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Feasibility study on the use of hydrogen as an alternative fuel for conventional passenger aircraft

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Abstract

Aviation is at a turning point. To meet the 1.5-degree climate target, technological innovation is essential. Although recent advancements have partially decoupled air traffic growth from fuel consumption, projected growth rates of 3 to 5 percent render current measures insufficient. Cost-efficient and sustainable solutions are required – hydrogen offers such potential. This paper investigates the suitability of hydrogen as an alternative to fossil fuels, focusing on its integration into conventional tube-and-wing aircraft during the conceptual design phase, with an anticipated entry-into-service around 2035. Liquid hydrogen is stored in non-integral aluminum tanks located in the rear fuselage. Hydrogen-capable engines are assumed, with no further propulsion system analysis. Three existing aircraft types are selected as references and redesigned using a modular design tool, alongside a baseline variant that reflects future state-of-the-art developments in mass and efficiency. The hydrogen-powered variants retain the external geometry of the reference aircraft to ensure high commonality and retrofit potential, with a fuselage extension allowed for tank accommodation. Design methods follow standard handbook approaches, augmented by dedicated modules for hydrogen integration, particularly for tank sizing and placement, using manufacturer data as benchmarks. Initial results show that hydrogen-powered aircraft have higher operating empty masses due to tank mass but require less fuel mass. Environmentally, hydrogen aircraft eliminate CO2 and reduce NOx emissions, though increased water vapor emissions warrant further examination. Operational flexibility is slightly reduced compared to conventional aircraft. These findings highlight the feasibility and limitations of integrating hydrogen into existing aircraft configurations, offering a promising step toward sustainable aviation.

Article Highlights

- This paper investigates the integration of liquid hydrogen propulsion in conventional tube-and-wing aircraft for entry into service around 2035.
- Design results show increased empty weight due to hydrogen tanks but reduced overall fuel mass and zero CO2 emissions.
- The study highlights both the feasibility and operational limitations of hydrogen-powered aircraft as a step toward sustainable aviation.

Keywords

Overall aircraft design, hydrogen fueled aircraft, conceptual liquid hydrogen tank design, sustainable aviation

Acronyms

A320neo	Airbus A320neo
ACAP	Aircraft characteristics airport and maintenance planning
Al-2219	Aluminum 2219
APM	Airport planning manual
APU	Auxiliary power unit
CAD	Computer aided design
CRJ1000	Bombardier CRJ1000
CO2	Carbon dioxide
Dash-8	Bombardier Dash-8 Q400
EIS	Entry-into-service
EU	European Union
H_2	Hydrogen
LH2	Liquid hydrogen
MFFF	Modified fuel fraction factor
NOx	Nitrogen oxides
PAX	Passengers
PRD	Payload range diagram
PU	Polyurethane
RFFF	Roskam fuel fraction factor
SAF	Sustainable aviation fuel
TLAR	Top level aircraft requirement
TRL	Technology readiness level
UNICADO	UNIversity Conceptual Aircraft Design and Optimization

1 Motivation

In December 2015, the international community pledged to limit global warming to well below 2°C, ideally 1.5°C, above pre-industrial levels. This objective, established in the Paris Agreement, emphasizes the paramount importance of addressing climate change as both a scientific imperative and an ethical obligation. ([1], [2])

Human activity, particularly the emission of greenhouse gases such as carbon dioxide (CO2), is the primary driver of global warming ([3], [4], [5]). Even a 1.07°C rise in global temperature since the pre-industrial era has already resulted in irreversible damage, with far-reaching consequences that affect natural systems, human health, and global stability [6]. To mitigate the most severe consequences, global CO2 emissions must reach net zero by 2050 [2]. This necessitates a fundamental transformation across all sectors, including aviation.

In 2022, aviation contributed nearly 14 percent of transport-related CO2 emissions in the European Union (EU). Although fuel consumption per passenger has decreased by more than half over the past three decades, overall emissions continue to rise due to increasing global demand for air travel. Even with optimistic assumptions about annual efficiency improvements of 2 percent, aviation-related emissions are projected to double by mid-century. Incremental gains will not be sufficient. The path forward necessitates a paradigm shift. ([7], [8], [9], [10])

Short- and medium-haul flights, covering distances between 500 km and 4 500 km, account for about two-thirds of aviation's CO2 emissions and 71 percent of the global fleet, making this segment a prime target for decarbonization (see ***Fig. 1***). Single-aisle aircraft dominate this segment and will account for a significant proportion of future aircraft deliveries. Fleet modernization is accelerating as older, less efficient aircraft are retired. Over 85 percent of the current fleet is expected to be replaced by 2040, with more than 75 percent consisting of new-generation aircraft like the A320neo or the Boeing 737max. Consequently, this segment offers the greatest potential for transformative change. ([8], [9], [10])

From idea to certification, it takes an average of 15 to 20 years. Another ten years will pass before this aircraft type is widely represented in the global fleet. With the introduction of the Airbus A320neo in 2015, the last generation of new short- and medium-haul aircraft was launched. Consequently, there is an opportunity for the introduction of a new, low-carbon aircraft around 2035. In order not to miss the EU's ambitious targets, the launch of a revolutionary aircraft is essential by this time at the latest. [8]

Among the most promising solutions for the decarbonization of aviation is the development of hydrogen-powered aircraft. Hydrogen propulsion, particularly when combined with green hydrogen production methods, can enable nearly emission-free flight. This approach represents a technological leap that addresses both environmental and energy challenges. Despite considerable hurdles, such as fuel storage, infrastructure development, and regulatory adaptation, the pursuit of hydrogen aviation is not merely a technological ambition but a climate imperative. Innovation in this domain requires interdisciplinary collaboration, systems thinking, and a long-term commitment to sustainability. The introduction of a hydrogen-powered aircraft by 2035 is both a formidable challenge and a critical opportunity to redefine the future of aviation. ([8], [11])

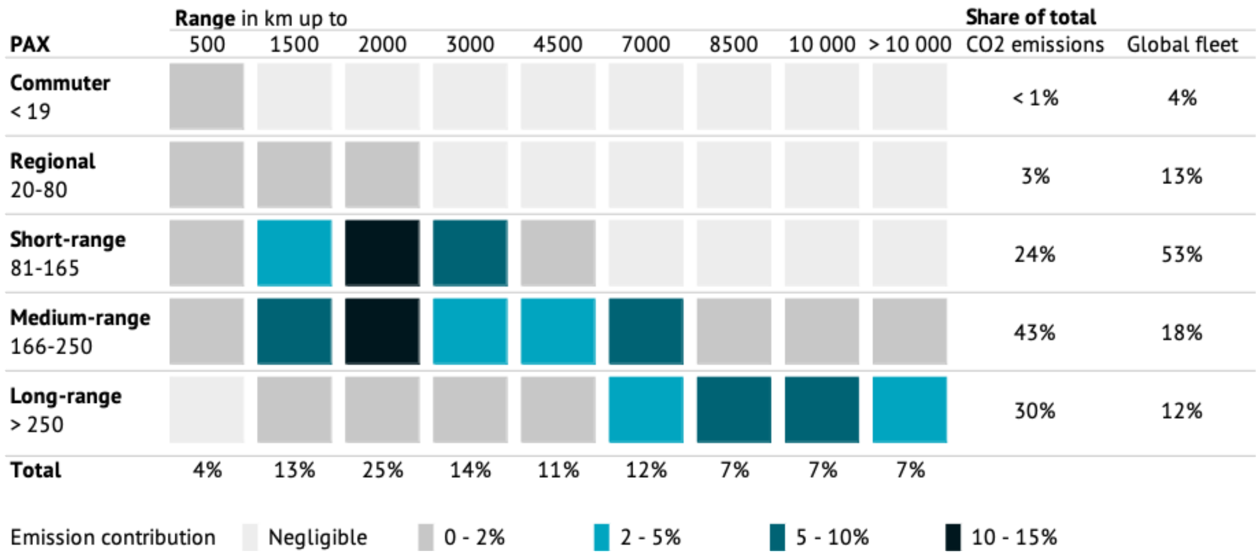

Fig. 1: CO2 emissions per segment and range 2018 (own illustration according to [8])

For this reason, this paper assesses the feasibility of using hydrogen as a substitute for conventional fossil fuels in commercial aviation.

To provide the necessary theoretical foundation, in Chapter 2 the paper highlights both the opportunities and limitations associated with the use of hydrogen in aviation. Furthermore, important design decisions are made on a well-founded basis. Building on this, Chapter 3 describes the overall design methodology. It explains the selection of reference and baseline aircraft and outlines the specific adjustments required for hydrogen integration, including the tank sizing approach and associated design constraints. The results section presents the outcomes of the conceptual aircraft design, compares different configurations, and discusses emerging trends and trade-offs. Finally, the paper concludes with a summary of the key findings and offers an outlook on future research directions.

