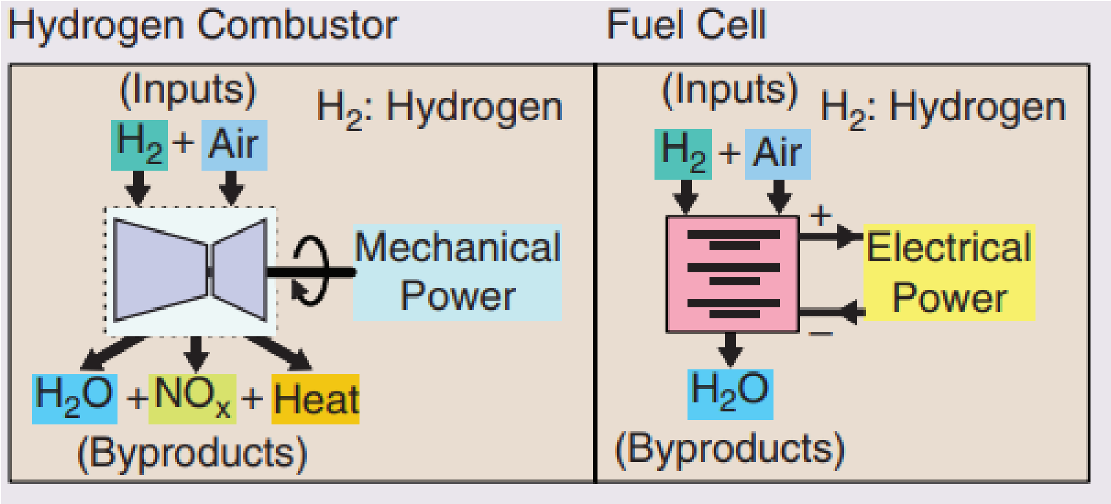


Figure 2.1: A comparison between the hydrogen combustor and the fuel cell conversion system, elucidating the inputs and outputs

The 2.1 illustrates a typical configuration of the fuel cell propulsion system, incorporating an internal battery buffer to accommodate transient events, representing one of the straightforward arrangements of a standard system with a single propulsor. In the commuter segment (comprising 19 passengers over a distance of 500 km), the likelihood of contrail formation is minimal, thereby resulting in a climate impact approaching a state of "true zero" when utilizing the FCPS.

Nonetheless, commuter aircraft serve as a modest initial phase towards achieving broader climate mitigation within the aviation sector. Subsequently, the regional segment (this time accommodating 80 passengers across a 1,000 km distance) presents another suitable application for the FCPS. In this context, the formation of contrails remains improbable, while the overall system efficiency remains high.

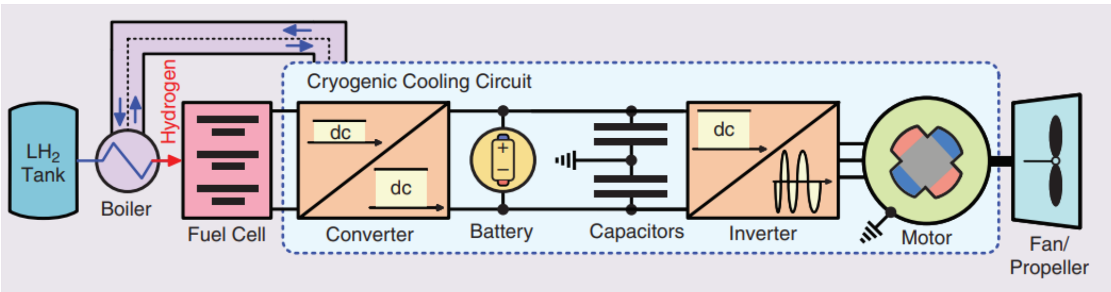


Figure 2.2

As depicted in 2.2, the fuel cell stack must receive gaseous hydrogen that must evaporate in a boiler, the boiling of the fuel could be considered where heat sinks are needed.

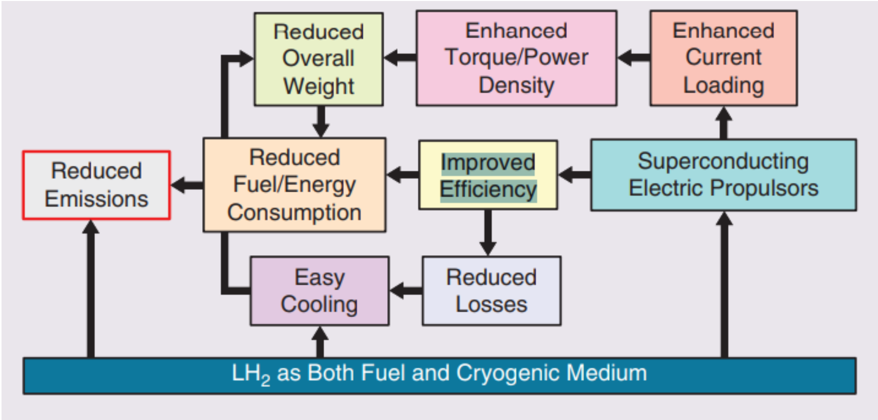


Figure 2.3

Even attaining superconducting power conversion for one or multiple components within the electric propulsion system. Operating the fuel cell at low temperatures allows to exploit this type of operation and potentially reduce its own degradation.[9]

Type	PEMFC	PAFC	AFC	SOFC	MCFC	DMFC
Advantages	-Low operating temperature -Fast charging, less corrosion, simplified electrolyte management	-Higher efficiency with CHP -Increased tolerance to fuel impurities	-Higher performance -Faster cathode reaction and start -Lower material cost -Low operating temperature	-Suitable for CHP -Higher efficiency -Fuel flexibility -Hybrid/gas turbine cycle	-Suitable for CHP -Higher efficiency -Fuel flexibility	-Low cost due to lack of fuel reformer
Disadvantages	-Expensive catalyst cost -Sensitive to impurities	-Expensive catalyst cost -Long start time	-Sensitive to CO_2 levels in O_2 and H_2	-High operation temperature, corrosion, and breakdown -Long start time	-High operation temperature -Long start -Power density	-Intermediates poisoning catalyst surface
Efficiency (%)	40–60	40	60	60	50	40
Fuel	Hydrogen	Hydrogen	Hydrogen	Hydrogen	Hydrogen	Methanol
Operating Temp. (°C)	<100	150–200	90–100	500–1000	600–700	60–200
Cell Voltage (V)	1.1	1.1	1	0.8–1	0.7–1	0.2–0.4
Stack Power (kW)	1–250	50–100	1–100	1–3000	300–3000	0.001–100

Figure 2.4: Typology of fuel cell

The fuel cells of this paper could be categorized into two types:

- Low temperature PEMFCs (90^oC)
- High temperature SOFCs (1000^oC)

The first type is a Polymer Electrolyte Membrane (PEM) fuel cell, it is able to reach high efficiencies and high power densities. [25] The electro-chemistry mechanism of the PEM fuel cell relies on the oxidation of hydrogen and the reduction of oxygen, the manner occurs at the anode electrode the latter at cathode electrode.

$$\frac{1}{2}O_2H_2 \rightarrow H_2O$$

$$H_2 \rightarrow 2\ H^+ + 2\ e^-$$

$$\frac{1}{2}O_22\ H^+ + 2\ e^- \rightarrow H_2O$$

The only other products of the above chemical reaction are heat and water (which is in vapour state). One single cell is able to create a current in the circuit about of 1 V, this is the reason why multiple cells are put in series as voltages add up. A series of single cell produce a voltage with an approximate current density:

$$\rho_A = 10000\frac{A}{m^2}$$

Considering the total desired output power of the stack and knowing the number of cells, the area required for each cell can be computed. [10]

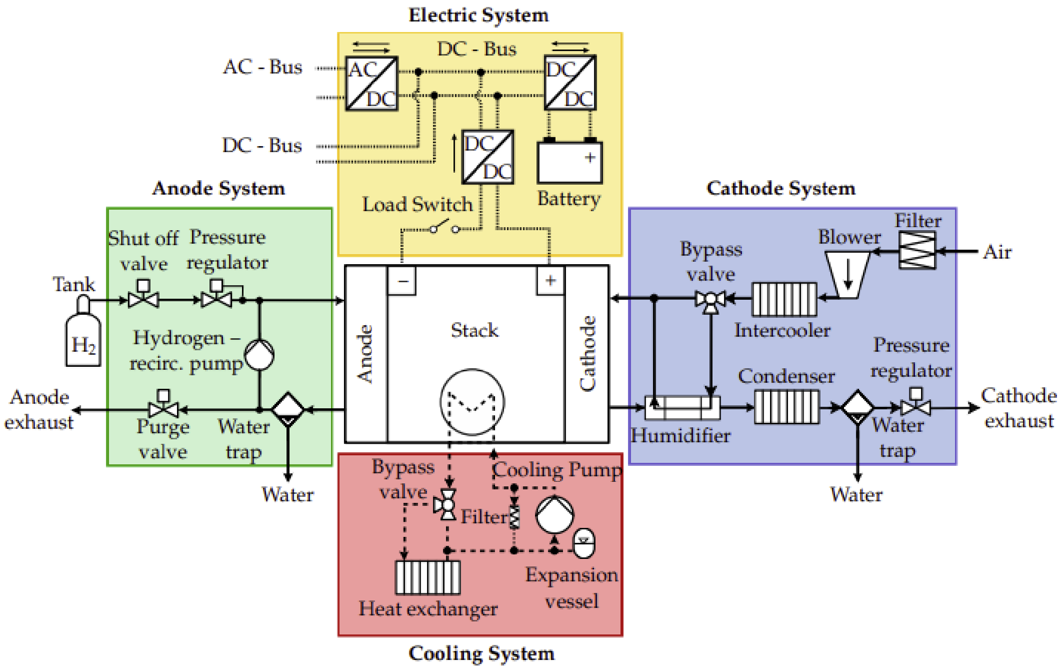


Figure 2.5: [11]

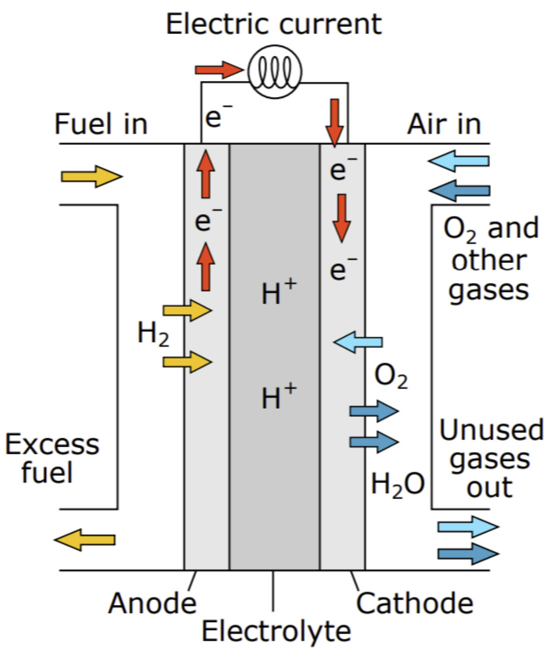
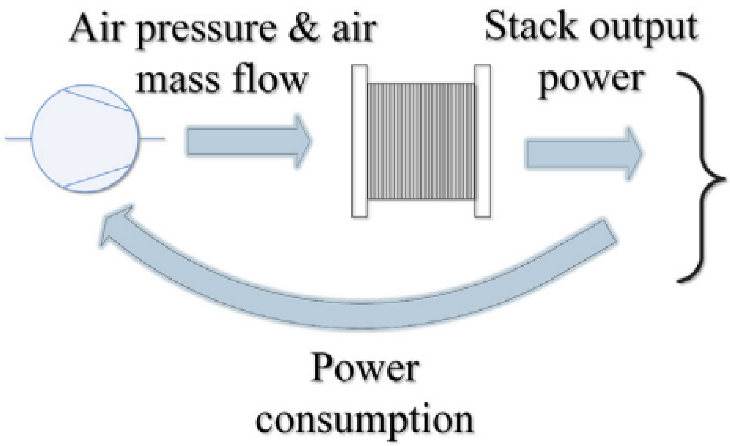


Figure 2.6: PEM operation

The protons (H^+) are transferred into the cathode electrode through the PEM and electrons (e^-) are carried into the cathode electrode through an external circuit. Air is used to grant the oxygen to the cathode electrode. Hydrogen from the tank is supplied to the anode electrode, the hydrogen is produced through a reforming process of kerosene or by the electrolysis of water which represents a greener solution.



The air compressor is a key component of a PEM, the air flow coming in the stack influences the efficiency of the fuel cell. Depending on the flight condition, the air is coming from either the cabin or atmospheric air. The presence of oxygen in the air directly impacts the stack voltage, consequently affecting its efficiency. By varying the air mass flows and pressure levels supplied to the stack, the air compressor can alter these operational parameters, thereby influencing both the stack and system efficiency. [11]

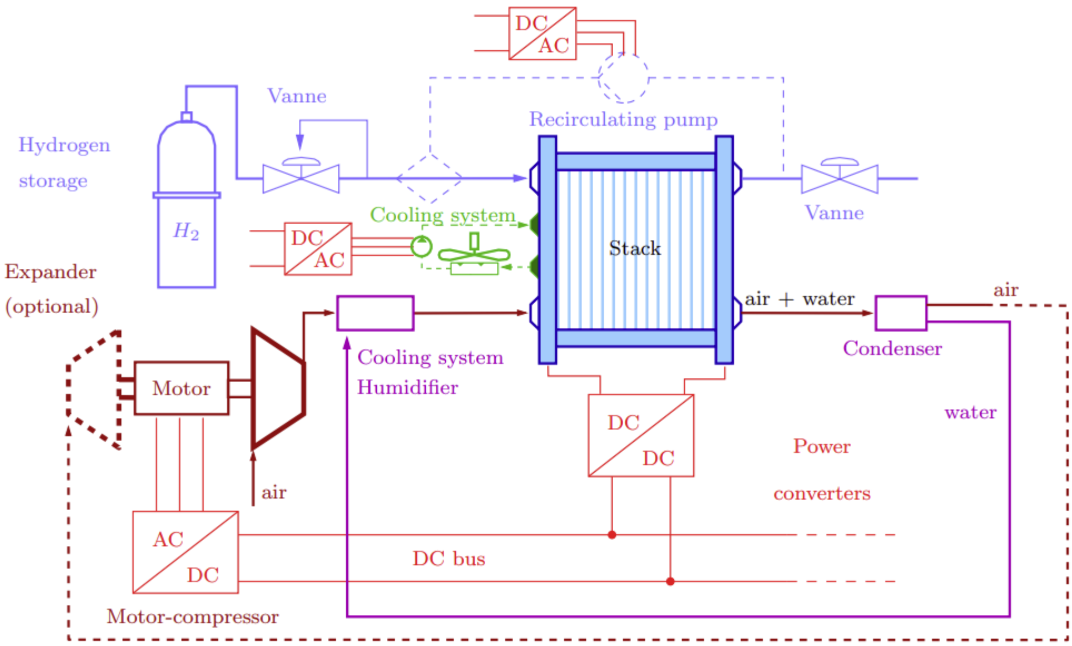


Figure 2.7

As the air mass flow gets higher the stack voltage increases. At lower mass flows, the stability of the process cannot be guaranteed due to the risk of water condensation and oxygen deprivation. High velocity air flow is essential to avoid accumulated water on the cathode area of the stack. On the other hand, at higher air mass flows, the elevated oxygen partial pressure leads to an increase in stack voltage that may result in insufficient humidification of the membranes, potentially causing drying up. A parameter is shown to evaluate the air excess ratio, it represents the actual air mass flow through the stack divided by the air mass flow required for complete oxygen consumption within the stack:

$$\nu = \frac{\dot{m}_{air}}{\frac{InM_{air}}{4F\chi_{O_2}}}$$

Typical air excess ratios ν values are around 1.5 and 3.0, this parameter depends on the system's design. For ν greater than 3, the voltage doesn't have positive values as shown in 2.8.

- $\dot{m}_{air}$ is air mass actually flowing within the stack
  The other parameters are computed for stechiometric air mass flow
- M_{air} molar mass of air
- χ_{O_2} is the mole fraction
- I is the stack current,
- n is the number of cells of the stack
- F is the Faraday constant

Then, the air supply system has a key role in order to let PEM work. Its major tasks are the following:

1. Air transportation: the system must ensure an adequate flow of reactants, maintaining the desired oxygen excess ratio across the entire power range. The air mass-flow rate (q_{air}), the air excess ratio (ν), the fuel cell stack power (P_{gross}) and the cell voltage for a cell (V) are computed in this equation:

$$q_{air} = 3.57 \cdot 10^{-7} \nu \frac{P_{gross}}{V}$$

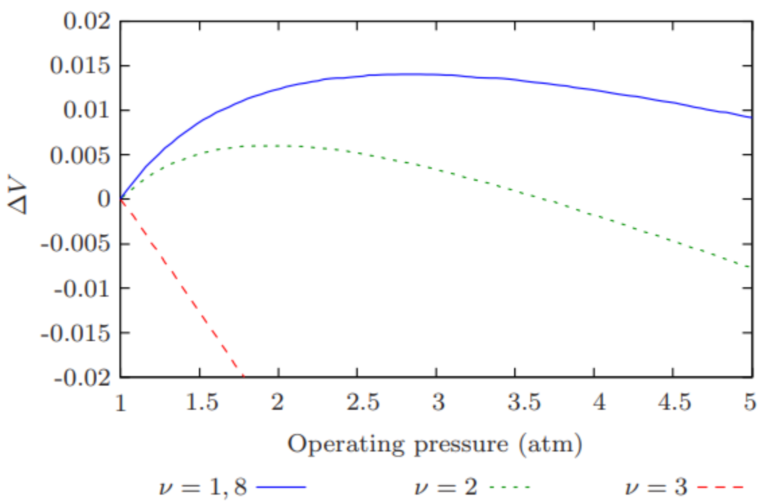


Figure 2.8: Delta V

2. Air cleaning: is essential as any particle/chemical substance, such as carbon monoxide (CO), represents a threat to the catalyst and membrane. [12]

3. Pressurization plant: in any cases, the air is supplied with a pressure range between atmospheric pressure to 2.5 bar. Optimal pressure values are around 2-2.5 bar.

4. Humidification: the membrane of the polymer requires to be fully hydrated to have optimal working conditions. Drying process reduces the overall performance, increasing the membrane resistance that degrade the membrane.

