DESIGN OF DUAL-FUEL AIRCRAFT CONCEPTS: A POTENTIAL INTERMEDIATE STEP IN THE TRANSITION TOWARDS HYDROGEN-POWERED AVIATION

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Abstract

The aviation industry is at a critical crossroads, facing the challenge of significantly reducing its environmental impact while maintaining efficiency and performance. One of the most promising long-term strategies is the transition to hydrogen-powered aircraft, which offer the potential for zero carbon emissions during operation. However, the complete shift to hydrogen propulsion presents significant technological, infrastructural, and economic challenges that require time to overcome. In this context, a dual-fuel aircraft, capable of operating on both kerosene and liquid hydrogen (LH_2), emerges as a pragmatic intermediate step. The dual-fuel strategy analyzed considers LH_2 as primary fuel, and kerosene as an additional fuel to be exploited in a separate subsequent mission, in case hydrogen is not available at the destination airport. The aim of this work is to design dual-fuel aircraft concepts, in order to investigate the performance of such a hybrid option as well as the complexity of the modifications needed to use two energy carriers. The analysis of the performance of dual-fuel compared to pure liquid hydrogen concepts, evaluated over a wide variety of possible missions, is the main result of the work. The study shows, given an expected worsening of the aircraft efficiency due to the increased weight and wetted area coming from inclusion of an additional fuel, the extent of these penalties, opening up to the possibility for a future assessment on the trade-off between an operational ease in the transition-to-hydrogen phase and performance losses. In this context, the specific energy is evaluated over two consecutive missions with diverse range values combinations, and compared for dual-fuel, operating on LH_2 in the first leg and on SAF in the second, liquid hydrogen (refueled for the second mission) and liquid hydrogen tankering concepts.

Keywords
Aircraft Design; Dual-Fuel; Liquid Hydrogen

NOMENCLATURE

Symbols

E	Energy	MJ
LHV	Lower heating value	MJ/kg
m_{fuel}	Fuel mass	kg
$m_{payload}$	Payload mass	kg
R_B	Block range	kg
SBE	Specific block energy	MJ/(kg*NM)
SE	Specific energy	MJ/kg

Abbreviations

CO_2	Carbon dioxide
EIS	Entry into service
KPI	Key performance indicator
LH_2	Liquid hydrogen
MTOM	Maximum take off mass
OEM	Operating empty mass
SAF	Sustainable aviation fuel
TLARs	Top level aircraft requirements
TOM	Take off mass

1. INTRODUCTION

The aviation industry faces increasing pressure to reduce its environmental footprint as global awareness of climate change intensifies. With a contribution of about 2.4% to the global anthropogenic CO_2 emissions in 2019, the projected growth of the sector and the de-carbonization efforts made in other industries

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appears to only lead to a worsening of this number [1]. By addressing the amount of carbon emissions produced to the energy carrier used, sustainable aviation fuels (SAFs) have emerged as a drop-in replacement for conventional kerosene, offering significant life-cycle CO_2 reductions with relatively minor modifications to existing infrastructure. Nonetheless, SAFs alone are insufficient to fully decarbonize long-term aviation, especially considering constraints in feedstock availability, scalability, and residual non-CO_2 climate effects [2].
In this context, the use of hydrogen as an energy carrier for aviation appears to be a game changer, but the switch to such an alternative solution comes with several challenges. Especially in its liquid form (LH_2), hydrogen pledges what the industry is looking for, net-zero carbon emissions, along with a high specific energy that makes it promising for aviation.
However, liquid hydrogen comes with the need for cryogenic storage and complex insulation systems [3], which in turn leads to more complex aircraft architectures and an increase in the weight of the on-board systems. Given then the effort for new designs and production, one of the biggest issues on the way to the transition is represented by the adaption of the existing refueling infrastructures. By assuming that a re-design phase is needed, and therefore a complete renewal of the fleets to achieve full de-carbonization, the modification of the ground infrastructure could still be a difficult and lengthy process [4].
In this transitional scenario, dual-fuel aircraft concepts, capable of operating on both liquid hydrogen and conventional fuels such as kerosene or SAFs, emerge as a pragmatic solution to bridge the gap. By maintaining compatibility with existing refueling and storage infrastructure, while gradually integrating hydrogen technologies, dual fuel designs can significantly ease the operational and logistical barriers associated with a full switch to hydrogen.
These configurations could allow partial de-carbonization in the near term, while enabling a progressive validation of hydrogen systems in commercial service. As such, dual-fuel aircraft may represent a critical step in the evolutionary path toward fully hydrogen-powered aviation, offering a flexible and scalable approach to mitigation of climate impacts without requiring an abrupt overhaul of the global airport network.
In this work, several conceptual designs of dual-fuel aircraft are presented in order to investigate the potential of this type of configuration for the previously described operational scenario. The description of the design methodologies and frameworks used for the development of different concepts (section 2) is followed by a detailed overview of the design strategy (section 3), with a display of all the aircraft concepts developed. Finally, the dual-fuel option is compared to pure LH_2 tankering designs, which carry additional hydrogen mass to achieve the same operational capabilities of dual-fuels concepts in scenarios where LH_2 refueling is not available at all locations section 4.