2 Hydrogen Potential

This chapter outlines the role of hydrogen in aviation decarbonization and examines the technical requirements and design considerations for integrating liquid hydrogen storage into aircraft systems.

2.1 Role of Hydrogen in Aviation Decarbonization

Hydrogen is widely considered a key enabler for achieving net-zero emissions in aviation. When produced from renewable sources, it enables nearly emission-free flight, emitting no CO2 during combustion. [12] However, the implementation of hydrogen in aviation presents considerable challenges, particularly due to its physical properties and system-level implications.

While hydrogen offers an excellent gravimetric energy density of around 120 MJ/kg (almost three times that of Jet A-1) its volumetric energy density is significantly lower. In gaseous form, it provides only about 10 MJ/m³, and even as cryogenic liquid hydrogen, it reaches just 8.5 GJ/m³, compared to 34 GJ/m³ for kerosene. This means that, to store an equivalent amount of energy, significantly larger tank volumes are required. ([13], [14])

Although storage as liquid hydrogen is more suitable than high-pressure gas due to its higher energy content per volume, it necessitates large, heavily insulated tanks that cannot be accommodated in the wings like conventional kerosene tanks. Instead, these tanks must be integrated into or above the fuselage, which affects aircraft geometry, aerodynamic performance, and payload distribution. [15] Furthermore, storing hydrogen at -253 °C introduces significant complexity in terms of materials, insulation, and safety [16]. Tank materials must be resistant to embrittlement and hydrogen diffusion, and the overall system must minimize risks such as leakage or ignition ([16], [17]). Although liquid hydrogen offers nearly three times the mass-specific energy content of Jet A-1, this advantage can only be realized if the tank system is optimized for weight, insulation performance, and aerodynamic integration ([14], [16]). These interdependent design factors affect not only aircraft performance but also operational flexibility and the path to certification. Additionally, supporting infrastructure and regulatory frameworks for large-scale hydrogen use in aviation are still under development.

2.2 Tank Concepts and Selected Configuration

High-pressure gaseous hydrogen storage is not viable for aviation due to excessive mass, volume requirements, and safety risks. Liquid hydrogen storage in cryogenic pressure vessels, currently at a technology readiness level (TRL) of 6 ([18], [19]), is the more promising solution. A review of current studies indicates that placing tanks fore or aft of the passenger cabin is preferable to configurations above or outside the fuselage, due to aerodynamic and structural considerations ([20], [21]).

Non-integral tanks, mounted within the fuselage structure, offer practical advantages. Unlike integral tanks, which must be tailored to specific airframe designs and structural load paths, non-integral tanks only need to withstand internal pressure and thermal loads. Cylindrical or conical tanks with torispherical domes efficiently utilize available space in the aft fuselage or tail section. [16]

Designing liquid hydrogen tanks involves a careful balance between mechanical strength and thermal insulation. Effective insulation is essential to minimize heat ingress and reduce hydrogen boil-off. Internal tank placement allows operation at ambient temperatures and simplifies access, but it exposes the insulation to direct hydrogen contact, increasing the risk of embrittlement and thermal degradation. To mitigate this, insulation is applied externally. Polyurethane (PU) foam, with a typical thickness of 20 cm, has proven to be a suitable material, keeping boil-off losses within acceptable limits. ([16], [22])

As a result, the tank wall material must be both resistant to hydrogen embrittlement and as impermeable to hydrogen as possible. Aluminum 2219 (Al-2219) offers favorable properties in this context [23]. Wall thickness calculations are based on a design stress of 172 MPa [16] and account for internal pressure fluctuations between a filling pressure of 1.2 bar and a venting pressure of 1.5 bar during operation. ([17], [24])

The propulsion system relies on hydrogen combustion in gas turbines. Although currently at TRL 4-5 [25], this technology is expected to reach TRL 6 in the near future, supported by ongoing research efforts. Its inclusion in concept studies from Airbus [26], DLR [27], and FlyZero [28] underlines its relevance and feasibility for an entry-into-service (EIS) around 2035.

The selected tank configuration is compatible with conventional tube-and-wing aircraft layouts, minimizes aerodynamic penalties, and allows for retrofit potential – an important factor in facilitating a practical transition to hydrogen-powered aviation.

3 Conceptual Aircraft Design

This chapter outlines the methodology used for the conceptual design of hydrogen-powered aircraft. Three existing aircraft configurations are selected as reference to calibrate and validate the design approach and to derive key requirements for the hydrogen concepts. For each, an optimized baseline variant is defined to improve comparability. Subsequently, the overall design philosophy is explained, followed by necessary modifications to the conventional design process to enable hydrogen integration. Particular attention is given to the implementation of a hydrogen tank sizing approach, which plays a central role in the feasibility of the overall aircraft concept.

3.1 Reference, Baseline, and Concept Aircraft

First, representative reference aircraft are selected to calibrate and validate the design method. Based on these, design targets for the hydrogen-powered concept aircraft are derived. A baseline variant is also introduced for each aircraft to enable consistent comparison.

3.1.1 Reference Aircraft

As indicated by the market analysis at the beginning, a possible design space covers the short- and medium-range segment (81 to 250 PAX) with ranges between 500 km and 4 500 km. To offer significant potential for improving the climate impact of aviation, possible reference aircraft should therefore be aligned to market needs. In addition to considering the market analysis, the reference aircraft are selected based on current research programs, three of which are briefly presented below.

- ZeroAvia targets hydrogen-electric aircraft, with initial 10 to 20 seat models by 2024 and larger 200-seat aircraft expected by 2035. A partnership with De Havilland Canada aims to offer retrofit and line-fit hydrogen engine solutions for the Bombardier Dash-8 Q400. [29]
- Airbus ZEROe explores hydrogen combustion using modified gas turbines. An Airbus A380 is being converted into a testbed, with a goal of introducing zero-emission aircraft by 2035. ([26], [30])
- EXACT study evaluates concepts from fuel-cell regional aircraft to 250-seat medium-range jets using hydrogen combustion. ([27], [31])

Three aircraft are selected considering the preceding, whose conversion appears feasible by 2035. Those reference aircraft cover various design ranges and configurations (wing location, engine placement, tail configuration) to facilitate extensive investigation.

Smaller aircraft with shorter operating ranges are often seen as the most likely initial entry point for hydrogen aircraft [32]. Therefore, the Bombardier Dash-8 Q400 (Dash-8) is selected as a representative reference aircraft. With its rear-mounted engines, the Bombardier CRJ1000 (CRJ1000) presents a configuration that is particularly interesting to study concerning the positioning of the tanks in the tail section. Finally, the Airbus A320neo (A320neo) is selected as a typical representative of a narrowbody configuration in the medium-range segment. ***Table 1*** lists the top level aircraft requirements (TLARs) of the chosen aircraft. The values are derived from the documents provided by the manufacturers ([33], [34], [35]).

The modeling of the reference aircraft serves as a starting point for concept study analysis and validation.

3.1.2 Baseline Aircraft

Alongside the reference aircraft, baseline derivatives are also developed. These are modified variants of the reference aircraft. Specifically, the technologies are adapted and improved in anticipation of EIS in 2035. Implementation of these adjustments is achieved through the introduction of technology factors. These are applied to the masses and represent the overall shift towards the increased use of lightweight materials. In this respect, the following technology assumptions are made [36]:

- Fuselage mass reduction of 5 percent due to new aluminum alloys and new manufacturing methods

- Wing mass reduction of 15 percent due to new materials
- Empennage mass reduction of 3 percent due to new assembly and manufacturing methods

Assumptions can also be made regarding engine efficiency. By 2045, performance is expected to improve (in the case of the geared turbofan engines of the A320neo) by 15 percent. This will be achieved mainly through improvements in the individual components, which will result in a higher bypass ratio on the one hand and an increased turbine entry temperature and overall pressure ratio on the other. The latter also entails a slight increase in mass due to the need for multiple compressor stages. [20]

Furthermore, it is assumed that the baseline aircraft will no longer operate solely on kerosene but will use a certain proportion of sustainable aviation fuel (SAF) to address the impact on the climate accordingly. The term SAF denotes fuel obtained from sustainable sources and thus promises to reduce carbon emissions by up to 80 percent [37].