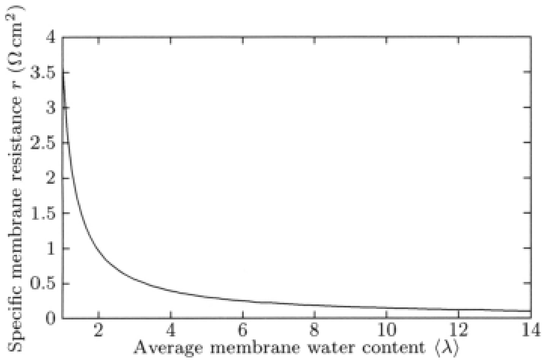


Figure 2.9

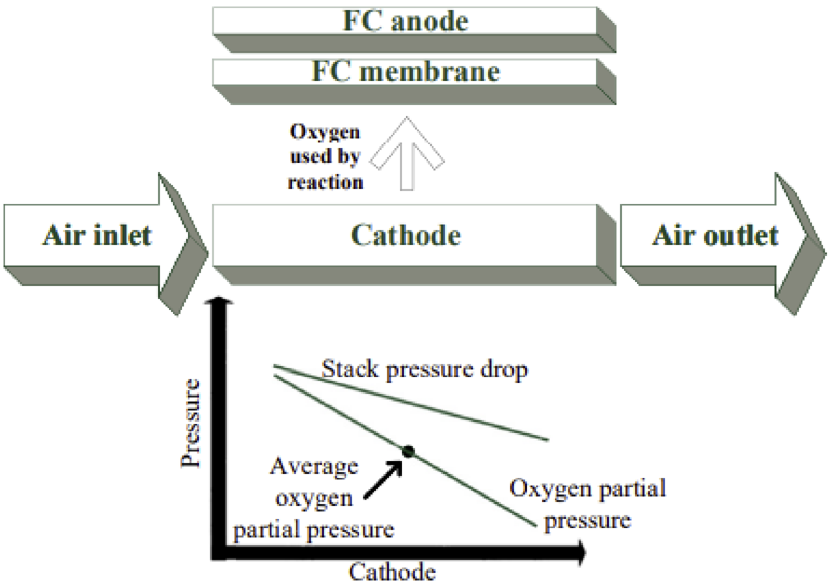


Figure 2.10: Schematic overview of the oxygen partial pressure drop inside the fuel cell stack

2.1 Sizing a fuel cell

A stack is made up to a finite number of single cells, the single cell is constitued of the membrane electrode assembly (MEA). Between the single cells the bipolar plates (BP) deliver the reactants through the gas diffusion layer (GDL) in the direction of the reaction sites. The BPs role is to transport the electrons from one cell to the adjacent, in order to form a complete electric circuit through the stack. Other elements are the gaskets, which aim to avoid any leakages. The MEA, GDL, BP and gasket are repeated until the endplates (EPs), the bolts sits at the end of the stack whose main function is to guarantee sufficient clamping force on the cells.[8]

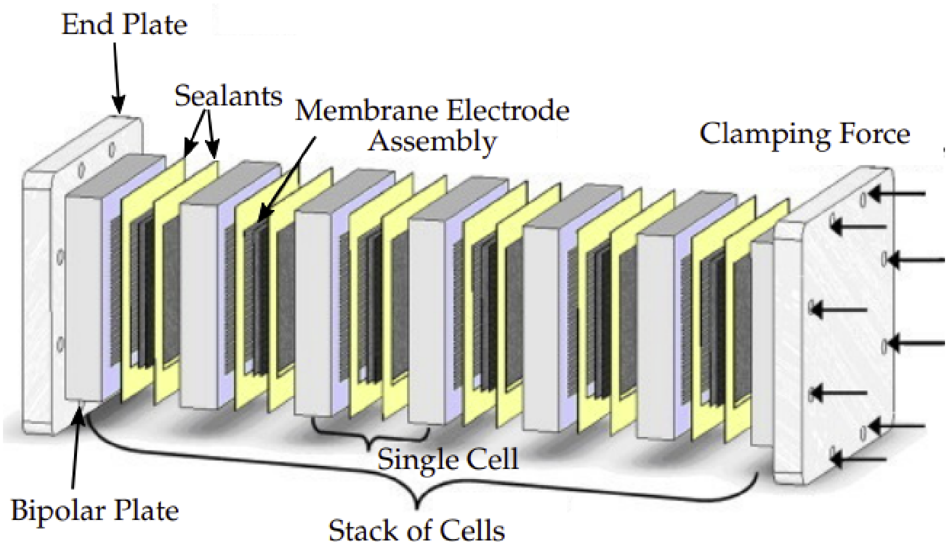


Figure 2.11: Implementation of Fuel Cells in Aviation from a Maintenance, Repair and Overhaul Perspective

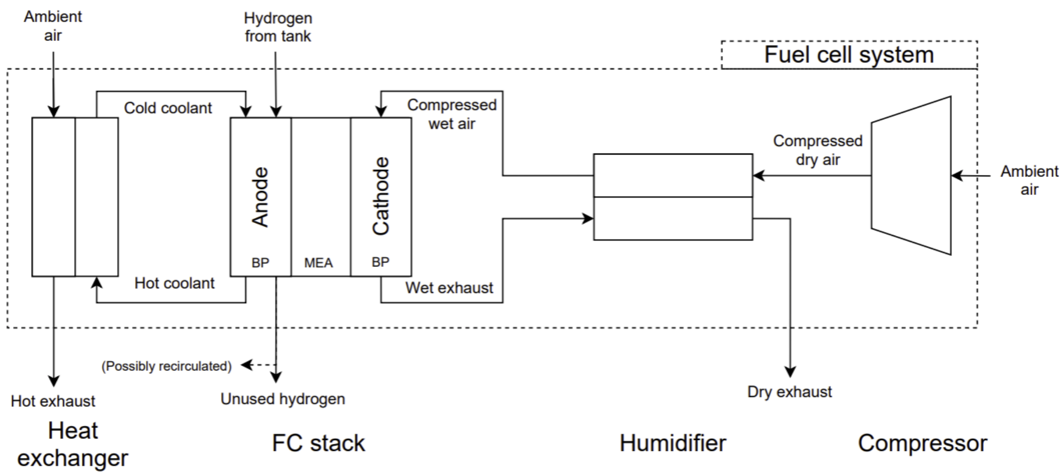


Figure 2.12: PEM overview

The term *Balance of Plant* (BOP) embed all the auxiliary systems and supporting components essential for the functioning of the fuel cell, besides the generating unit itself, but necessary for energy delivery. For the PEM the three principal BOP subsystems are likely required for this energy application:

- The compressor
- The heat exchanger
- The humidifier

2.1.1 Procedures to size

The fuel cell operation depicted in the previous section will be analyzed in an analytical procedure.(Ref: It is important to define the required P_{Peak} in order to size the fuel cell that will deliver:

$$I = \frac{P_{peak}}{\eta V_{cell}}$$

The number of cells depends on the reference voltage, for paper purpose it is asked to provide $270V\ DC$ as a single cell produces $V_{cell} = 0.7\ V$.
The fuel cell works if supplied with the right amount of hydrogen:

$$\dot{m}_{H_2} = \frac{n_{H_2} \cdot M_{H_2}}{U_f}$$

Where, n_{H_2} represents the moles of H_2, M_{H_2} the molar mass and U_f refers to the fuel utilization (typically 85%).
The fuel cell requires air as much molecular Oxygen contained:

$$\dot{m}_{O_2} = n_{O_2} \cdot M_{O_2}$$

Higher oxygen partial pressure levels rise the voltage level. This can be realized requiring a higher overall air *pressure* or *mass* level. Both result in higher electric energy consumption of the air compressor. The air mass flow is computed, assuming $M_{air} \simeq \chi_{O_2} \cdot M_{O_2} + \chi_{N_2} \cdot M_{N_2} = 28.85 \frac{g}{mol}$:

$$\dot{m}_{air} = \nu \frac{n_{O_2} \cdot M_{Air}}{\chi_{O_2}}$$

The air flow is provided either by external air or by cabin air. Considering external air, it must be compressed via a dedicated compressor, whose typology may differ depending on the architecture required and the overall BOP's available space:

1. Single level compressor

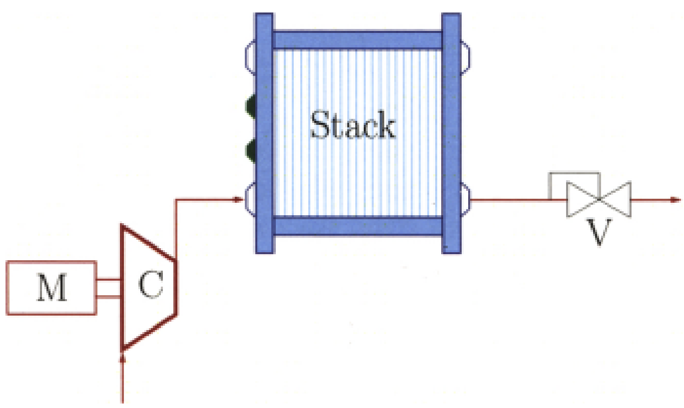


Figure 2.13

2. Compressor-Expander, the turbine aims to recover energy from the cathode exhaust gases. Increasing efficiency by 5%

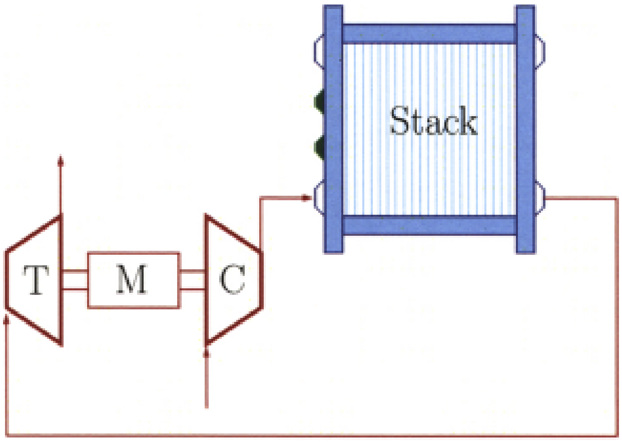


Figure 2.14

3. Serial booster

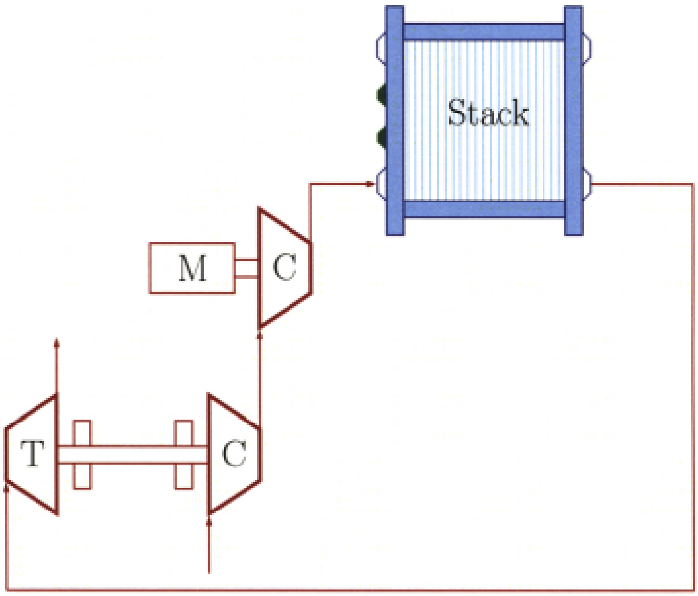


Figure 2.15

By the chemical balance's equation, it is possible to state that for each mole of H_2, a mole of H_2O is generated:

$$\dot{m}_{H_2O} = n_{H_2O} \cdot M_{H_2O}$$

This equation can be used to understand the potential impact of fuel cell by-product for subsystems that need water storage or cooling circuit. Usually thermal power produced by the stack is considered a negative by-product. In aircraft's domain, could be re-cycled to supply hot air pneumatic tubes. It could be also considered in PEM architecture as LH_2 needs to be boiled for anode's chemical reactions.

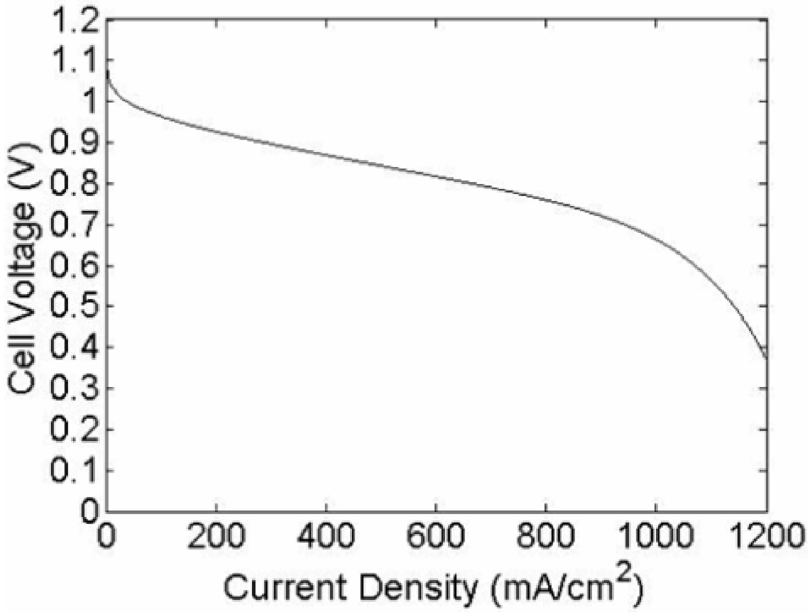


Figure 2.16

From 2.16 it is possible to link the voltage with the current density.

$$V_{cell} = 0.7\ V \qquad \delta_i = 0.950 \frac{A}{cm^2}$$

The overall mass is computed as follows, considering:

- Thickenss of Base Plate (BP) $t_{BP} \leq 1\ mm$
- Thickenss of Membrane Electrolyte Assembly (MEA) $8\ \mu m \leq t_{MEA} \leq 25\ \mu m$
- Thickenss of Gas Diffusion Layer (GDL) $75\ \mu m \leq t_{MEA} \leq 400\ \mu m$
- Thickenss of Base Plate (BP) $t_{BP} \simeq 30\ mm$
- Diameter for the bolts: $10\ mm \leq D_{bolts} \leq 20\ mm$

$$m_{stack} = S \cdot (N_{cell} \cdot (t_{BP} \cdot \rho_{BP} + t_{MEA} \cdot \rho_{MEA}) + 2 \cdot t_{EP} \cdot \rho_{EP}) + n_{bolts} \cdot \pi \cdot (D_{bolt}^2 \cdot l_{bolt}) \cdot \frac{\rho_{bolt}}{4}$$

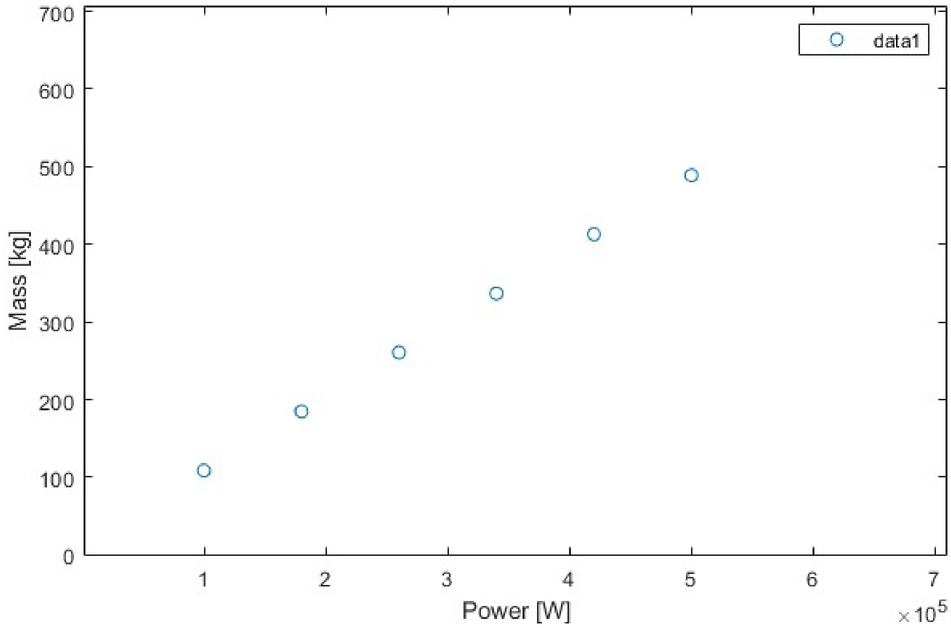


Figure 2.17: Variation of FC's mass in function of Output power

One expedient method for estimating the thermal power generated by the stack involves utilizing the following equation:

$$Q\ [W] = P_{peak}\left(\frac{1.25}{V_{cell}} - 1\right)$$

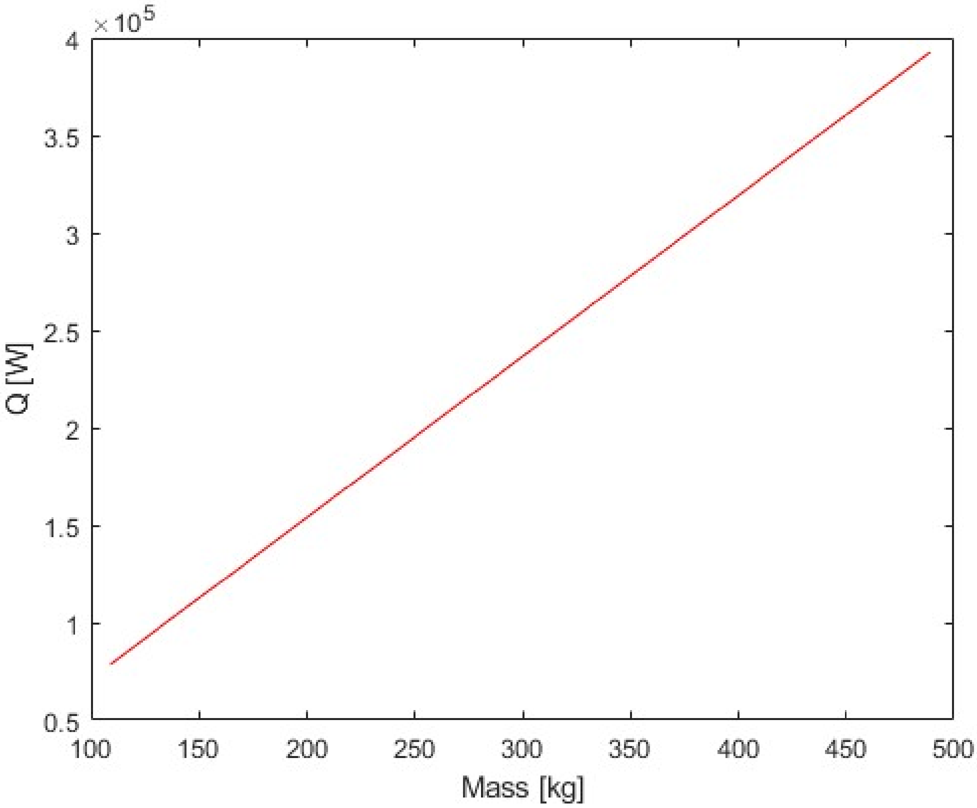


Figure 2.18

2.2 Other architectures: hybrid-electric solutions

One of the primary limitations of the fuel cell all-electric propulsion system is its relatively low power density. To address this issue, the **fuel cell hybrid electric propulsion system** can capitalize on the higher power densities offered by hydrogen turbines while maintaining the climate neutrality associated with fuel cells

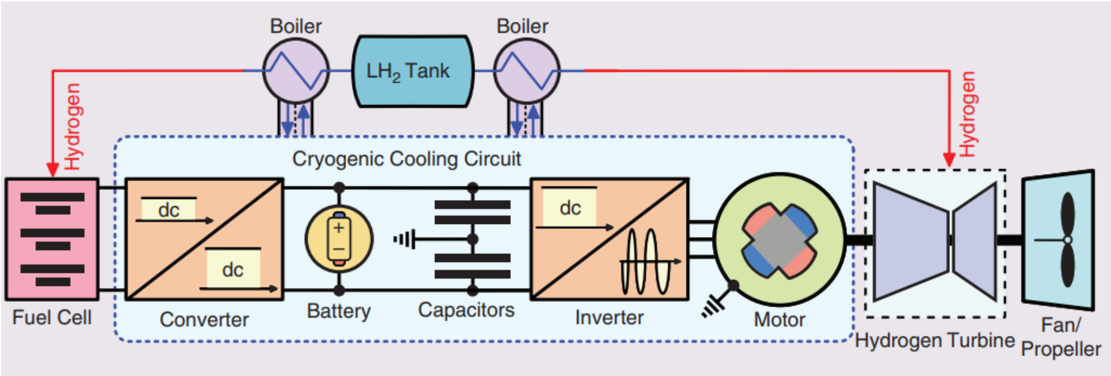


Figure 2.19

The hydrogen turbine is sized strategically to provide the necessary thrust during take-off and ascent, resulting in minimal NO_X emissions during the majority of the flight and potentially reducing contrail formation.

