On the Use of Hydrogen as the Future Aviation Fuel

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December 2018

Abstract

The present work was performed during a six-month internship at Airbus CTO and describes the conceptual design of hydrogen-fueled regional aircraft using a Multidisciplinary Design Optimization (MDO) tool. The implementation of the aircraft models inside the tool is detailed, notably with regard to the propulsion plant and the hydrogen tanks design and integration. Distinct hydrogen aircraft architectures are studied and alternative scenarios are modeled so as to explore a greater number of potential solutions for the main issue addressed: the environmental impact of aviation. The main aircraft performance figures to be compared with the kerosene-powered reference are energy consumption and pollutant emissions. The life cycle assessment of the different fuel types and a preliminary discussion on the economic viability of hydrogen as a fuel reveal the paradigm shift inherent to the energy transition. The results prove the feasibility of hydrogen aircraft from a design perspective and its benefits from an environmental point of view as long as produced using renewable energies. Liquid methane appears as a very interesting candidate to enable a potential transition scenario given the current economic challenges related to the hydrogen production.

Keywords: Multidisciplinary Design Optimization, Overall Aircraft Design, Life Cycle Assessment, Alternative fuels, hydrogen

1. Introduction

1.1. Motivation

Aircraft engines' emissions contribute to the greenhouse effect and lead to a loss of local air quality, mainly in the vicinity of airports. By 2007, it was acknowledged that global aviation was responsible for 2% of anthropogenic CO_2 emissions. This number seemed, however, doomed to rise, according to the air traffic forecast, that anticipated passenger and freight traffic annually growths of 4.9% and 5.8%, respectively, during the following twenty years (Airbus Global Market Forecast 2007, [1]). Thus, the aviation industry came together in 2009 under the lead of the ICAO (International Civil Aviation Organization), during the United Nations Climate Change Conference in Copenhagen and set itself three goals to minimize its environmental footprint: to improve fuel efficiency by 1.5% per year to 2020, to stabilize CO_2 emissions through carbon-neutral growth from 2020 and to halve CO_2 emissions by 2050 compared to 2005 [2]. Some ambitious goals addressing the aviation's environmental impact were also set by the European Comission, that aims at reducing CO_2 emissions by 75%, NO_x emissions by 90% and noise pollution by 65% in 2050 compared to 2000 (Flightpath 2050, [3]). Therefore, several activities aiming at mitigating the environmental impact of aviation have been arising, comprising not only technological improvements but also political agenda. In 2012, emissions from aviation were included in the European Union Emissions Trading System (EU ETS), meaning that airlines have to surrender allowances against emissions from flights within the EEA (European Economic Area) [4]. More recently, in 2016, the ICAO agreed on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) that will require airlines to offset the growth of their CO_2 emissions after 2020. The International Air Transport Association (IATA) also introduced a Carbon Offset Program that offers airlines' customers the possibility to compensate for their flights' environmental footprint by paying extra fees that are invested in carbon reduction projects. Many improvements on aircraft technology have also been achieved throughout the years. The use of lighter materials on the airframe, aircraft designs with enhanced aerodynamic properties and more fuel-efficient engines are some examples that result in less pollutant emissions. However, these advances fall short of the ambitious goals set by the ICAO and the European Comission. In order to achieve them, a transition towards sustainable alternative fuels is of paramount importance, which is further reinforced by the depletion of oil resources. Liquid hydrogen appears as an interesting candidate to re-

place kerosene as energy carrier, since it has a very high specific energy (energy per unit mass) and a very low environmental impact (its combustion only releases water vapor and small amounts of NO_x). Nevertheless, as this compound cannot be found naturally, when accounting for the whole product life cycle, its environmental impact may increase depending on its production method. Furthermore, liquid hydrogen has a low volumetric mass density and needs to be stored at cryogenic temperatures (approx. 20 K), which poses serious challenges to transportation and storage, since large tanks with good insulation properties must be used. Adopting hydrogen as a fuel will not only lead to a considerable change in ground infrastructures but to different aircraft configurations as well, which will ultimately increase costs.

1.2. Objectives

The present work aims at studying the potential of liquid hydrogen as an aviation fuel. Bearing in mind this main purpose, some more specific objectives may be derived:

- Discuss the main advantages and disadvantages of using liquid hydrogen for propulsion and the changes it would lead to in aviation;
- Establish a fair comparison between hydrogen and standard kerosene configurations, both in terms of aircraft design and performance;
- Assess the environmental impact and carry out a preliminary discussion on the economical viability of hydrogen-fueled aircraft.

2. Hydrogen as an Aviation Fuel

This section essentially based on literature review contains information on the hydrogen properties and presents an overview of the changes it would lead to in aviation.

