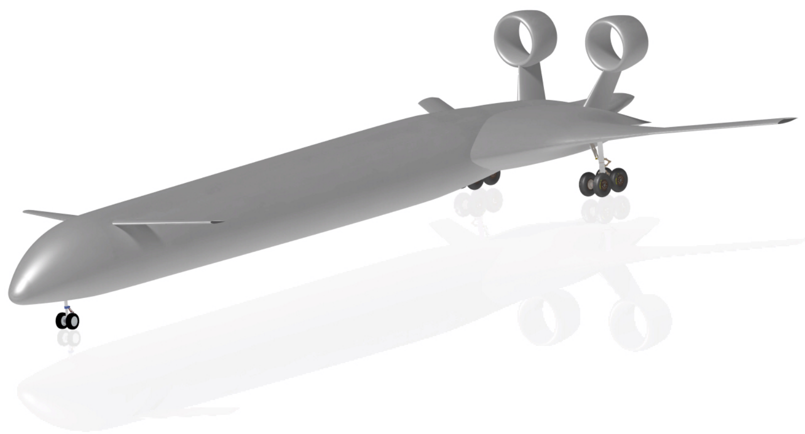
Universität Stuttgart
Institut für Flugzeugbau

Hy2Sky

NASA/DLR Design Challenge 2021



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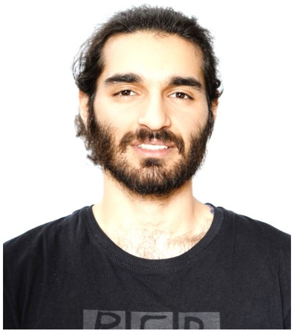

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Executive Summary

The Hy2Sky is a hydrogen-powered, 150-passenger aircraft designed for the NASA/DLR Design Challenge 2021 by the team at the University of Stuttgart. The aircraft is capable of flying two design missions - 600 km with the lowest possible environmental impact and 2000 km with the lowest possible environmental impact as well as lowest possible operating costs.

The Hy2Sky is designed for entry into service (EIS) in 2035 and uses many advanced technologies that are still in development today as well as an aircraft design philosophy focused on efficiency, sustainability and innovation. It is powered by two ultra high-bypass (UHB) turbofan engines. Liquid hydrogen (LH_2) tanks for the 600 km range are fixed in the aircraft and extra tanks can be added for the 2000 km range mission. Details about the refuelling and operating concept as well as the direct operating costs (DOCs) are provided in this report. The fuselage is similar to that of an Airbus A320 to keep manufacturing costs low.

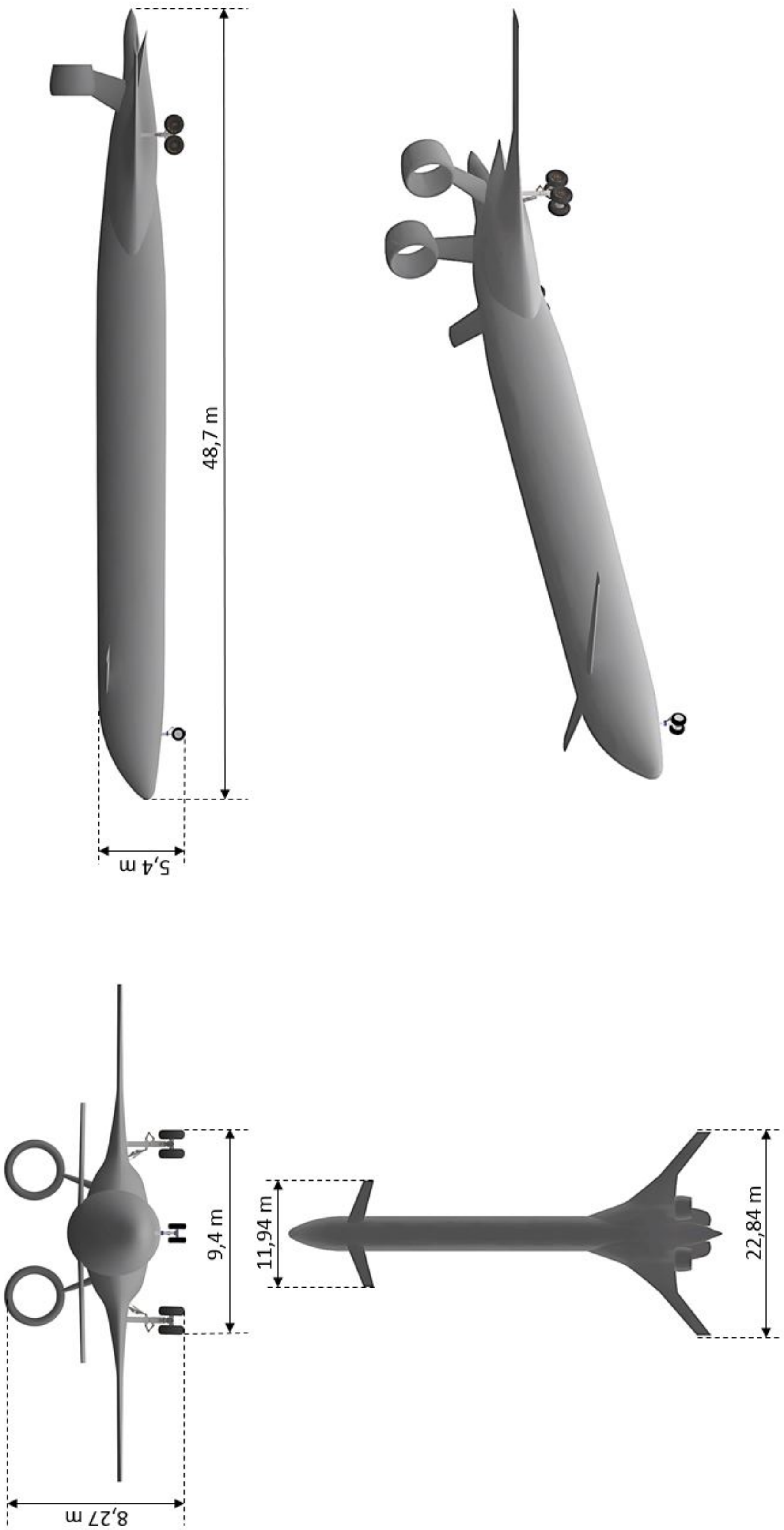
With the reduction of emissions being a priority, a detailed analysis of emissions from hydrogen combustion was undertaken. New technologies to be implemented in the engines to reduce emissions have been identified. Sample mission profiles have been created and are optimised to reduce time at high engine thrust settings.

A summary of the operational parameters of the aircraft is given in Table 1. The drawings provided on the following pages show the layout of the aircraft.

Table 1: Summary of Hy2Sky operational parameters

Parameter	Value	Units
Aircraft length	48.7	m
Max height	8.27	m
Wing span	22.84	m
Wing area	115	m^2
Aspect ratio	4.5	-
Max engine thrust (each)	88	kN
MTOW	58000	kg
Cruise altitude	9000	m
Cruise speed	M0.7	-

Three-side and isometric view of Hy2Sky



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List of Abbreviations

Abbreviation	Meaning
AoA	Angle of attack
ATL	Attachment line
BLS	Boundry layer suction
BPR	Bypass ratio
CAEP	Committee for Aviation Environmental Protection
CROR	Contra Rotating Open Rotor
CS25	Certification Specifications 25
CG	Centre of Gravity
DOC	Direct operating costs
EIS	Entry into service
ER	Equivalence ratio
FAR25	Federal Aviation Regulations 25
FC	Flow control
FL	Flight level
HLFC	Hybrid laminar flow control
ISA	International Standard Atmosphere
LFC	Laminar flow control
LH_2	Liquid hydrogen
MLW	Maximum landing weight
MTOW	Maximum takeoff weight
MWE	Manufacturer weight empty
MZFW	Maximum zero fuel weight
NLF	Natural laminar flow
OPR	Overall pressure ratio
OEW	Operating empty weight
SFC	Specific fuel consumption
TOFL	Take off field length
UHB	Ultra high-bypass

1 Introduction

The future of the aviation industry needs to be built around sustainability. Low-emission fuels produced using renewable energy are needed to power aircraft. Hydrogen presents an excellent solution in this regard. It has a very high energy density and can easily be stored in liquid or gaseous forms. Turbofans adapted for hydrogen combustion reduce emissions greatly compared with jet fuel-burning turbofans and future hydrogen technologies such as fuel cells produce zero emissions in theory. The properties of hydrogen are discussed in Appendix A.

Hydrogen-powered aircraft are not an entirely new concept. The Soviet Union built and flew their hydrogen-powered Tupolev Tu-155 in the late 1980s. [13] In the past, economical hydrogen production using non-renewable energy sources could not compete with jet fuel. However, due to advancements in renewable energy technology such as solar and wind, hydrogen can be produced using clean energy sources and be easily stored in gas or liquid form. [14] Although the hydrogen infrastructure is still in its infancy compared with hydrocarbon-based fuels, there are many new solutions regarding the storage and distribution of hydrogen in this emerging market. [15]

Airline and operator requirements, passenger expectations, minimising emissions as well as hydrogen storage requirements need to be considered in the design of a hydrogen-powered aircraft. From the airlines' perspective, it is important to compare the maintenance and operating costs of conventional and hydrogen-powered aircraft when making decisions about aircraft purchasing or leasing. At the same time, passengers expect to have a spacious cabin to enjoy a comfortable flight as well as increased space for cabin luggage. [16] Furthermore, the integration of fuel tanks is a big challenge as hydrogen requires more storage volume and cannot be stored in wing tanks unlike jet fuel and the safety of the aircraft has to be guaranteed.

This report discusses the design, aerodynamics, propulsion system and operating concept of the Hy2Sky aircraft designed for the NASA/DLR Design Challenge 2021. This challenge requires a 150-passenger aircraft to be designed to fly 2 missions - 600 km and 2000 km. Both missions need to have the lowest possible environmental impact and the 2000km mission also needs to have the lowest possible operating costs. The required performance is similar to modern, short-haul aircraft but requires a lower than usual maximum approach speed of 130 knots which helps to reduce noise and emissions at low altitudes. The Airbus A320-200 is chosen as the reference aircraft to compare performance.

Table 2 compares the challenge requirements with the capabilities of the Hy2sky aircraft.

Table 2: Challenge requirements compliance table

Parameter	Challenge requirements	Hy2Sky	Compliance
Take off field length (TOFL)	2000 m	2000 m	✓
Cruise speed	M0.7	M0.7	✓
Approach speed	≤130 knots	130 knots	✓
Range	≥ 2000 km	≥ 2000 km	✓
Altitude	≥ 3000 m	9000 m	✓

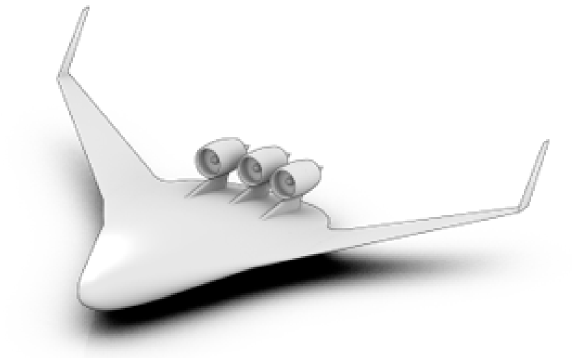
2 Aircraft Configuration

The first task of the design process was to evaluate configurations of aircraft that meet all the requirements for an efficient, hydrogen-powered aircraft. Tank integration was a crucial factor in this evaluation and is also discussed in this section.

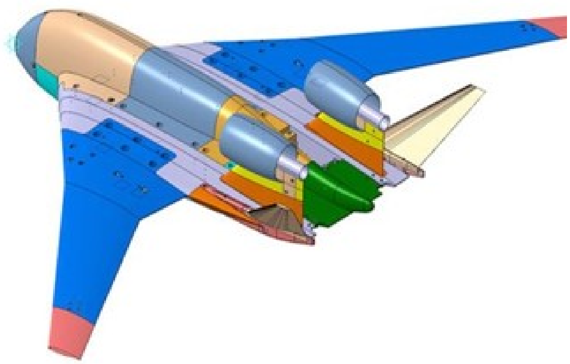
2.1 Configuration analysis

The short to medium-range aircraft market was studied and as there were no existing hydrogen aircraft configurations, a basic design analysis using OpenVSP with configurations such as BWB, semi-BWB, tandem-fuselage, and unconventional fuselage was completed. Configurations that would not allow for bulky hydrogen tank storage were quickly discarded. The configurations that could accommodate the required volume without compromising on other design factors such as suitable emergency exit access for passengers and engine placement for low noise were considered for further analysis. This was narrowed down to four final viable configurations, shown in Figure 2. A trade-off study of these concepts can be found in Table 3.

(a) Tube & Wing [17]



(b) Blended Wing Body (BWB) [18]



(c) Semi-Blended Wing Body [19]

(d) Rear-wing-concept [20]

Figure 2: Selected aircraft configurations

A conventional tube and wing concept (Figure 2a) was chosen for evaluation as it is the most common design for modern aircraft. It helps to keep development costs as well as risks for components low. Additionally, the certification process is easier as modern certification standards are made for conventional designs. However, significant design changes would be required to this conventional design as hydrogen fuel cannot be stored in the wings. The cylindrical fuselage would have to be elongated to accommodate tanks in the rear section, leading to further design complexities. Another reason for not developing this concept further was to pursue a more unconventional and innovate aircraft design.

Table 3: Trade-off study of selected aircraft configurations; best: ++, worst - -

Parameters	Tube & Wing	BWB	Semi-BWB	Rear BWB-Wing
Aerodynamic	+	++	+	+
Fuel storage	+	++	+	+
Ground Handling	+	-	0	+
Production	+	-	-	0
Pressurisation	+	-	+	+
Evacuation	++	- -	-	+
Cabin space utilization	+	-	+	+
Family concept	+	-	-	0

A blended wing body configuration, shown in Figure 2b was evaluated as the concept has many advantages at first glance. A blended wing allows for good aerodynamic characteristics and more efficient flying. [21] The increased fuselage volume provides more storage space for hydrogen tanks. New cabin concepts can be designed to increase passenger comfort. However, a detailed analysis revealed that the new cabin concept, in particular, could be a bottleneck. While the increased cabin width allows flexibility, only 3 seats can be located next to an aisle, as stipulated in CS25. This would mean more aisles would be required. The placement of emergency exits to ensure quick and safe evacuations is also an issue. CS25 does not allow emergency exits to be located such that passengers need to go upwards or downwards to exit the aircraft. A further disadvantage of the blended wing body is the need to completely change airport infrastructure, such as airport gates and service vehicles due to its unconventional configuration. This would imply significant additional costs for operators and airports.