The 2.19 depicts the potential arrangement of such a system. In this configuration, the fuel cell serves as the primary power source during cruise mode, emphasizing the importance of minimizing emissions.
This system demonstrates feasibility and interest within the short-range aircraft segment. For this specific application, the fuel cell system's will have a power rating greater than 10 MW, granting optimal utilization of cryogenic cooling opportunities from liquid hydrogen (LH2). Another significant consideration is the added complexity to the certification process due to the parallel hybrid configuration. Ensuring seamless and efficient interactions between the electric propulsor, hydrogen combustor, and other components poses important challenges that must be addressed.
In a **hydrogen combustion propulsion system** featuring an auxiliary electric component, aircraft propulsion can be entirely driven by direct combustion of hydrogen fuel, similar to kerosene, to generate thrust.

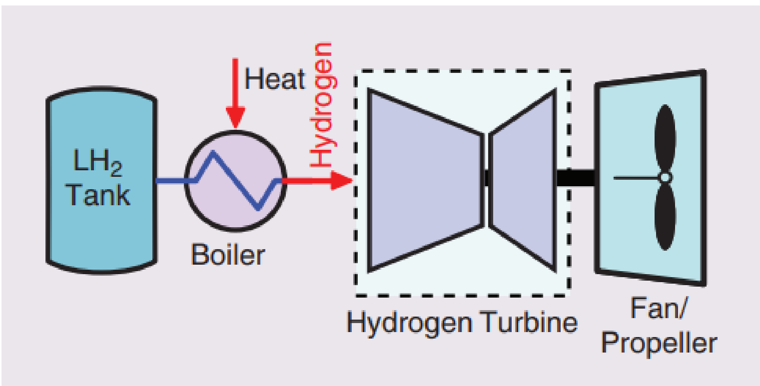


Figure 2.20

The 2.20illustrates the configuration of the system, comprising a single fan with minimal components. This setup is employed in scenarios where the weight of the Fuel Cell System (FCS) would be excessive for propulsion purposes. However, the FCS could still be employed to generate auxiliary electrical power in such aircraft.
The system is technically adapt for medium-range aircraft, with significantly higher costs compared to conventional aviation methods.
As an alternative to direct hydrogen combustion, a **turbo electric propulsion system** presents itself as a viable option. It facilitates turbo electric distributed propulsion, which holds potential as the next disruptive technological advancement. On the other hand it may suffer from slightly lower energy conversion efficiency during cruise mode compared to direct burning, TEPS offers opportunities for enhancing propulsive efficiency and flexibility in implementing new ultra-efficient aerodynamic designs. Moreover, it can optimize efficiency during takeoff and climbing phases.
The efficacy of propulsive efficiency largely depends on the bypass ratio of the fan/propeller, which can be finely controlled electrically. However, incorporating electrical power conversion components adds weight penalties to the system. To mitigate this, superconducting power conversion becomes imperative to reduce added weight and minimize electrical losses. Superconducting solutions have the potential to elevate conversion efficiency to levels comparable to cruise mode while further enhancing propulsive efficiency.
The turbo electric solution has the added advantage of reducing overall power consumption by allowing the hydrogen turbine to operate at its optimal point throughout the entire flight, thereby improving the gas turbine cycle.
Furthermore, it can effectively leverage the significant synergy of LH2 as both a fuel and a cryogenic cooling medium for superconducting power conversion.

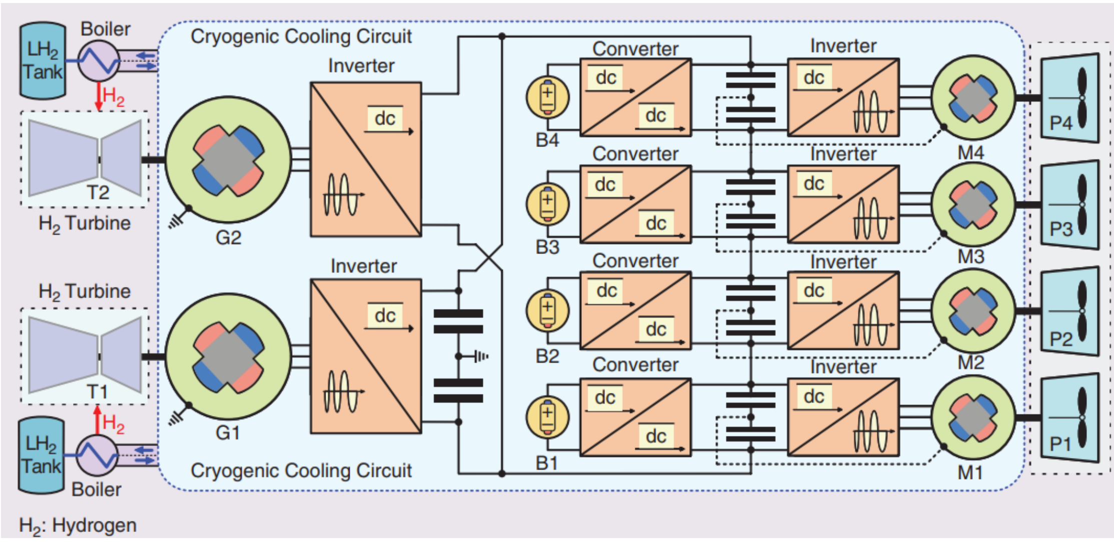


Figure 2.21

2.21 and 2.22 illustrate two distinct turbo electric architectures incorporating batteries as an energy buffer. The first one features modular series-connected propulsors. This design offers the potential for high-voltage transmission, thereby reducing overall weight. Additionally, series-connected propulsors provide the advantage of a floating ground for each propulsor, resulting in low voltage across the insulation and improved reliability. Alternatively, propulsors could be connected in parallel, as depicted in 2.22.

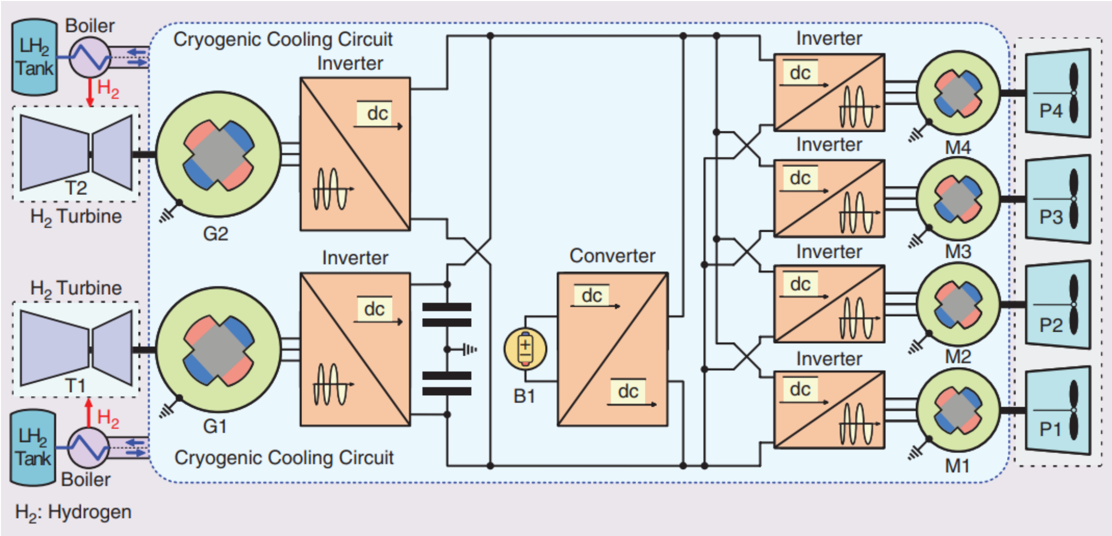

Boiler
LH_2 Tank
H_2
Cryogenic Cooling Circuit
Inverter
dc
T2
H_2 Turbine
G2
Inverter
Converter
H_2 Turbine
T1
G1
B1
LH_2 Tank
Boiler
Cryogenic Cooling Circuit
H_2: Hydrogen
M4
M3
M2
M1
P4
P3
P2
P1

Figure 2.22

Chapter 3

Conceptual design of A320-like configuration with hybrid propulsion system

Conceptual design is the first of three sequentially phases of the design process of complex systems:

- Conceptual design
- Preliminary design
- Detail design

Conceptual design as well as all other design phases is an iterative and recursive process, as shown in the diagram below. The conceptual design starts from stakeholder needs and identifications of mission objectives, then defines requirements and eventually it proceeds with the creation of concepts, the accomplishment of trade studies and the selection of the design alternative.

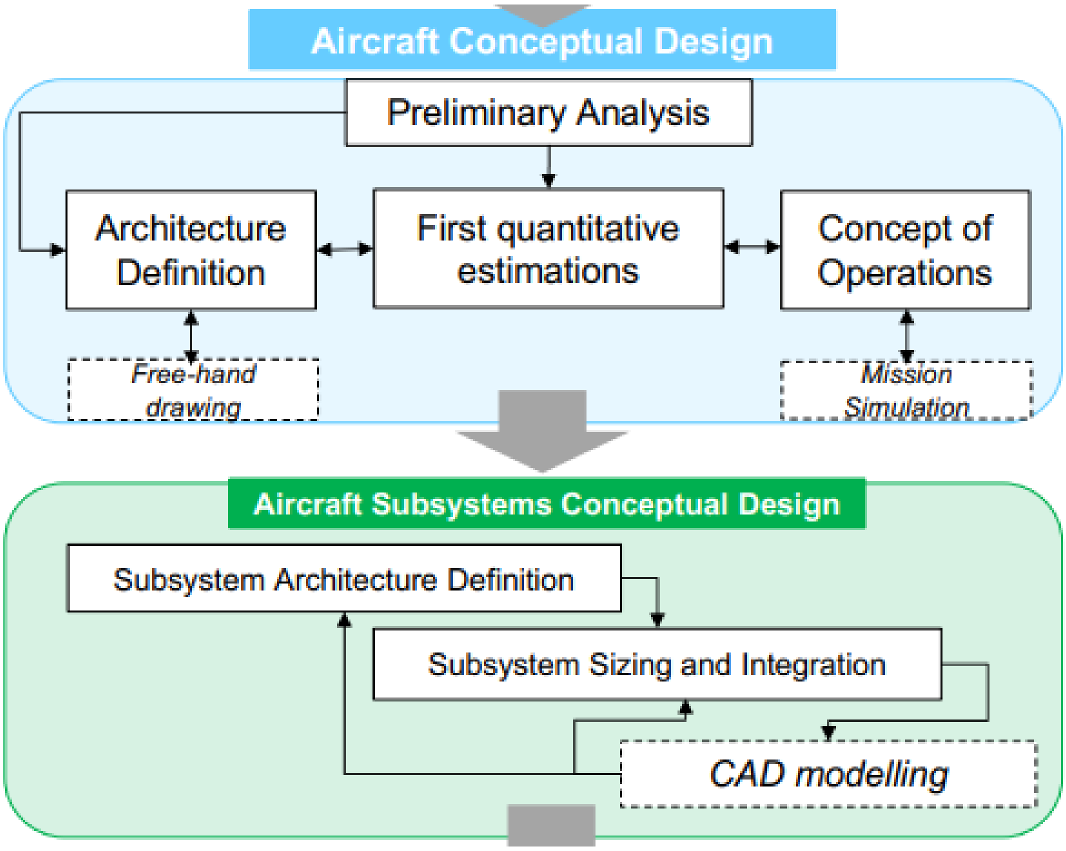


Figure 3.1

3.1 Reference model: A320

Paper's aim is to study the impact of hybrid propulsion architecture on subsonic aicraft whose geometric characteristics are similar to Airbus A320.
The reference model has the following characteristics:

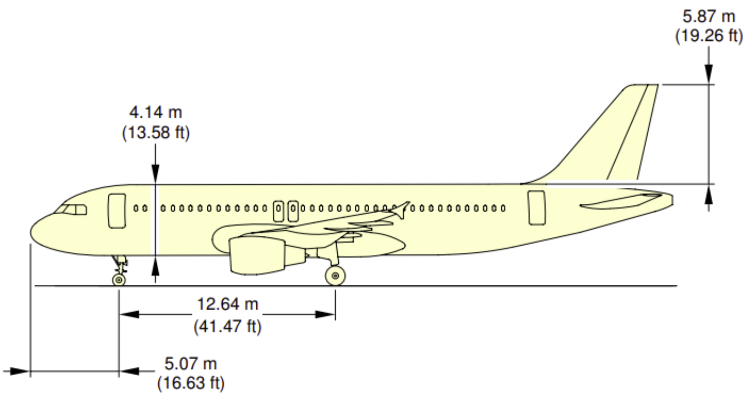


Figure 3.2

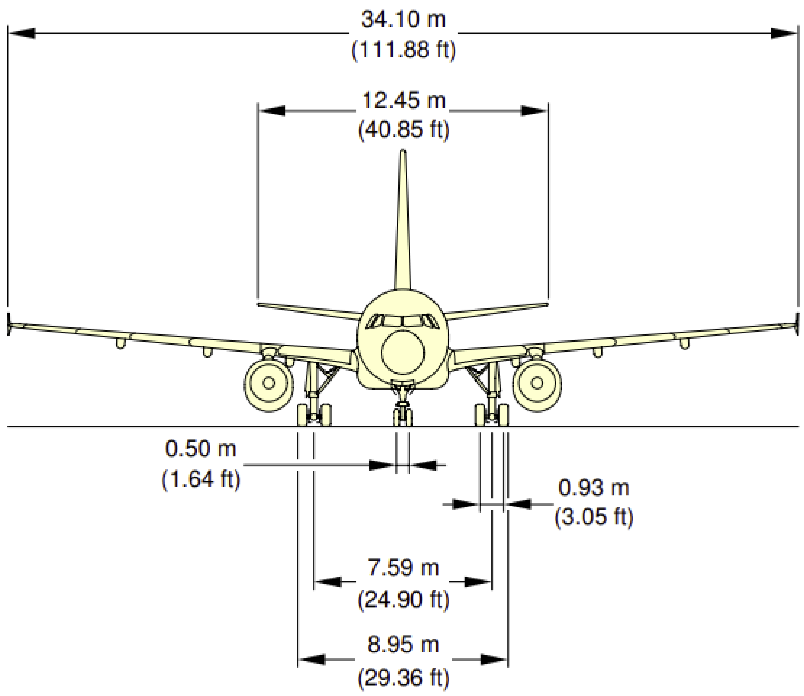


Figure 3.3

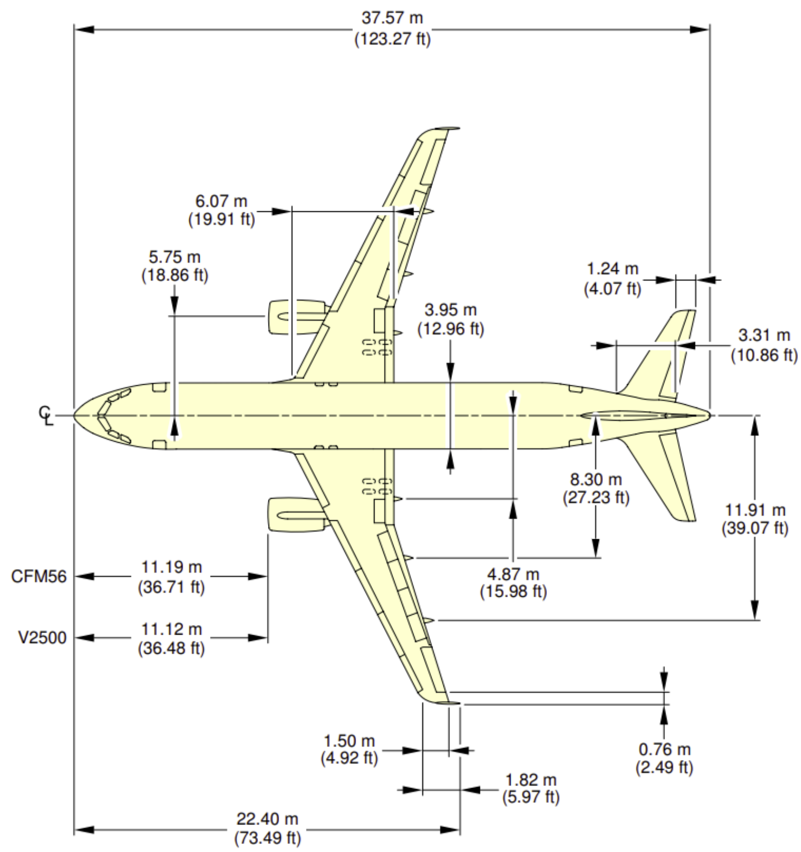
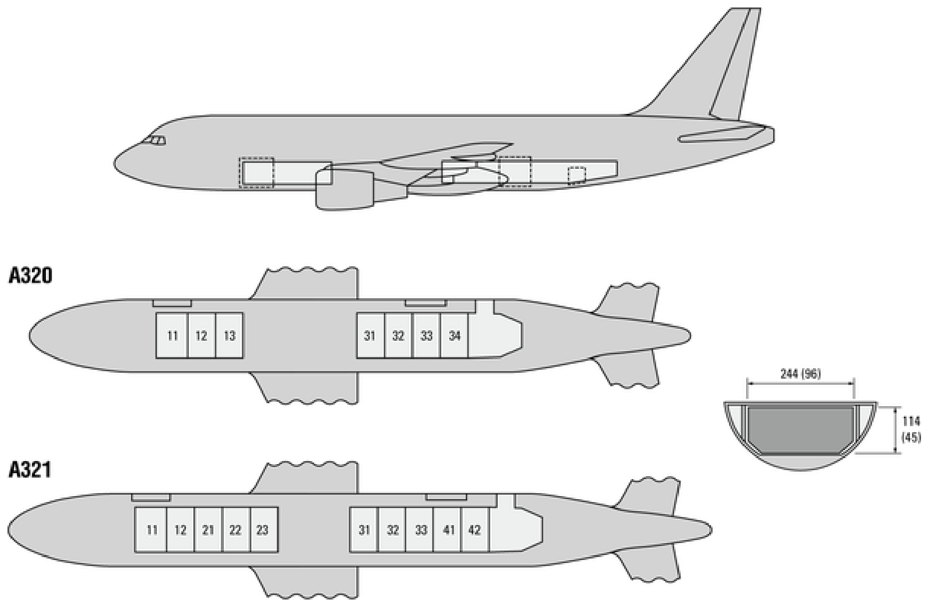


Figure 3.4

Aircraft Characteristics						
Maximum Taxi Weight			73 900 kg			
Maximum Take-Off Weight			73 500 kg			
Maximum Landing Weight			64 500 kg			
Maximum Zero Fuel Weight			60 500 kg			
Operative Empty Weight			42 400 kg			
Standard Seating Capacity			180	(Single Class)		
Fuel Capacity			23 859 L	18 729 kg		
Pressurized fuselage volume			330 m^3			
Passenger Compartment Volume			139 m^3			
Cockpit Volume			9 m^3			
Usable Volume FWD CC			13.28 m^3			
Usable Volume, AFT CC			18.26 m^3			
Usable Volume, Bulk CC			5.88 m^3			
Water Volume, FWD CC			15.56 m^3			
Water Volume, AFT CC			20.77 m^3			
Water Volume, Bulk CC			7.76 m^3			



3.2 High level requirements

Mission parameters constitute the fundamental elements of the flight plan, requiring a selection to fulfill high-level requirements. Moreover, ensuring compatibility between the necessary fuel volume and the available space on board is essential.