2.1. Hydrogen Properties

Some hydrogen properties and the corresponding kerosene values are summarized in table 1. Hydrogen's specific energy is about three times higher than that of kerosene. On the other hand, the hydrogen state at STP conditions (Standard Temperature and Pressure - 0°C and 1 bar) is gaseous and its density is 0.0899 kg/m^3. Such a low value makes liquid hydrogen the only viable option for aviation. Nevertheless, not only liquid hydrogen has still a very low density when compared to kerosene but it must be stored in cryogenic conditions (approximately 20K) as well. If we compare the fuel masses of same energy content we realise liquid hydrogen is almost three times lighter than kerosene but occupies a volume four times bigger. Therefore, the installation of large hydrogen tanks with special insulation properties on the aircraft presents a serious challenge.

Property	**Unit**	**Kerosene**	**H_2**
Boiling temp.	°C	150-300	-252.87
Melting temp.	°C	-40	-259.14
Specific energy	MJ/kg	42.8	122.8
Density	kg/m^3	775-840	70.8 *

* In liquid state

Table 1: Liquid hydrogen and kerosene properties

2.2. Safety

A detailed safety analysis was conducted in the framework of the Cryoplane study developed by Airbus Deutschland GmbH and its final technical report [5] states that "there is no fundamental problem, which would prevent the successful operation of a commercial aircraft running on liquid hydrogen". Nevertheless, safety measures must obviously be adopted because hydrogen gas is very flammable and yields explosive mixtures with air and oxygen. During flight, hydrogen burns at concentrations considerably below the limits for detonation which is rather reassuring. The hydrogen tanks should nevertheless be designed to prevent leakages and should not be located in impact areas such as the rotor disk burst cones. Hydrogen accumulation on ground infrastructures is also a potential risk. A good safety measure to prevent catastrophic events on the ground would be to burn the hydrogen whenever it is leaked since it rises fast in the atmosphere and causes a standing flame that is quickly extinguished instead of detonating.

2.3. Propulsive Unit

As suggested by Vestraete, 2009 [6] hydrogen is a very attractive fuel alternative because it allows a very stable combustion over a wide range of operating conditions. According to [7], a heat exchanger has to be installed in the engine to heat hydrogen from the tank temperature to injection conditions. The heat exchanger vaporizes the hydrogen heating it up to temperatures between 150 K and 250 K. In addition, the SFC (Specific Fuel Consumption) of a hydrogen-fueled engine is nearly three times lower than that of a kerosene engine. Previous studies in Airbus concerning the Cryoplane showed this SFC reduction can be estimated as follows:

$$SFC_{LH_2} = SFC_{ref} \times \frac{SE_{kerosene}}{SE_{LH_2}} \qquad (1)$$

where SE stands for the specific energy per unit mass of fuel.

2.4. Hydrogen Tanks

The hydrogen tanks design and integration in the aircraft is certainly the most challenging task of this study. The choice of the vessel's shape and materials is of crucial importance since the overall system should be as light as possible while keeping good mechanical and thermal properties. A cylindrical shape with hemispherical end caps was adopted in this work because, according to [8], it minimizes the tank wall surface-to-volume ratio making it lighter. From a mechanical point of view, the tank wall should prevent hydrogen permeation and its material's properties should include a high strength, stiffness and fracture toughness. Moreover, the vessels must have good insulation properties in order to reduce the heat flux through its structure that causes the pressure to rise inside the tank and the hydrogen to be vented in case the maximum allowable pressure (venting pressure) is reached. In this work's scope, double-walled hydrogen tanks were chosen and two different tank wall structures were modeled and compared. The first corresponds to the one proposed in [8] that is a foam-insulated structure while the second uses multilayer insulation (MLI). Although the MLI has better insulation properties, it is more costly to implement and maintain and requires heavier tank walls due to the high vacuum level between them.

The installation of large hydrogen vessels in the aircraft is a difficult task that needs special attention. Several possible aircraft configurations regarding the tanks location are identified in the Cryoplane final technical report [5]. The simplest solution would be to install a single tank behind the aft pressure bulkhead. This could however pose some issues regarding the center of gravity of the whole system, that could be avoided if a second hydrogen tank would be installed in the forward part of the plane, between the cockpit and the cabin. Although it helps fixing the center of gravity issue, this solution also has a problem: the forward tank would disconnect the cockpit and the cabin. Installing the tanks in the fuselage would either lead to a reduction of the number of passengers or to a considerable stretching of the aircraft. Other possible solutions are the intallation of the tanks over the fuselage or even under the wings, as suggested in the Green Freigher Project [9].