As shown in Figure 2c, a semi-blended wing body configuration was also investigated. This configuration uses a tube-shaped fuselage, which brings some improvements to the overall design concept. As the fuselage is cylindrical, passenger evacuation can be better planned and managed, pressurization would be easier to implement, and cabin space can be better utilized. However, due to the certification problems that this configuration would present (deboarding on the wings, passenger-engine distance, etc.), the semi-BWB concept was not be considered further.

Shifting the wing to the rear, as seen in Figure 2d, was also considered to improve aerodynamics. Due to the short moment arm between the control surfaces and the center of gravity, a canard is needed in order to maintain the aircraft's manoeuvrability. The fuselage's shape will not be changed compared with a classic tube-wing configuration. Several other concepts with similar configurations have been in development, such as the Sonic Cruiser, developed by Boeing. [20]

From the evaluation process, the conventional fuselage with a semi-BWB aft wing was chosen. This configuration allowed the placement of liquid hydrogen tanks in the wing root and aft part of the fuselage as well as safe separation of the cabin from the entire propulsion system. This has several advantages as the noise produced by the propulsion system would have less impact on the passenger cabin. It also offers good protection against any hydrogen leaks or an uncontained engine burst of the passenger cabin while also giving passengers an undisturbed view from their windows. The use of a conventional fuselage from the A320-200 reduces the investment required in the design and building of new tools and manufacturing facilities. This concept also allows two tank storage areas to be used, increasing the flexibility of the aircraft by allowing more cargo to be accommodated for short haul operations.

Furthermore, it is possible to realize a family concept without drastic changes to the aircraft structure. The unification of the powerplant system with the wings and the clear separation from the cabin and passenger section allow for a modular approach to a family concept. Newer versions of the aircraft can be made longer by replacing the fuselage and passenger section with a longer module and utilizing the previously developed wing/powerplant arrangements. With the advancements of passenger recovery and fatality prevention technologies such as self-recovering cabins with parachutes, the divide of the passenger section can make the implementation of such futuristic ideas easier.

After deciding on the final configuration, a design diagram using methods proposed by Roskam was created to determine the required wing and thrust loadings for the aircraft. [22]

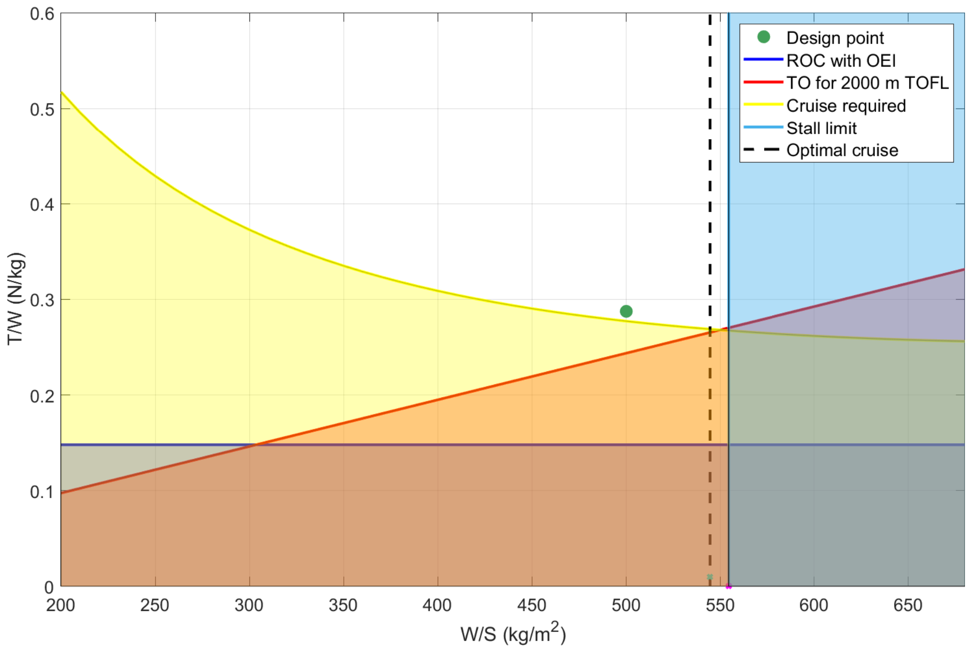


Figure 3: Matching diagram for Hy2Sky

The lower wing loading of 500 kg/m^2 was chosen as the design point for this aircraft, assuring a big enough wing and canard surface for lift generation. The design point is chosen such that a stretched aircraft version is possible for a later family concept. The wing loading has room for a 10% increase, meaning the MTOW can be increased to 63 tons without the need for changes in the wings and fuel storage area. With this decision the S_{ref} is chosen to be 100 m^2.

2.2 Tank Integration

A major challenge of designing a hydrogen powered aircraft is the integration of the fuel tanks. Conventional aircraft store jet fuel in the wings and sometimes in a central tank in front of the landing gear bay in the longitudinal direction. A big advantage of this is that no additional structure is needed. Additionally, storing fuel inside lift generating components has structural advantages, as it reduces the bending moment at the wing root.

The volumetric energy density of hydrogen is 2.8 times lower than that of jet fuel. [23] This effect can be reduced by storing hydrogen at high pressure or low temperature but it is still a big difference compared with jet fuel. Therefore, additional tank weight has to be considered to maintain pressure and temperature. An increase in operating weight of 20% compared to a conventional fuel system has been taken into account for the hydrogen fuel system. [24]

A way of reducing structural weight needs to be found due to the additional tank weight. The challenge sets requirements for two different ranges (600km and 2000km). If the aircraft only needs to fly the 600 km range, it would be disadvantageous to carry unused tank weight required for the 2000 km range. Therefore, tanks for the 600 km range are fixed in the wing root of the Hy2sky and additional 'range extender' tanks can be added to fly the 2000 km mission.

As mentioned previously, hydrogen has a lower volumetric density than jet fuel. In order to store LH_2 in wing sections, a blended transition between the wing and fuselage is designed, with enough storage space in the wing root for the fixed (600 km) tanks.

For the replaceable tanks, there are companies developing concepts for a modular tank infrastructure. Universal Hydrogen, a company based in California, have developed small tanks which can be stored inside the cargo compartment of an aircraft and replaced after each flight leg. As the Hy2Sky needs to be conventionally fueled due to the integral tanks, the additional tanks should also be conventionally fueled and not replaced after each flight leg. However, the additional tanks can be replaced during a maintenance event when the desired range of the aircraft needs to be changed. This means that between maintenance events, the range of the aircraft is fixed based on its fuel tank configuration.

The additional tanks are to be placed between the wings behind the cabin. This is done as storing hydrogen in the pressurized section can be dangerous in case of accidental leaks or a tank blow-off. To improve safety, a venting system is provided behind the tanks and engines at the end of the fuselage section. Using this, the fuel can easily be released in case of an evacuation after an emergency landing or other similar situations.

Figure 4 shows the fuel tank configuration of the Hy2sky. The integral wing tanks are shown in blue and the additional range extender tanks shown in green. The space in longitudinal direction between the wing tanks is needed for the retracted landing gear. The figure also shows the position of the tanks in relation to the engines. The short distance allows the fuel lines to be kept short, saving weight.

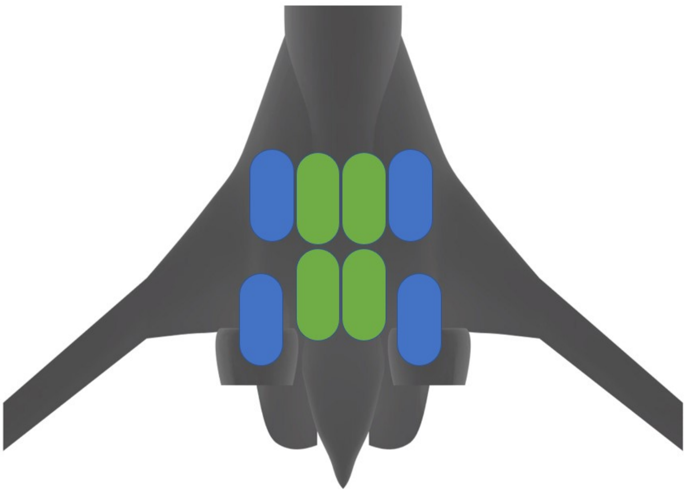


Figure 4: Fuel tank integration

2.3 Mass Breakdown

A mass breakdown was created to show the different masses of the aircraft and how they relate to each other. This is shown in Table 4.

Table 4: Mass Breakdown

Component	Mass (kg)
Structure weight	17023
Hydrogen Tanks	5600
Engines	3920
Systems	3000
Furnishings	3000
Operator Items	4500
Manufacturer weight empty (MWE)	32543
Operating empty weight (OEW)	37043
MZFW	52793
MTOW	58000
MLW	58000

3 Aerodynamics

The aerodynamic concept is driven by two main factors: the wing needs to contain the fixed LH_2 tanks while also delivering improved efficiencies to accommodate for the further weight additions that such an aircraft concept implies. With a seamless wing-fuselage transition and a resulting thick wing root, the wing almost accounts for 54% of the total parasite drag. It is beneficial to aim for a natural laminar flow using flow control (FC) technologies over the wing while simultaneously taking advantage of the higher thickness ratio airfoils in the NACA 6-Series to create sufficient volume in the wing root proximity.

In order to create natural static stability, guarantee a trimmable aircraft, and minimize drag, a lifting canard is placed at the front of the aircraft. This leads the aerodynamic centre (AC) being located in a not so drastically aft position and also divides the required lift-generating surface area into two parts, a smaller canard surface and a bigger wing surface.

At a trimmed condition in cruise, the aircraft uses lift forces generated by both the wing and canard to be balanced. In this way, losses that conventional empennage creates due to the downforce it has to exert in order to trim an aircraft in cruising condition are avoided. Inspired by the benefits of the three-surface configuration, this setup leads to a small forward wing producing lift required to trim the nose-down pitching moment created by the main wing in combination with the rest of the aircraft. The trimmable horizontal stabilizer (located on the canard) produces negligible positive or negative lift in cruise. The total lift generated by the canard and the main wing is equal to the weight of the aircraft. The lower lift requirement results in lesser wing area and hence lower profile drag, induced drag, and structural weight. [25]

Inspired by the various benefits of a BWB, the design of the wing aims to make use of the volume that a blended transition from the wing to the fuselage creates. The wing is thicker at the root while the fuselage body needs to be narrower near the root section of the wing. The goal is to achieve a seamless transition in order to avoid excessive interference drag while creating volume for the bulky hydrogen fuel tanks in the wing roots. This also minimizes wetted area and therefore reduces drag and interference effects. The blended wing also provides space to store the landing gear. The blended region is shaped such that it provides a significant amount of lift during critical phases of flight such as take-off and landing. The aspect ratio of the wing is small, and the wing is swept to avoid wave drag at the cruise Mach number. To avoid stalling at lower speeds and to decrease drag, a laminar airfoil is also used. Detailed analysis on the wing design is presented in Section 3.1.

A lifting canard solves stability issues while also adding much-needed lift during phases of flight such as take-off, cruise and landing. At high angles of attack during take-off and climb, the canard has high wing loading, due to which it generates more lift per square meter than the wing. At a high wing loading, an increase in the angle of attack causes a smaller increase in lift than at a low wing loading. [26] The wing loading brings a downside of more induced drag which is countered by increasing the aspect ratio of the canard. The canard is designed at a higher angle of incidence than that of the wing and therefore prevents the main wing from stalling in critical phases of flight. The stability analysis is discussed further in Section 3.4.

3.1 Wing Design

A trapezoid blended wing-body planform with the airfoils given in Table 5 was analyzed in OpenVSP to check for C_{L_α} and C_{M_α} slopes as well as the appropriate lift distribution on the wing.

Table 5: Airfoil distribution

Parameter	$2y/b = 0$	$2y/b = 0.24$	$2y/b = 0.54$	$2y/b = 1$
t/c	18%	18%	13%	13%
Design C_l	0.4	0.5	0.4	0.5

To avoid excessive water vapour emissions and contrail formation, a flight altitude below 10000 m had to be selected for the Hy2Sky. [27] This requirement in combination with the relatively high cruise speed for these lower altitudes as well as the relatively light weight of the aircraft leads to a lower cruise lift coefficient as compared with other higher and/or slower flying aircraft. It can be concluded that induced drag due to lift will be less and a greater component of the drag would be parasitic drag.

3.1.1 Airfoil selection

With the goal of implementing a hybrid laminar flow control (HLFC) scheme for the wing, laminar airfoils from the NACA 6-series were considered as they are optimized for high velocities and provide laminar flow (NLF) in combination with suction and blowing (LFC). The airflow approaches the leading edge as suction slots ingest air from the boundary layer through a perforated surface. Due to this, the velocity profile is modified to improve stability and prevent early turbulent transition. Additionally, the boundary layer thickness is reduced which also positively influences the associated Reynolds number. [28] In addition, a high local sweep at the root leading edge is used, making the transition from the fuselage to the leading edge of the aircraft less abrupt. All airfoils used are from the NACA 66-series, meaning they will have 60% laminar flow at their design lift coefficient. In the case of this aircraft, the appropriate laminar airfoils would be NACA 664– with thickness ratios varying from 18 to 13 %. The sweep for each wing section was selected to avoid local velocities reaching critical Mach numbers (M_{cr}) during flight and ensuring that they stay below $M_{local} < 0.6$ when cruising at M0.7.

3.1.2 Wing geometry

Knowing the weight of the aircraft from preliminary sizing and weight regressions as discussed in Section 2.1, the actual $C_{L_{cruise}}$ for cruising conditions in the given mission was calculated. [22] The calculated value was 0.35. It was then assured that this flight condition with the given C_L value was also the most efficient lift coefficient for the wing to fly at. In order to check for this, the methods shown in Appendix B were used. The ideal aspect ratio for the aircraft was found to be 4.5, creating a good synergy between the bulky wing root section and avoiding high wingspan requirements to fit the hydrogen tanks in the wing without drastically increasing structural weight. The calculated aspect ratio is lower compared with other conventional aircraft and also proves that the main source of drag is parasitic and not induced drag, meaning a stretched wing is not required to minimize lift-induced effects.

3.2 Canard Design

A canard is a small wing placed at the front section of the fuselage, that can vary in function and design. Some canards act as small wings and generate only lift. A lifting canard generates positive lift which is opposite to the function of a conventional horizontal stabilizer which generates negative lift. A canard allows the main wing to be smaller as the lift generated by the aircraft is distributed between two surfaces. However, the most important rule is that the canard must stall before the main wing. This allows the aircraft to have longitudinal pitch stability and good stall recovery.