Then this section, the requirements of the aircraft to be considered which is powered by LH_2 (liquid hydrogen):

Requirements		
Fuel	LH_2	
Range	3000	km
Pilots	3	pax
Flight attendant	6	pax
Passengers	156	pax
Mach	0.78	
Payload Passengers	19820	kg
Payload Cargo	–	kg
Propulsion system	APU/Systems	PEM FC
Propulsion system	Engines	PEM FC / Direct combustion

It is important to emphasise the key point of this thesis work, the final objective concerns the comparison between the hybrid aircraft and the direct combustion aircraft. In this regard, the conceptual design bifurcates into direct combustion and fuel cell assisted direct combustion. The different hybridisation strategies that are dealt with are therefore compared with the pure direct combustion aircraft as a measure of comparison used to assess the performance, characteristics or results of hybridisation.
The fuel cell technology as primary source of energy is meant to be active while taking off and partially during climb. The reason behind this assumption is linked to the mere FC's aim, it needs to alleviate the engine's turbine in the most critical phase, reducing the specific fuel consumption of direct combustion.
Then the considerations in section 3.3 refers to the pure combustion, as benchmark model.

3.3 Estimation of ratios: Raymer's approach

Once the mission parameters are determined, the take-off mass is calculated as the sum of the cabin crew mass, payload mass, Operational Empty Weight (OEW), and fuel mass. Then the iteration process is repeated for each hybridization degree as it modifies MTOW and fuel quantity. The equations employed for computing the take-off mass for the pure direct combustion aircraft's model, are showed below:

$$m_{TO} = m_{crew} + m_{payload} + m_{OEW} + m_{fuel} + m_{2^{nd}\ fuel\ cell}$$

Not all terms on the right side of the equation are known. The second fuel cell mass depends on the desired output power. Which is described in the next section (3.6.1).

Using Raymer's approach, it is necessary to evaluate some ratios to compute the m_{TO} and it is reformulated as follows:

$$m_{TO} = \frac{m_{payload}}{1 - \frac{m_{fuel}}{m_{TO}} - \frac{m_{OEW}}{m_{TO}}} + m_{2^{nd}\ fuel\ cell}$$

To estimate the empty mass fraction:

$$\frac{m_{OEW}}{m_{TO}} = A \cdot m_{TO}^{c}$$

Where the parameter $A = 0.97$ and $c = -0.06$ are two coefficients supplied by Raymer. However the approach is considered to be different from the original Raymer one, in fact in this paper fuel cells influence the conceptual design.
The mission profile selected is composed of these following phases:

- Take-off;
- Climb;
- Cruise;
- Descent;
- Landing;

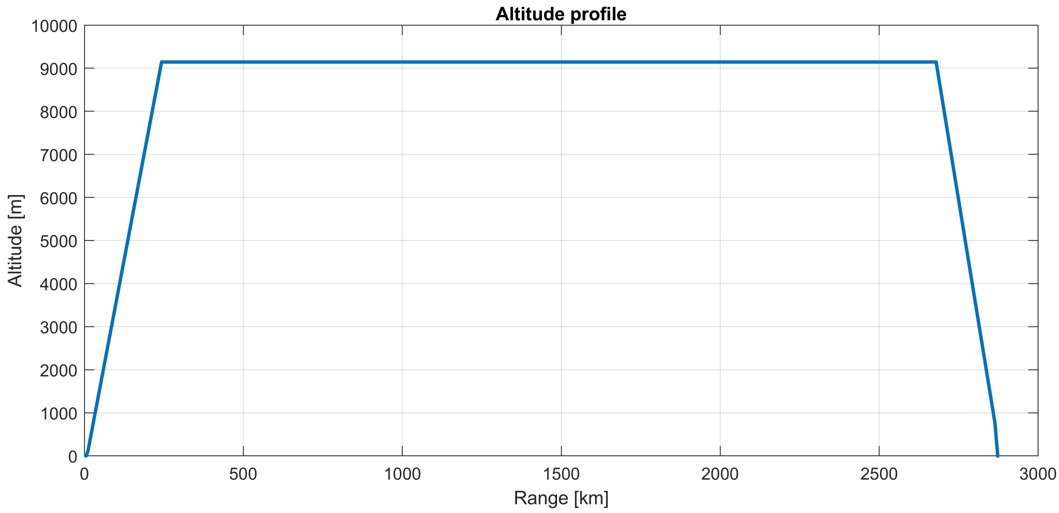


Figure 3.5: Altitude Profile

The estimation of fuel mass fraction is now showed below:
The cruise segment (2-3) includes only the SFC relative to the pure combustion:

$$\frac{m_{end_3}}{m_{end_2}} = e^{-\frac{R}{V}\frac{SFC}{L/D}}$$

In general terms the SFC_{H_2} is computed as follows:

$$SFC_{H_2} = 0.36 \cdot SFC_{JetA1}$$

The equivalent specific fuel consumption for hydrogen engines has been determined by handling the traditional CFM56 multiplying for the lower heating value ratio (LH2-JetA1):

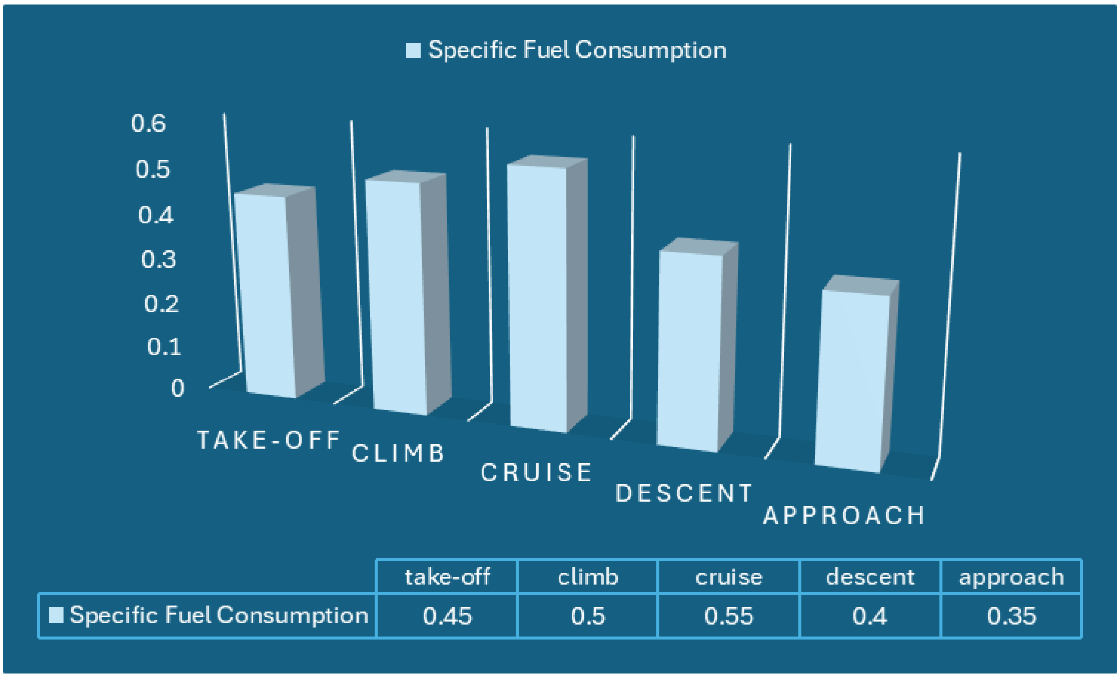


Figure 3.6: Specific fuel consumption for a Jet A1 CFM-56 [1/h]

Where $k_{LD} = 15.5$ for civil jets, $AR = 10.3$ for a typical A320 and $\frac{S_{wet}}{S_{ref}} = 6$
The efficiency E in cruise is computed as

$$\frac{L}{D} = \frac{L}{D}_{max} \cdot 0.866 = k_{LD}\sqrt{A_w} \cdot 0.866 = k_{LD}\sqrt{\frac{AR}{\frac{S_{wet}}{S_{ref}}}} \cdot 0.866 = 17.58$$

$$m_{fuel} = \sum_{i=1}^{n} M_{fuel_i} = k_{allow}(m_{TO} - m_{end_n})$$

and

$$\frac{m_{fuel}}{m_{TO}} = \frac{k_{allow}(m_{TO} - m_{end_n})}{m_{TO}} = k_{allow}(1 - \frac{m_{end_n}}{m_{TO}})$$

$$\frac{m_{end_n}}{m_{TO}} = (\frac{m_{end_1}}{m_{TO}})(\frac{m_{end_2}}{m_{end_1}})(\frac{m_{end_3}}{m_{end_2}})(\frac{m_{end_4}}{m_{end_3}})$$

To estimate the take-off mass, one needs to initially compute the mass m_i of the aircraft at the conclusion of each i-th phase. For instance, m_1 refers to the mass at the conclusion of take-off. The ratio of the aircraft's mass at the end of the i_{th} segment to its initial mass at the beginning of the same mission segment is referred to as the mission segment weight fraction. This fraction is crucial for estimating the unknown mass. By multiplying them together, the ratio between the mass at the mission's conclusion and the take-off value is obtained. Subsequently, the fuel fraction is determined using the following formula considering a 6% margin (required by regulations):

$$\frac{m_{fuel}}{m_{TO}} = 1.06 \cdot (1 - \frac{m_{fuel}}{m_{TO}})$$

$\frac{m_1}{m_{TO}}$	0.9998	$\frac{m_4}{m_3}$	0.9950
$\frac{m_2}{m_1}$	0.9956	$\frac{m_5}{m_4}$	0.9995
$\frac{m_3}{m_2}$	0.9433		

$$\frac{m_{end_n}}{m_{TO}} = 0.9339$$

3.4 Evaluation of masses/performance

3.4.1 A320 passenger H_2 version

The volume of hydrogen must be distributed in the various tanks that are inside the airplane. Assuming a tank of cylinder-spherical volume at the rear, the tank should contain:

$$V = \frac{4}{3}\pi r^3 + \pi r^2 \cdot h$$

Considering the A320 traditional geometry space's requirements and the extra space for tank insulation, the semi-spheres with radius r and the cylinder length h are capable of:

$$V = 2 \cdot \frac{4}{3}\pi r^3 + \pi r^2 \cdot h = 9.63 + 18.38 = 28.01 m^3$$

The remaining volume must be allocated in the tanks on the lower floor. In 4 cylinder-semi spheres (2 parallel and 2 in series) with the following characteristics:

$$h = 6.17\ m$$

$$r = 0.5\ m$$

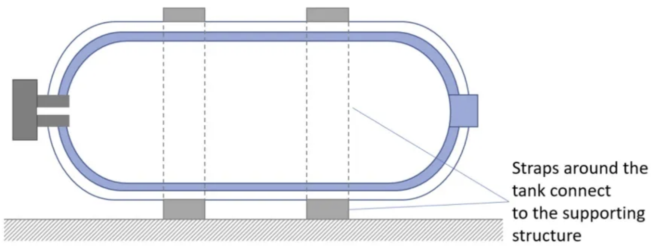


Figure 3.7

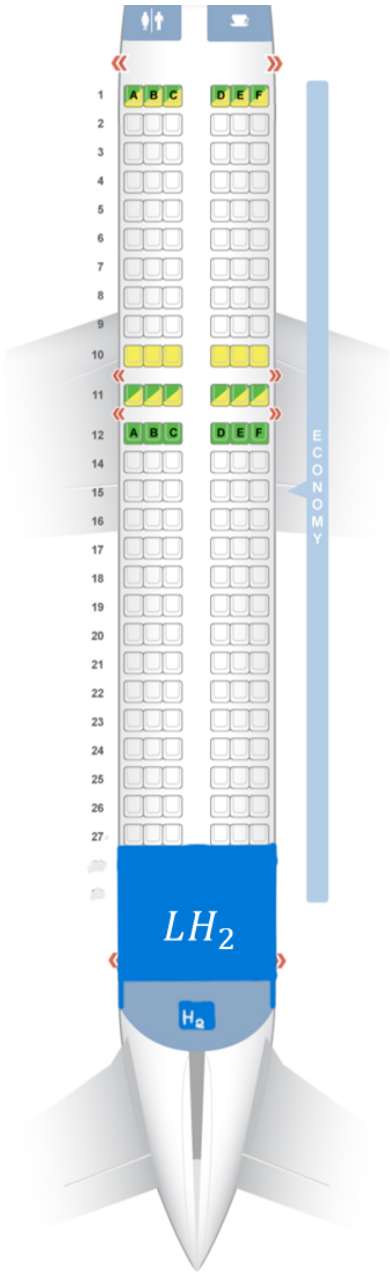


Figure 3.8

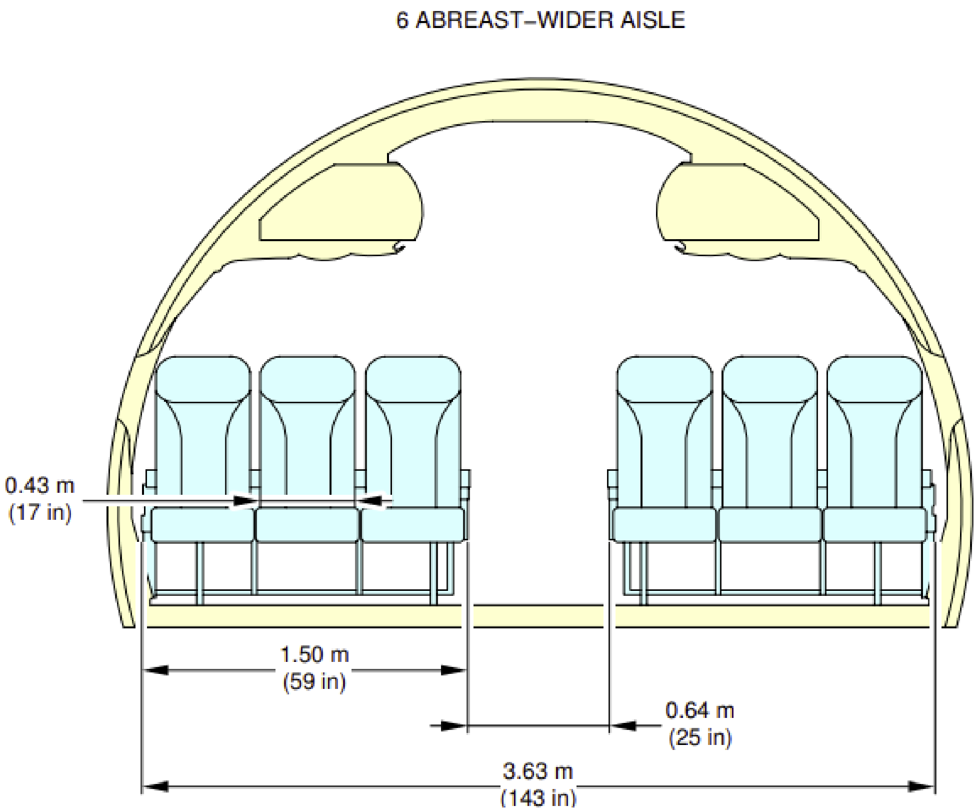

6 ABREAST–WIDER AISLE
0.43 m
(17 in)
1.50 m
(59 in)
0.64 m
(25 in)
3.63 m
(143 in)

Figure 3.9

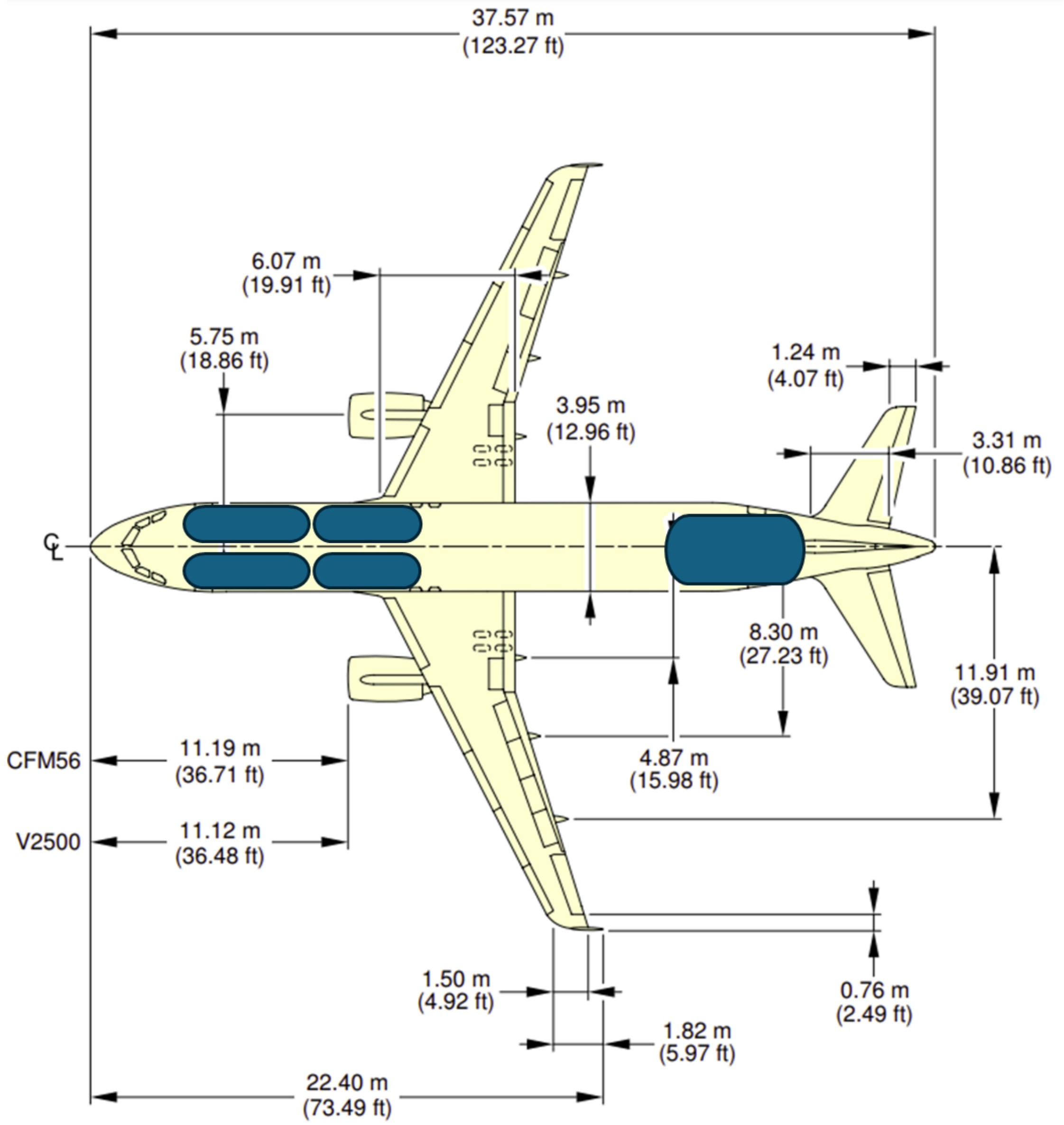

37.57 m
(123.27 ft)
6.07 m
(19.91 ft)
5.75 m
(18.86 ft)
1.24 m
(4.07 ft)
3.95 m
(12.96 ft)
3.31 m
(10.86 ft)
CL
8.30 m
(27.23 ft)
11.91 m
(39.07 ft)
CFM56
11.19 m
(36.71 ft)
4.87 m
(15.98 ft)
V2500
11.12 m
(36.48 ft)
1.50 m
(4.92 ft)
0.76 m
(2.49 ft)
1.82 m
(5.97 ft)
22.40 m
(73.49 ft)