2.5. Environmental and Economic Impacts

To conclude about the environmental impact of hydrogen as an alternative fuel, its whole life cycle needs to be analyzed. As previously mentioned, hydrogen combustion only releases water vapor and very small amounts of NO_x. However, although the hydrogen combustion is carbon-free, its current production processes are not. According to [10] 99% of hydrogen is currently produced through fossil fuel reforming since it is the most economic pathway. Hydrogen can alternatively be obtained through the electrolysis of water and, in order to eliminate carbon dioxide emissions, this process can be powered by renewable energy sources. This option is currently expensive but the Hydrogen Council [10] expects its costs to decrease by 50% with increasing application. After being produced, hydrogen still has to be liquefied, transported and stored. Hydrogen transport options include truck/ship transport both for gaseous and liquid hydrogen and pipelines for gaseous hydrogen. In terms of storage, the most common options include cryogenic liquid or compressed gas vessels, or even metal hydride storage. In order for this energy transition to happen, considerable investments regarding the deployment of hydrogen infrastructures on the ground are necessary. Besides the costs related to the hydrogen operations on the ground, the hydrogen aircraft architectures and their maintenance will also be more costly than the kerosene-powered aircraft as suggested by [9]. A trade-off between emissions and costs will then allow us to understand how much should we be willing to pay to become greener.

3. Multidisciplinary Design Optimization

This section consists of an introduction to the Multidisciplinary Design Optimization (MDO) methodology and to the XMDO platform used to carry out aircraft conceptual design studies.

3.1. MDO Overview

MDO is an engineering method that aims at automating the design process of a certain multidisciplinary system through optimization techniques. The largest number of applications have been in the field of aerospace engineering because it studies highly multidisciplinary and complex systems. According to [11], "optimization is the process of choosing the design variables that yield an optimum design" respecting certain equality and/or inequality constraints. The most challenging part of the design process is normally the definition of the optimization problem under the form:

$$\begin{aligned} \text{minimize} \quad & f(x) \\ \text{with respect to} \quad & x \in \Omega, \qquad \Omega \subset \mathbb{R}^n \\ \text{subject to} \quad & \hat{c}_j(x) = 0, \qquad j = 1, 2, ..., n_j \\ & c_k(x) \geq 0, \qquad k = 1, 2, ..., n_k \end{aligned} \tag{2}$$

where f is the objective function, x is the vector of design variables which are the parameters that vary during the design process, Ω is the design space defined by the bounds set for the design variables, $\hat{c}$ and c are the vectors of equality and inequality con-

straints, respectively. Choosing the models that relate the constraints and the objective to the design variables is a very important part of the designer's job.

Introducing cutting-edge technologies in the conventional design process loop may be difficult given the lack of knowledge both on the technology itself and on the way it interacts with other sub-systems of a certain product. On the other hand, preliminary physical models concerning a technology can first be developed and integrated on the MDO process and then be improved as the related knowledge expands.

3.2. XMDO Platform

XMDO is a platform that enables the development of rapid (but high quality) concept studies. It is an MDO tool programmed in Python under the object-oriented paradigm. XMDO performs both trajectory and vehicle optimization by coupling the vehicle design to the mission description and it can operate either in mono- or multi-mission mode.

3.2.1 Mission and Vehicle Description

XMDO is composed of several parametric models that couple the input data describing the mission(s) and the vehicle to the vehicle performance throughout the flight. The vehicle architecture is defined by specifying its different "components" that represent its sub-systems. Vehicles' components are modeled by discipline meaning that for each component exist several models, one for each concerned discipline. There is then a dual view of the vehicle, per components and per disciplines. The disciplines modeled in the platform are: geometry, mass, aerodynamics, propulsion, energy, thermal management and costs. Just as a vehicle is decomposed in several sub-systems, a mission is decomposed in several segments that correspond to the different flight phases. The segments composing a mission are represented by B-splines with a set of control points describing altitude and distance and the whole trajectory is constructed as a linear combination of splines. Top level requirements concerning the mission can either be defined as input variables or as constraints.

3.2.2 Operation Modes

The platform can run a simple performance evaluation or an optimization mode. The evaluation of the aircraft's performance figures during flight is done by progressively solving the longitudinal trajectory equations:

$$\begin{cases} m.a_x = Thrust.cos(\alpha + \varepsilon) - Drag - m.g.sin(\gamma) \\ m.a_y = Thrust.sin(\alpha + \varepsilon) + Lift - m.g.cos(\gamma) \end{cases}$$

where m is the mass of the vehicle, a_x and a_y the accelerations in the flight path direction and its normal, respectively, V the ground speed, α the angle of attack, ε is the engine angle relatively to the aircraft longitudinal axis, and γ is the flight path angle. To solve each flight point, the angle of attack and the rating (power setting defined by the pilot) are calculated by numerically solving the trajectory equations using the Newton-Raphson method. After computing an entire mission, a post-processing analysis including the cost discipline is conducted.