On the other hand, a control canard primarily acts as a control surface for pitch control during manoeuvres and does not need to generate lift. It is usually set at a zero angle of attack and predominantly used as a complex control surface, dynamically controlled using a flight computer. The position of the canard relative to the C.G. of the aircraft is 23.3 m. The canard has a span of 11.94 m, mean chord of 1.6 m and an aspect ratio of 7.5. The projected area of the canard is 19 m^2. To avoid wave drag, the canard has a sweep angle of 22° from the root to tip. The relative vertical placement of the canard is above the wing to avoid the downwash of the canard interfering with the main wing. However, in high negative angles of attack, the aircraft will be harder to control since the canard will have downwash on the wing.

The challenge for this design was to determine the geometry of the canard, its airfoil selection, the high AR planform shape and the sweep. Two most significant conditions are also satisfied here: Cm_α is negative which is controlled using the CG location and Cm_o, controlled by the geometry, is greater than zero. The canard incidence angle of 3°, a NACA 0013 airfoil at the root and a NACA 38012 at the tip. A detailed static analysis is presented in Section 3.4.

The canard is equipped with a Flapevator - a combination of flaps and elevators as one control surface. This allows the canard to generate lift, even at higher angles of attack during take-off and landing. Additionally, the canard has a long moment arm relative to the CG of the aircraft. This enables effective elevator controls for pitch. The flaps on the canard allow for trimming of the aircraft. The flaps can also be used to counter the movement of the center of pressure without changing the angle of attack of the main wing, reducing the induced drag. [29] The stability of the aircraft in different flight phases in a combination of canard and wings is elaborated in Section 3.4.

3.3 Control Surfaces

Control surfaces are located on the main wing, one surface pair acting as flaps and one pair acting as ailerons. The canard is equipped with flapevators, combining the function of flaps and elevators, along with trimmable surfaces, enabling trimmed flight in cruise. Due to its high sweep angle, the wing provides less elevator authority at high angles of attack. As the canard has lower sweep and a longer moment arm, positioning the elevators on the canard provides control benefits.

3.4 Static Stability

In this section, the longitudinal stability of Hy2Sky is discussed.

To allow an aircraft to recover from a stall in all phases of flight, it needs to have a natural tendency to have a nose-down attitude before and during stall. Compared with a conventional aircraft, an airplane with a canard has very different longitudinal stability, controllability and stall characteristics. Aircraft equipped with a canard have an advantage as the canard is always designed to stall first. This prevents the wings from stalling and prevents the aircraft from diving and entering a spin. A stall to spin situation would be very dangerous to an aircraft equipped with a canard. A canard design also brings complications such as the range of allowable CG locations and controllability.

The longitudinal stability is highly dependent on the moment coefficient of the wings and the canard. The combination of both these moments along with the fuselage and the moment produced by the pylon-mounted engines on the Hy2Sky results in a resultant moment for the aircraft for different phases of flight. Phases such as take-off, climb and cruise are critical for the stability and controllability of any aircraft. A negative moment ensures that the aircraft has a nose-down attitude and can be considered stable without the use of the elevators The point where C_M is zero, is the trim point. [30] The canard has an AoA of 3°. This, in combination with the airfoils on the root and the tip allows it to stall before the wing.

Using OpenVSP, the $C_{m_{alpha}}$ diagram for the aerodynamic body without the engine moments was calculated and a negative slope of the $C_{m_{alpha}}$ line was observed. This is shown in Figure 5. It should be noted that engine height and cruising thrust settings can be optimized to minimize trim drag.

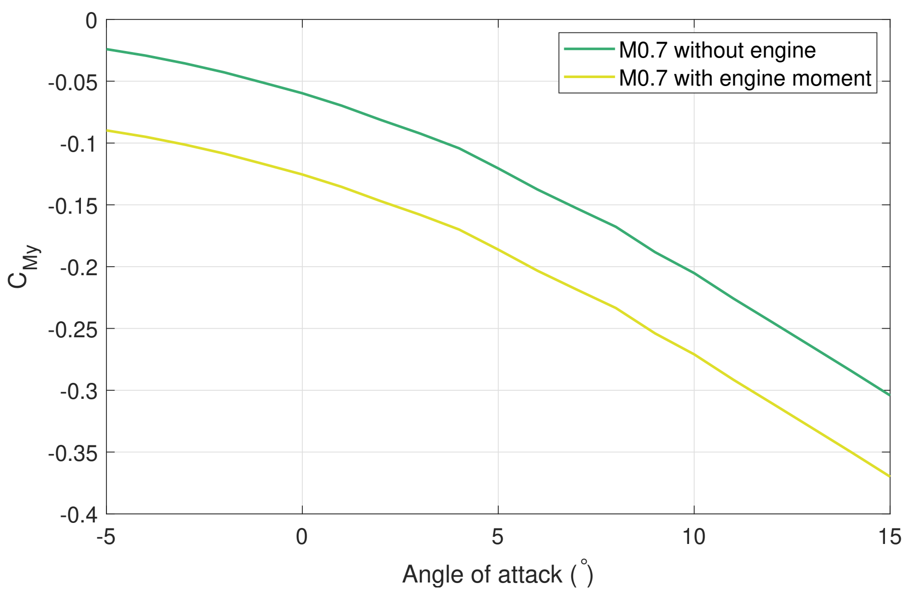


Figure 5: $C_{m_{alpha}}$ diagram for the flight condition of Mach = 0.7 and flight altitude of 9000 meters, with and without engine induced pitching moment

3.5 Advanced technologies

Two major technologies are suggested to further enhance the aerodynamics of the aircraft. These are a HLFC system, which itself consists of a boundary layer suction (BLS) system, and a natural laminar flow (NLF) airfoil in combination with a low hinged flap exposed to a tangential jet stream just before the hinge point to induce the Coanda effect. This can be seen in Figure 6. The Coanda system can used on both the wing and the canard to generate the required landing $C_{L_{Max}}$ of 3. Using OpenVSP, it was seen that the wing accounts for 52% of the total parasitic drag of the aircraft. If 60% laminar flow is achieved on the wing, this number drops to 34% of the total parasitic drag.

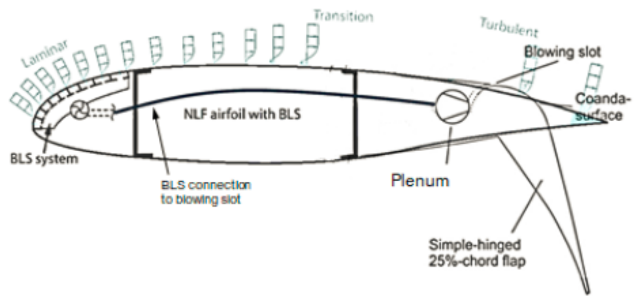


Figure 6: Depiction of an HLFC scheme with BLS [1] and a Coanda system [2]

For the Coanda flap system to work over a reasonable range and avoid low stall angles, the flap deflection should be coupled with a nose deflection of the airfoil. [2] This deflection can be achieved with rigid or flexible droop noses that can avoid creating a gap or discontinuity in the airfoil contour.

Older experiments such as the Jetstar Leading-Edge Flight Test have shown that in order for the HLFC system to operate, a shielding device, such as a Krueger flap, is required in the nose section to protect the upper surface of the airfoil from foreign objects such as insects. [31] This nose-mounted device extends during the high C_L phases of the flight such as take-off and landing where the aircraft is near ground and foreign object damage is a major risk. After a climb to approximately 2000 m, the Krueger flap is retracted, leaving a clean upper surface for the cruising segment and optimal conditions for the HLFC system. [31]

The idea is to combine the Krueger flap function with the droop nose requirement of the Coanda flap as both devices are only needed when flaps are extended in phases such as take-off or landing. The use of both devices leads to a higher camber at the leading edge, which is essential for both the Coanda function and the upper surface cleanness for the HLFC system.

Both the HLFC system and the Coanda flap require air suction from the airfoil surface. It has been proven that the Coanda flap is more efficient the closer its suction slots are located to the leading edge of the airfoil. [2] Simultaneously, the HLFC operates using suction slots starting from the attachment line of the wing up to the front spar of the wing, as seen in Figure 6. The required pressure difference on the wing (ΔC_P) is 0.2 or 28.4 kPa. [32] For a similar aircraft, the power requirements of the HLFC system is calculated to be 85.5 W at an overall pump efficiency of 0.6. The required power can be supplied from the bleeding air of the engines. One pump system for each side of the wing is positioned after the root section. [1]

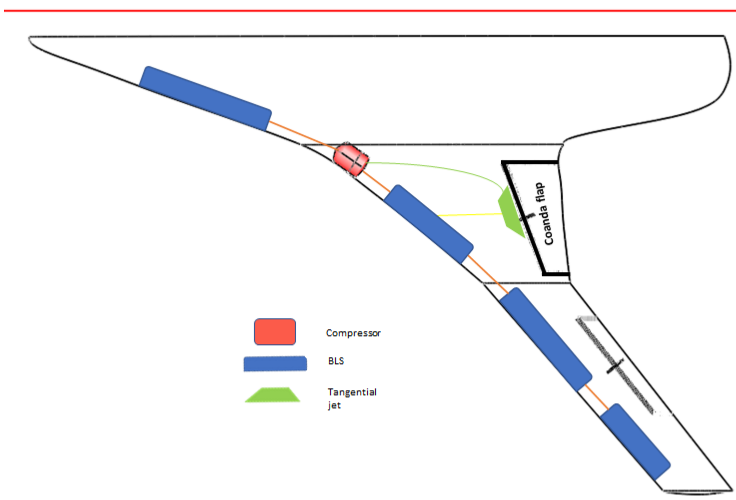


Figure 7: Flow control system layout on the wing

Suction should be directed from the HLFC area towards the aft-located jet and be used to induce the Coanda effect during flap deflections shown in Figure 7. The suction of the slots starts in the take-off condition with the extended nose devices supplying the Coanda system. When cruising conditions are reached, the nose device retracts into the airfoil and the suction slots work to sustain laminar flow over the airfoil. Using OpenVSP, a final calculation of the aircraft's aerodynamic properties was performed and the results are presented in Table 6.

Table 6: Aerodynamic characteristics of the Hy2Sky and the A320-200

Parameter	Hy2sky	A320-200	Parameter	Hy2sky	A320-200
L/D_{max}	19	17	C_{L_α}	$0.0571 \cdot \alpha$ °	-
Aspect ratio	4.5	10.3	$C_{D_{total_{clean}}}$	0.023	0.28
e	0.918	0.922	$C_{D_{0_{clean}}}$	0.010	0.023
$C_{L_{cruise}}$	0.35	0.42	C_{D_α}	$0.0042 \cdot \alpha$ °	-
$C_{L_{max}}$	3	-	$C_{D_{induced_{clean}}}$	0.0135	0.0058

4 Propulsion

Engine manufacturers are actively researching how modern turbofans can be modified to use hydrogen, while also looking to develop other types of propulsion systems. As the Hy2Sky has to enter service in 2035, ultra high-bypass (UHB) turbofans are selected to propel the aircraft. This section explains the reasons for using UHB turbofans, engine specifications and sizing process as well as emissions and environmental considerations.

4.1 Engine technology selection

The selection of the engine concept is one of the most important aspects in an aircraft design. It needs to provide thrust efficiently while also producing low emissions and noise. As hydrogen has to be used as the fuel, the following current and future technologies were considered and analyzed for the Hy2Sky: turboelectric propulsion with two different electric motor configurations (fan and contra-rotating open rotor-CROR), ultra-high bypass turbofans (UHB) and fuel cells.

Turboelectric propulsion systems (also known as hybrid propulsion systems) combine gas turbine engines with electric motors, generators and in some cases, batteries. This leads to a high system complexity (generators, heavy cabling, power converters and additional electrical components) and a high weight, which is disadvantageous for the aircraft.

Table 7: Trade-off study of possible propulsion concepts; best: ++, worst - -

Parameter	Turboelectric propulsion		UHB	Fuel Cell
	Fan	**CROR**		
Efficency	0	0	+	+
System complexity	-	-	++	–
Weight	-	-	0	-
Noise	+	-	+	++
Environmental impact	0	+	+	++

Fuel cells involve zero emissions in principle, making them very advantageous. However, just as with hybrid concepts, a very high level of complexity, increased weight and a relatively low power to weight ratio must be taken into account. These factors, along with a lengthy certification process make the implementation of fuel cells in an aircraft that needs to be operational by 2035 difficult.

Hydrogen combustion using turbofans would require modifications to the engine, tank integration, fuel supply lines and and other components. Although this would lead to new designs and a lengthy certification process, the conversion would require fewer changes than for fuel cells or turboelectric propulsion options. [33] As it can be seen from the evaluation in Table 7, and also due to the many advantages that this technology implies, the UHB concept provides a suitable propulsion solution for the Hy2Sky. In the following section, the UHB concept in correlation with hydrogen is discussed.

4.2 Ultra-high bypass turbofan

An important parameter for classifying turbofan engines is the bypass ratio, defined as the ratio of the mass flow of the bypass flow to the mass flow entering the engine core. Generally, the higher the value, the more efficient the engine. Moreover, the bypass flow usually provides up to 60-70% of the thrust in modern turbofans. High bypass ratio engines also lead to reduced fuel costs and DOCs. Ultra high bypass turbofans are the next stage of development of a proven technology with potential for significant reductions in fuel burn, noise and emissions. Several UHB engines were analyzed for the selection of engines for the Hy2Sky. As hydrogen combustion does not produce CO_2, the choice of the engine was limited by technologies that produce as low NO_x emissions as possible, are efficient and operate at low noise levels. Several high and ultra high bypass ratio engines that are currently in development were considered for use on the Hy2Sky. These are given in Table 8.

Table 8: Engines considered in the development of the Hy2Sky propulsion units

Engine	BPR	Status
Rolls Royce Ultra Fan	15+	In development [34]
PW1100G-JM	12.5	In use on the A320neo [35]
Safran Ultra-High-Bypass-Ratio	15+	In development [36]
ENOVAL	16.2	In development [37]

Based on the data currently available and potential for future development, the ENOVAL engines were found to meet the initial performance requirements of the Hy2Sky. However, as the design developed, the need to develop new engines to deliver the performance required became apparent. the ENOVAL engines were used for reference as well as to scale engines based on the Hy2Sky requirements, as explained in Section 4.3.

4.3 Hy2Sky engines

The previous section justified the selection of ultra high-bypass (UHB) turbofans as the preferred engine option for the Hy2Sky aircraft. This section describes the process used to size the engines as well as the specifications of the chosen engines.