Table 1: Top level aircraft requirements of the reference aircraft

PARAMETER	DASH-8	CRJ1000	A320NEO
NUMBER OF PAX	74	100	180
MASS PER PAX		80 kg	
BAGGAGE PER PAX	10 kg	10 kg	17 kg
CABIN LAYOUT		All-economy	
ADDITIONAL CARGO MASS	1 140 kg	2 880 kg	1 790 kg
DESIGN RANGE*	963 km	1 815 km	4 550 km
TAKE-OFF DISTANCE (ISA+15, MSL)	1 425 m	2 650 m	2 300 m
INITIAL CRUISE FLIGHT LEVEL	230	310	320
CRUISE MACH NUMBER	0.45	0.80	0.78
MAX. CRUISE MACH NUMBER	0.57	0.84	0.82
AIRCRAFT APPROACH CATEGORY		C	

* DERIVED FROM POINT B OF THE PAYLOAD RANGE DIAGRAM

3.1.3 Concept Aircraft

The concept aircraft are designed with the promise of minimal climatic impact through operation on liquid hydrogen. They are conventional tube-wing configurations powered by hydrogen-burning engines. The TLARs for the hydrogen-based concepts can be derived from the performance data of the reference aircraft (see ***Table 1***).

3.2 Design Philosophy

To understand the effects that are reflected in the results presented in the next chapter, a description of the design philosophy is crucial. Calculations for conventionally fueled aircraft are established in accordance with common aircraft design principles and recent literature to provide a valid basis for reference for evaluating the advantages and disadvantages of using hydrogen in aviation. The underlying overall aircraft design process is not described in detail. To ensure maximum comparability, the present design process is based on the following assumptions:

- Passenger cabin and cargo compartment capacity are kept constant.
- Assuming a constant tail volume coefficient, the tail moment arm increases proportionally with fuselage length. Consequently, the longitudinal position of the wing is indirectly defined by this geometric relationship. No detailed center of gravity analysis is performed, however.
- Further adjustments to the wing geometry are refrained from to ensure comparability with the reference.

3.2.1 Aircraft Design Algorithm

A modular aircraft design approach was adopted to allow for a more straightforward change when switching from kerosene to hydrogen.

The adoption of hydrogen as a fuel has consequences for the design of the aircraft. As part of this thesis, a standard tool is developed to assess the differences between both fuels on a fair basis to the highest possible extent. This approach ensures that the same models and assumptions are used for both fuels. It also prevents favoring one fuel over the other. The calculations used are standard handbook methods based on the works of Torenbeek [38], Roskam [39], and Nicolai [40].

The design process was carried out in MATLAB, as the existing tool provided a flexible foundation and the researcher was already familiar with its structure. Several algorithmic modules had to be adapted or newly developed to accommodate hydrogen-specific configurations. These were prototyped and validated within the MATLAB environment, allowing for rapid iteration and testing. The resulting algorithms were subsequently implemented within the UNICADO platform and integrated into the overall design framework. A general overview of the design algorithm implemented is given in ***Fig. 2***. An essential feature of the design process is its highly iterative nature, which ultimately leads to the best possible design that meets the given TLARs. Since the process is a conceptual design that is not preceded by any design phases, the associated uncertainties must be considered. These arise from the necessity to rely on data from statistical considerations or pertinent literature initially.

3.2.2 Modifications for hydrogen aircraft

Although the introduction of hydrogen requires significant changes to the conventional aircraft system architecture, the number of calculation modules that need to be adapted at aircraft level is relatively limited. These are described in the following.

Tank design

The main modification to the existing aircraft architecture is storing the fuel in highly insulated fuel tanks located inside the fuselage instead of in the wings. The design of the tanks is a crucial challenge to enable hydrogen flights for transport aircraft. The sizing is based on the detailed considerations in Chapter 2. This important topic will be discussed in more detail in the following section.

Fuel fraction modification

A refined method for calculating the fuel mass is based on the fuel fraction method according to Roskam [39]. The flight is subdivided into segments as in ***Fig. 3***. The fuel which is needed for the execution of the mission (mission fuel) is determined over the segments (1) to (7a). The reserve fuel contains the fuel mass for a possible subsequent flight to an alternate airport, a holding pattern, or potential incidents (contingency). During the flight, the only weight change occurs due to the burning of the fuel. Therefore, specific fuel fractions (Roskam fuel fraction factor (RFFF)) can be determined for each flight segment. These give the mass ratio between the end of the leg and the beginning of the same.

The product of all fuel fractions gives the ratio between the mass at the beginning of the flight and the end of the flight. This ratio can be used to determine the total fuel fraction required. The approach devised as part of the NASA/DLR Design Challenge [41] is used to determine the amount of hydrogen required for the mission. The method introduces adjusted fuel fraction factors (modified fuel fraction factor (MFFF)) for each segment j. These are based on the original factors to achieve an equivalent factor. The equations below compare the original RFFF with the modified MFFF:

$$\mathrm{RFFF}_{\mathrm{K},j} = \frac{m_{\mathrm{K,end},j}}{m_{\mathrm{K,start},j}}$$

$$\mathrm{MFFF}_{\mathrm{H2},j} = \frac{m_{\mathrm{H2,end},j}}{m_{\mathrm{H2,start},j}}$$

Using the ratio of the gravimetric energy densities of kerosene and hydrogen $f_{\mathrm{KtoH2}} = \frac{e_{\mathrm{K}}}{e_{\mathrm{H2}}}$, the MFFFs can be determined.

The following equations provide the calculation basis for the phases before and after takeoff:

$$\mathrm{MFFF}_{\mathrm{H2,a},j} = \left(f_{\mathrm{KtoH2}} \cdot \left(\frac{1}{\mathrm{RFFF}} - 1\right) + 1\right)^{-1}$$

$$\mathrm{MFFF}_{\mathrm{H2,b},j} = 1 - f_{\mathrm{KtoH2}} \cdot (1 - \mathrm{RFFF})$$

According to the Breguet range equation, the fuel fraction factors for cruise flight are determined using the range formula. This can be written as a fuel fraction:

$$\frac{m_{\mathrm{end}}}{m_{\mathrm{start}}} = e^{-\frac{\mathrm{SFC}\cdot\varepsilon\cdot g}{v}}$$

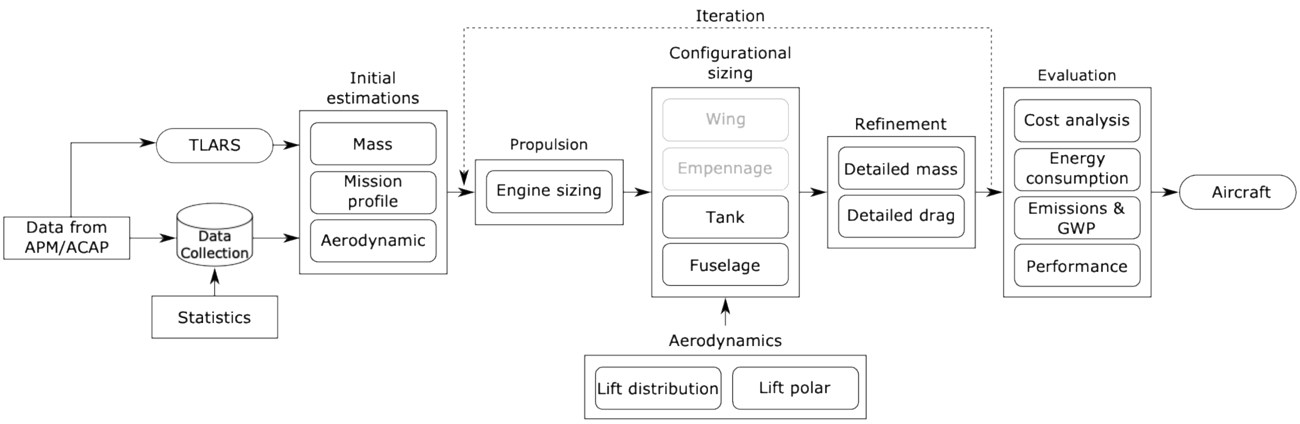

Fig. 2: MATLAB aircraft design algorithm

The only parameter dependent on the fuel used is the specific fuel consumption. Using the factor f_{KtoH2} again, these values can be determined based on the specific fuel consumption of the reference aircraft:

$$\mathrm{SFC_{H2}} = \mathrm{SFC_K} \cdot f_{\mathrm{KtoH2}}$$

3.3 Hydrogen Aircraft Tank Sizing

An essential point in developing an aircraft tailored to accommodate hydrogen is the determination of the tank geometry without an existing 3D model. The process developed is explained below.

3.3.1 Initial Fuel Mass and Volume

An initial estimate of the required fuel mass assumes that the same amount of energy is needed to perform the flight as for the reference aircraft. The amount of energy in a kilogram of fuel is given by the gravimetric energy density (specific energy) e.