The optimization mode makes use of the performance evaluation capabilities of the platform to compute the objective function and the constraints at each iteration. The L-BFGS-B optimization algorithm was used the most during this work for being well suited for problems with a large number of design variables. A Multidisciplinary Feasible (MDF) architecture was used to solve the MDO problem, meaning that the optimizer always returns a vehicle design that satisfies the consistency constraints [11].

4. Implementation

Here the work conducted to design and study the environmental impact of hydrogen-fueled aircraft is described.

4.1. Aircraft Configurations

In order to study hydrogen as an aviation fuel, a regional kerosene-fueled twin turboprop aircraft was chosen as a reference from which the hydrogen-fueled vehicle configurations will be derived. Following the discussion in section 2.4, two aircraft configurations with different hydrogen tank locations were studied. The first one is a double tank configuration with both hydrogen vessels being installed over the fuselage and will be referred to as our baseline solution. The second is an architecture with a single rear hydrogen tank. The exact dimensions of each aircraft will be an output of the optimization process.

4.2. Mission Requirements

The top-level aircraft requirements are specified in table 2. It is still important to stress that the reserves requirements include both a 45-minute continued cruise phase (for possible holding periods) and a 100NM range extension to fly to an alternate airport for some unforeseen circumstances such as extreme weather conditions, terrorist activity, crash, etc. The optimization was launched in multi-mission mode due to the two mission ranges specified in table 2. A take-off engine failure case was added as well since it may be sizing for the engines along with the take-off field-length constraint.

TLARs	Value
Range (at max pax)	Max range
Range (at max payload)	30% max range
Cruise Mach	0.5
Cruise altitude	25000ft
TO field length	< 1400m
Approach speed	< 110kt

Table 2: Top-level requirements

4.3. Physical Models

New physical models had to be implemented in XMDO in order to define and size the hydrogen-fueled aircraft configurations. These models concern aircraft components that were already part of the kerosene-fueled reference but were modified (fuselage and turboshaft) and components that did not exist at all in the reference aircraft (hydrogen tanks). Therefore, some models were just updated from the previous kerosene version while others were built from scratch.

4.3.1 Turboshaft

The kerosene-powered turboshaft model was updated in order to enable the use of hydrogen as its fuel. This model uses the instant power/thrust command (rating) to compute the shaft output power and the fuel mass flow rate at each time step. The only modification that was made to this model concerned the calculation of the specific fuel consumption. The SFC of the hydrogen-powered turboshaft is computed from that of the kerosene-powered using the simple relation previously introduced (eq. 1).

4.3.2 Hydrogen Tanks

The implementation of a parametric model of a cryogenic tank was one of the most important tasks of the present work. The implemented model computes the tank dry mass, the tank capacity and the time before venting during holding periods on the ground. The input parameters are the tank dimensions (length and the diameter), the insulation material and thickness, and the filling and venting pressures.

The fraction of liquid hydrogen inside the tank was computed as a function of the tank sizing pressures, as suggested by Verstraete [6]. Knowing the liquid fraction and the tank dimensions one can easily calculate the liquid hydrogen mass that we refer to as the tank capacity.

The tank mass was calculated using the density and the volume of each material layer of the vessel wall. In order to so, the thickness of each layer has to be specified. For both wall structures the insulation thickness is specified as an input parameter while the thickness of the internal aluminium wall depends on the maximum allowable pressure, being calculated according to the following relation:

$$t_i = \frac{p_{vent}.d_i}{\upsilon(2K/FoS - p_{vent})} \tag{3}$$

where p_{vent} is the venting pressure, d_i the internal diameter, υ the weld efficiency, K the limited stress and FoS the safety factor. While the external fairing of the foam-insulated structure is made of epoxy composite and has a fixed thickness of 1.57 $\times 10^{-2}$ m defined by Winnefeld et al. [8], the external wall of the MLI-insulated structure is made of aluminium and its thickness is computed by multiplying the internal wall thickness by an additional safety factor. The foam-insulated structure is also composed of two very thin vapor barriers with 1.524 $\times 10^{-5}$ m of thickness each. The tank dry mass is finally calculated as the sum of the wall mass and the auxiliary systems mass (piping and valves). Using the tank's capacity and its dry mass, we can define the tank gravimetric index that we want to maximize:

$$\text{grav. index (\%)} = \frac{m_{LH2}}{m_{\text{dry tank}} + m_{LH2}} \times 100 \tag{4}$$