Data for modern engines as well as engines that are in development with a view to be introduced in the coming years was interpolated for the sizing process. This allowed for a realistic estimate of engine technology development by 2035. The list of engines, the data used for the interpolation as well as the plots produced are given in Appendix C. As the aircraft is designed for short-medium haul operations and is likely to spend significant time climbing, the engines sizing is based on climb requirements. The specifications are given in Table 9.

Table 9: Hy2Sky engine specifications (each)

Parameter	Value	Units
Max Thrust (sea level)	88	kN
Mass	1960	kg
Fan diameter	1.65	m
Engine length	3.04	m
Bypass ratio (BPR)	18.6	-
Overall pressure ratio (OPR)	50	-
SFC (cruise)	5.225	g/KNs

The maximum thrust of 88 kN from each engine (176 kN total) allows for a strong climb performance (at 85% power) while also remaining under the 89 kN threshold, where the emissions regulations change, as per the Committee for Aviation Environmental Protection (CAEP), as explained in Appendix D. [38] As a result, the Hy2Sky operates in a lower emissions bracket. The mass, fan diameter and engine length are obtained from interpolation with required thrust.

As turbofan engines develop and engine cores become smaller, higher bypass ratios are possible. Engines with bypass ratios of 15-16 are currently in development for introduction around 2030. Interpolation shows that a bypass ratio of 18.6 is possible by 2035. Increase in overall pressure ratio (OPR) increases engine thermal efficiency, but also adds complexity. A higher OPR means a heavier engine. Higher pressures also result in higher compressed air temperatures, meaning more advanced and heavier materials are needed to manage thermal stresses on engine components. The data in Table 14 shows that OPR values of 50 or higher are only available for engines designed for long-haul aircraft and high thrust requirements. Engines used on aircraft such as the Airbus A320neo, the Boeing 737MAX and the Airbus A220 have OPR values of 40. It can be assumed that with advancements in engine and material technology, OPR values of 50 will be possible for smaller engines in the coming years, as can be seen in the case of the ENOVAL 1 engine.

Figure 8: Size of the Hy2Sky engine, compared with a 1.8 m person [3]

5 Emissions

The biggest benefit of using hydrogen as a fuel is the significant reduction in emissions. Carbon-based emissions (CO, CO_2 and unburnt hydrocarbons) are completely eliminated and NO_x emissions are greatly reduced. A detailed analysis of emissions from hydrogen combustion, current and future emission regulations and emission reduction technologies has been conducted and is explained in this section.

5.1 Emissions from hydrogen combustion

The only emissions produced by hydrogen combustion are water vapour and oxides of nitrogen (NO_x). Other emissions described in Appendix E.1 are completely emitted. Pure hydrogen also contains no contaminants, meaning particulate emissions from the engine are also reduced.

5.1.1 Water vapour

In comparison with a jet fuel burning aircraft, water vapour emissions are approximately 2.6 times higher. While water vapour emissions from jet fuel burning engines today are not considered to have a significant climate impact, the increased emissions with hydrogen combustion mean that the impact of water vapour has to be studied in much greater detail. [39]

The presence of contrails and cirrus clouds is likely to increase due to the higher quantities of water vapour present in hydrogen emissions. However, as exhaust gases will not contain particles, the contrails formed are likely to contain fewer but larger ice crystals. Research has concluded that "the net effect of contrails from hydrogen combustion is likely to be less positive than for contrails from conventional aircraft, because smaller optical depth dominates over higher occurrence frequency on the global scale." [4] It is also important to note that the although an increase in radiative forcing due to contrails will be noted, carbon-based emissions (CO, CO_2) are absent. As CO_2 has a residence time of a few decades as compared with a few hours for water vapour, the net effect on radiative forcing will be seen years after the implementation of a hydrogen powered aircraft fleet as atmospheric CO_2 slowly decays. The effects of radiative forcing are explained in detail in Appendix E.2.

An estimate of an annual mean contrail cover resulting from a pure LH_2 powered aircraft fleet is shown in Figure 9. Excessive contrail buildup can be reduced by avoiding flights through areas with supersaturated air masses. [5]

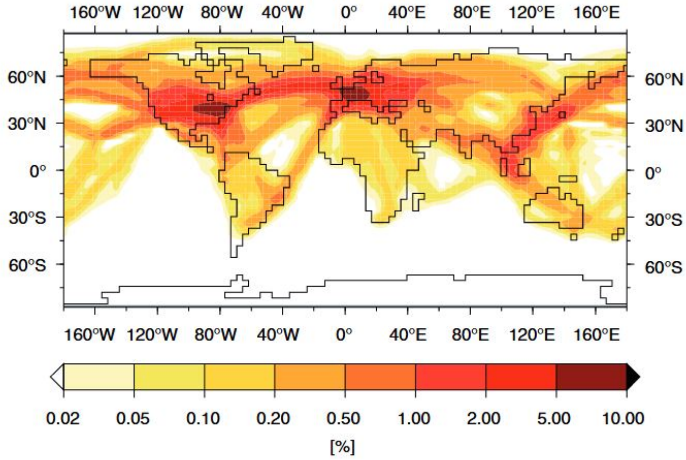
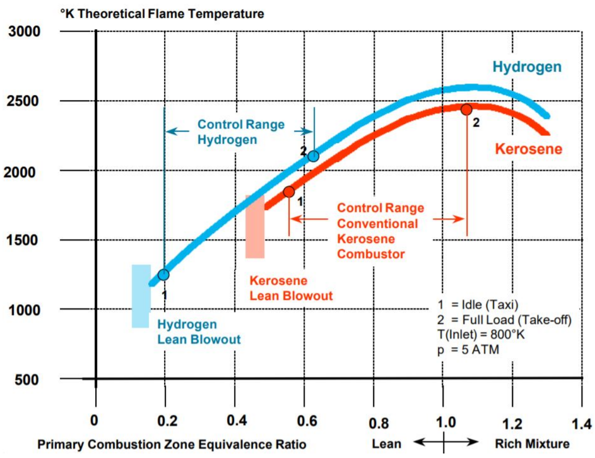


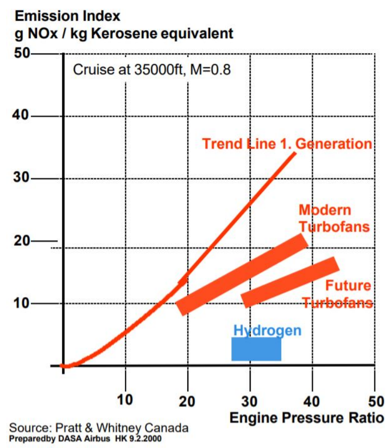
Figure 9: Annual mean contrail coverage due to a purely LH_2 burning aircraft fleet operating at 2015 traffic levels [4]

5.1.2 Nitrous oxides

A significant reduction in nitrous oxide emissions (NO_x) is seen with using hydrogen to power the engines. The wide flammability limits as well as the high burning velocity of hydrogen result in a shorter combustion chamber being required than for a conventional jet-fuel burning engine. Hydrogen also has a low lean blowout limit, meaning that combustion at lower equivalence ratios and flame temperatures is possible as compared with jet fuel. This is shown in Figure 10a. Hydrogen can be introduced into the combustion chamber as a gas and also has a high diffusivity, resulting in extremely low accumulation and avoidance of fuel-rich pockets inside the combustion chamber. All these factors contribute to lowering the NO_x emissions produced as a result of its combustion. [39] As shown in Figure 10b, NO_x emissions are significantly lower than modern and future jet fuel-burning turbofans. Using a Micromix combustor as described in Section 5.2 also helps to lower emissions further. Detailed explanations to the lean blowout limit and equivalence ratios are provided in Appendix E.3. Properties of hydrogen and its flammability limits are discussed in Appendix A.



(a) Combustion potential conditions



(b) Low NO_x potential of hydrogen

Figure 10: Combustion conditions and low NO_x potential of hydrogen [5]

5.2 Micro-Mix combustor

Modifications must be made to the engine when using hydrogen as a fuel and aiming for low NO_x emissions. One way to significantly reduce NO_x emissions when burning hydrogen is based on using the Micro-Mix combustion principle. [11] In essence, this can be accomplished by optimizing the mixing of the reactants and shortening the residence time of these in the hot flame regions. The Micro-Mix combustor, shown in Figure 25 in Appendix E.4, consists of three ring segments supplied with hydrogen. The gaseous hydrogen is injected perpendicularly into the air crossflow through small injectors located on each ring segment. This leads to faster and more intensive mixing, which takes place concomitantly with the combustion process. The combustor can be integrated into a conventional can-type combustion chamber without any difficulties. A comparison of NO_x emissions with a Micro-Mix combustor and conventional combustors is shown in Figure 24 in Appendix E.4.

5.3 CAEP regulations

The Committee on Aviation Environmental Protection (CAEP) is a technical committee set up in 1983 under ICAO. CAEP is responsible for the creation of emissions and environmental standards for global aviation. CAEP has provided equations for permissible NO_x emissions for different sizes of engines since 1996. These equations are given in Appendix D.

Using these equations, regulatory values for NO_x emissions for the Hy2Sky engines over the years were calculated. These values were interpolated to estimate a value for permissible NO_x emissions in 2035, found to be 57.22 g NO_x per kN thrust. This is shown in Figure 22.

Although CAEP have not released NO_x emission limit regulations beyond CAEP/8 (engines certified up to 1 January, 2023), a mid-term technology goal of limiting NO_x emissions to 54% of CAEP/8 levels by 2027 was revealed at the 2019 ICAO Environmental Symposium. [12] This would put the maximum permissible NO_x emissions value at 58.83 g/kN thrust for the Hy2Sky engines in 2027, with further reductions expected for 2035.

It is important to note that these limits are set for jet fuel-burning engines. Emissions from engines developed in recent years such as the CFM LEAP 1A and 1B and the PW1500G are seen to be 60-90% of regulatory levels. As mentioned in Section 5.1.2, there are several factors which contribute to the low NO_x potential of hydrogen as a fuel. Coupled with the use of a Micromix combustor, it can be concluded that the Hy2Sky engines will have NO_x emission values well below regulatory levels in 2035.

6 Cabin and Payload

When designing a passenger aircraft, it is important to take the transport of passengers as well as cargo into account. The main requirements given in the challenge are to carry 150 passengers weighing 80 kg each as well as baggage of 25 kg per passenger.

At first the cross section is explained. As a lot of new technologies are to be implemented into this design, it is important to keep the development costs as low as possible. Otherwise, aircraft manufacturers may not invest in a new aircraft design project. The idea is to therefore use the cross-section of an existing aircraft. The biggest advantage of this is that tools and facilities for production as well as operational items for airlines do not need to be redesigned and updated, saving costs. To choose the correct cross-section, another set of requirements was set. 18-in standard seats are required to fit in the aircraft to improve passenger comfort. [40] Furthermore, a maximum of three seats should be fitted to an aisle. This is a requirement set in the CS25 regulations and an extra aisle would be required if fitting more seats.

For short-haul aircraft, it is important to have large passenger luggage storage bay as it reduces turnaround time. Still, it is important to have a specific cargo compartment inside the aircraft. The COVID-19 pandemic has shown that aircraft need to be flexible in case fewer passengers are flying. Therefore, it is important to load cargo efficiently into the aircraft. To guarantee this the cargo area of the Hy2Sky needs to be capable of carrying standardized LD3-45 containers. To match these requirements, the cross-section of the Airbus A320 family has been chosen for use on the Hy2Sky and can be seen in Figure 11.

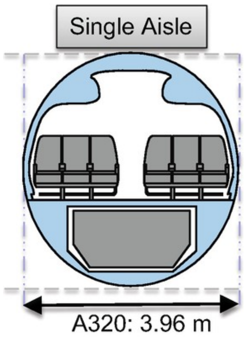


Figure 11: Cross section of the A320 aircraft [6]

As the A320 is an almost 50 year old aircraft design, its cabin needs to be modernized. Manufacturers have developed ongoing concepts such as the Boeing Sky Interior and the Airbus Airspace Cabin. A useful recommendation is to use passenger seats which can be easily folded in order to create space for carrying extra cargo. As mentioned previously, the current COVID-19 pandemic shows the need for extra cargo transport. An example of such a configuration is shown in Figure 12.

Figure 12: Seats usable for cargo storage proposed by HAECO [7]

The cabin will be accessible through two main doors (Type III doors as described in CS25.807 [41]) located at the front and the rear of the cabin. In longitudinal direction, the wing starts behind the rear passenger door to allow a quick boarding process via two doors. In case of emergencies, two smaller emergency exits (Type I doors as described in CS25) will assist the evacuation of the aircraft in the required 90 seconds. The twin emergency exit doors will need two big emergency slides as the wing is located in the rear, unlike conventional passenger aircraft. The configuration can be seen in Figure 13.

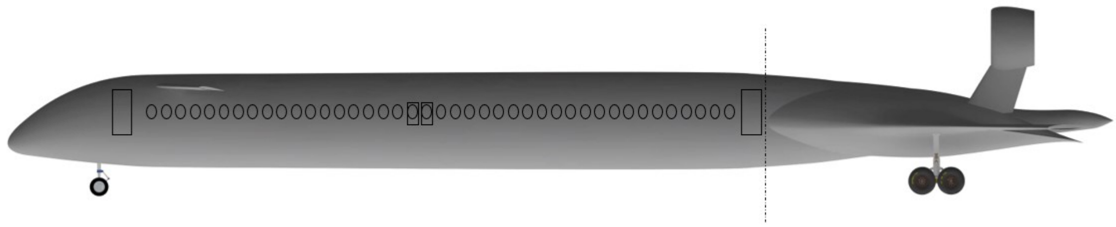


Figure 13: Door configuration (Dotted line shows end of A320 fuselage sections)

The cockpit section contains the canard wing which is placed in the upper area of the fuselage to not disturb the pilot entering the cockpit. Furthermore this position of the canard helps to place cockpit related systems such as avionic computers as well as emergency crew oxygen supply can easily be placed beneath the cockpit as it is done on today's aircraft.

7 Structural considerations

This section describes the structural considerations in the Hy2Sky design. Critical load locations have been estimated and a flight envelope is also provided.

7.1 Critical loads

Due to the oval cross-section of the A320 family used for this design, loads generated by differential pressure can be well introduced into the structure. With the help of a CAD model, a CATIA-based FEM analysis shown in Figure 14 was conducted to determine the critical sections of the aircraft.