Consequently, the following applies:

$$m_{\mathrm{K}} \cdot e_{\mathrm{K}} = E_{\mathrm{K}} \overset{!}{=} E_{\mathrm{H2}} = m_{\mathrm{H2}} \cdot e_{\mathrm{H2}}$$

The corresponding volume of the required amount LH2 can be determined by the energy density $\rho_{\mathrm{E,LH2}}$:

$$V_{\mathrm{LH2}} = \frac{E_{\mathrm{LH2}}}{\rho_{\mathrm{E,LH2}}}$$

Volume allowances $f_{\mathrm{allowance}}$ of 7.2 percent shall also be provided [16]. These consider, among other things, the contraction of the tank when refueled with the cryogenic liquid hydrogen and non-usable fuel. In addition, volume losses due to installed sloshing baffles are considered. Consequently, the required tank volume results in:

$$V_{\mathrm{LH2,req}} = V_{\mathrm{LH2}} \cdot \left(1 + \frac{f_{\mathrm{allowance}}}{100}\right)$$

3.3.2 Tank Sizing Methodology

The detailed tank geometry can subsequently be determined based on the required volume. Since no CAD model is available, considering the rear section in two separate planes is purposeful and sufficiently accurate. In this way, geometric compatibility can be ensured. The side view and the top view from the Aircraft Characteristics Airport and Maintenance Planning (ACAP) [35] and the Airport Planning Manual (APM) ([33], [34]) serve as the basis. Using the A320neo as an example, the following subsection discusses the tank design procedure.

Initially, the complex tail geometry is simplified. This avoids complex geometry computation. The data is based on dimensions from the ACAP [35]. To simplify the calculations, the bottom of the tail was linearized, and a constant tail clearance angle was assumed along the complete length. The top of the tail cone is considered to be straight. In the explicit case of the A320neo, the installation space to the rear end of the aircraft is limited by the attachment of the tailplane. A corresponding installation space is provided for this purpose, which cannot be used to place the tank. In the example of the Dash-8, the installation space is limited by the APU.

The aim is to achieve a tank in the form of a truncated cone with circular end faces in the aircraft's tail section. A circular cross-section is chosen because it provides the most efficient geometry for withstanding internal pressure loads, minimizing stress concentrations and reducing material usage [42]. This truncated cone then continues as a cylinder in the constant fuselage section, depending on the required volume. The tank is sealed off with dished ends. According to Brewer [16], these represent the more favorable solution in terms of cost compared to hemispherical closures. The tail cone

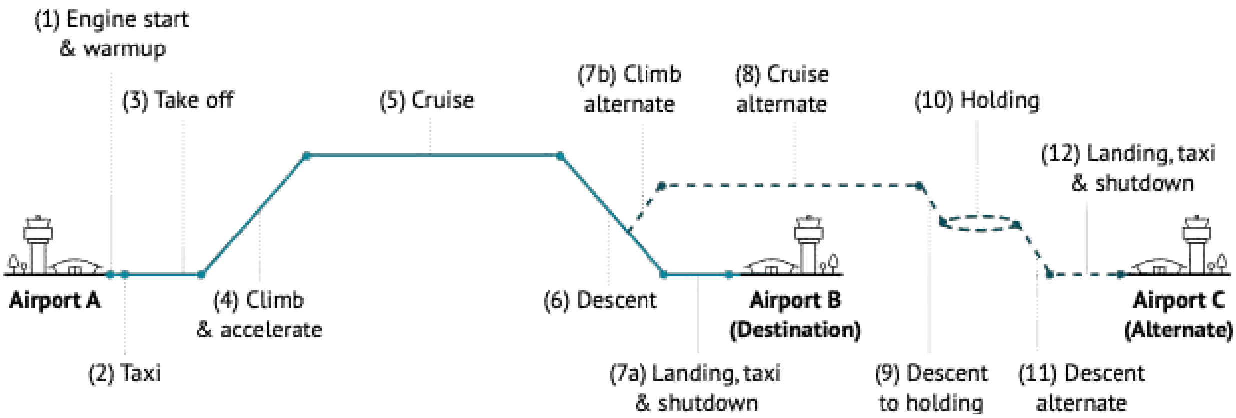

Fig. 3: Mission profile (based on [37], [39], [40])

should not be changed geometrically to the reference aircraft to ensure the maximum possible conformity.

The subsequent procedure is summarized in the following steps:

1. Determination of the rearmost position: Basically, the identification of the tank geometry starts at the possible rearmost position in the longitudinal direction of the aircraft. This can be defined either by the presence of an APU or the position of the horizontal stabilizer.
2. Determination of restrictive parameters regarding the installation space: The side view and the top view are used to identify which geometry or diameter is more restrictive at the rearmost end. The restrictive parameter is the smaller diameter. If the larger diameter is selected, the tank will no longer conform to the geometry in one of the two planes considered, i.e., it will be too large for the available installation space. Clearances for the fuselage structure are already considered in this step. The limiting factor here is primarily the profile height of the frames. The ring frames have an average profile height of 90 mm to 150 mm [43]. Subsequently, the tail angle and the angle of the cross-sectional narrowing from the top view are compared. The smaller angle serves as the basis for defining the outer tank geometry.
3. Starting from the end face with the diameter selected in Step 2, a truncated cone can be fitted in the nose direction of the aircraft. The angle between the surface line and the axis of the cone is set by the angle specified in the previous step.

The determination of the tank geometry is an iterative process. The iteration of the tank geometry calculation converges once the existing tank volume equals the required tank volume. For this purpose, the length of the tank is increased step by step. Consequently, the diameter changes as well.

Particular attention must be paid to the fact that the fuselage cross-section is usually elliptical instead of circular. Furthermore, it may change depending on the position in the longitudinal direction of the aircraft. In ***Fig. 4*** the maximum possible tank diameters of the A320neo, depending on the projection, are shown as an example. It should be noted that

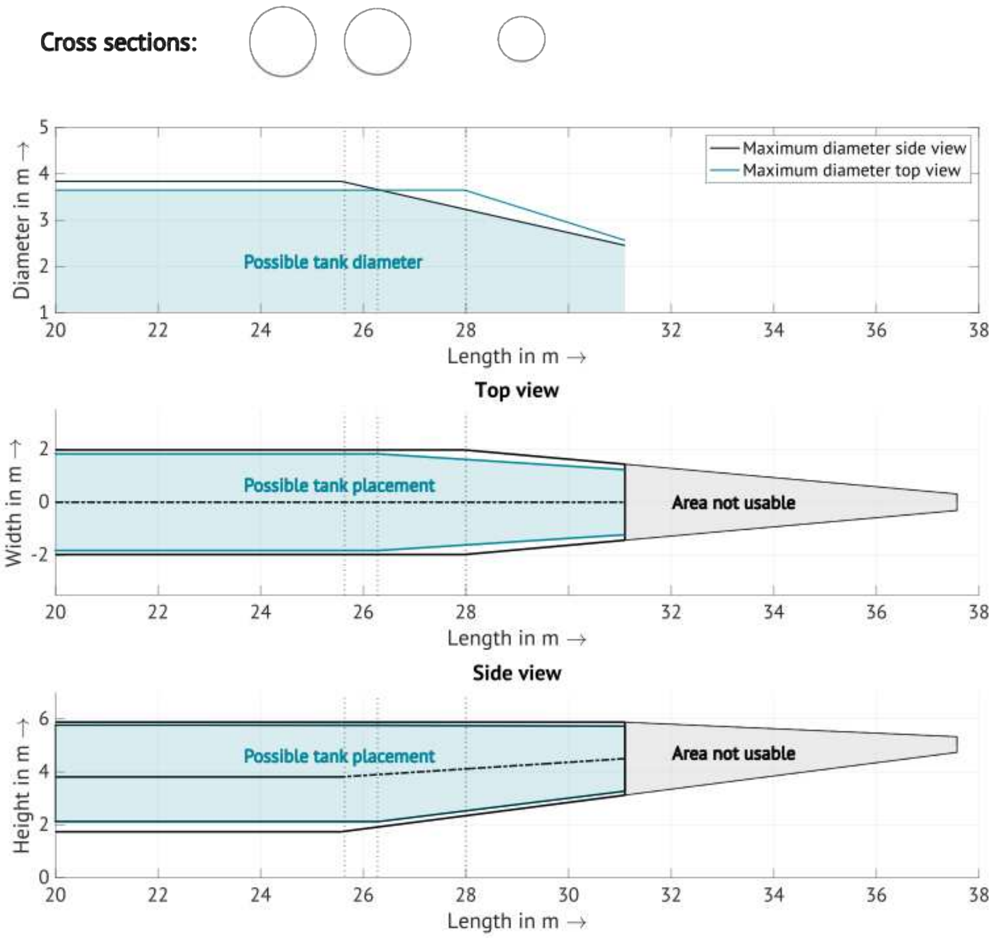

Fig. 4: Maximum side and top view tail section diameters of the A320neo

the ends of the graphs do not indicate the end of the aircraft but the aftmost position at which a tank can be placed.