Figure 3.10

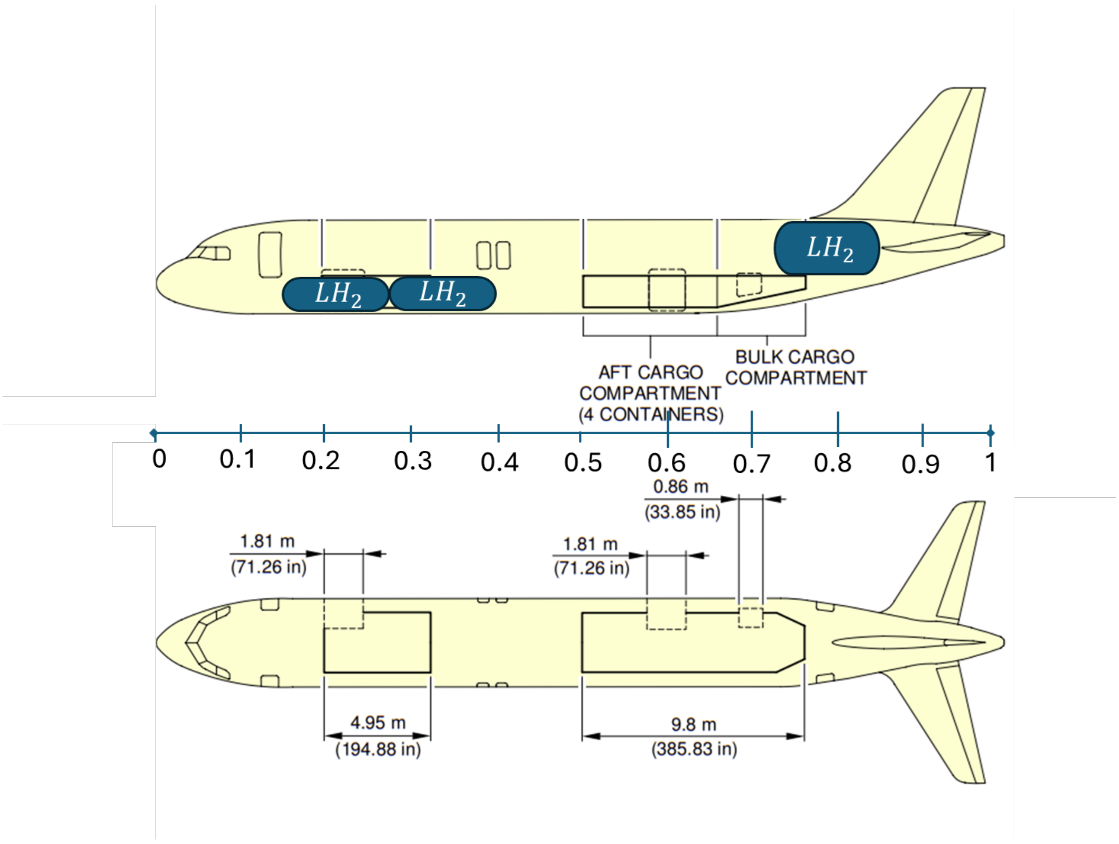


Figure 3.11

3.4.2 A320 cargo H_2 version

Assuming four tanks of cylinder-spherical volume at the belly, the tanks should contain:

$$V = \frac{4}{3}\pi r^3 + \pi r^2 \cdot h$$

As depicted in 3.11 the volume at the belly could be distribueted as follows:

$$V_{belly} = \underbrace{\frac{1}{3} \cdot V_{belly}}_{Forward} + \underbrace{\frac{2}{3} \cdot V_{belly}}_{Aft}$$

Considering the A320 cargo compartment geometry space's requirements and the extra space for tank insulation and inspections, the semi-spheres with radius r and the cylinder length h are could fit in:

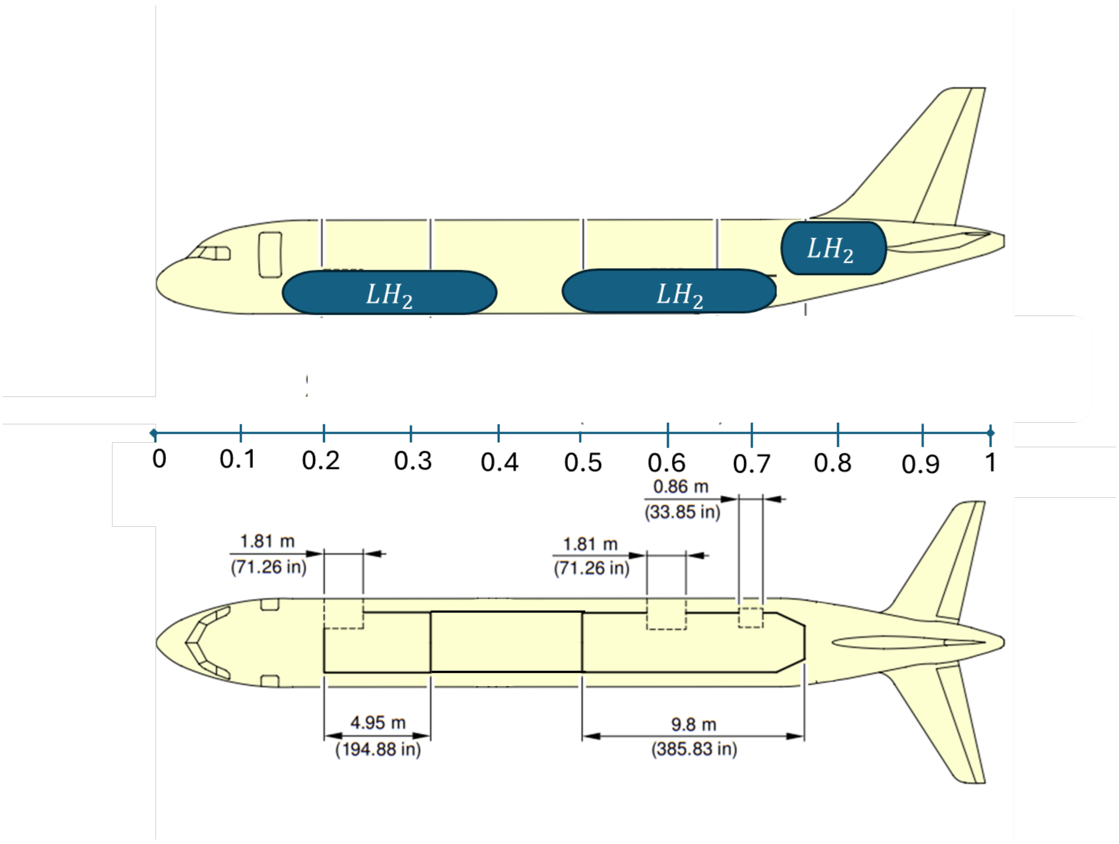


Figure 3.12

3.5 Hybridization degree

The core concept behind aircraft hybridization is the gradual substitution of conventional power sources with PEM-FC solutions and the replacement of traditional fuel with liquid hydrogen, considering also a future electrical architecture in which electrical motors will be ligther than the state-of-the-art as the hydrogen supplied to the PEMFC serves a dual purpose: it powers the system and is also utilized for cryogenic cooling of the Superconducting Magnetic Bearings (SCMs) and high-temperature superconductor (HTS) wires or to cold down power electronics (CPEs). [13]

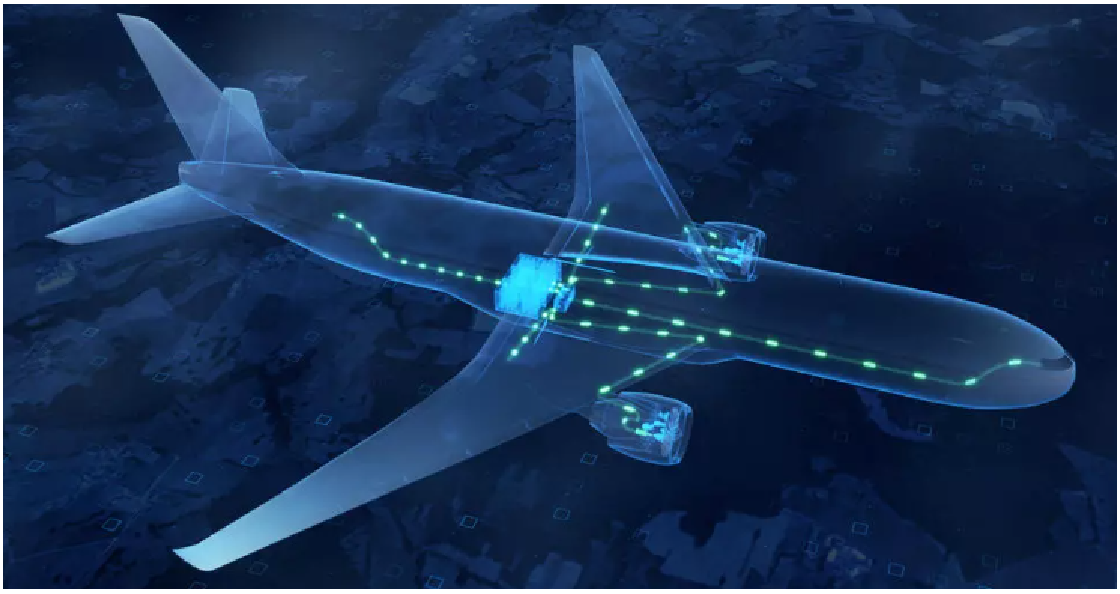


Figure 3.13: [14]

This paper aims to analyze a general architecture capable of accommodating shadows of operational modes for both power and energy distribution. Hybrid Propulsion (HP) deals with drawing energy from pure jet-A1 to pure hydrogen across any flight segment ($0 \leq$ hybridization degree ≤ 1).

The power distribution is divided into the Fuel Cell and the internal combustion of hydrogen, this configuration enables the realization of two distinct powertrains. [15].
A more electric aircraft has lower emissions if compared to the traditional internal combustion engine (ICE). However, the specific fuel consumption of the fuel cell is much lower than that of kerosene. The number of elementary fuel cells is computed, as shown, in the previous section in relation to the output power requested from the various systems. The required power could be fed entirely by the FC or by an hybrid configuration, where th FC is coupled with a battery system or FC is in parallel with a direct combustion.
An hybridization parameter ϕ is now introduced and defined as follows:

$$\phi = \frac{W_{fuel\ cell}}{W_{direct\ combustion} + W_{fuel\ cell}}$$

The hybridization parameter is accomplished by the architecture typology:

- A serial architecture, a single mechanical power source feed the engine. The engine is always driven by an electric motor, enabling distributed propulsion.
- In a parallel architecture, the air-breating engine could operate below peak efficiency. A parallel scheme is more indicated for hybrid applications as it could exploit both fuel cell and direct combustion.

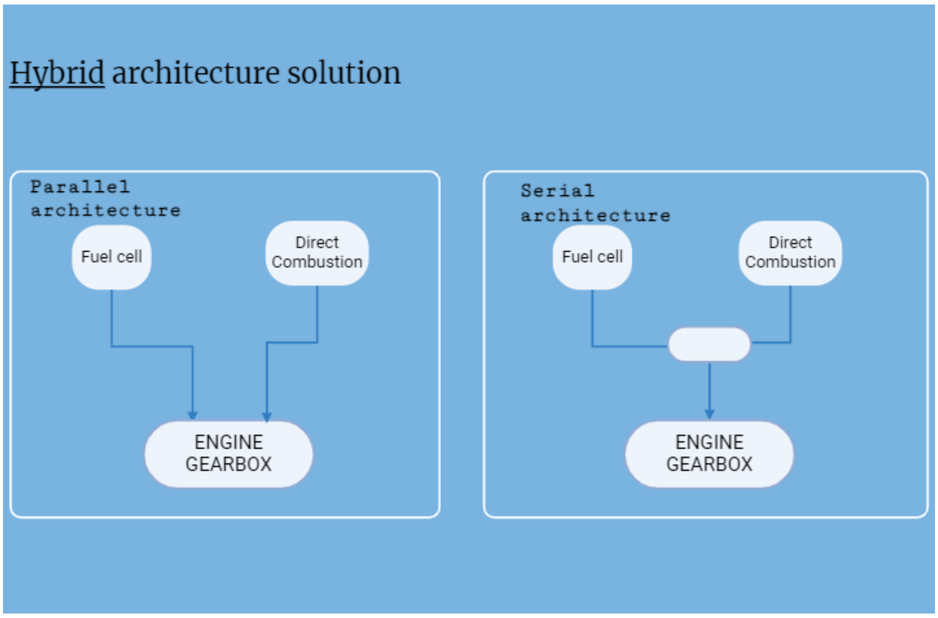


Figure 3.14: Hybrid architecture solution

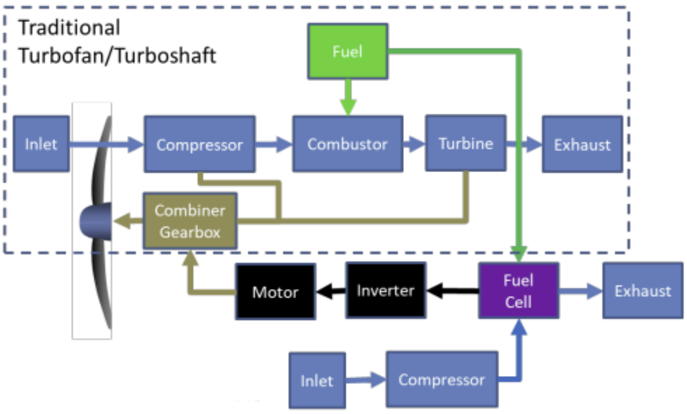


Figure 3.15

The iteration process has been implemented on Matlab and different macro areas can be observed:

- Aircraft/Engine data
- Data Fuel Cell
- Flight mission profile

- Iteration process to estimate MTOW
- Post Processing: Matching chart

Inside the iteration process, different considerations have been made: delta reduction due to FC active in flight, specific consumption fuel related to phase's mission and power requirements. The project's core relies on power requirements and allocation. To begin simulations some considerations have been assumed regarding the hybridization degree and power allocation on-board. Fuel cells are considered as primary propulsive source and are activated in parallel to the direct combustion. Depending on the phase, the hybridization degree establishes the split of power during the phase itself.

3.5.1 Hybridization degree: $\phi = 1$

Despite hybridization degree refers to electric vehicles, hydrogen-powered airplanes could be categorized into hybrid technology as belonging to electric category when the fuel utilized to feed a PEM-FC is hydrogen, instead of directly burned in the combustion chamber. [26]
The maximum degree of hybridization (DH) is given when all the fuel cells provide the electric energy to power the engines and the secondary systems, while a lower DH refers to only a few users feed by fuel cells.

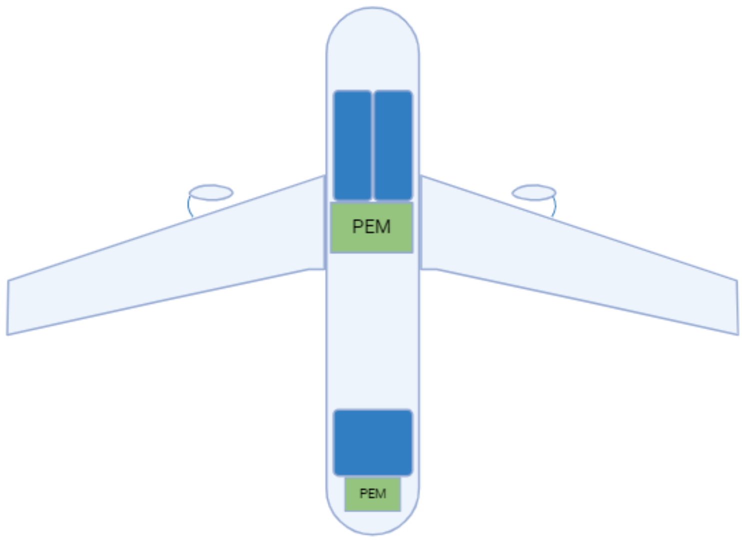


Figure 3.16

3.5.2 Hybridization degree: $\phi < 1$

Other degrees of hybridization are given when all the fuel cells provide the electric energy to power the aircraft with the secondary systems while direct combustion occurs to feed the engines.