The last output of the tank model is the time before venting which is the amount of time the pressure inside a filled tank takes to rise from the filling to the maximum allowable level causing the venting valve to open and the gaseous hydrogen to start being released in the atmosphere. The thermal behaviour of the tank has to be modelled in order to estimate this pressure change. Lin et al. 1991 [12], introduce a model assuming an homogeneous mixture of liquid and gaseous hydrogen inside the tank, even if in reality there exists a certain degree of stratification. Using the first law of thermodynamics and the conservation of mass the pressure change is given by:

$$\frac{dp}{dt} = \frac{\phi}{V_{tank}} \left[\dot{Q} - \dot{m}_{out}.h_{lg}.\left(x_{lg} + \rho^*\right)\right] \tag{5}$$

where ϕ is the energy derivative that represents the pressure rise per volume per energy input, V_{tank} the volume of the tank, $\dot{Q}$ the heat flux, $\dot{m}_{out}$ the outlet flow rate, h_{lg} the heat of vaporization at the tank pressure, x_{lg} the quality of the fuel (x_{lg}=0 for saturated liquid and x_{lg}=1 for saturated vapor) and $\rho^* = \rho_g/(\rho_l - \rho_g)$. Since the homogeneity assumption under-predicts the pressure change, the tank model of this study uses twice the pressure change rate given by equation 5, as suggested by

Lin et al. [12]. To calculate the heat that flows between the atmosphere and the hydrogen inside the tank, different thermal mechanisms were considered and the corresponding heat transfer coefficients were calculated according to [6]. These heat transfer coefficients and the wetted surface area S of the respective material layers allow us to calculate the successive thermal resistances R between the hydrogen and the atmosphere using the simple relation:

$$R = \frac{1}{\sum_i h_i.S_i} \tag{6}$$

Finally, the heat flux is computed by solving the following system of equations that assumes one-dimensional heat transfer:

$$\begin{pmatrix} -1 & 1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & -1 & 1 \end{pmatrix} \cdot \begin{pmatrix} T_{H_2} \\ T_C \\ T_H \\ T_{skin} \\ T_{atm} \end{pmatrix} - \begin{pmatrix} R_{in} \\ R_{ins} \\ R_{ex} \\ R_{out} \end{pmatrix} .\dot{Q} = 0 \tag{7}$$

Figure 1 presents a schematic view of the problem, identifying the material layers that are accounted in each thermal resistance.

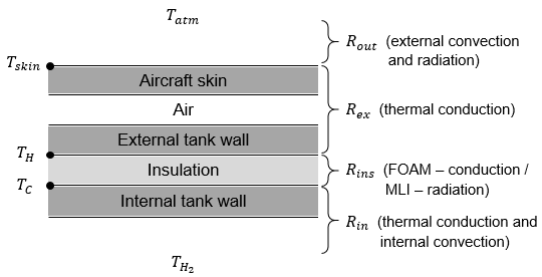

Figure 1: Schematic distribution of the temperature and thermal resistances

The temperature of the atmosphere was fixed at a certain value and the temperature of the hydrogen is exclusively function of its pressure. Therefore, the unknowns of the problem are the heat flux ($\dot{Q}$), the temperature of the aircraft skin (T_{skin}) and the temperature of the hot and cold boundaries of the insulation (T_H and T_C respectively). The Newton-Raphson method was used to solve this system of equations at each time step until the venting pressure level was reached. The gravimetric index was plotted in function of the normalized time before venting for different insulation types and thickness and the results can be observed in figure 2.

It becomes clear that despite the lower gravimetric indexes the MLI is much more effective than the foam insulation since it can hold for longer periods

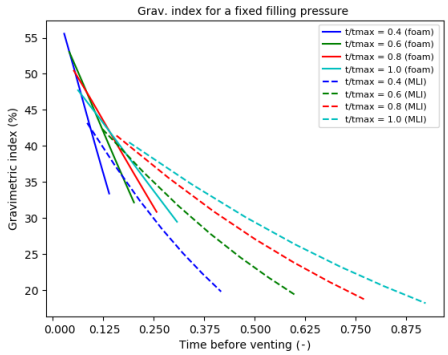

Figure 2: Gravimetric index in function of the time before venting for different insulation types and thickness

on the ground without releasing hydrogen. We can also conclude that increasing the insulation thickness leads to longer holding periods before venting with no major drawbacks in terms of mass. Another interesting solution to increase the time before venting is to widen the gap between the filling and the venting pressures, but always keeping in mind that higher venting pressures require thicker and heavier tank walls.

4.3.3 Fuselage

The single rear tank configuration's fuselage is longer but holds the same shape of the reference aircraft. On the other hand, the integration of two hydrogen tanks over the cabin leads to a slightly different fuselage shape in our baseline solution. The integration of the tanks is achieved thanks to an external fairing illustrated in figure 3 that leads to mass and drag penalties. A new fuselage model was thus derived from the standard one in order to compute the new fuselage wetted area and mass depending on the hydrogen tanks dimensions. Even if in reality they are detached, the external fairing is assumed to be tangent both to the fuselage and the hydrogen tanks in the new fuselage model. The length of the fairing cross-section (red contour in figure 3) is then estimated through trigonometry principles and used to calculate the fairing surface in the constant cross-section zone of the aircraft's fuselage. An additional fairing surface is estimated for the forward and rear zones of the fuselage by connecting the tangency points to the fuselage ends.