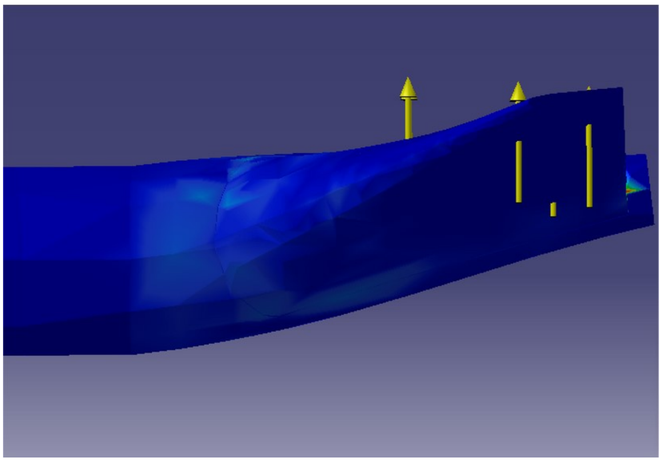


Figure 14: FEM analysis to show critical fuselage section

It is seen that the section where the wing starts in longitudinal direction is critical and must be strengthened by additional stringers. This is at the rear of the fuselage section where the conventional A320 fuselage ends.

Just as with the A320 as well as other modern short-haul aircraft such as the Airbus A220 and the Comac C919, aluminium is chosen for the fuselage material. This is explained by the high number of cycles during the aircraft's life time. Furthermore, the aluminium fuselage has environmental advantages as aluminium is easier to recycle compared with composite materials.

7.2 Flight envelope

The flight envelope contains the operational and design specifications that an aircraft needs to meet in order to be certified as airworthy. Also known as a v-n diagram, the flight envelope contains the speeds calculated to achieve desired performance as well as load factors, which outline the minimum design requirements. All aircraft are designed to meet the regulations governing the flight envelope as well as operate safely at all points on this graph.

The flight envelope for the Hy2Sky is shown in Figure 15. The calculations for the flight envelope were done in accordance with CS25/FAR25 regulations. A summary of the calculated parameters is given in Table 10. The maximum positive manoeuvre load factor (n_{max}) was calculated to be 2.5 g and the maximum negative manoeuvre load factor (n_{min}) was calculated to be -1 g. The red lines represent the gust loading as specified in FAR25. As a result, points C and F on the plot represent the maximum load factors due to gusts in cruise (n_g). [42]

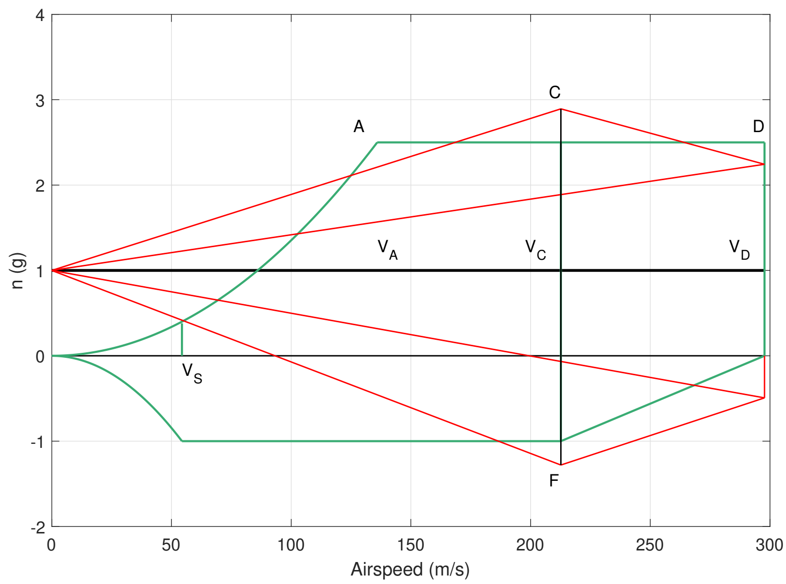


Figure 15: The flight envelope of the Hy2Sky aircraft

Table 10: Values shown in the Hy2Sky v-n diagram in Figure 15

Parameter	Explanation	Value
V_S	Stall speed	105.7 kts
V_A	Design manoeuvring speed	264.25 kts
V_C	Cruise speed	413.38 kts/M0.7 at FL295, ISA
V_D	Design dive speed	518.72 kts
n_{max}	Max positive manoeuvre load factor	2.5 g
n_{min}	Max negative manoeuvre load factor	-1 g
U_g	Gust speed at FL295	36.54 ft/s
$+n_g$	Max cruise gust load factor	2.89 g
$-n_g$	Negative cruise gust load factor	-1.28 g

8 Landing gear and other systems

This section explains the landing gear an the air conditioning systems used on the Hy2Sky.

8.1 Landing gear

The aircraft is equipped with a landing gear in a conventional configuration. A small, rotatable one is located beneath the cockpit section and fitted with two tires allows maneuvering on ground. The main landing gear consists of two single gears, oriented symmetrical to the longitudinal axis under the wing. Compared with modern aircraft, the gear is located further outwards, helping to stabilise the wing. Each main landing gear is fitted with two axles and four tires. The double-axle helps to better stabilise the aircraft, as it has a length comparable with that of a Boeing 757. There are many other systems apart from the fuel that need to be integrated into the aircraft.

A tailstrike analysis has been created to see the clearance at high angle of attacks during take-off. This can be seen in Figure 16, where an angle of attack of 20° is shown.

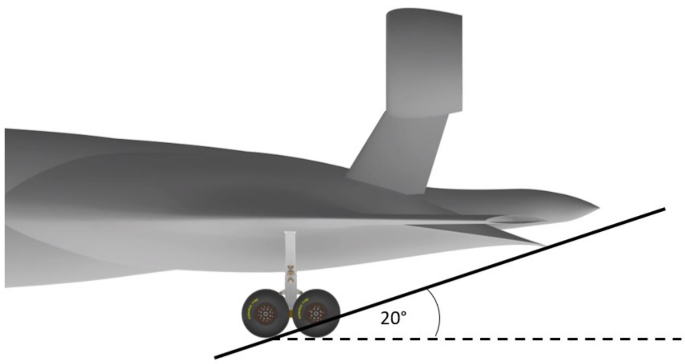


Figure 16: Geometric clearance during take-off with 20° angle of attack

8.2 Air conditioning systems

To generate differential pressure as well as deliver fresh air for the passengers, air conditioning packs will be needed. Due to the blended wing, there will be space in the belly fairing to place an air conditioning pack on each side driven by each engine. To increase passenger comfort and cabin air quality, electric heaters similar to those on a Boeing 787 Dreamliner will be used instead of a bleed air system.

9 Mission Design

This section discusses the operational considerations for the Hy2Sky. Sample mission profiles for the 600 km and 2000 km ranges have been created and payload range diagrams are also presented.

9.1 Mission profile

One of the main goals of this challenge is to minimise emissions during both missions. Although mission profiles for aircraft vary based on a range of conditions (ambient temperature and pressure, aircraft MTOW, engine preservation, local traffic regulations and airspace congestion, etc.), a sample mission profile has been created here with minimising emissions as the driving factor. Both mission profiles account for a 200 NM (371 km) additional range, in case a flight to an alternate airport is required. The sample mission profiles for both missions are shown in Figure 17 and the profile for the 2000 km mission is described in the following steps -

- **Initial climb:** Aircraft climbs to 5000 ft at 3000 fpm and airspeed of 205 knots, time: 100 s
- **Level-off:** Aircraft levels off at 5000 ft, gains airspeed to 250 knots, time: 45 s
- **Climb:** Aircraft climbs to FL150 at 2000 fpm and an airspeed of 250 knots, time: 300 s
- **Level-off:** Aircraft levels off at FL150, gains airspeed to 325 knots, time: 60 s
- **3rd climb phase:** Aircraft climbs to FL200 at 1700 fpm and 325 knots, time: 176.5 s
- **Level off:** Aircraft levels off at FL200 to gain airspeed to 385 knots/M0.63 (10% below cruise speed), time: 60 s
- **Final climb:** Climb to cruising altitude of FL295 at 1000 fpm and M0.63, time: 570 s
- **Level off and cruise:** Aircraft levels off at FL295, accelerates to M0.7 and commences the cruise phase, time: 119.4 minutes
- **Descent:** The descent phase The descent phase is highly dependant on local traffic regulations and ATC instructions at the arrival airport, only a sample is shown here

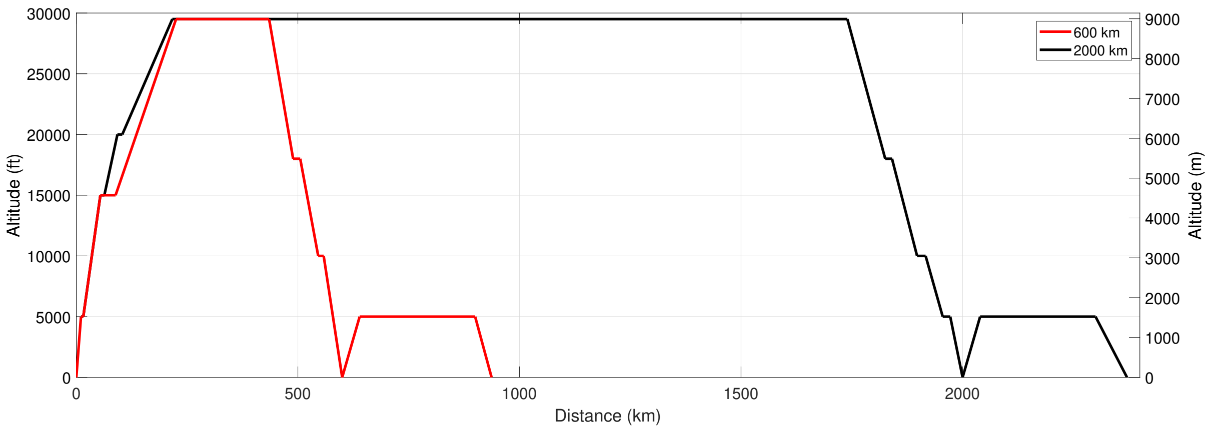


Figure 17: Sample mission profile for both missions

The climb phases for both missions (2000 km and 600 km) are identical up to FL150. For the 600 km mission, the aircraft climbs at 1000 fpm and 355 knots above FL150. This ensures that the engines are operated at a lower thrust setting during climb, reducing fuel burn and emissions. Plots showing the thrust available to climb at different altitudes are given in Appendix F. The approximate total time for the 2000 km mission has been calculated as 2 hours and 51 minutes. The approximate total time required for the 600 km mission is 1 hour and 11 minutes.

9.2 Payload-Range Diagram

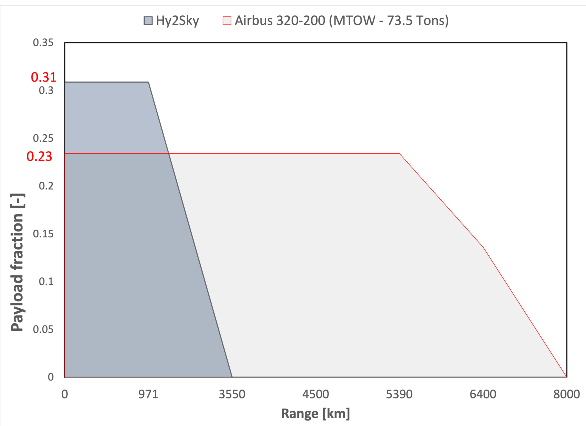
In this section, a comparison of payload fraction and range with an Airbus 320-200 as a reference aircraft is done. [43] Payload is divided by the MTOW of each aircraft to give a dimensionless payload fraction. The reference aircraft here (A320-200) has a MTOW of 73.5 tons. [44] Table 11 holds the payload-range data of the Hy2Sky in both the 600 km and the 2000 km missions as well as the A320-200. The MTOW for the 600 km and 2000 km missions of Hy2Sky are different as they carry different quantities of fuel for the different mission requirements. However, the payload weight is the same for both missions.

Table 11: Payload fraction-range diagrams of the Hy2Sky, Airbus 320-200

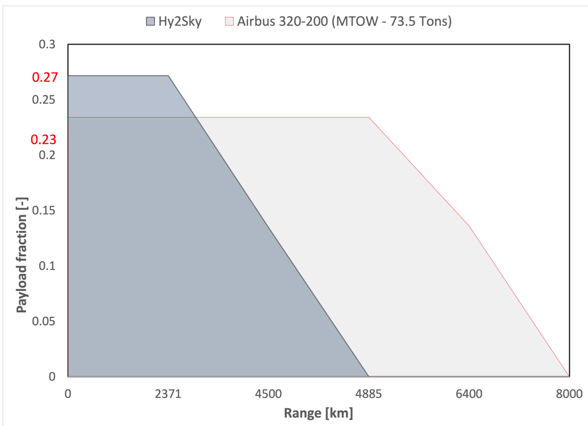
Parameter	Unit	Hy2Sky [600km]	Hy2Sky [2000km]	Airbus A320-200
MTOW	t	51.5	58	73.5
Max payload	t	15.75	15.75	18.5
Range at max payload	km	971	2371	4500
Payload at max fuel	t	15.75	15.75	15.2
Range at max fuel	km	971	2371	6400
Ferry range	km	4885	3550	8000

The payload-range diagrams of the Hy2Sky in each design mission have been compared with that of the A320-200 in Figures 18a and 18b. The A320-200 is represented by red lines and the Hy2Sky in black. As the A320 is a conventional, jet fuel-burning aircraft and Hy2Sky is hydrogen-fueled, their payload fraction-range diagram vary significantly. The Hy2Sky for the 600km mission has maximum range with maximum payload of 971 km and a ferry range of 3550 km. The Hy2Sky for 2000 km has maximum range at maximum payload of 2371 km and a ferry range of 4995 km.

It is seen that the hydrogen-powered aircraft lack the flexibility in range compared with jet fuel-powered aircraft. However, the hydrogen aircraft have a higher payload fraction compared with modern conventional aircraft. This is because the weight of hydrogen tanks is likely to decrease in the future. [45] As jet fuel is heavy, fuel burn during the flight reduces aircraft weight significantly and allows modern aircraft to fly longer ranges. On the other hand, hydrogen is extremely light and fuel burn on a hydrogen-powered aircraft does not reduce aircraft weight significantly. The ranges are therefore not comparable with a jet fuel-powered aircraft. The hydrogen tanks are heavier than jet fuel tanks. This increases the MZFW of the aircraft and hence the reduction in range.



(a) 600 km mission



(b) 2000 km mission

Figure 18: Payload fraction - range diagrams for the 600 and 2000 km missions

10 Infrastructure and Turnaround

This section describes the ground handling component for the Hy2Sky.