At the rearmost end, the tail has a flattened shape, i.e., it is marginally wider than it is tall. Consequently, the maximum possible diameter results from the side view, i.e., the height of the fuselage. With increasing distance from the tail, the geometry of the fuselage changes. At about 26.28 m, the fuselage has a circular shape before the height becomes larger than the width of the fuselage.

The intersection of the two diameter curves is decisive for obtaining the tank geometry. The tank diameter must always be within the envelope (marked in color). Consequently, from the point of intersection, it is no longer the height but the width of the fuselage that is limiting. From this point on, the diameter can no longer be increased without violating the geometry. This point, therefore, marks the transition from the truncated cone to the cylinder. This continues in length until the required tank volume is finally reached, and the algorithm converges. The goal of this methodology is to optimize the use of space. Therefore, the diameter is chosen to always correspond to the maximum possible diameter. Since the lateral constriction and the tail clearance angle are not forced to start at the same position in the longitudinal direction of the aircraft, this leads to the fact that the available space in the tail cone cannot be fully utilized with this approach. However, this is initially neglected since this is a preliminary design level estimate.

It should be noted that the fuselage length increases as a function of the required tank length. For safety reasons, each engine of an aircraft must always be fed from a separate tank for take-off. For this reason, the tank is divided lengthwise by inserting a plate. It is assumed that both tank sections are subject to the same internal pressure.

3.4 Evaluation Parameters

To enable a comprehensive assessment of the hydrogen-powered aircraft concepts, a set of evaluation parameters is defined. These parameters cover mass characteristics, performance parameters, ecological impact, and economic feasibility. This section outlines the methods and assumptions used to calculate these values during the conceptual design process. All calculations refer to direct flight operations and exclude manufacturing or infrastructure-related emissions and costs.

3.4.1 Aircraft Masses

Accurate mass estimation is critical in early aircraft design. The design algorithm iteratively calculates key mass properties based on statistical and handbook methods.

In hydrogen configurations, the mass of the cryogenic tank system is included in the operating empty mass. To assess tank efficiency, the gravimetric efficiency is calculated as

$$\eta_{\text{grav,tank}} = \frac{m_{\text{fuel}}}{m_{\text{fuel}} + m_{\text{tank}}}$$

where m_{fuel} is the usable hydrogen mass and m_{tank} includes structural components, insulation, and auxiliary elements.

It is assumed that the tank is located in the unpressurized aft fuselage, which generally allows for a lighter structural design. However, this distinction between pressurized and unpressurized sections is not explicitly represented in the current tool and is therefore not reflected in the structural mass calculation.

The integration of the cryogenic tank system increases both mass and volume, potentially affecting other components. For instance, a higher maximum landing mass may necessitate landing gear reinforcement, triggering a snowball effect in the overall mass breakdown. While such interdependencies are captured through iterative mass estimation, detailed subsystem-level adjustments remain outside the scope of this study.

3.4.2 Sustainability

To assess sustainability, the analysis considers energy consumption, emissions, and resulting climate impact.

Energy demand

The energy demand is based on fuel consumption across the defined mission profile that is depicted in ***Fig. 3***. The total mission energy is calculated as

$$E_{\text{total}} = m_{\text{fuel}} \cdot e_{\text{fuel}}$$

whereas the energy consumption per passenger can be calculated as

$$E_{\text{PAX}} = \frac{m_{\text{fuel}}}{n_{\text{PAX}}} \cdot e_{\text{fuel}}$$

where e_{fuel} is the fuel's lower heating value and n_{PAX} the number of passengers.

Emissions

Emissions are calculated per flight segment based on fuel type and altitude. For kerosene, CO2 emissions are assumed at 3.15 kg per kg fuel [44]. Hydrogen combustion produces no CO2 but emits water vapor and nitrogen oxides (NOx), the latter at a reduced rate due to lower flame temperatures [45].

Climate impact

To quantify and compare the climate effects of aircraft emissions, this study uses the concept of CO2 equivalents, based on the global warming potential (GWP) framework. GWP expresses the relative warming effect of a greenhouse gas compared to CO2 over a specified time horizon. A 100-year time frame under summer conditions at mid-latitudes (30°–60° N) is assumed, in accordance with common aviation climate models. [44]

The GWP of a specific emission i is defined as

$$\mathrm{GWP}_i(T) = \frac{E_i(T)}{E_{\mathrm{CO2}}(T)}.$$

Here, $E_i(T)$ and $E_{\mathrm{CO2}}(T)$ refer to the time-integrated radiative forcing of the emission i and CO2, respectively, over time horizon T. CO2 has a defined GWP of 1 by default. [44]

To estimate the total climate impact of a flight mission, the GWP contributions from CO2, water vapor, and NOx are calculated for each of the 12 mission segments and summed:

$$\mathrm{GWP} = \sum_{i=1}^{3}\sum_{j=1}^{12} m_{ij} \cdot E_i(h)$$

Where $m_{ij}$is the mass of emission i in segment j and $E_i(h)$ is the GWP factor of emission i at the average altitude h. The GWP factors used for conversion are taken from [44].

This segment-wise approach allows altitude-dependent climate effects to be considered in a simplified yet meaningful way for preliminary aircraft design. Indirect effects such as contrail and cirrus cloud formation are not included due to their high dependence on atmospheric conditions and their complex modeling requirements. However, studies suggest that contrail formation may be mitigated through operational measures such as slight adjustments in cruise altitude or flight path, which can avoid ice-supersaturated regions [46].

3.4.3 Payload Range Diagram

Key performance outputs include the payload range diagram (PRD), which maps operational flexibility. The PRD is generated by varying payload and fuel load combinations, showing maximum achievable range under given payload constraints. This enables a direct comparison of operational capabilities between reference, baseline, and hydrogen concepts.

3.4.4 Direct Operating Cost

To assess cost competitiveness, direct operating costs (DOC) are calculated based on a simplified model from Thorbeck [47]. DOCs include fuel, maintenance, and operational costs. Fuel prices are assumed at €0.70 per kg (US-$3.73 per gallon) for Jet A and €1.40 per kg [48] for liquid hydrogen, based on conservative projections. Capital costs are excluded.

4 Results and Discussion

Initially, the reference aircraft were redesigned using the MATLAB design algorithm depicted in ***Fig. 2***. To consider the integration of hydrogen, essential functionalities were added to this algorithm. Subsequently, valid designs could be determined for all three selected aircraft. The take-off mass, the operating empty mass, and the fuel mass were used as iteration parameters. The convergence threshold is $1 \cdot 10^{-4}$. The results presented below represent the valid designs. All designs will be compared with the respective reference configurations concerning the determined evaluation parameters and critically evaluated.

4.1 Tank Sizing and Fuselage Stretch

The determination of the required fuel mass and the volume of fuel needed, in combination with the determination of the available installation space, form the basis for the design of the cryogenic tanks. ***Table 2*** provides an overview of the final tank data for all three aircraft concept designs.

The required tank volumes were achieved for all variants, and thus, sufficient fuel can be carried for the design mission.

A conservative insulation thickness of 20 cm was selected for all configurations [16]. The wall thickness is uniformly set at the minimum thickness of 3 mm required by AD 2000 [49]. A breakdown of the tank mass provides information on the pure structural and the insulation mass. Based on this, a gravimetric efficiency was determined for all tanks. Due to its larger fuselage diameter and more suitable tank integration geometry, the Airbus A320neo configuration shows superior gravimetric efficiency compared to the smaller aircraft concepts.

Considering the minimum and maximum possible tank diameters (derived from the geometry), the required tank length to fulfill the volume criterion was determined. As the tank volume increases, the length of the tank needed increases. Since there is insufficient installation space in the rear of the reference aircraft in any configuration, extending the fuselage is necessary.