The wetted area is then used to compute the friction drag within the aerodynamics discipline of the platform. The mass of the new fuselage is derived from the previous one by considering not only the fairing mass but also an integration factor to account for the brackets and local structural strengthening:

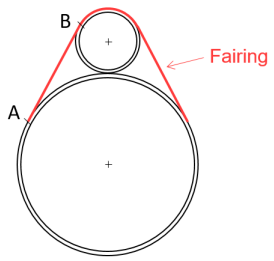

Figure 3: Hydrogen tanks integration and external fairing

$$m_{fus} = m_{ref}.(1 + \eta_{int}) + S_{fairing}.\rho_{A_{fairing}} \quad (8)$$

where m_{ref} represents the reference fuselage mass, η_{int} the integration factor, $S_{fairing}$ and $\rho_{A_{fairing}}$ the fairing surface and surface density, respectively.

4.4. New XMDO Functionalities

Another part of the present work involved the development of some new functionalities in the XMDO platform. First of all, the main motivation of this work being to explore sustainable alternatives to kerosene, a routine to calculate the harmful emissions on the ground and throughout the flight was implemented in the post-mission analysis module of the platform. Another feature implemented concerned the single rear tank configuration. The propulsion and energy disciplines of the platform were related in a way that did not allow the use of a single fuel tank to feed more than one propulsive units. This capability was thus added to the platform by rethinking the way the energy source was linked to the propulsion train. Finally, it was developed the capability of running multi-fuel aircraft configurations on XMDO. As it will later be explained in section 5, following the results of the first optimizations, some interesting alternative solutions to our hydrogen configurations were explored, one of which involving an aircraft powered by multiple energy sources. Therefore, as it was not yet implemented, a multi-fuel mode was developed allowing a vehicle to carry and use different fuel options.

4.5. Life Cycle Assessment

Life Cycle Assessment (LCA) is a technique to assess the potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal [13]. Within the present study, the purpose of the LCA analysis is to quantify and compare the global warming potential (GWP) of kerosene and liquid hydrogen used as aircraft fuels. Two different hydrogen production pathways will be looked at, namely steam methane reforming (SMR) and electrolysis of water powered by wind energy. The functional unit of the study is passenger-kilometer meaning that it will be assessed the impact of transporting a passenger over a distance of one kilometer. The system boundaries include the fuel production and its combustion during flight.

Global warming potential is a relative measure of the contribution of a certain GHG to the radiative forcing. It compares the amount of energy the emissions of a certain mass of a GHG absorb over a given period of time, to the amount of energy absorbed by a similar mass of CO_2 emissions. The most commonly used time period is 100 years and the unit indicator for GWP is kg CO_2eq (equivalent carbon dioxide) [14]. The overall GWP for each fuel type and production pathway are presented in table 3

GWP	Prod.	Combust.	**Total**
Kerosene	14.5	73.6	**88.1**
Hydrogen			
(via SMR)	100.2	-	**100.2**
(via electrol.)	7.9	-	**7.9**

Table 3: Global warming potential (in g CO_2eq/MJ fuel) of kerosene and hydrogen

In spite of being generally perceived as a green fuel, hydrogen can have a greater environmental impact than kerosene. Consuming 1 MJ of hydrogen produced via steam methane reforming results in a global warming potential higher than burning the mass of kerosene with the same energy content. A very low GWP can however be reached in case hydrogen is obtained through the electrolysis of water using wind power. The GWP values of each fuel and production pathway and the aircraft energy consumption figures will be used to assess the overall environmental impact of performing the design mission. The results of this analysis are presented in the following section.

5. Results

This section presents the results of the aircraft design process and the LCA analysis.

5.1. Problem Description

The objective chosen to be minimized was the Maximum Take-Off Weight (MTOW) which is the maximum weight at which the pilot is allowed to attempt to take-off. The design variables concerning the aircraft are the dimensions of the cryogenic tanks, the MTOW, the Maximum Zero Fuel Weight (MZFW), the carried fuel mass, the wing span and root chord, the diameter of the main components of

the propulsive train (turboshaft, gearbox and propeller). Following the results of the previous section, the MLI-insulated structure was chosen over the foam-insulated due to the longer times before venting. At the mission level, the design variables are the altitude, the longitudinal position and the speed at the control points of the splines used to define the aircraft trajectory. Several inequality constraints were defined. The field length and the approach speed were set to respect the missions requirements (table 2). The aircraft take-off and zero fuel weights were constrained to be lower than the MTOW and the MZFW, respectively. The rating is limited by the maximum available power. Finally, the fuel tanks capacity must be higher than the fuel needed to complete the mission.