10.1 Turn Around

The turnaround process is the time from on-block to off-block for the aircraft. This is an extremely important component of the operational concept of the aircraft and is useful information for airlines and other commercial operators. Short turnaround times are necessary for an airline to stay profitable. An overview of needed vehicles and their positions in relation to the aircraft can be seen in Appendix G.

One of the biggest advantages of using a fuselage similar to that of modern aircraft is that the turnaround process remains very similar and very few modifications to ground handling equipment are needed. Deboarding and boarding, cleaning, catering as well as loading and unloading baggage and cargo will take similar amounts of time as with conventional aircraft and will not need new procedures or equipment. This keeps the costs low and the dispatching smooth. Nevertheless, a reduction in boarding time can be achieved due to larger overhead compartments, which means more comfort for the passengers and more time for cleaning and refuelling. The usage of both the front and the aft doors helps to speed up the boarding process. As boarding is the slowest part of the turnaround process, no further efforts to shorten the turnaround time are implicitly necessary as the limiting factors are the brakes that need to be cooled before attempting another takeoff and the pilots who need to prepare the upcoming flight. [46] This takes an average of 30 minutes with most airlines nowadays.

10.2 Refuelling

Another important part of the turn around process is refuelling. In the early stages of using hydrogen as fuel, using refuelling trucks to fuel the aircraft could be the fastest and most economical solution as it would require minimal changes to existing infrastructure. [47] However, more refueling hoses will be needed due to the lower volumetric density of liquid hydrogen compared with jet fuel. [48] To stay within acceptable limits for turnaround times, this issue can be solved by doubling the number of refuelling trucks. [47] In the long term, setting up pipeline systems at airports may become the preferred option.

10.3 Further Considerations

Establishing a new fuel on the market also means developing new safety regulations and procedures. Although liquid hydrogen appears to be safer than conventional fuels, it is still flammable, meaning that personnel at airports will need special training on the safety risks with hydrogen. [49][47] Moreover, it is important to consider that hydrogen is the lightest element and hence very volatile. This results in a loss of energy in case of a leakage but also in a higher risk for flammability. Correct ventilation can provide a solution here. If a leak occurs and the gas gets ignited, the flames will rise straight up instead of spreading in all directions and risking large uncontrolled fires, as with jet fuel. This makes hydrogen safer than jet fuel. [49] However, hydrogen is not completely hazard-free. The flames from burning hydrogen can be almost invisible in daylight. [50] This could put airport staff at high risk and is a factor that should be considered when devising safety training for them.

In the early stages of using hydrogen, it should also be considered that not every airport will have the necessary equipment for refuelling. This is an important point when it comes to diversions which are a common procedure in aviation. [47]

11 Life Cycle Assessment

When designing a modern industrial product, it is important to consider environmental aspects as well. The entire life cycle, including production and disposal of the product has to be considered. Important requirements for the product are to produce the lowest possible emissions as well as reduce non-recyclable/reusable waste.

In planning the production of the aircraft presented in this report, it is important to note that the need for new factories and tooling is reduced by basing the fuselage design on that of the A320. This is highly economical and also reduces emissions caused due to production of new tools and facilities. Additionally, the whole production process can be made carbon neutral. Daimler AG has announced that their vehicle production will be carbon-neutral from 2022. [51] Based on this target, it is hoped that aircraft manufacturers will be able to produce aircraft in a carbon-neutral way by the target EIS of 2035. Details about how this production process needs to be designed are not in the scope of this challenge.

During the usage of the aircraft, the hydrogen propulsion concept reduces emissions significantly compared with current aircraft. To reduce waste as well, exchange parts have to be identified. The cabin contains many parts that need to be replaced several times during the operational lifetime of the aircraft, such as seat covers, seat pockets and galley parts. These parts should be made from recyclable and sustainable materials. [52]

An economical and environmentally friendly disposal process needs to be designed for the end of the service life of the aircraft. Strategies to disassemble the aircraft have been created. [53] From an environmental point of view, the best strategy is to randomly cut the aircraft into small pieces to be able to recycle it. This is known as the 'Smart Shredding' process. Before the aircraft is shredded into small pieces to be prepared for recycling, it is divided into zones with a high number of similar materials, helping to reduce costs. Furthermore, the aluminium fuselage has a big advantage compared with a fuselage made from composite materials as the shredding and recycling process is simpler and cheaper.

12 Direct Operating Costs

Finally, the direct operating costs (DOCs) for the aircraft have been calculated. The calculations are done with the help of the DOC-method developed by Thorbeck from the Technical University of Berlin. [54] It divides the fixed and the variable costs of the aircraft into five main categories: fuel costs, capital costs for buying or leasing the aircraft, fees for airport and navigation services, costs for cabin and cockpit and crew and maintenance costs. The unit *€ /100Skm* represents the costs per 100 seat kilometres. The DOCs for the Hy2Sky are given in Table 12. The DOCs of the Hy2Sky are higher compared with the reference aircraft (A320-200). The total DOCs for Hy2Sky have been calculated to be 9.57€ /100Skm with the initial assumptions for predicted costs in 2035. In comparison, the A320 has DOCs of approximately 6.60€ /100Skm as per Alaska Airlines in December 2018. [55]

Table 12: Direct Operating costs for 2000km range
*** Values based on market prices, * Values based on EUR2010 guideline*

Parameter	Unit	Value
Fuel price	€ /kg	3.0**
Structure price	€ /kg	1150*
Engine price	€ /kg	2500*
Insurance rate	%	0.5*
Annual rate	%	5
Flights per year	1/a	1095
Landing fees	€ /kg	0.01*
Airport service fees	€ /kg	0.10*
Navigation fees	€ /km	1*
Number of passengers	1	150
Range	km	2000
DOC Fuel	€ /100Skm	5.28
DOC Capital	€ /100Skm	0.82
DOC Fees	€ /100Skm	1.44
DOC Crew	€ /100Skm	0.84
DOC Maintenance	€ /100Skm	1.2
DOC Total	**€ /100Skm**	**9.57**

13 Conclusion

Designing a hydrogen powered aircraft leads to many challenges. The aircraft design process described in this report has tried to balance low production and operational costs with the introduction of new technologies. The biggest difference between the Hy2Sky and conventional designs that use kerosene-based fuels is that fuel storage is not a given, as LH_2 cannot be stored in wing tanks as with jet fuel on modern, conventional aircraft. This leads to new design concepts for the integration of the new, more voluminous and insulated hydrogen tanks. The tank weight of such future aircraft will be a sizable fraction of the MTOW. Due to this, carrying excess tank weight for shorter missions requiring less fuel is not an efficient option. To address the issue, it is clear that tank weight itself should be treated as a payload that can be shed in a modular manner and removed from the aircraft. Reducing excess tank weight for shorter missions reduces the MZFW of the aircraft and leads to increased fuel savings.

The conventional fuselage helps to keep production costs low as it reduces the need for new manufacturing equipment. The rear section of the aircraft, containing the fuel storage, propulsion system and new wing design provides an innovative solution, improves aircraft performance and helps to reduce fuel burn. The more conventional approach to the Hy2Sky engines decreases development risks and also makes the entry in service target of 2035 more realistic. NO_x emissions are significantly reduced thanks to further modifications, helping this aircraft meet the design challenge targets.

Overall, the Hy2Sky aircraft demonstrates a good blend of modern and futuristic components in an aircraft design with sustainability and innovation at its core. This is the ideal approach required to ensure a smooth transition to a new era of aviation.

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Appendix A Properties of hydrogen

Hydrogen is the most abundant material in the universe, constituting 75% of all matter. It is the first and the lightest element in the periodic table. [8] The properties of hydrogen are summarized in Table 13. The flammability limits of hydrogen are shown in Figure 19 and are compared with other fuels in Figure 20. It is clear that hydrogen has wider flammability limits than other commonly used fuels, increasing the range of conditions it can be combusted under. This helps to pick optimum combustion conditions to minimise the formation of NO_x emissions as well as reduce the amount of fuel needed for efficient combustion.

Table 13: Properties of hydrogen [8]

Property	**Value**
Chemical formula	H_2
Melting point	-259° C
Boiling point	-253° C
Density at boiling point	70.8 kg/m^3
Vapour density (at 20° C)	0.08376 kg/m^3
Lower Heating Value (LHV)	119930 kJ/kg
Higher Heating Value (HHV)	141860 kJ/kg
Auto-ignition temperature	585° C
Energy density	10050 kJ/m^3 (gas)
	8491000 kJ/m^3 (liquid)
Flammability limits in air	4-75% volume

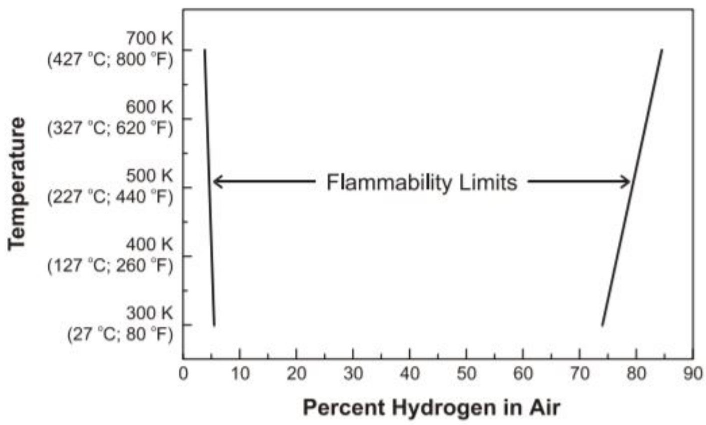

Figure 19: Flammability limits of hydrogen [8]

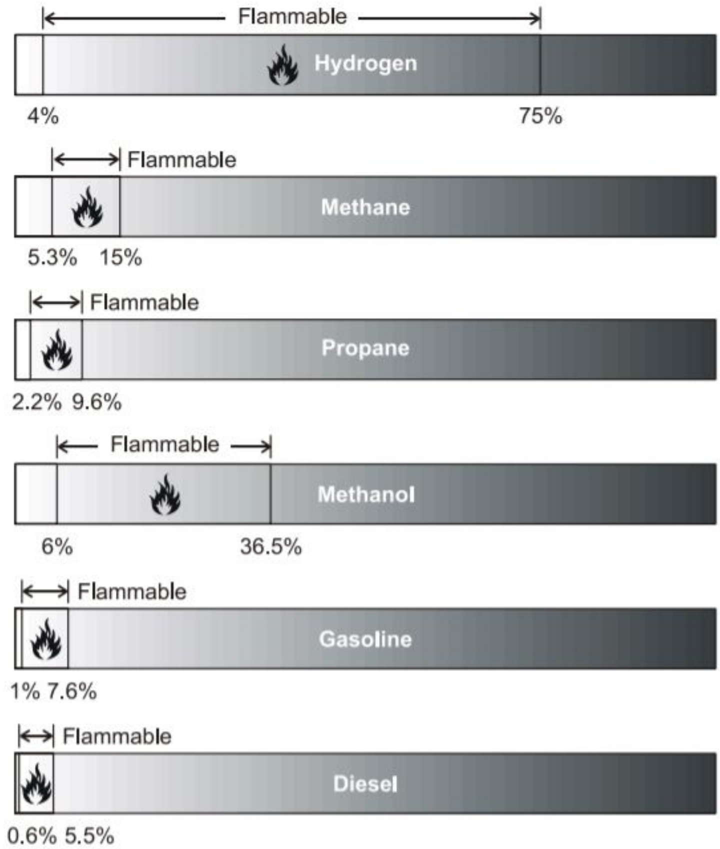

Figure 20: Flammability limits of hydrogen compared with other fuels [8]

Appendix B Wing geometry determination

Using the weight in the cruise flight segment, the dynamic pressure in this segment, the cruise C_L is calculated as 0.35:

$$C_{L_{cr}} = \frac{W \cdot g}{S \cdot q} \tag{1}$$

It now has to be assured that this flight condition with the given $C_{L_{cr}}$ value is also the most efficient lift coefficient for the wing to fly at. In order to check for this we use the following formula according to [56]:

$$C_{L_{md}} = \frac{\pi \cdot AR \cdot e}{2 \cdot E_{max}} \tag{2}$$

with this equation we see that a minimum drag lift coefficient can now be described using only wing properties and a desired E_{max}. Furthermore, the Oswald factor as well as E_{max} can be rewritten into a function of the aspect ratio as well, using methods proposed in [56], thereby we can consider a fixed and achievable glide ratio for the aircraft by changing only the aspect ratio until the following stands:

$$C_{L_{md}} = C_{L_{cruise}} \tag{3}$$

The E_{max} can be attributed to AR as follows:

$$E_{max} = k_E \sqrt{\frac{AR}{S_{wet}/S_W}} \tag{4}$$

With k_E and the relative wetted area values calculated according to [56] methods.

Appendix C Engine sizing interpolation

As described in Section 4.3, the interpolation process used to size the engines is detailed here. Data given in Table 14 was used to interpolate values of fan diameter, SFC, BPR, engine mass and length. A linear fit plots a straight line through the data, meaning that predicted values constantly increase or decrease depending on the trend. This was not seen as a good way to realistically estimate properties for this engine sizing process and a quadratic fit was therefore used. The interpolation was done using Python and the plots obtained are given in Figure 21.