Table 2: Tank parameter overview of concept aircraft

PARAMETER	DASH-8	CRJ1000	A320NEO
FUEL MASS	934 kg	1 870 kg	5 128 kg
STORAGE VOLUME REQ.	14.1 m^3	28.3 m^3	77.6 m^3
STORAGE VOLUME AVAIL.	14.2 m^3	28.3 m^3	77.8 m^3
LENGTH OVERALL	7.7 m	9.3 m	10.4 m
MIN. DIAMETER	0.34 m	1.95 m	2.46 m
MAX. DIAMETER	2.39 m	2.00 m	3.65 m
STRUCTURE MASS	626 kg	1 021 kg	1 741 kg
INSULATION MASS	241 kg	400 kg	714 kg
TANK TOTAL MASS	867 kg	1 421 kg	2 455 kg
GRAVIMETRIC EFFICIENCY	0.52	0.57	0.68
FUSELAGE STRETCH	3.81 m	8.41 m	7.26 m

Fig. 5 shows the change in fuselage length of the A320neo. The dashed gray line represents the reference aircraft, and the black line depicts the concept aircraft. It should be noted that the external aircraft geometry and essential elements (such as the empennages or engines) are digitized curves based on figures from the ACAPs and APMs, respectively. Therefore, they are primarily for illustrative purposes. Creating a detailed 3D model for further refinement must follow in a subsequent design phase.

The length of the A320neo has increased from 37.57 m to 44.83 m. It is thus roughly equal to the length of the longer aircraft version, the Airbus A321. The same can be noted for the Dash-8 and CRJ1000, respectively. The overall length of the Dash-8 has increased from 32.83 m to 36.64 m, whereas the length of the CRJ1000 aircraft is 47.54 m in the concept aircraft instead of 39.13 m in the reference configuration. A striking feature of this configuration is the engine located at the tail. Due to the configuration, only a small portion of the tail compartment is available for tank placement. Due to the small fuselage diameter of 2.695 m, the fuselage aspect ratio is much larger than in the case of the Airbus A320neo compared to the required tank volume.

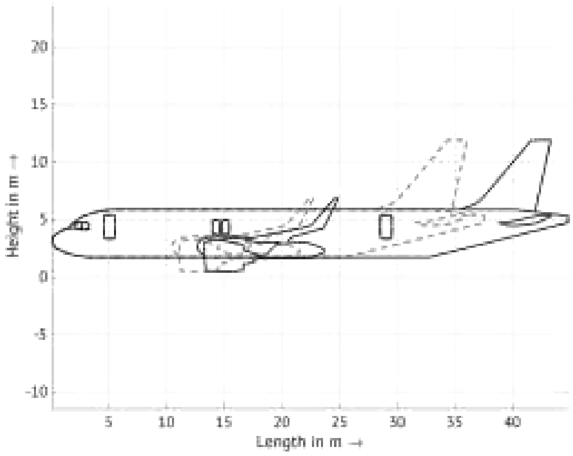

Fig. 5: Airbus A320neo side view

From an aircraft systems perspective, the CRJ1000 with the engines at the rear fuselage offers the advantage of short paths from the tank to the engines. As required in the Dash-8 or A320neo concepts, long and heavily insulated lines can be avoided. That said, space might need to be allocated for auxiliary systems such as vaporizers to convert liquid hydrogen into gaseous form before entering the turbine engines. Additionally, the tank placement between the engines must be considered critically. In a blade-off, the tank structure must be adequately protected to prevent damage. For both the Airbus A320neo and the CRJ1000, critical consideration must be given to whether it will be necessary to reposition the overwing exits in the course of the extension. However, the cabin design is not part of the present work.

In the kerosene-powered reference configurations, the center of gravity migration in flight is relatively small due to the integral tanks in the wings. Even if only about one-third of the fuel mass is required for the hydrogen concepts, the heavy tank structure introduces a relevant mass far from the center of gravity. Consequently, in the course of fuselage stretching, a detailed consideration of the center of gravity must follow in any case.

The great length also influences the fuselage mass, the aerodynamics, and the rotation process during takeoff. To guarantee the latter, a redesign or realignment of the main landing gear must occur. The ratio of fuselage diameter to fuselage length changes from 0.082 to 0.073 for the Dash-8, while the CRJ1000 sees a reduction from 0.068 to 0.056. For the A320neo, the value decreases from 0.108 to 0.090.

4.2 Aircraft Masses

In the following section, the results of the mass determinations are presented. The mass changes influence all subsequent parameters and are therefore particularly important. Since comparable correlations can be seen in all aircraft, the change in aircraft mass is explained and discussed using the Airbus A320neo as an example. Any deviations that may occur are specifically addressed. ***Fig. 6*** compares the percentage mass breakdowns of the reference, baseline, and concept aircraft. The absolute mass values can be taken from ***Table 3***.

The baseline variant shows an average 4 percent total mass saving in the operating empty mass due to the technology factors introduced. This applies to all aircraft. In addition, due to the improved engine efficiency, and because of the lower operating empty mass, the required fuel mass decreases. In percentage terms, there are only minor deviations from the reference.

When comparing the reference with the concept aircraft, significant differences become apparent. Due to the heavy cryogenic tanks, the operating empty mass increases in absolute and percentage terms. In the example of the Airbus A320neo, an increase of 8 percent occurs compared to the reference aircraft, and an increase of 13 percent compared to the baseline variant. The A320neo is thus positioned between the Dash-8 and the CRJ1000. In the case of the latter, the poor gravimetric efficiency already discussed is particularly noticeable, leading to an increase in operating empty mass of 14 percent over the reference and 19 percent over the baseline aircraft. This mass increase is such that the CRJ1000 has a minimally larger take-off mass than the baseline variant. This is offset by the approximately 33 percent lower fuel mass for all aircraft due to the high gravimetric energy density of hydrogen.

Table 3: Masses of Airbus A320neo variants

MASS	REFERENCE	BASELINE	CONCEPT
BASIC EMPTY MASS	39 894 kg	38 092 kg	43 549 kg
OPERATIONAL EMPTY MASS	43 931 kg	42 129 kg	47 586 kg
PAYLOAD	19 250 kg	19 250 kg	19 250 kg
ZERO FUEL MASS	63 181 kg	61 379 kg	66 836 kg
FUEL MASS	16 219 kg	15 729 kg	5 128 kg
MAXIMUM TAKE-OFF MASS	79 399 kg	77 107 kg	71 964 kg

4.3 Sustainability

The sustainability of an aircraft is assessed based on the energy consumption, the emissions emitted, and the associated global warming potential (GWP).

All these values are determined as a function of the fuel mass consumed per segment.

The fuel consumption from the third segment, the take-off (TO), is considered in the present work. This is followed by the phases of typical mission climb (CLB), cruise (CR), and descent (DES). To

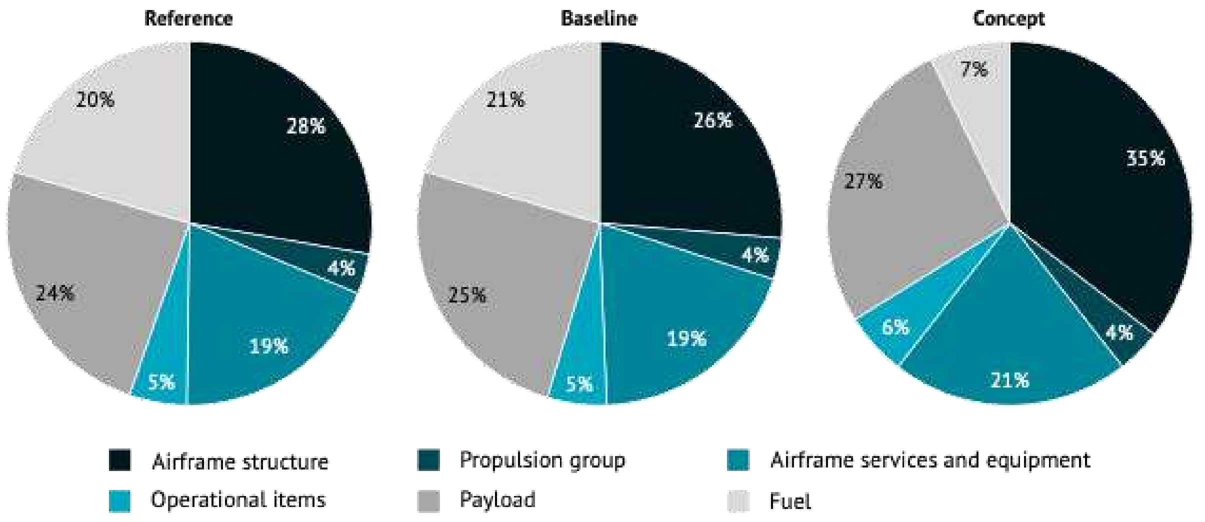

Fig. 6: Mass breakdown comparison of Airbus A320neo

cover the worst case, the following segments climb (CL ALT), cruise (CR ALT), and descent alternate (DEC ALT), as well as a holding (HLD), is considered. Finally, the landing and taxiing to the gate are included (LD, TI). For the descent segments DES and DES ALT, it was assumed that no fuel consumption takes place. This is reflected in consideration of all subsequent sustainability parameters.