5.2. Solution and Alternatives

The results of the optimizations regarding the hydrogen configurations using XMDO are summarized in table 4 in relative relative deviations with respect to the kerosene reference aircraft.

A/C config.	Baseline	Rear Tank
MTOW	+7.5%	+7.8%
Energy cons.*	+12.9%	+10.4%
CO_2 emissions*	-100%	-100%
NO_x emissions*	-87.6%	-87.9%

* For the design range at maximum payload

Table 4: MDO results for the hydrogen-fueled aircraft. Relative deviation (in %) with respect to the kerosene reference aircraft.

It can be observed that despite being heavier and consuming more energy than the kerosene-fueled architectures, the hydrogen configurations drastically reduce the harmful emissions throughout the flight, as expected. The rear tank configuration presents a higher MTOW due the heavier fuel supply system when compared to our baseline. However, due to the integration of the tank inside the fuselage and the absence of an external fairing, the fuselage wetted area is smaller, resulting in a lower friction drag and consequently in a lower overall energy consumption. Figure 4 shows the normalized payload-range diagrams of the reference and the hydrogen-fueled aircraft. From these diagrams it can be concluded that the hydrogen aircraft is optimized to fly short ranges carrying great payloads.

In light of these results, two alternative scenarios aiming at minimizing the energy consumption were explored, without however losing sight of the main objective: reducing the environmental impact of aviation. The use of liquid methane instead of hydrogen was the first alternative that seemed potentially interesting, since methane is denser than

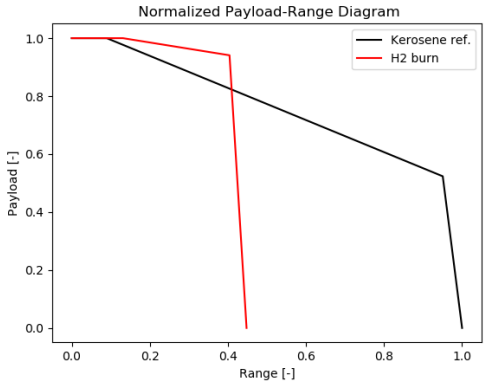

Figure 4: Payload-range diagram of the kerosene- and the hydrogen-fueled aircraft configs.

hydrogen and very cheap even when compared with kerosene. From the optimizations it was observed that using methane results in smaller fuel tanks and thus in lower MTOW and lower energy consumptions (+7.8% and +9.4% for the rear tank and the baseline configurations, respectively). This alternative is not however as green as hydrogen during flight since the methane combustion still generates CO_2. The GWP throughout methane's entire life cycle is 65.6 g CO_2eq/MJ of methane used. The second alternative was using liquid hydrogen as the main fuel and kerosene for the reserves. The MDO results proved this solution to be heavier but more energy-efficient than the baseline hydrogen solution (+8.6% and +11.7% for the MTOW and the energy consumption, respectively), while keeping the emissions during the block mission to a minimum.

5.3. LCA

Figure 5 presents the results of the GWP assessment in relative deviations with respect to the kerosene reference. These values concern the double tank aircraft configuration and the block fuel consumption.

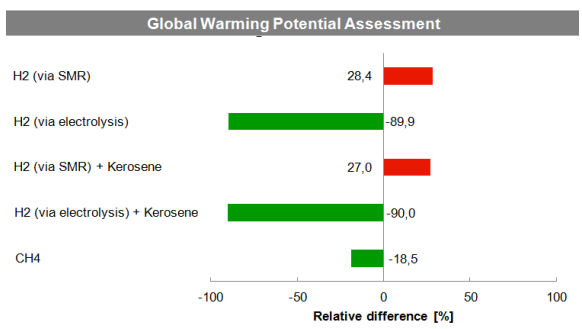

Figure 5: Assessment of the design mission GWP. Relative deviation (in %) with respect to the kerosene reference aircraft figures

The life cycle assessment shows that achieving the environmental goals set by the European Comission and the ICAO depends greatly on the fuel production pathway. Powering aircraft with hydrogen produced through steam methane reforming, for instance, results in a greater GWP than using standard kerosene. Using liquid methane, on the other hand, despite also falling short of the CO_2 reduction targets would reduce the impact of aviation on the climate change. It can finally be concluded that using hydrogen produced through the electrolysis of water powered by renewable energy sources is the only alternative that would not just meet but push beyond aviation's environmental targets. Choosing the rear tank aircraft architecture and carrying kerosene reserves are two solutions that could still bring small gains in GWP reduction.