Table 14: Aircraft engine data used for interpolation

Aircraft	Engine	Max thrust (kN)	Fan diameter (m)	Cruise SFC (g/kNs)	Mass (kg)	BPR	OPR	Length (m)	EIS Year
-	Enoval 1	85.8	2.03	13.98	4000	16.2	54.7	3.85	2027
-	Enoval 2	252	3.17	13.73	10136	16.2	73	5.58	2028
-	Enoval 3	340	3.84	13.47	11625	16	59	6.44	2030
A320-200	CFM56B	133	1.73	15.4	2500	5.5	33.6	2.6	1993
777-300	GE90	500	3.3	14.7	8762	9	42	7.29	2001
A350 XWB	Trent XWB	375	3	13.5	7277	9.6	50	5.82	2010
A330 NEO	Trent 7000	310	2.84	14.3	6445	10	50	4.78	2015
A340-500	Trent 500	245	2.47	15.4	4990	7.6	36.3	4.69	1999
737 MAX	CFM LEAP1B	127.62	1.76	15	2780	9	40	3.15	2017
A320 NEO	CFM LEAP 1A	140.96	1.98	14.4	3100	11	40	3.33	2016
A220	PW1500G	108.54	1.85	14	2177	12	40	3.18	2010

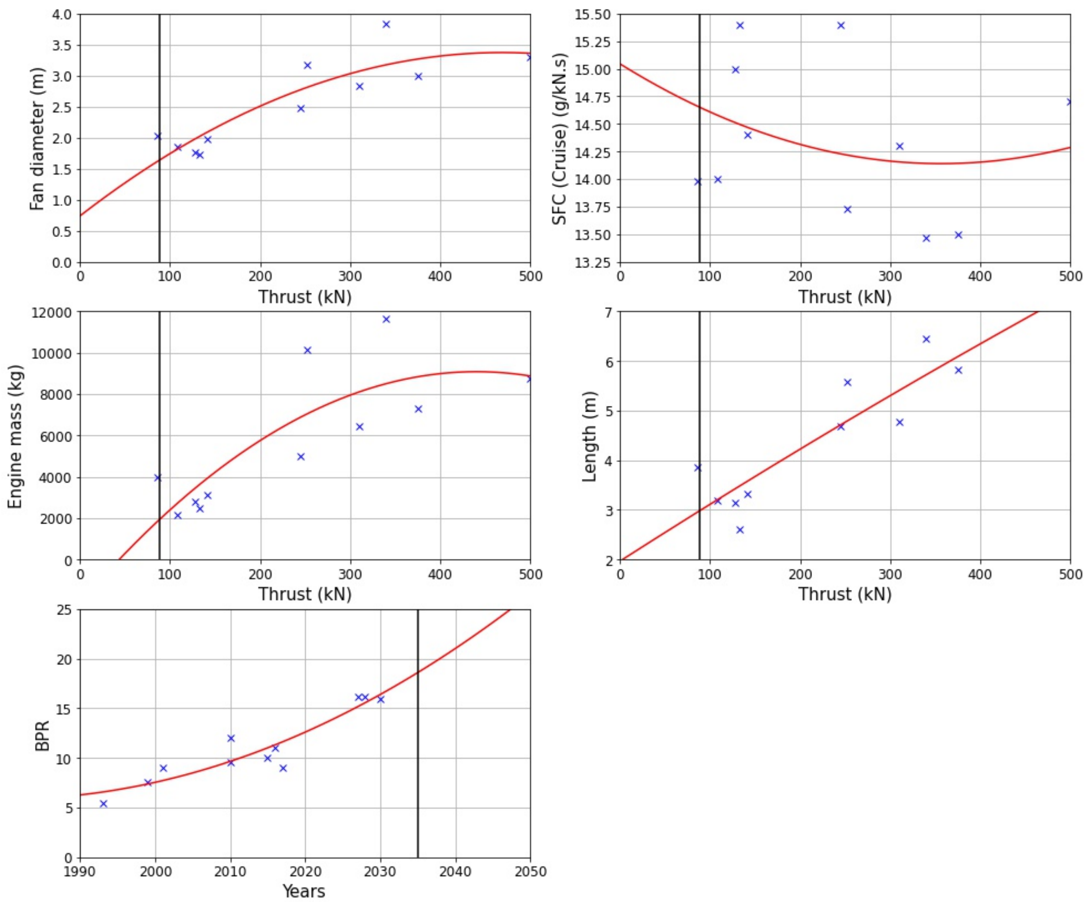

Figure 21: Hy2sky engine sizing plots, created using the data in Table 14

Appendix D CAEP specifications

As mentioned in Section 5.3, the equations provided by the Committee on Aviation Environmental Protection (CAEP) governing the permissible NO_x emissions are described in this section.

It is important to consider the change in emission regulations over time to make assumptions for the future. Regulations surrounding permissible NO_x emission limits are provided by CAEP and have changed significantly over time. The emissions depend on the maximum thrust available from the engine (F_{oo}) and the engine OPR (π_{oo}). Equations are specified by CAEP to determine these regulatory limits (D_p/F_{oo}) in g/kN (grams of emissions per kN of thrust). Only the relevant equations for an engine producing 88 kN and having an OPR of 50 are discussed here, the rest can be found in the CAEP/8 report. [38]

1. For engines of a type or model for which the date of manufacture of the first individual production model was before 1 January 1996 and for which the date of manufacture of the individual engine was before 1 January 2000 -

$$D_p/F_{oo} = 40 + 2\pi_{oo} \tag{5}$$

2. For engines of a type or model for which the date of manufacture of the first individual production model was on or after 1 January 1996 or for which the date of manufacture of the individual engine was on or after 1 January 2000 -

$$D_p/F_{oo} = 32 + 1.6\pi_{oo} \tag{6}$$

3. For engines of a type or model for which the date of manufacture of the first individual production model was on or after 1 January 2004; for engines with a pressure ratio of more than 30 but less than 62.5; for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN -

$$D_p/F_{oo} = 42.71 + 1.4286\pi_{oo} - 0.4013F_{oo} \tag{7}$$

4. For engines of a type or model for which the date of manufacture of the first individual production model was on or after 1 January 2008 or for which the date of manufacture of the individual engine was on or after 1 January 2013; for engines with a pressure ratio of more than 30 but less than 82.6; for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN -

$$D_p/F_{oo} = 46.1600 + 1.4286\pi_{oo} - 0.5303F_{oo} + 0.00642\pi_{oo}F_{oo} \tag{8}$$

5. For engines of a type or model for which the date of manufacture of the first individual production model was on or after 1 January 2014; for engines with a pressure ratio of more than 30 but less than 104.7; for engines with a maximum rated thrust of more than 26.7 kN but not more than 89.0 kN -

$$D_p/F_{oo} = 41.9435 + 1.505\pi_{oo} - 0.5823F_{oo} + 0.005562\pi_{oo}F_{oo} \tag{9}$$

The values obtained for the Hy2Sky engines were interpolated to estimate a permissible emissions value for 2035. The value was found to be 57.22 g NO_x per kN thrust. This is shown in Figure 22.

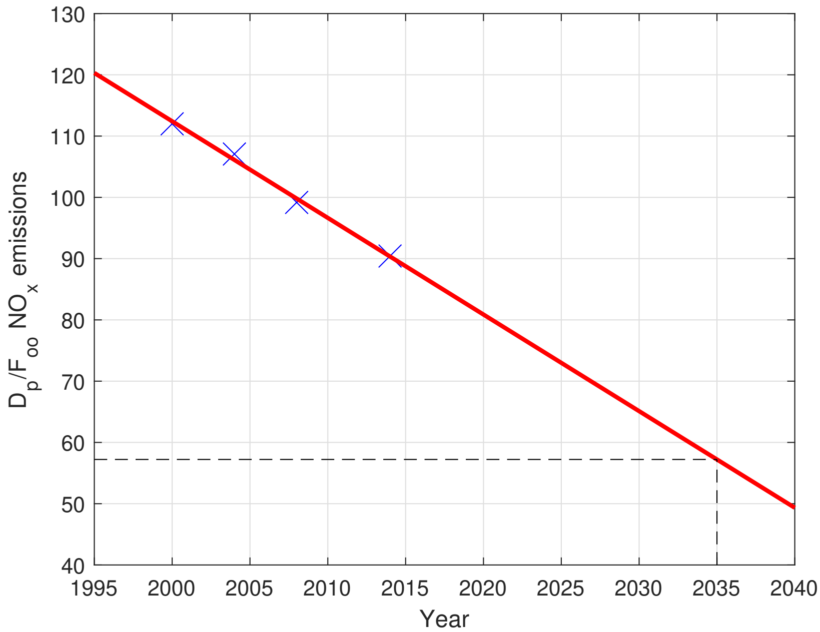

Figure 22: Change in permitted NO_x emissions over the years

Appendix E Emissions

Hydrocarbon-based fuels generate several greenhouse gases and other pollutants that impact the atmosphere and the climate negatively. The introduction of hydrogen as a fuel is therefore extremely important to drastically reduce pollution due to aviation and completely eliminate carbon-based emissions. This section explains emissions from hydrocarbon-based fuels as well as the impact of radiative forcing. Terms used in Section 5.1.2 are defined and more details about the Micro-Mix combustor (Section 5.2) are also provided.

E.1 Emissions from jet fuel burning aircraft

Section 5.1 describes the emissions produced from the combustion of hydrogen. This section describes the emissions from modern, jet fuel burning aircraft.

The pollutants produced by a jet fuel burning turbofan in cruise are summarised in Table 15.

Table 15: Emissions from a jet fuel burning turbofan in cruise [12]

Pollutant	**Quantity (g/kg fuel)**
CO_2	3160
H_2O	1290
NO_x	15
SO_x	1.2
CO	< 0.6
UHC	< 0.1
Particulates	< 0.05

Carbon dioxide (CO_2) constitutes the biggest proportion of pollutants resulting from combustion of jet fuel. It has a residence time of several decades in the Earth's atmosphere and significantly impacts the radiative forcing of the Earth, thereby contributing heavily to the greenhouse effect.

The second most significant combustion product is water vapour. At lower levels of the atmosphere, water vapour disperses quickly as precipitation and does not cause long-term climate impacts. However, at altitudes above 9000 m, it can induce the formation of contrails and cirrus clouds. Contrails are long clouds of small ice crystals, formed due to water droplets in aircraft engine exhausts freezing at high altitudes. Depending on atmospheric conditions (air temperature and humidity), they may just be present for a few seconds or persist for hours. Water vapour emissions are the primary emissions from hydrogen combustion, as explained in Section 5.1.1.

Nitrous oxide emissions (NO_x) are formed by the interaction of oxygen and dissociated atmospheric nitrogen at high temperatures in the engine. NO_x emissions encourage the formation of ozone at lower levels in the atmosphere, which has an adverse effect on the human respiratory system. At high levels, they encourage the breakdown of ozone, affecting the ozone layer and indirectly increasing UV radiation transmission through the earth's atmosphere. [39] NO_x emissions are the main secondary emissions from hydrogen combustion and are explained further in Section 5.1.

Extremely small amounts of SO_x emissions (soot) are also produced. However, the small quantities ensure that they have a minimal impact on global warming.

E.2 Radiative forcing

The change in energy flux through the Earth's atmosphere is known as radiative forcing. It may occur due to natural or human-induced causes. Radiative forcing is the cause of the greenhouse effect and its level affects changes in Earth's climate. [57] It can also be thought of as a change in the global mean surface temperature relative to a standard baseline temperature due disturbances in Earth's radiation budget. Radiative forcing is measured in Watts per square meter (W/m^2). [9]

Energy enters the Earth's atmosphere through solar radiation. The energy released from the Earth's atmosphere consists of reflected solar radiation as well as radiation emitted from the Earth. As long as the incoming and outgoing radiation levels are in balance, the overall mean temperature of the Earth's atmosphere remains relatively constant. A positive value of radiative forcing indicates that the incoming radiation is greater than the outgoing radiation, resulting in warming of the atmosphere. A negative value implies cooling. The incoming and outgoing radiation is depicted in Figure 23.

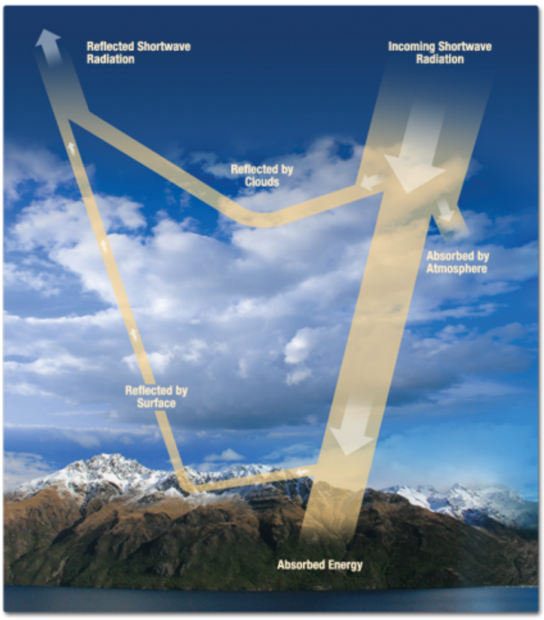

Figure 23: The Earth's radiation balance [9]

Pollutants from aircraft engine exhausts released in the upper atmosphere accumulate and make long-term contributions to radiative forcing. Gases such as CO_2 have extremely long residence times in the atmosphere and the ever-increasing concentrations restrict outgoing radiation. The radiation gets trapped by these gases, thereby increasing the temperature of the lower atmosphere and causing the greenhouse effect. If CO_2 emissions were stopped immediately, the greenhouse effects of the gas would continue to be noted for decades due to the long residence time. The concentration would eventually decay as the gas gets absorbed into the atmosphere. [58]

Compared with CO_2, contrails formed due to water vapour have extremely short residence times in the atmosphere. Radiative forcing due to contrails is therefore of lower significance. An increase in contrail and cirrus cloud cover due to hydrogen combustion would make water vapour one of the main contributors to radiative forcing. However, the short residence time would ensure that the contrails decay within hours.

E.3 Definitions

Terms mentioned in Section 5.1.2 are defined as follows -

- **Lean blowout limit:** The lean blowout limit of a fuel is the point of flame extinction during lean combustion. Hydrogen has a lower lean blowout limit than jet fuel, meaning it can be combusted using a leaner mixture (low fuel to air ratio) than jet fuel.
- **Equivalence ratio:** The equivalence ratio (ER) is defined as the ratio between the actual fuel-to-air ratio and the fuel-to-air ratio required for stoichiometric combustion. The formula is given as -

$$ER = \frac{(m_{fuel}/m_{air})_{actual}}{(m_{fuel}/m_{air})_{stoichiometric}} \quad (10)$$

  No molecular oxygen (O_2) is present in the combustion products in case of stoichiometric combustion. This means that the combustion is lean (excessive air) if the ER is less than 1 and rich with incomplete combustion (unburnt fuel in combustion products) if the ER is greater than 1. If the ER equals 1, combustion is stoichiometric. [59]

E.4 Micro-Mix combustor

As mentioned in Section 5.2, the Micro-Mix combustor helps to significantly reduce Hy2Sky's engines NO_x emissions. In essence, the NO_x molar fraction is five times smaller than other compared combustors at a given mass flow factor. This is a clear advantage and is therefore taken into consideration for Hy2Sky. The lower NO_x emissions achieved with the Micro-Mix combustor compared to other conventional combustors, can be seen in the following plot.