To ensure comparability with the masses presented in the previous subsection, the values of the Airbus A320neo variants are used again at this point. All phenomena already described in the previous chapters about mass relations can be transferred to this chapter, as it were.

4.3.1 Energy demand

Multiplication of the fuel mass by the gravimetric energy density of the fuel yields the energy requirement. This provides comparability between the variants.

In ***Fig. 7***, the energy consumption per variant is shown as a bar chart depending on the flight phases. Here it can be seen that no energy is consumed during descent. This stems from the assumption that no fuel is consumed during descent flights. Most emissions, regardless of aircraft or variant, are emitted during cruise flight, as this is the longest segment of the flight.

The reference aircraft consumes the most energy in a direct comparison.

Compared with the baseline, the conceptual design has a higher energy requirement. On the one hand, this is due to the high calorific value of hydrogen. On the other hand, the concept aircraft has higher drag and a higher gross mass. The last is since this variant has a higher operating empty mass and a lower mass loss during flight. This statement is true for all aircraft. The observation of the CRJ1000 shows a deviating behavior in cruise flight. The reference aircraft exhibits the lowest energy consumption. One possible reason for this is the reduced aerodynamic parameters.

4.3.2 Emissions and global warming potential

Knowing the greenhouse gas emissions per kilogram of fuel, the emissions per flight segment were determined. The bar chart in ***Fig. 8*** illustrates the advantage of hydrogen in terms of carbon emissions – these are eliminated entirely. In contrast, however, the concept plane has higher water emissions. Although the concept aircraft also emits NOx emissions, these are significantly reduced compared to the reference and baseline aircraft. There is a negative GWP during the take-off and climb phases.

Table 4 finally summarizes all sustainability parameters of the A320neo. For all aircraft considered, the energy consumption and also the energy consumption per passengers of the reference configuration is the highest while the energy consumption of the concept aircraft is the lowest. However, as the mass of the concept aircraft increases, this percentage savings decreases. The Dash-8 concept airplane shows a 31 percent reduction in energy consumption compared to the reference. While the CRJ1000 still saves 22 percent, the A320neo only shows an energy saving of 12 percent.

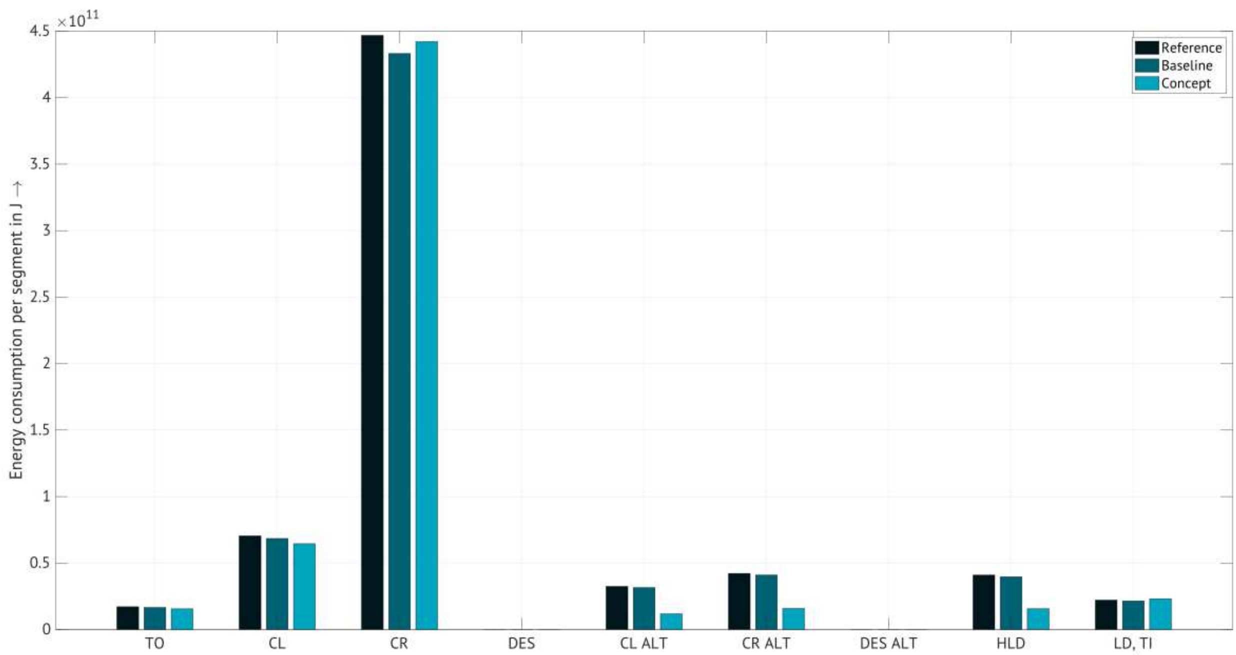

Fig. 7: Energy consumption per segment of A320neo

CO_2 is only emitted by the reference and baseline aircraft. Due to the dependence of the emission output on the fuel consumed, the reference variant dominates here as well for all aircraft.

All aircraft derivatives considered discharge water, with the concept aircraft's emissions being approximately twice as significant as those of the reference. The GWP of water emissions is striking at this point. According to the calculation approach used, water emissions are only impacting the greenhouse when introduced at altitudes greater than 10 000 m [44]. As altitude increases, so does climate effectiveness. At altitudes below 10 000 m, the GWP per kilogram of water emitted is given as 0. However, due to the complex nature of related effects, such as cirrus clouds or contrail formation, this result is critical and should be investigated in more detail in further work.

The available data illustrate that, regarding emissions, absolute data in physical quantities are only meaningful to a limited extent. The example of NOx emissions illustrates this. Due to hydrogen's physical and chemical properties, it is possible to reduce nitrogen oxide emissions compared with the reference and baseline aircraft. Despite the comparatively low NOx mass, the associated GWP is very high. The global warming potential of nitrogen oxide emissions shows a strong dependence on the altitude at which they are introduced. Up to 4000 m, the GWP is negative, then increases up to an altitude of 10 000 m, and then decreases again. This behavior can be explained by the mode of action of NOx in the atmosphere. Depending on the altitude, nitrogen oxides either promote the formation of ozone and thus influence warming or enforce the destruction of methane and cause cooling. [50]

In summary, the concept aircraft have lower energy consumption. However, compared to the reference, this reduction shows a decreasing trend with increasing mass.

Table 4: Sustainability parameter of A320neo variants

PARAMETER	REFERENCE	BASELINE	CONCEPT
CONSUMED ENERGY PER FLIGHT	672 GJ	652 GJ	588 GJ
CONSUMED ENERGY PER PAX	3.74 GJ	3.62 GJ	3.27 GJ
EMITTED CO2	49 293 kg	47 803 kg	0
GWP CO2	49 293 CO2e	47 803 CO2e	0 CO2e
EMITTED WATER	20 123 kg	19 515 kg	44 188 kg
GWP WATER	0 CO2e	0 CO2e	0 CO2e
EMITTED NOX	234 kg	227 kg	21 kg
GWP NOX	10 097 CO2e	9 768 CO2e	10 182 CO2e
GWP PER FLIGHT	59 390 CO2e	57 590 CO2e	10 182 CO2e

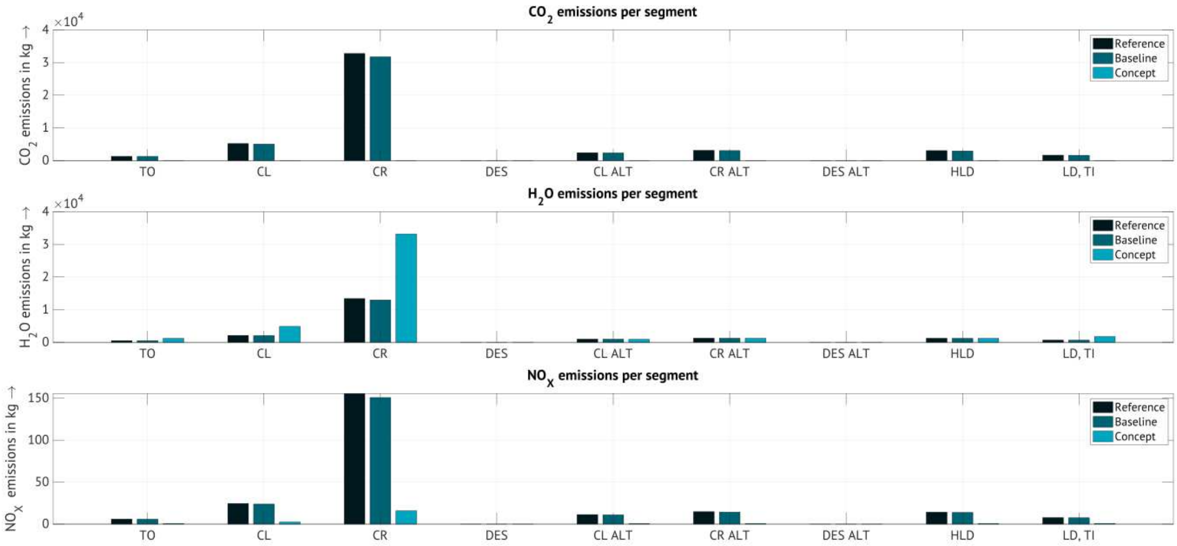

Fig. 8: Emissions per segment of A320neo

4.4 Payload Range Diagram

Fig. 9 shows the payload range diagram of the A320neo (right axis). Seat kilometer cost is plotted on the left axis. The results presented show the same qualitative characteristics and trends regardless of the aircraft.