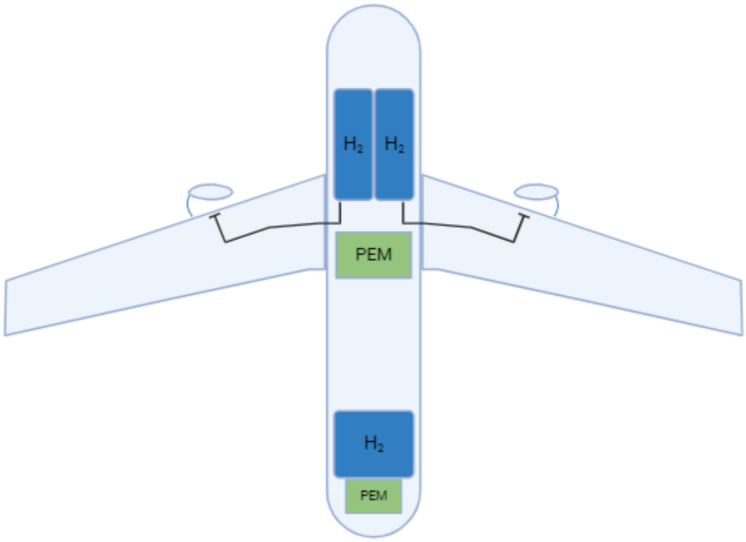


Figure 3.17

3.5.3 Hybridization degree: $\phi \simeq 0$

This degree of hybridization refers to direct combustion as only power source for engines, secondary systems are fed by engine gear box. APU is fuel cell based:

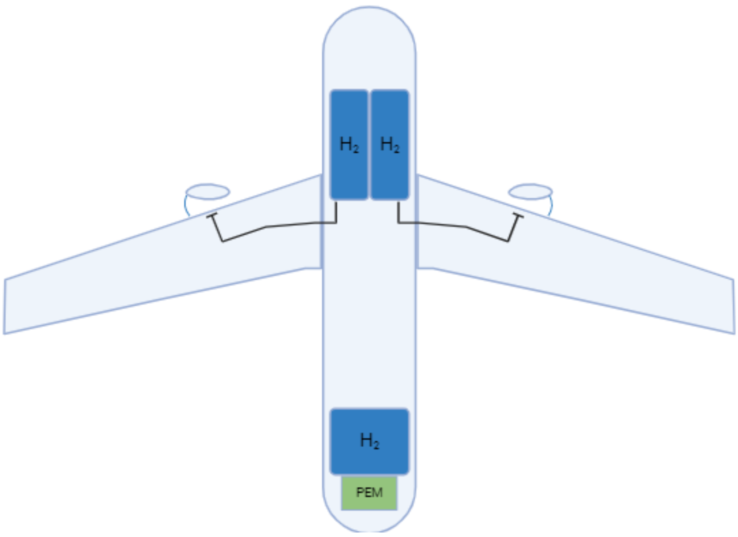


Figure 3.18

For parallel hybrid turbofan gas turbine engine combined with the fuel cell allows to supply power when maximum power is required (as for takeoff or climb) or when the gas turbine is not efficient (the remaining phases idle, descent, or taxi). The first fuel cell influences directly, the second one is fixed to secondary power demand. Considering the figure 3.19, for a medium range aircraft 10 MW could be assumed as electric power requests. [16]

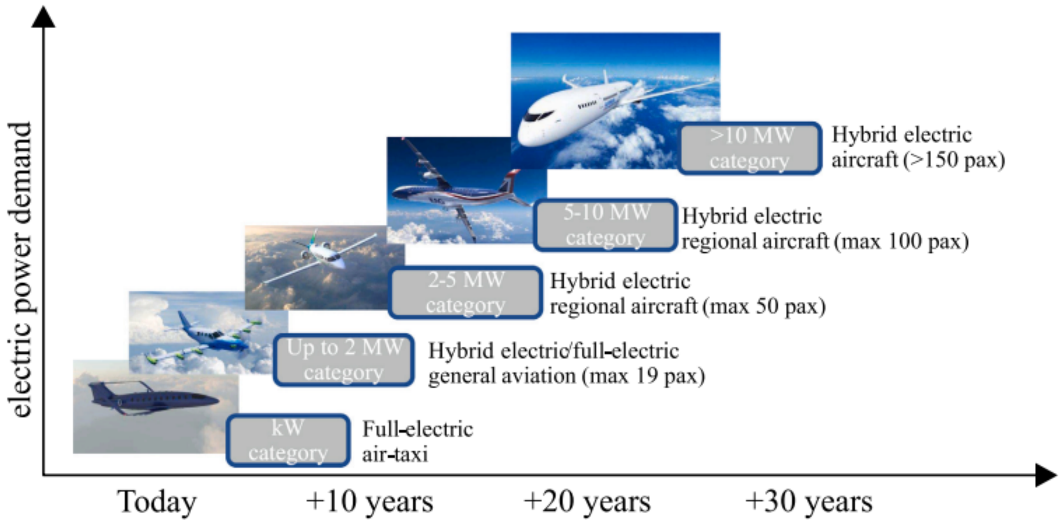


Figure 3.19: Electric power demand in the future

3.5.4 Estimating the fuel cell mass

Since two fuel cell plants are installed on-board, they are distinguished in primary and secondary FC. The primary fuel cell refers to the main propulsion system, the secondary fuel cell refers to the systems and subsystems. The first one needs to be estimated in iterations with the maximum take off weight, while the second one is fixed to the average required power for medium-range aircraft.
Since two different stacks are thought for this paper, the hybridization degree influences the overall mass. Then the iteration process is repeated for each hybridization degree as it modifies MTOW and fuel quantity. The equation representing this calculation is:

$$m_{TO} = m_{crew} + m_{payload} + m_{empty} + m_{fuel} + m_{1^{st}\ fuel\ cell} + m_{2^{nd}\ fuel\ cell}$$

Consequently, the iterative calculation of the take-off mass will take into account the variation of the weight of the primary fuel cell.
The parameters which need to computed by analytic formula:

$$\frac{m_{end_3}}{m_{end_2}} = e^{-\frac{R}{V}\frac{SFC}{L/D}}$$

In general terms the SFC_{H_2} is computed as follows:

$$SFC_{H_2} = 0.36 \cdot SFC_{JetA1} + SFC_{H_2\ fuel\ cell}$$

The specific fuel consumption is computed as follows:

$$SFC_{H_2\ fuel\ cell} = \frac{m_{H2}}{3600}\frac{Power}{V \cdot MTOW \cdot g}$$

where V represents the phase's speed (m/s)

Where $k_{LD} = 15.5$ for civil jets, $AR = 10.3$ for a typical A320 and $\frac{S_{wet}}{S_{ref}} = 6$
The efficiency E in cruise is computed as

$$\frac{L}{D} = \frac{L}{D}_{max} \cdot 0.866 = k_{LD}\sqrt{A_w} \cdot 0.866 = k_{LD}\sqrt{\frac{AR}{\frac{S_{wet}}{S_{ref}}}} \cdot 0.866 = 17.58$$

The presence of the fuel cell influences the Raymer approach and modifies the ratios which are multiplied themselves to obtain:

$$\frac{m_{end}}{m_{TO}} = 0.8696$$

And the ratio:

$$\frac{m_{fuel}}{m_{TO}} = 1.06 \cdot (1 - \frac{m_{fuel}}{m_{TO}}) = 0.0675$$

HD | Fuel ratios	w1/w0	w2/w1	w3/w2	w4/w3	w4/w5	w5/w0
Full Direct combustion	0.9998	0.9956	0.9433	0.9950	0.9995	0.9339
FC during TO	0.9995	0.9888	0.9526	0.9950	0.9995	0.9363

Table 3.1: Impact of the fuel cell on raymer's approach ratios between the benchmark and the hybridization strategy

3.5.5 Matching chart

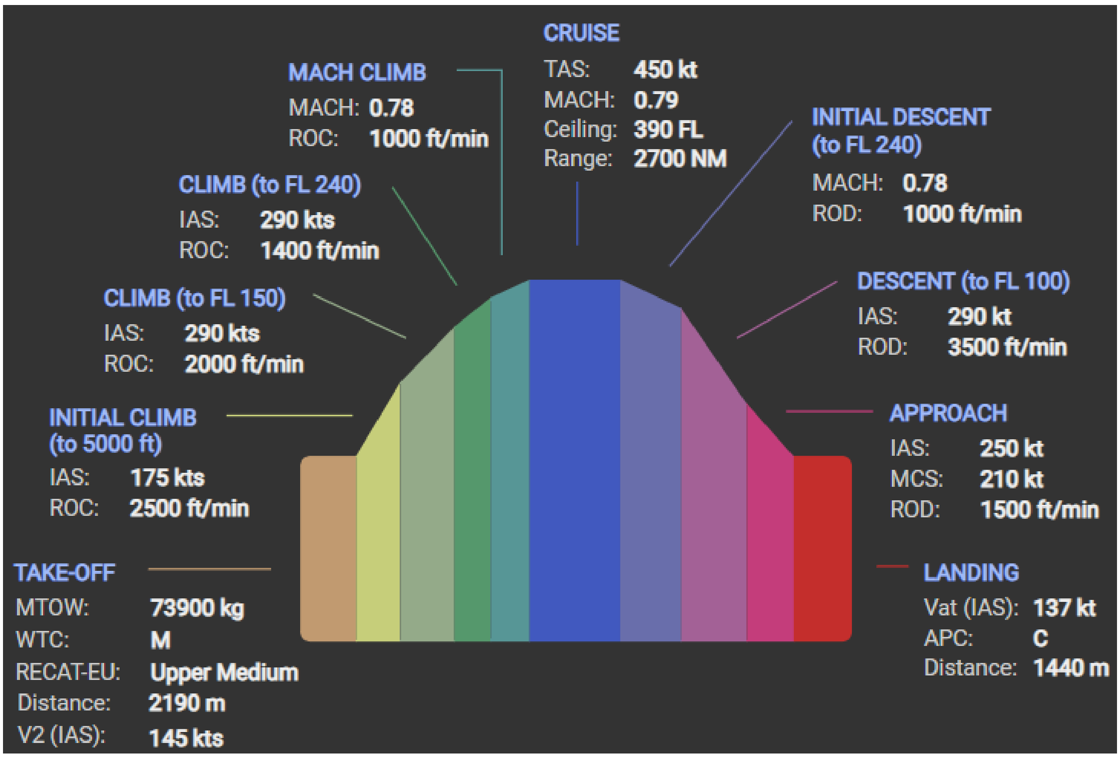


Figure 3.20

The matching chart is a clever way to observe power requirements that correspond to this precise vehicle configuration. This chart shows the ratio Power-to-Weight ratio

($\frac{P}{W}$) and Wing Loading ($\frac{W}{S}$).
The first parameter shows how to generate power in relation to its weight, i.e. high $\frac{P}{W}$ value indicates better climb capabilities.
The following curves are showed:

- Take off run (l_{TO});
- Climb (ROC);
- Cruise;
- Landing;
- Power: Total available, fuel cell and turbine engine power.

The equation are derived from in-flight equilibrium and from Casarosa (citare libro):
Take-off

$$\frac{P}{W} = \frac{\frac{MTOW}{S_{wing}}}{l_{TO} \cdot CL_{TO} \cdot \rho} \cdot V_{speed}$$

Climb:

$$\frac{P}{W} = \left(\frac{0.5 \cdot \rho \cdot V_{CL}^2 \cdot C_{D0}}{g \cdot \frac{MTOW}{S_{wing}}} + \frac{V.Speed}{IASspeed} \cdot \frac{1}{\frac{\rho(cl)}{\rho_{SL}}} \cdot \mathrm{Throttle}_{CL}\right) \cdot V_{speed}$$

Cruise:

$$\frac{P}{W} = \left(\frac{0.5 \cdot \rho \cdot V_{CR}^2 \cdot C_{D0}}{g \cdot \frac{MTOW}{S_{wing}}} + \frac{V.Speed}{IASspeed} \cdot \frac{1}{\frac{\rho(cr)}{\rho_{SL}}} \cdot \mathrm{Throttle}_{CR}\right) \cdot V_{speed}$$

Landing:

$$\frac{P}{W} = \rho \cdot V^2 \cdot \frac{CL}{2g}$$

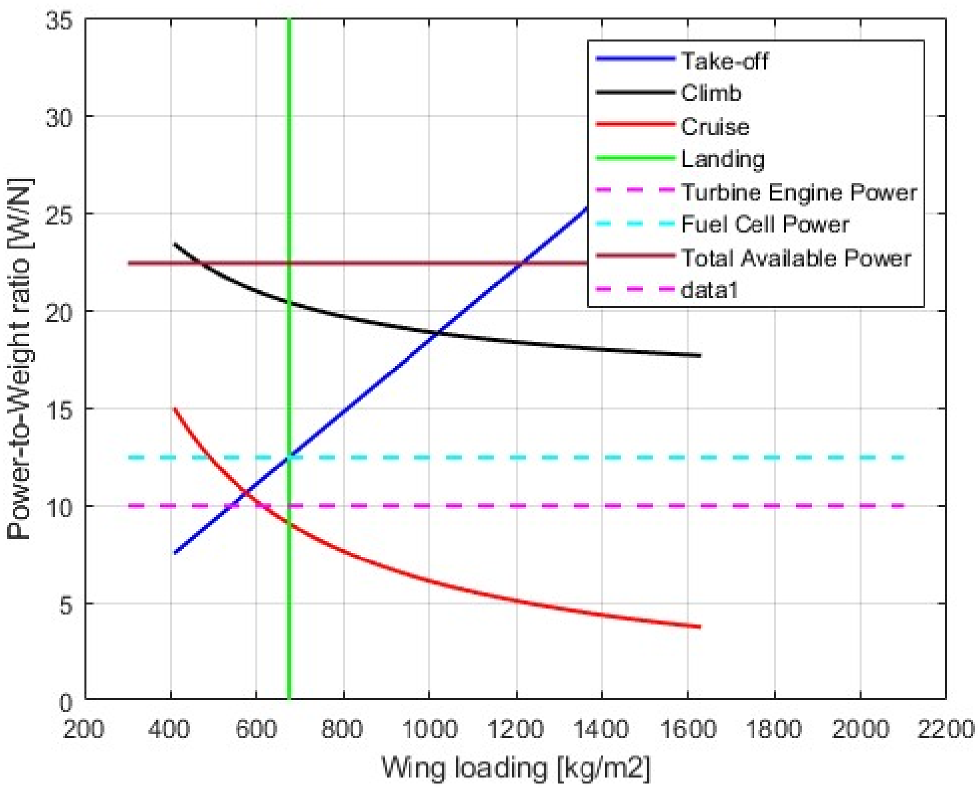


Figure 3.21: Matching chart: Fuel Cell 100 % active during take off

The aforementioned equations illustrate the power distribution for full fuel cell technology active in-flight, different configurations are illustrated below:

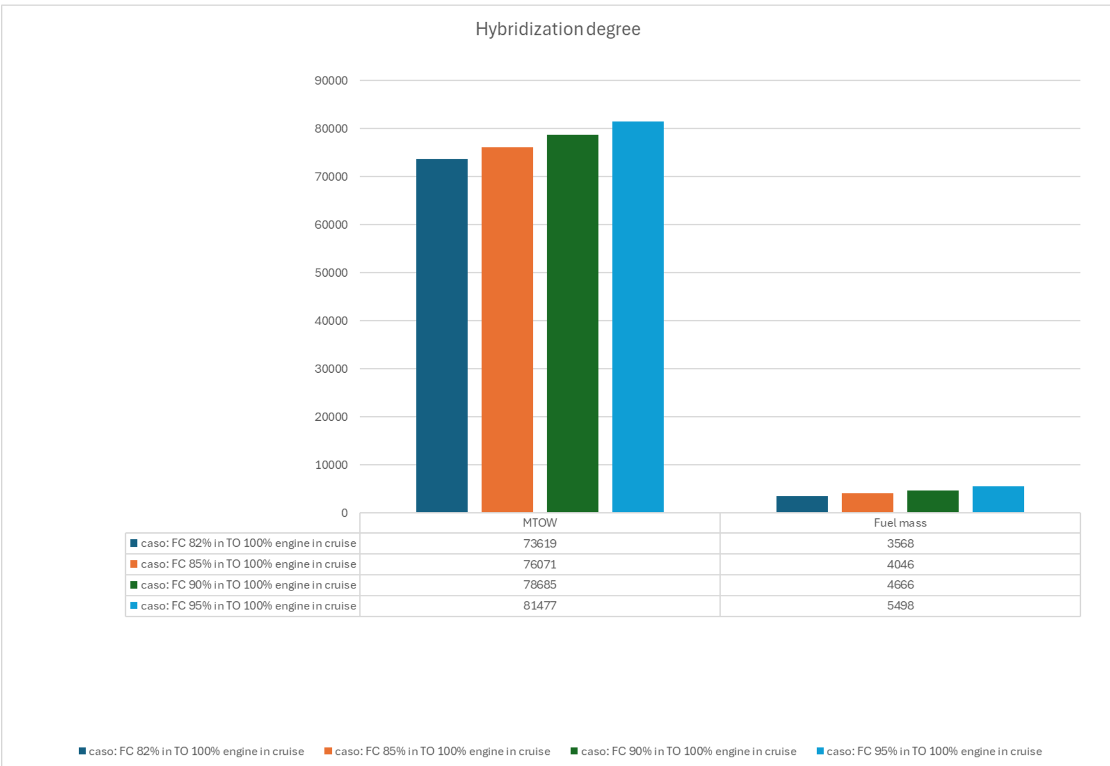


Figure 3.22

Fig:3.22 shows the development of the mass as the degree of hybridisation changes, each degree of hybridisation was calculated considering the operation of the fuel cell only in the critical take-off phase, any excess power during take-off is to be considered as surplus power to assist the cruise phase.

3.6 On-board systems

The fig 2.17 depicted the linear variation of the mass in relation to the requested output power, for this project the second fuel cell on-board is properly sized to fed the secondary systems/APU. Since the objective of this master thesis is the evaluation of the degree of hybridization, the fixed configuration is set to a request power equivalent to $P = 450\ kW$ as reported in Tab 3.2.

The Airbus A320 is provided of this main equipment composed by:

- Fuel System
- Avionic System
- Environmental Control System
- Ice Protection System
- Landing Gear
- Electric Power System

3.7 Key considerations in the conceptual design of a hydrogen powered aircraft

The concept design considerations made so far consider the elements present in the traditional way of carrying out concept design analyses. This aircraft presents characteristics that have not been mentioned and discussed yet in this thesis work:

- H_2 tanks for storing hydrogen
- APU dedicated for secondary power plant

3.7.1 H_2 Tanks

Depending on the amount of hydrogen to be transported on board, the weight of the tanks varies. The table below shows how as the volume of hydrogen to be transported varies, the ratios allow us to include the weight of the tanks on board.