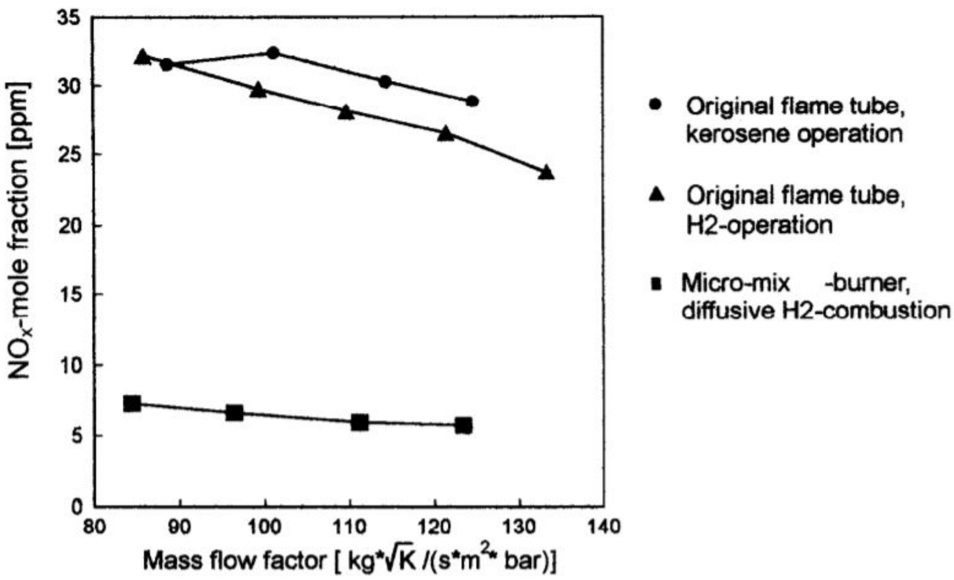

Figure 24: NO_x emissions from a Micromix combustor compared with conventional combustors [10]

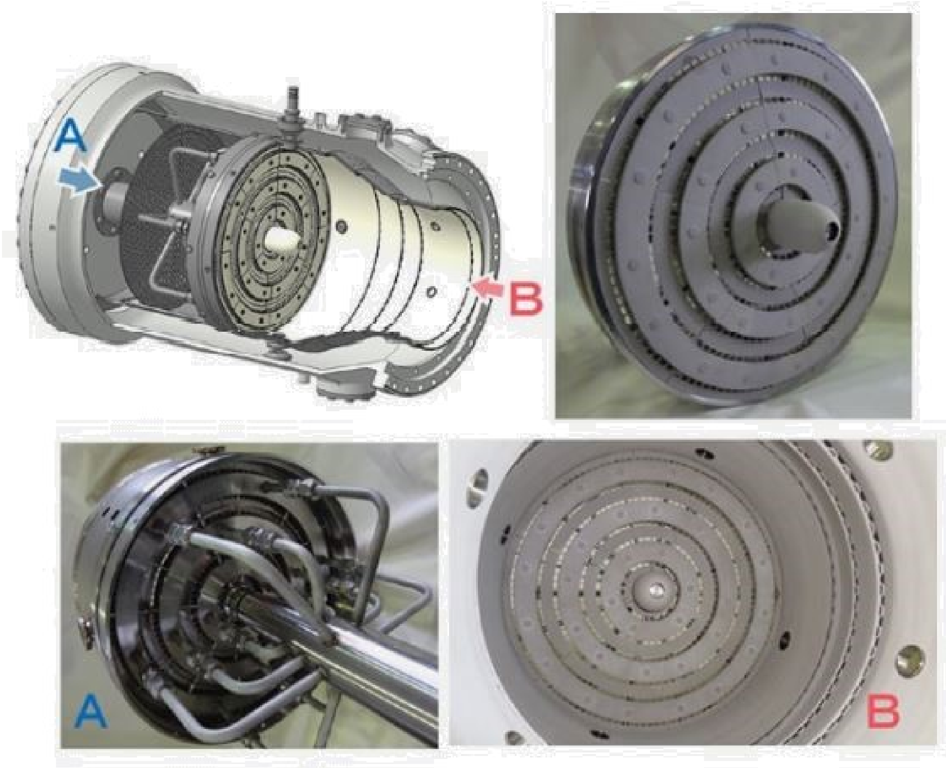

Figure 25: Design of a Micro-Mix combustion burner [11]

Appendix F Thrust available at different altitudes

The thrust available to climb at different altitudes was calculated using MATLAB. In climb, the engines operate at 85% maximum available thrust. Available thrust reduces at higher altitudes due to the decrease in air density. The graphs shown here represent the sample climb profile of the 2000 km mission. Different climb rates have been plotted to show the available climb profiles. The climb rates chosen, as well as the mission profile are described in Section 9.1.

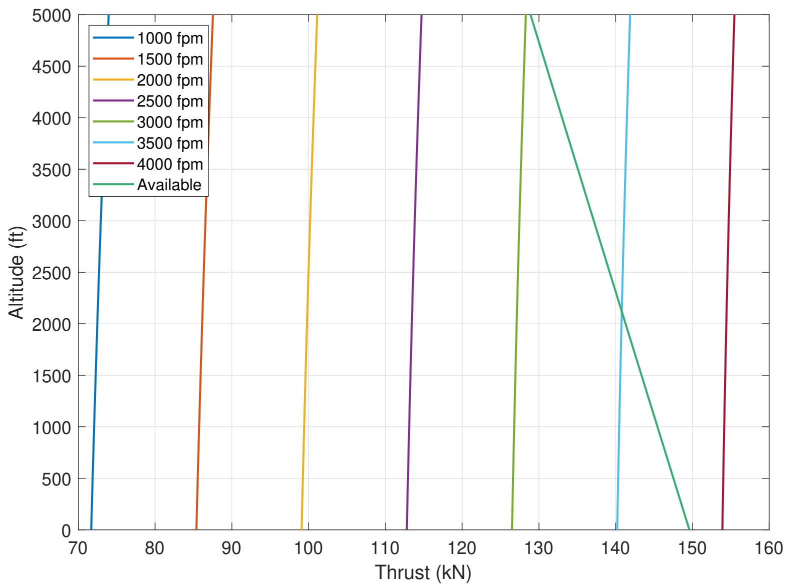

Figure 26: Climb thrust and rates available at 85% max power to climb from 0 to 5000 ft at 205 kts

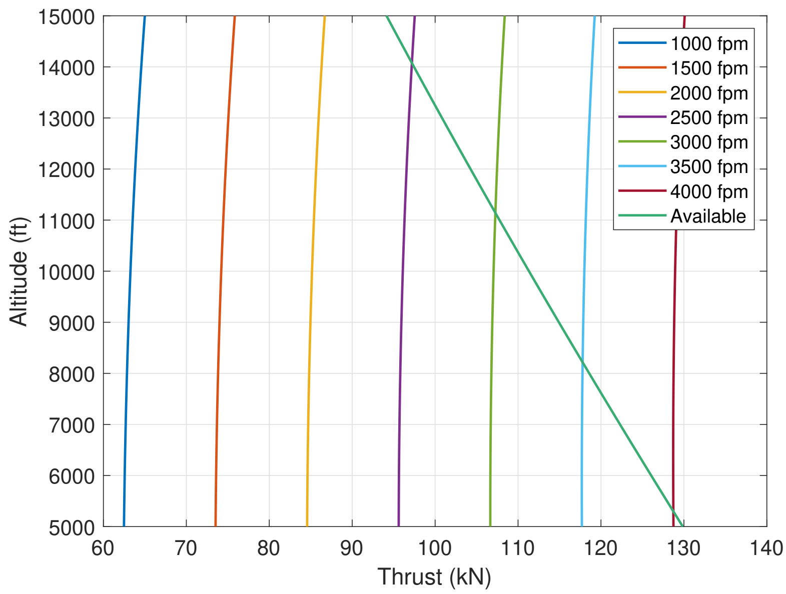

Figure 27: Climb thrust and rates available at 85% max power to climb from 5000 ft to FL150 at 250 kts

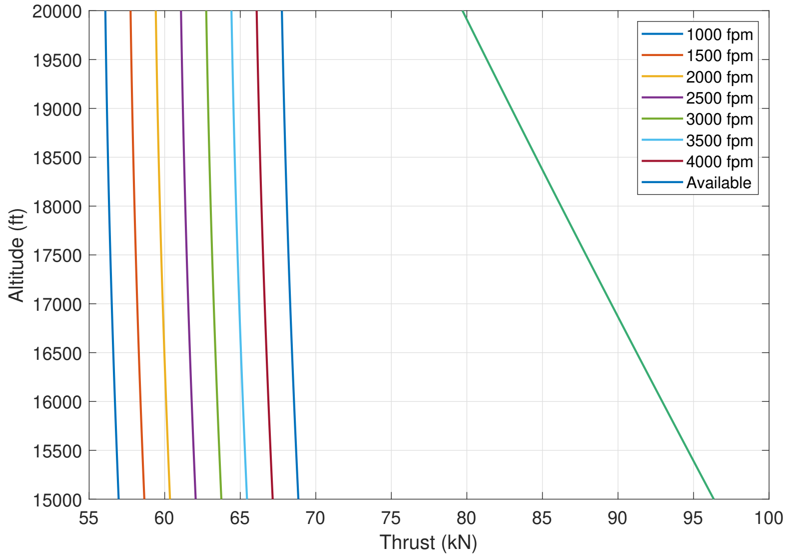

Figure 28: Climb thrust and rates available at 85% max power to climb from FL150 to FL200 at 325 kts

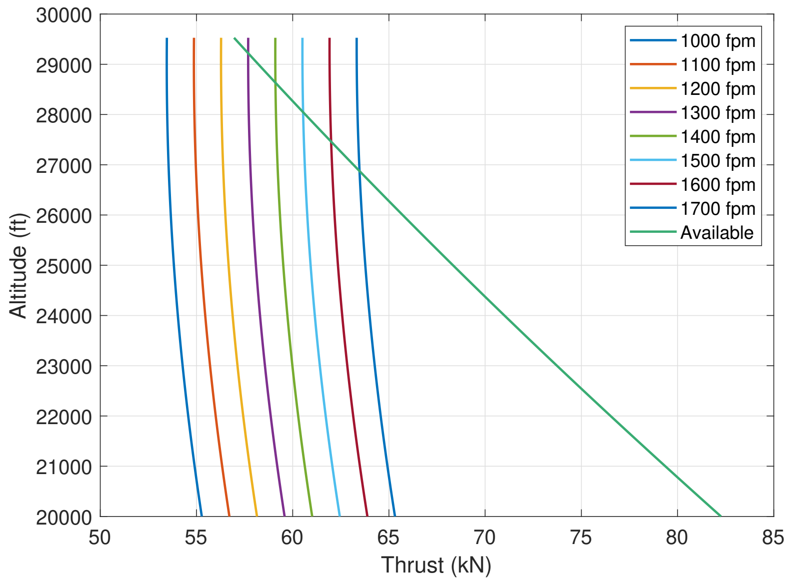

Figure 29: Climb thrust and rates available at 85% max power to climb from FL200 to FL295 (cruising altitude) at 385 kts

Appendix G Ground handling and turnaround vehicles

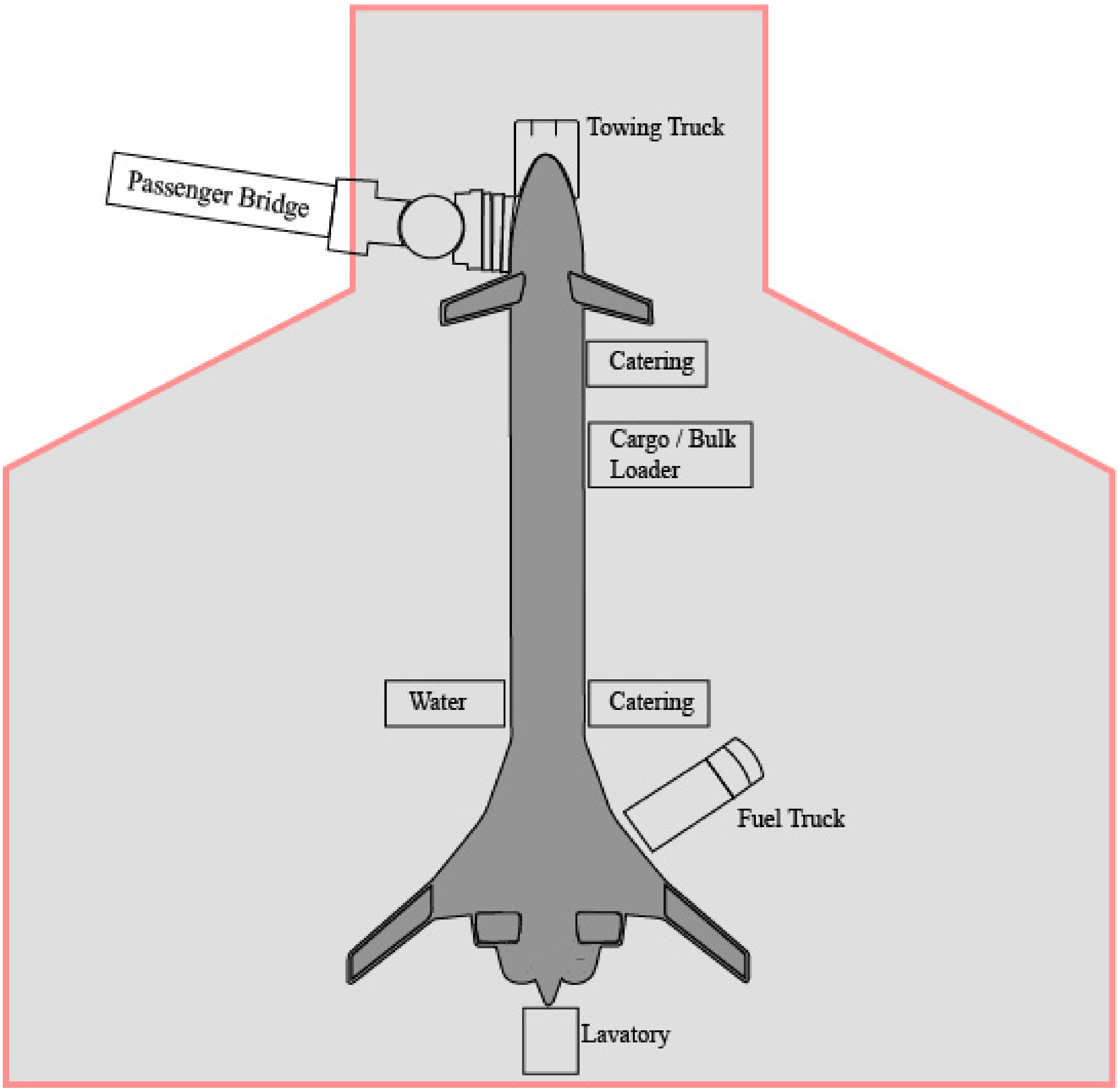

Figure 30: Service vehicles and their position around the aircraft. The red line shows a safety line for the turnaround crew