The design point of the aircraft of the present conceptual design is at point B of the PRD. The reference configuration exhibits the characteristic shape of a PRD. In contrast, the reference aircraft show a different pattern. Due to the point tank design, replacing the payload with additional fuel is not possible. Consequently, the second segment from point B to point C is missing. Therefore, an increase in the range can only be achieved by reducing the payload mass. This results in a reduced ferry range in all three concept designs. In the case of the Dash-8, this is reduced from 3466 km to 3158 km. The CRJ1000 hydrogen concept achieves a maximum range of 3851 km compared 4718 km of the reference and the concept design has a ferry range of 6720 km compared 8015 km of the reference variant. Due to the higher average mass, the segment from the design point to the ferry range exhibits a reduced slope for the hydrogen-based aircraft.

The operational flexibility of the hydrogen concepts is reduced compared to the reference configurations.

4.5 Direct operating cost

Based on the PRD, the DOC can be related to the transport kilometers offered transport kilometer offered. The resulting value is the seat kilometer cost (SKC).

The qualitative progression of the SKC is the same for both the reference configurations and the hydrogen concepts. The minimum of the seat kilometer cost is reached at the design point, as the transport kilometers reach their maximum in this point. However, the concept aircraft does not necessarily exhibit the lower cost in the segment after that.

For all aircraft, a reduction in SKC is observed compared to the reference aircraft. The Dash-8 concept design, at 0.032 €/kg, is about 14 percent cheaper than the reference variant at 0.037 €/kg. For the CRJ1000, SKC of 0.089 €/kg results in a cost savings potential of 17 percent compared to the reference with 0.106 €/kg. The hydrogen concept of the Airbus A320neo shows the largest cost reduction with 23 percent. The cost is reduced from 0.043 €/kg for the reference to 0.033 €/kg.

5 Conclusion and Outlook

This study examined the integration of hydrogen as a sustainable energy carrier in conventional tube-and-wing aircraft configurations for short- and medium-haul operations. The urgency to decarbonize aviation has increased significantly, especially considering the climate goals outlined by the Paris Agreement. Hydrogen, with its high gravimetric energy density and zero carbon dioxide emissions at

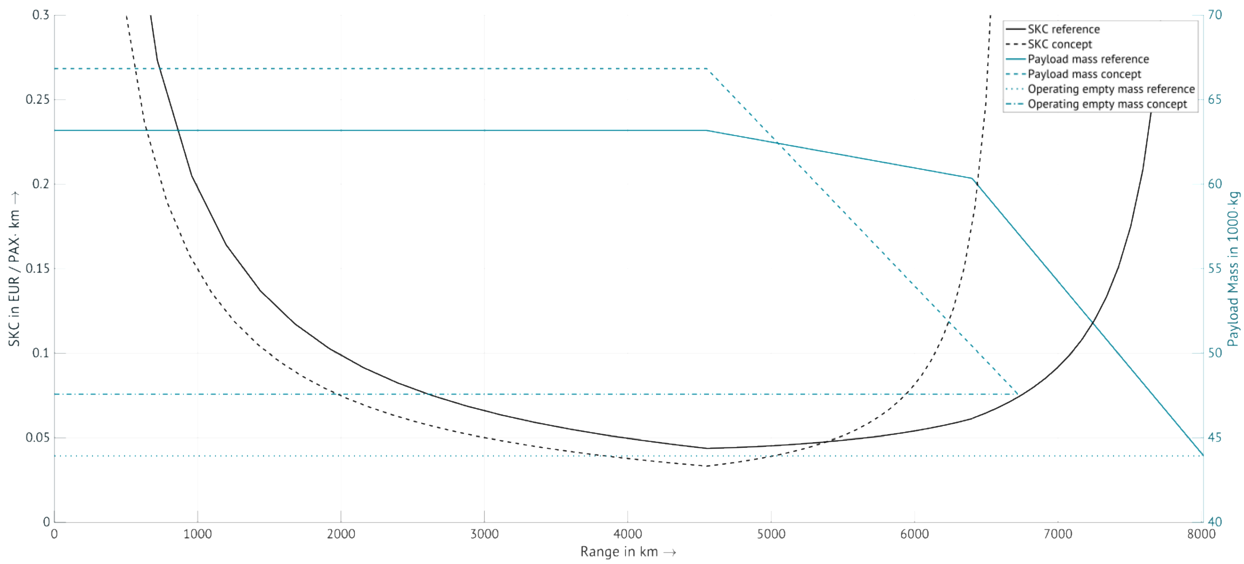

Fig. 9: PRD and SKC of A320neo

the point of use, presents a promising pathway toward achieving “true zero” aviation – provided it is sourced from renewable production processes.

By selecting three representative aircraft platforms (Dash-8, CRJ1000, and A320neo) this work established a design framework that allowed the consistent comparison between kerosene-powered reference aircraft and hydrogen-powered concepts. The methodology incorporated key aspects such as tank sizing, material selection, aerodynamic performance, emissions evaluation, and economic viability through DOC.

Results show that hydrogen integration is both technically feasible and ecologically advantageous. Although the concept aircraft exhibited increased operating empty mass due to the additional tank systems, this was outweighed by the significantly lower fuel mass, ultimately leading to a reduced maximum take-off mass across all configurations. The analysis also highlighted the influence of fuselage geometry on tank efficiency – wider fuselages yielded better gravimetric tank performance and lower design penalties.

From an environmental standpoint, the elimination of CO2 emissions is a major advantage of hydrogen propulsion. However, secondary effects, such as contrail and cirrus cloud formation due to increased water vapor emissions, require further investigation. The aircraft designed in this study operate at lower cruise altitudes, potentially mitigating these effects, though the complexity of atmospheric interactions demands more comprehensive research.

Economically, the hydrogen concepts demonstrated promising reductions in DOC, up to 23 percent, indicating that sustainable operation may not necessarily conflict with profitability. Nevertheless, a trade-off was identified in the form of reduced operational flexibility and shorter ferry ranges, suggesting that hydrogen propulsion is best suited for well-defined mission profiles.

5.1 Recommendations for Future Research

While this work focused on conceptual design and high-level evaluation, several areas remain open for detailed exploration in future studies:

- Cabin Optimization: Investigate lightweight interior configurations to counterbalance structural mass increases.
- Advanced Tank Designs: Explore integral tank solutions and composite materials for improved volume utilization and reduced structural weight.
- Wing Redesign: Examine aerodynamic and structural implications of kerosene-free wings, including novel concepts such as ultra-thin or morphing wings.
- Center of Gravity Analysis: Conduct detailed studies to evaluate and optimize the impact of rear-mounted cryogenic tanks on aircraft stability and controllability.
- Clean-Sheet Designs: Rather than retrofitting existing airframes, explore the design space of fully new hydrogen-optimized aircraft architectures to unlock synergies across systems.

5.2 Closing Thoughts

The transition toward hydrogen-powered aviation is not merely a technological challenge but a systemic transformation requiring coordinated efforts across industry, politics, and research. This study demonstrates that hydrogen propulsion, despite inherent challenges, can serve as a technically and economically viable cornerstone for sustainable air travel. However, its success ultimately hinges on the availability of green hydrogen at scale and supportive infrastructure.

In times of global change, the aviation sector has a unique opportunity and responsibility, to lead by example. By acting today, the industry can ensure that future generations continue to connect across borders in a manner that respects both people and the planet.

Availability of data and material: Data can be made available on request.

Compliance with ethical standards

Conflicts of interest:
On behalf of all authors, the corresponding author states that there is no conflict of interest.

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