	Nonintegral	Integral
Fuel weight fraction (lb/lb of LH_2)		
Tank[a]	0.113	0.196
Thermal protection system	0.079	0.060
Heat shield	0	0.060
Fuselage structure	0.152	0
Total	0.344	0.316
Volumetric efficiency[b]	0.855	0.927
Accessibility for inspection / repair	removal of tank	removal of heat shield

[a] Based on a 40000 psi (275.8 MPa) allowable stress
[b] Volume available for LH_2 divided by volume of fuselage section

Figure 3.23

At standard temperature and pressure, hydrogen gas exhibits an extremely low density, approximately $0.08238\frac{kg}{m^3}$. For instance, storing 5 kg of hydrogen necessitates a volume of around $60m^3$, containing an energy content of $600MJ$ (which are equivalent to 166.65 kWh).This underlines the necessity to enhance hydrogen density by reducing volume under standard temperature and pressure conditions. Compressed tanks as storage medium stand as the most developped method, categorized into four standard types: Type I, II, III, and IV. [18]

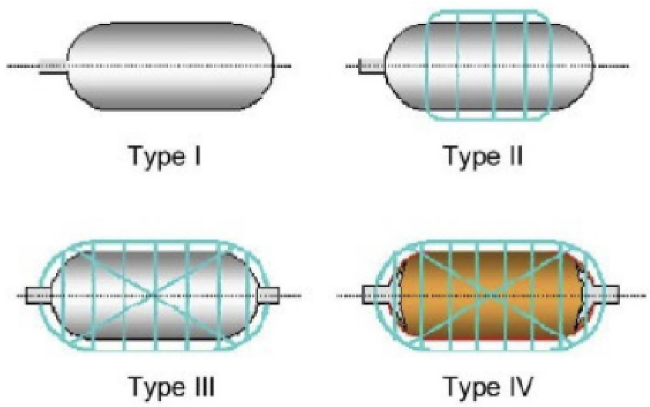


Figure 3.24: [19]

The classification of the vessel relies on factors such as the lightweight and cost-effective material of the tank capable of tollerate high pressures, the material's resilience against hydrogen diffusion.

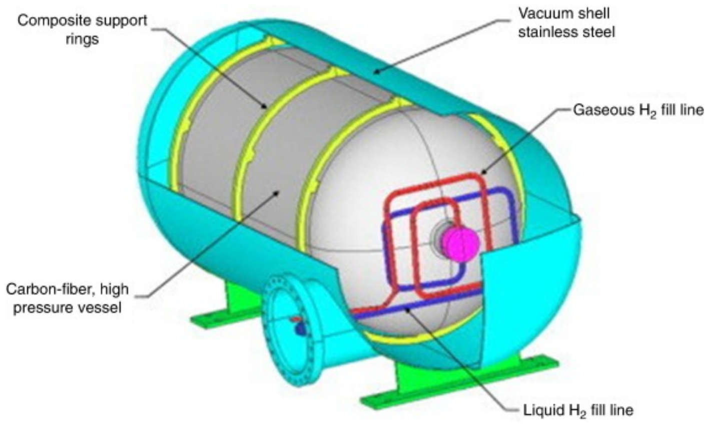


Figure 3.25: [23]

Cryo-compressed hydrogen storage typically operates at lower pressures, often below 300bar, in contrast to the higher pressures of 700bar used in compressed hydrogen storage. This difference in pressure may alleviate the need for more expensive carbon fiber composites.[22]

Type	Materials	Typical Pressure (bar)	Cost ($/kg)	Gravimetric Density (wt.%)
I	All-metal construction	300	83	1.7
II	Mostly metal, composite wrapped in the hoop direction	200	86	2.1
III	Metal liner, full composite overwrap	700	700	4.2
IV	All composite construction	700	633	5.7 (Toyota Mirai)

Figure 3.26

Then the first two configuration are taking into account considering the aerospace applications.

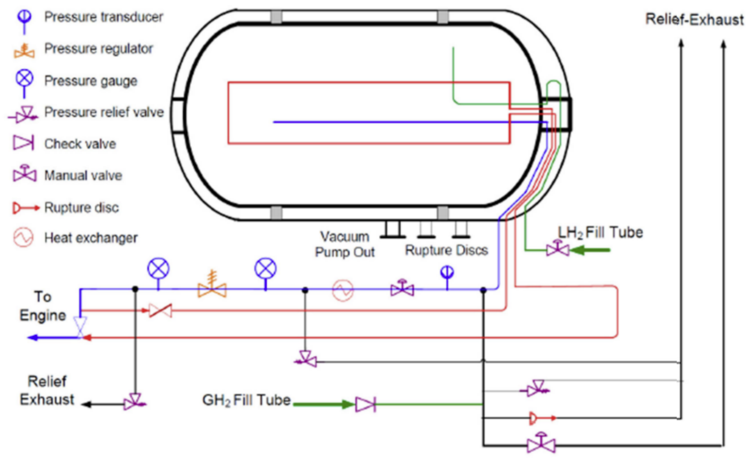


Figure 3.27: [24]

3.7.2 On-board systems sizing: Aircraft Subsystems Conceptual Design

Depending on the amount of hydrogen to be transported on board, the weight of the tanks varies. The table below shows how as the volume of hydrogen to be transported varies, the ratios allow us to include the weight of the tanks on board.
Depending on the degree of electrification (i.g number of electrical users) it is possible to estimate the electrical demand of an aircraft. All electric aircraft (AEA) as for Airbus A-380 require an electrical power that can exceed the order of $1MW$, more electric aircraft (MEA) power demand halves, about $500kW$.
[20] It is then summarized the order of electrical energy that is necessary to feed the main systems on-board. The configuration include PEM Fuel Cell technology which aims to hypothetically supply the electric power for the following subsystems:

- Avionics
- Ice and Rain protection (IPS)
- Environmental Control System
- Landing Gear
- Auxiliar Powe Unit (APU)

The aforementioned subsystems require specific considerations. Pneumatic IPS requires a bleed air at 2.1 *bar* and $190 - 230$ C in cruise, this air flow could be ideally granted (according to FC's safety rules) by the heat produced in the fuel cell.
A nominal CFM-56 distributes its amount of power generated by the Airbus A320 as follows:

- Generator Electric System $200kW$
- Compressor Pneumatic $1.2MW$
- Pump Hydraulic System $240kW$
- Fuel pump, oil pump, mechanical system $100kW$

For this thesis's project,a a second fuel cell was considered to power the systems, the output power of which was sized according to secondary power requirements. Conventionally, the APU system is switched off during flight, its operation being related to ground operations and emergency conditions. In this conceptual design, the use of the APU is also extended to the other phases of flight, the use of a fuel cell to power the secondary consumers during the cruise phase has an impact on specific fuel consumption even though without the APU providing bleed air, the aircraft's engines may need to run for a longer duration while on the ground to power systems like air conditioning and pressurization.
The conventional APU exploits the bleed system to run the APU engine, Using a bleedless system therefore has advantages with regard to fuel consumption(3.30). Considering the following graph, the reduction in fuel consumption is directly proportional to the percentage of power with which the fuel cell is to be sized. To explicitly account

for the Δ SFC in the context of both shaft power off-take and engine bleed, we need to incorporate their respective impacts.

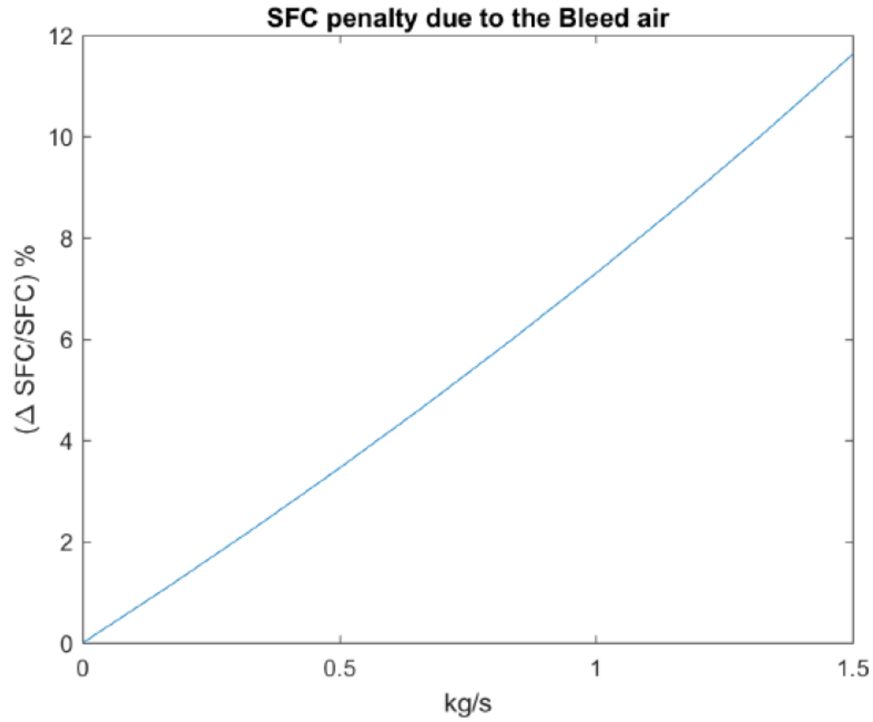


Figure 3.28: SFC reduction due to bleed

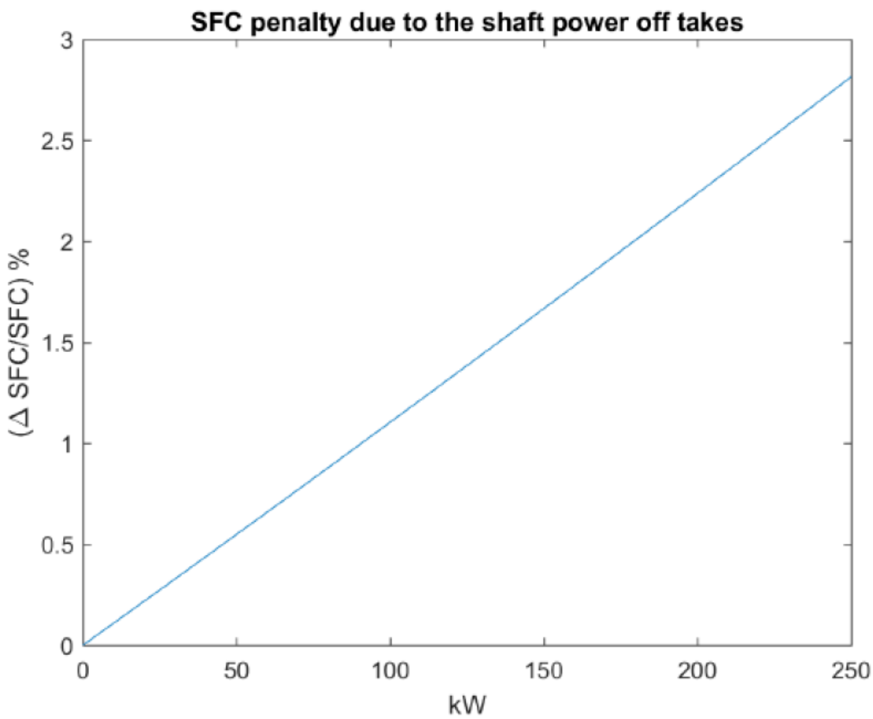


Figure 3.29: SFC reduction due to shaft power

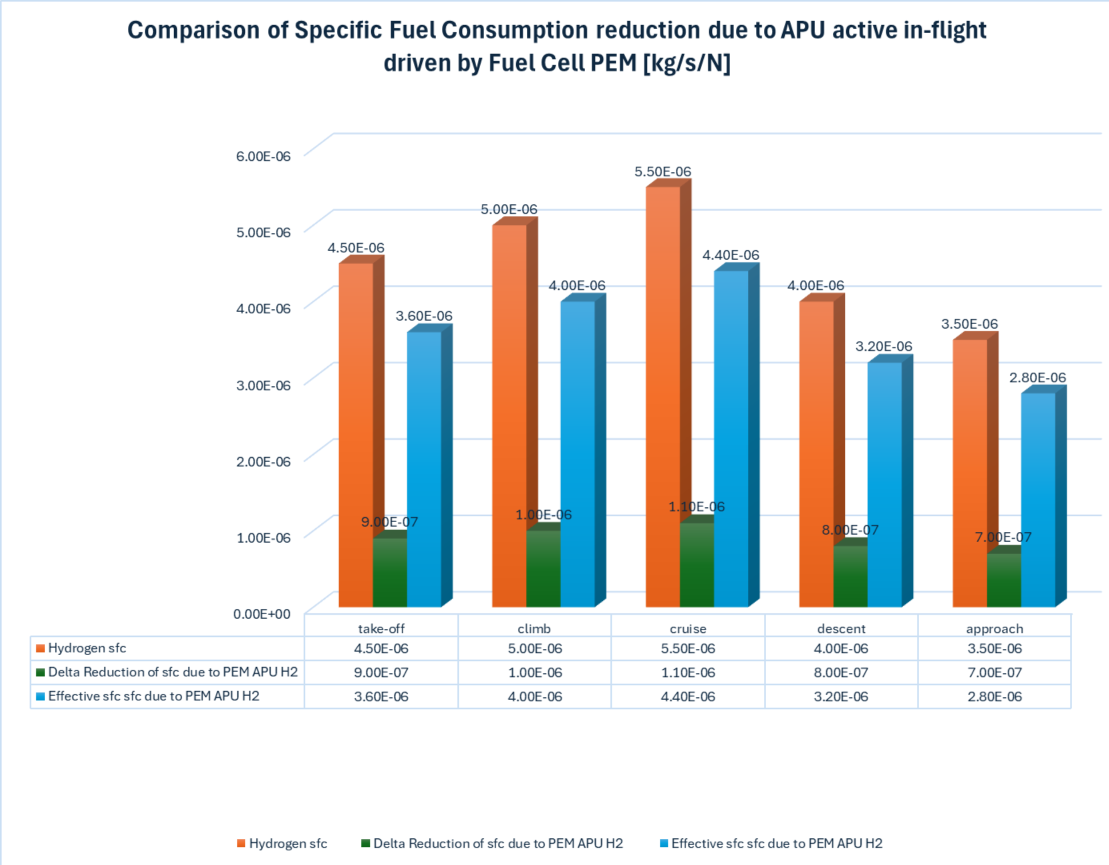


Figure 3.30

The turbofan jet engine weighs 2.3 tonnes and is characterised by a mass–power ratio of about 58 $\frac{kg}{MW}$. Electric engine drive with a similar power, has about 2055 $\frac{kg}{MW}$. Producing tens of megawatts with an electric engine, the weight 35.48 times greater than conventional turbofan engine. The weight of a conventional Airbus A320 converted into an electric version is influenced by the mass of the new electrical equipment to be installed.

Main Elect. Consumers	Conventional Architecture		MEA Architecture		AEA Architecture		System Power
	active else than in flight	active	active else than in flight	active	active else than in flight	active	[kW]
Auxiliary Pumps		(YES)		(YES)		(YES)	(60)
Lighting		YES		YES		YES	15
Commercial loads		YES		YES		YES	25
Avionic		YES		YES		YES	10
Galleys		YES		YES		YES	75
Cargo doors			YES		YES		15
Flight controls						YES	80
landing gear						YES	25
Engine starter			YES		YES		350
Wing Anti Ice (IPS)						YES	200
ECS				YES		YES	400
Total demand [kW]	145 (205)		910 (960)		1215 (1275)		
In flight demand [kW]	145 (205)		560 (720)		850 (910)		

Table 3.2: Range values for a typical A330

- Airbus A320 Passenger Configuration
- Airbus A320 P2F Cargo Configuration

Both configuration would have an impact in decarbonizing the aviation sector

Figure 3.31: CArgo options

3.7.3 Passenger A320

A two-class configuration for a nominal Airbus A320 Ceo is thought for transporting both passengers and cargo. In this paper different studies about configuration have been carried out in order to redistribute the electrical power. The main users that will benefit from introducing PEM Fuel Cell are the following:

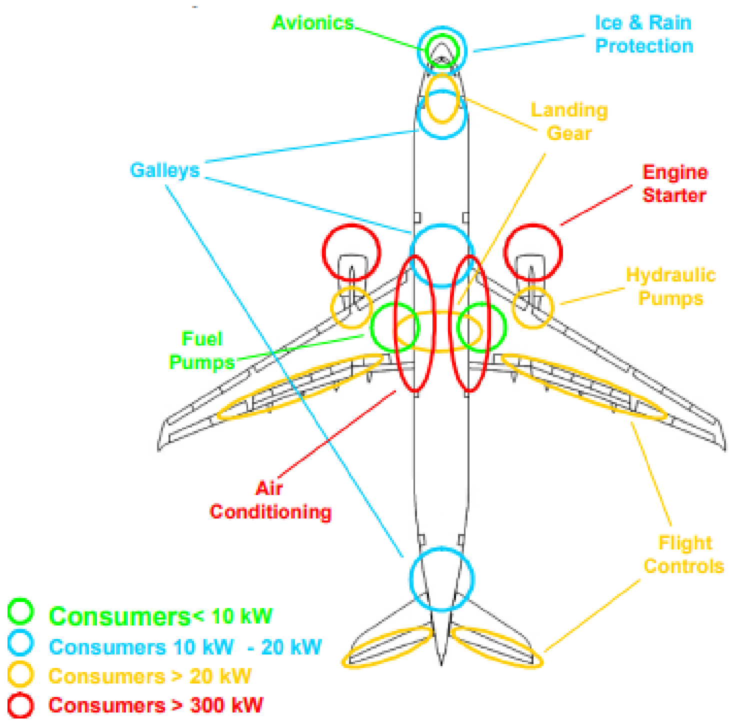


Figure 3.32

For all configurations the use of a PEM technology fuel cell has been chosen since its user-friendly architecture compared to SOFC.

3.8 APU at the state of the art

The APU can be driven via on-board batteries and an electric starter. The operating scheme involves the actuation of a flap motor to open an air intake. The power generation of the auxiliary system comes from the presence of a combustor, compressor and turbine.

3.8.1 APU operativity

Aircraft	Numbers of APUs	Usage according to Aircraft manufacturer
Boeing 727	1	Only on ground
Boeing 737	1	Both on ground and airborne
Boeing 747	1	Only on ground
Boeing 767	1	On ground for nominal cases Airborne for emergency cases
Boeing 777	1	Both on ground and airborne
Airbus 300	1	On ground for nominal cases Airborne for emergency cases
Airbus 320	1	On ground, during take-off and airborne
Airbus 340	1	Both On ground and airborne

APU [21] is operative during ground operations, it provides the supply of energy, compressed air and conditioning when engines are shut down. Its main task is to determine a satisfying environment for the passengers and the payload. Airports which not provide ground services such as electrical power or conditioned air, require aircraft to be equipped with APU because it is necessary to provide:

- Energy to cool down or warm-up the cabin.
- Bleed air to start the first engine.
- Secondary power during taxiing in.