5.4. Fuel Pricing

Although LCA does not involve cost assessment, its outcome may have a great influence on the economic domain. In this particular case, the fuel price depends on its global warming potential due to the carbon pricing initiatives aiming at mitigating the climate change. Figure 6 shows the impact of carbon taxes on fuel prices based on their whole life cycle GWP.

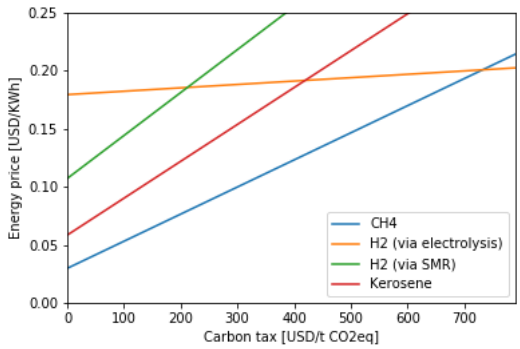

Figure 6: Influence of the carbon pricing policies on the fuel price

It can be seen that although renewable hydrogen production is very expensive, carbon pricing can make it competitive with the other fuel alternatives due to its low environmental impact. Hydrogen via electrolysis becomes cheaper than hydrogen via SMR and kerosene from carbon taxes of approximately 200US$ and 400US$ per tonne of CO_2eq, respectively. The current price of the EU ETS allowances is only 18US$/t$CO_2$eq but if the implementation of CORSIA follows the accelerated rate of increase of the carbon taxes worldwide [15] electrolysis can soon become economically competitive with SMR, or even kerosene. Methane's low price is, on the other hand, more difficult to overcome.

6. Conclusions and Future Work

The objectives set in the introductory chapter were accomplished. It is now necessary to draw the main conclusions of this study and map out the options for future work.

6.1. Conclusions

The feasibility of using hydrogen as an aviation fuel, for regional transport aircraft in particular has been proven from an aircraft performance perspective.

The cryogenic tanks design and integration were clearly identified as the main challenge related to the use of liquid hydrogen. It has been shown that finding the right balance between mechanical and thermal properties while aiming at minimizing the overall fuel supply system mass is far from being an easy job. Using the foam insulation results in lighter vessels which can be a good opportunity to explore. However, in the present work, the MLI technology was chosen over the foam to enable a more conservative design since there might be exigent constraints regarding holding periods on the ground. The choice of the fuel storage system location in the aircraft was proven to be of great importance because it drives the mass and drag penalties inherent to the larger fuselage and, ultimately, the energy consumption.

When compared to standard kerosene-powered planes, hydrogen aircraft are more energy-consuming but drastically reduce the harmful emissions during flight. Nonetheless, in order to achieve the environmental targets set by the ICAO, hydrogen production must be powered by renewable energy sources. Otherwise, if produced through steam methane reforming, the global warming potential of hydrogen throughout its life cycle is greater than that of kerosene.

From the payload-range diagrams it could be understood that hydrogen aircraft are best suited to fly shorter ranges with greater payloads. Although the impact on the aircraft's center of gravity was not analyzed, the single rear tank configuration was proven to be more energy-efficient than the baseline architecture. Two alternative solutions were also studied and led to interesting results. First of all, carrying kerosene reserves slightly reduces energy consumption while keeping the emissions very low during the block mission. The second alternative to hydrogen is using liquid methane as fuel that has been proven to have a lower global warming potential than kerosene over its life cycle despite still generating carbon dioxide emissions during flight. Furthermore, liquid methane is very cheap and significantly more energy-efficient than liquid hydrogen when used as an aircraft fuel. Methane could provide a transition scenario while the technological

and economic challenges regarding hydrogen production remain difficult to overcome.

Finally, it is important to conclude that the MDO approach was very well suited for this work since it enabled a quick exploration of many different aircraft configurations providing satisfying and coherent results.

6.2. Future Work

A complete study regarding the economic viability of using hydrogen can be carried out by assessing the costs related not only to the new aircraft architectures but also to infrastructure, hydrogen production and transport, and maintenance operations.

Some improvements can still be made in what concerns aircraft design. The rear tank configuration is expected to raise some issues regarding the center of gravity as previously explained. Therefore, building up a scissor chart and calculating the plane's center or gravity for different payload cases would enable sizing the horizontal tailplane (HTP) and repositioning the wing in order to meet control and stability requirements. The baseline configurations may also pose some problems regarding the aircraft's control surfaces since a big part of the vertical tailplane (VTP) will be hidden by the hydrogen tanks over the fuselage. For that reason, further studies concerning the sizing of the VTP should also be carried out.

A detailed structural analysis of the cryogenic tanks and respective integration in the fuselage can help maturing this technology.

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