An alternative way to supply the aircraft is to exploits ground power unit (GPU).
APU is necessary for pilots to provide electricity during ground operations, airlines consider APU an extra cost that could be avoided using GPU or finding a greener alternative to traditional architecture. Furthermore airports which provide electricity and compressed air would let APU be not necessary, then inoperative.
APU has a crucial role during in flight operations, in emergency situations such as bird strike with engines inoperative, it guarantees the extra power that Ram Air Turbine is not able to provide. If the APU has an impact on the safety, it is considered as an essential role on flight mission for producing bleed air and power to sub-systems.
By airport's point of view, Auxiliary Power Unit has an effect considering the decibel and pollutant emissions. Considering aircraft configuration without APU might be helpful in terms of air quality.
In this paper, the APU has been sized in order to be fed by a dedicated PEM fuel cell stack. The idea of not using APU during Ground Operation has been studied by Airbus, which funded a project whose aim for saving fuel during taxi operations. [27] The project aimed to let ground operations be greener using electric energy in place of engines thrust. The solution Airbus and Safran studied was called *eTaxi*, an electrical motor capable to tug the aircraft itself during push-back and taxi operations,

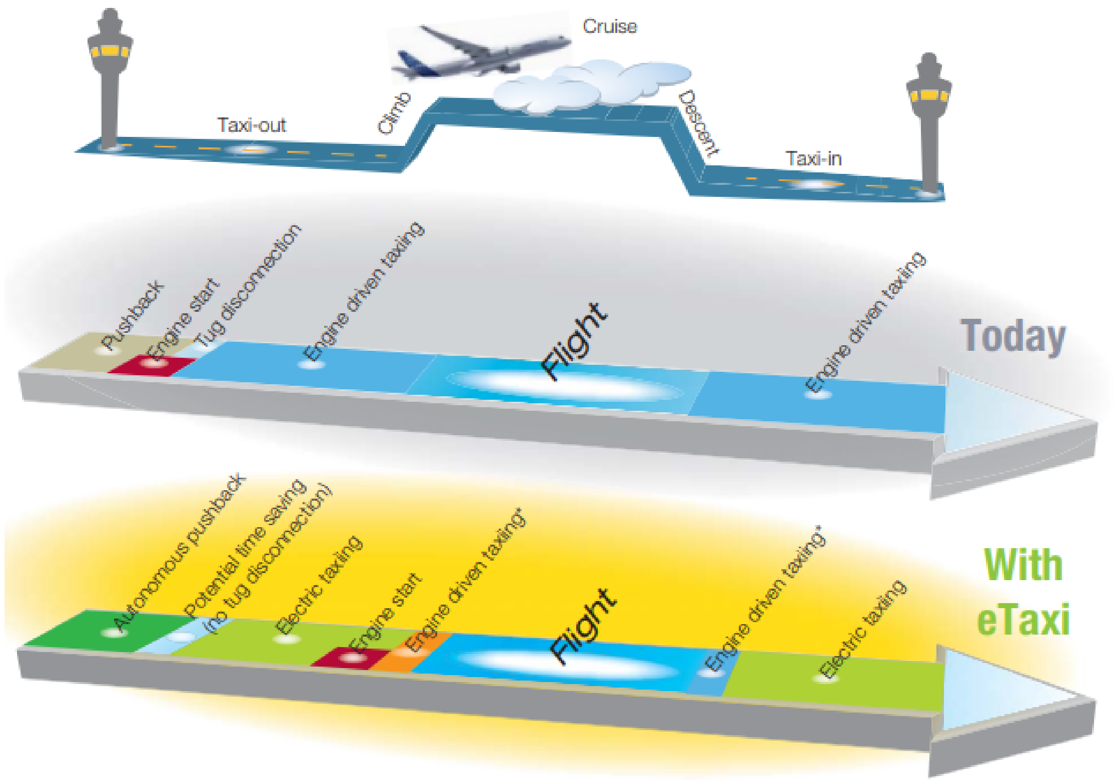


Figure 3.33

Fuel (*Jet A-1*) Burned during taxi operations can be computed as follows:

$$\text{Fuel Burn} = \underbrace{(9.5\ kg/min)}_{\text{One eng. taxiing+APU}} \cdot (\underbrace{20\ min}_{\text{Taxi Time}} - \underbrace{(5\ min\ +\ 3\ min)}_{\text{Eng. Warm-up}}) = 114\ kg$$

$$\text{Fuel Burn} = \underbrace{(12.5\ kg/min)}_{\text{Two eng. taxiing}} \cdot (\underbrace{20\ min}_{\text{Taxi Time}} - \underbrace{(5\ min\ +\ 3\ min)}_{\text{Eng. Warm-up}}) = 150\ kg$$

It could reasonable assumed that 1 kg of jet fuel burned generates 3.16 kg of CO_2, 1.24 kg of H_2O and others by-products.

Chapter 4

Conclusions: The Effects of the Degree of Hybridization

4.1 Impact on over-all mass no fuel consumption

The introduction of a degree of hybridisation made it possible to observe the variation of consumption as a function of the degree. The identification of an optimal degree of hybridisation is the result of attempts to implement an algorithm to be applied to the present conceptual design methods. These methods refer to models from previous years, in which the aircraft was fuelled by Kerosene, without considering the implementation of hybrid or innovative propulsion. Hydrogen-powered aircraft owe aspects to be taken into account: variation of the no-load mass due to the presence of hydrogen tanks, introduction of the degree of hybridisation in the case of non-conventional propulsion and the relative fuel cell mass required to produce the energy.
An initial attempt to study the degree of hybridisation involved a modification of the formulae used to estimate the fuel mass fractions used in the Raymer model. Following initial considerations, an approach involving the identification of high power demand phases was considered.
The thesis work was therefore carried out considering the possibility of totally or partially hybridising the mission profile. Considering the matching chart, constructed for each fuel cell power allocation, the power distribution between direct combustion and fuel cell is observed. Considering the entire mission profile, the most critical phase was soon identified and studied. In fact, the fuel cell support must consider peak power demand, overall mass and the delta mass between pure direct combustion and fuel cell use. Therefore, a study was conducted to determine how the variation in maximum fuel cell power could impact the aircraft configuration.

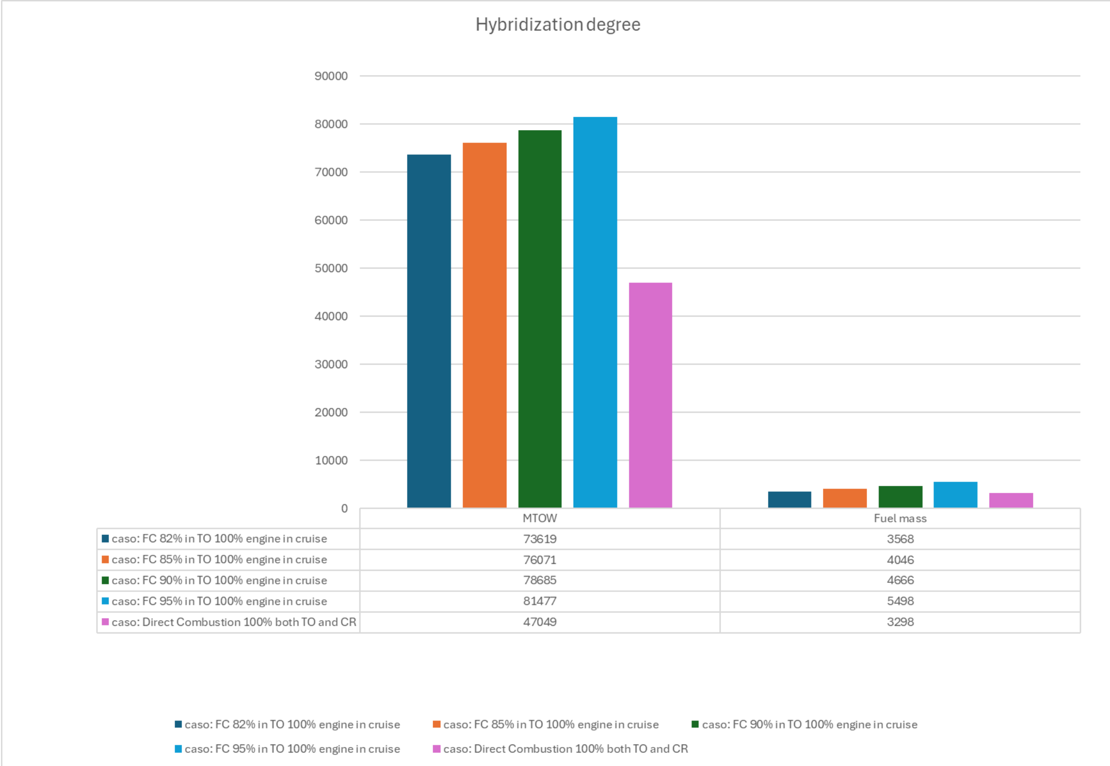
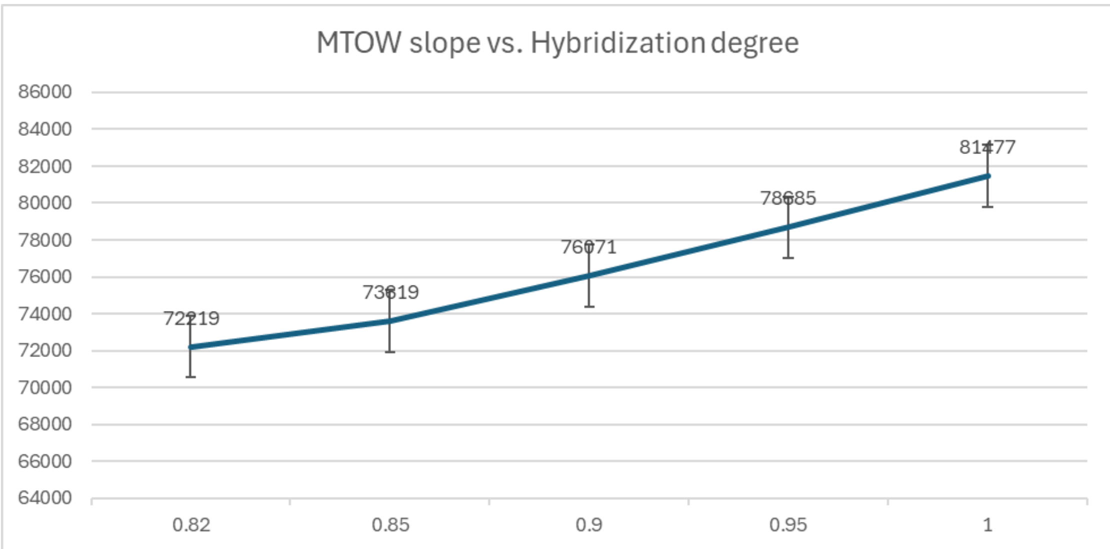
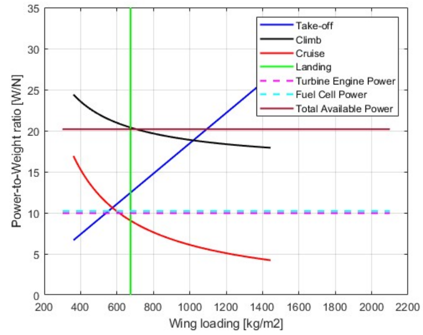


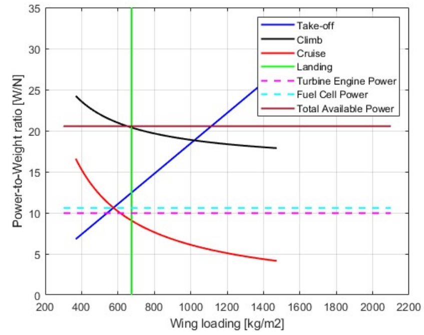
Figure 4.1: MTOW Comparison between direct combustion and fuel cell combustion

Figure 4.2

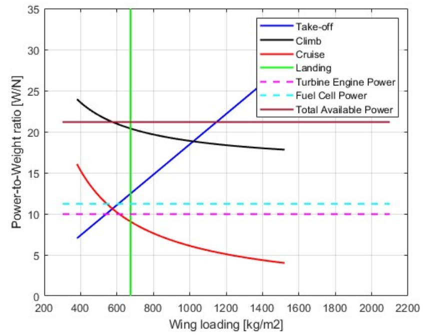




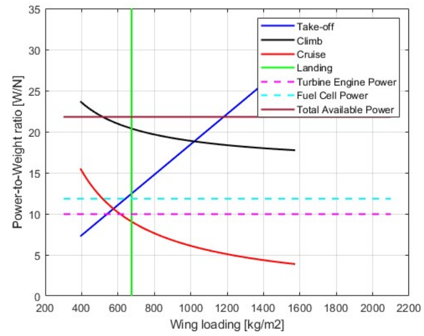
(a) 82% power allocated on Fuel Cell



(b) 85% power allocated on Fuel Cell



(c) 90% power allocated on Fuel Cell



(d) 95% power allocated on Fuel Cell

Figure 4.4: Matching chart

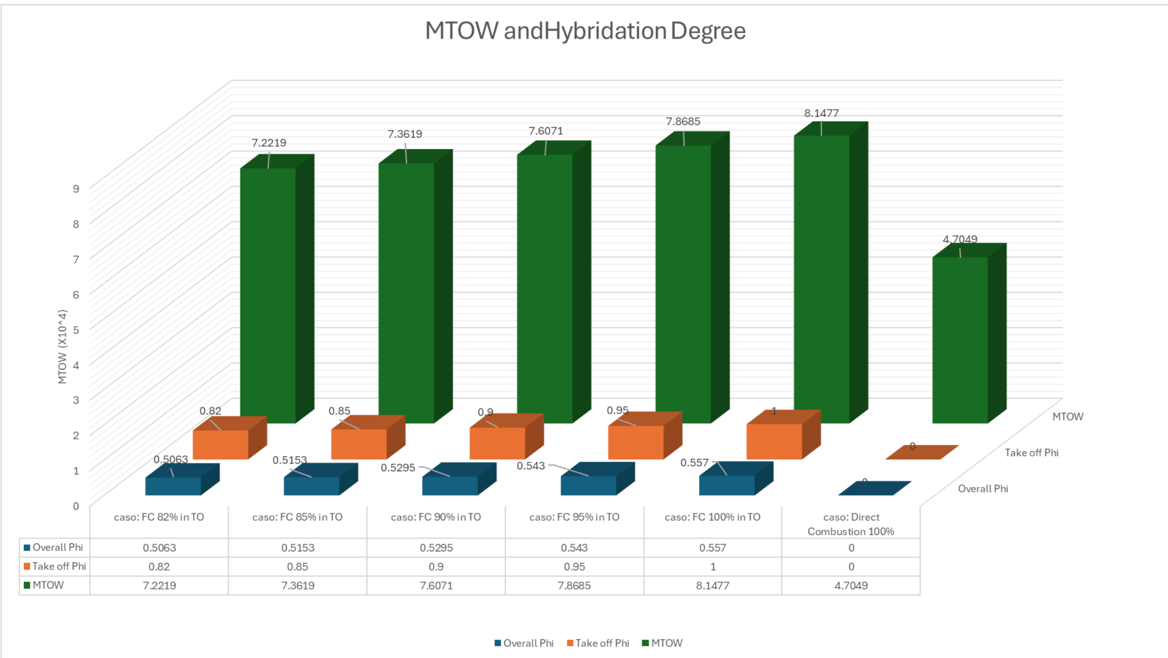


Figure 4.3: MTOW vs. Hybridation Degree

Analyses showed that the optimum degree of hybridization is found for higher fuel cell power allocations during take-off, according to this precise strategy of hybridization. In fact, this degree of hybridization, when compared to the pure combustion case, has an higher impact on the take-off mass MTOW and allows the take-off phase to be assisted from the point of view of power requirements. In this way, the first fuel cell not only manages take-off but also a small percentage of the mission's overall power, helping

reducing the global emissions.Clearly, this hybridization strategy does not allow for significant weight improvements.
Hybridization in aircraft, typically referring to the combination of traditional fuel-powered engines with electric propulsion systems, carries several disadvantages:

- Complexity : Integrating hybrid propulsion systems into existing aircraft designs can be highly complex. But could be important the impact on future.
- Increased Weight: Adding electric propulsion components compared to conventional engines increases the overall weight of the aircraft. In this work, the most worrying issue concerns the use of fuel cells. This added weight can reduce the aircraft's payload capacity and fuel efficiency, potentially offsetting any gains in efficiency from the hybrid system. Referring to 4.3, the weight is incredibly high compared to the pure combustion aircraft.
- Limited Range: Hybrid aircraft may have limited range compared to traditional fuel-powered aircraft due to the additional weight and space constraints imposed by the fuel cell and turbofan. This limitation could affect the aircraft's operational flexibility, especially for long-haul flights.
- Higher Costs: Hybrid aircraft tend to be more expensive to manufacture and maintain due to the complexity of their propulsion systems. The need for specialized components can significantly increase upfront costs as well as ongoing maintenance expenses.
- Technological Immaturity: The technology for hybrid aircraft is still relatively immature compared to traditional aviation propulsion systems and referring to the automotive industry. This immaturity let the technology less reliable.
- Infrastructure Requirements: Hybrid aircraft may require specialized infrastructure for recharging or refueling, which may not be readily available at all airports. Establishing a hydrogen refueling infrastructure for aviation presents significant challenges. Unlike conventional fossil fuels, hydrogen distribution networks are still underdeveloped, requiring substantial investment in infrastructure development to help the adoption of hydrogen-powered aircraft.
- Environmental Impact: While hybridization can reduce fuel consumption and emissions during certain phases of flight, it may also introduce new environmental challenges. For instance, the production and disposal of batteries used in electric propulsion systems can have significant environmental impacts if not managed properly.

Overall, while hybridization holds promise for improving the efficiency and environmental sustainability of aircraft, it also poses various challenges that need to be carefully addressed to realize its full potential.

But Hybrid technologies incorporating hydrogen propulsion systems offer several potential advantages for aircraft:

- Zero Emissions: Hydrogen fuel cells produce only water vapor as a byproduct, resulting in zero emissions of greenhouse gases and pollutants during operation. This can significantly reduce the environmental impact of air travel, contributing to efforts to combat climate change and improve air quality. As 1 kg of jet fuel burned generates 3.16 kg of CO_2, 1.24 kg of H_2O and others by-products, hydrogen propulsion can cut emissions off.

- Renewable Energy Source: Hydrogen can be produced from renewable sources such as wind, solar, or hydroelectric power, making it a sustainable energy option for aviation. Utilizing hydrogen in aircraft helps to diversify the energy mix and reduce dependence on fossil fuels. Although hydrogen must be produced in a sustainable process.

- High Energy Density: Hydrogen has a high energy density, this characteristic is advantageous for aircraft, as it allows for long-range flights without significantly increasing the weight of the aircraft.

- Technological Innovation: Investing in hydrogen propulsion technologies stimulates innovation in the aerospace industry, driving advancements in materials science, energy storage, and propulsion systems.

Regarding the Maintenance, repair and overhaul (MRO) and airport structures:
Maintenance is a relevant aspect to be considered during the development of a product, specially when introducing new technologies. Hydrogen propulsion requires extra maintenance, here a summary of essential maintenance tasks for an aircraft utilizing Proton Exchange Membrane Fuel Cells (PEMFC) in conjunction with Liquid Hydrogen (LH2) as primary propulsion source and Auxiliary Power Unit (APU):

- Tank maintenance
- Check for fluid leaks, air intake and air exhaust
- Check cell voltage
- Inspect stack air inlet filters
- Inspect pressure valves

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