2. DESIGN ARCHITECTURE

This section describes the overall aircraft design workflow used in the study, focusing on the main components and methodologies developed for the design of dual-fuel concepts. The workflow execution is supported by RCE (Remote Component Environment) [5], an open source workflow driven environment in which complex systems can be simulated. Data are managed using CPACS (Common Parametric Aircraft Configuration Schema), a data model that describes the characteristics of the aircraft and its components in a way that enables the exchange of information between different tools [6].
The workflow used for the design of the dual-fuel aircraft concepts has been developed by modifying an existing workflow created within the scope of the project *EXACT2* [1]. This is a multidisciplinary and multifidelity workflow that enables the design and sizing of different aircraft from regional to long-range, supporting different propulsion systems and energy carriers [7].
Although the capability to design hybrid propulsion system was already included in the workflow, the dual-fuel configuration has come with the need to include some modifications to the logic of the simulation structure. The final logical scheme developed for the design loop is shown in Figure 1.

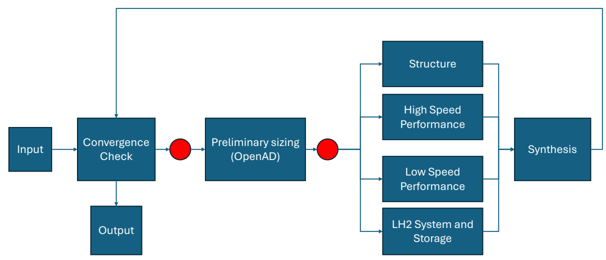

FIG 1. Design Workflow Architecture

The components integrated in the workflow are either python-based tools, or sub-workflows in which tools and logic connectors are organized as a set that covers a specific discipline of the aircraft design process. The design is initiated with a preliminary sizing by OpenAD [8]. This is the DLR conceptual aircraft design tool. It is based on well-understood and mostly publicly available handbook methods.
Before and after the preliminary sizing block, two red markers indicate the newly added components used for the dual-fuel aircraft sizing. They allow us to include a new fuel and fuel system configuration, and then adapt the model for the subsequent design phases in terms of mass distribution. The main aircraft design disciplines follow.

[1] EXACT2 project: exact-dlr.de

3. DESIGN STRATEGY

This section presents the employment of the previously described design architecture for the design of several aircraft concepts, followed by the results obtained and the comparison between the different concepts. In order to develop dual-fuel aircraft concepts, the design process was started with a reference aircraft, that is a model with geometry and performance similar to those of an existing aircraft. This procedure is used to calibrate the design architecture. From the reference aircraft, several technology assumptions were made to account for the technological advancements, especially production-wise, that may occur in the next years. The result of this type of study is a baseline aircraft designed for Entry Into Service (EIS) in 2040. As shwon by [9], building a Baseline with same EIS as the main design object (in this case the dual-fuel aircraft) is a necessary step to evaluate future technologies and concepts.
With the technology status levelled to the chosen EIS year, the design of a concept powered on liquid hydrogen, by mean of direct combustion, was carried out. In parallel, two tankering variants of the same aircraft were realized. Once the pure LH_2 concepts have been designed, the process has finally led to the design of dual-fuel concepts. The following paragraphs will show a more detailed explanation of the design steps described above, and display the modifications made passing from one concept to another, as well as some key performance indicators to compare the different models.

3.1. Reference Aircraft

Calibrating the design workflow with a reference aircraft is an essential first step in aircraft design, making sure that the results later obtained are consistent and reliable. The starting point of this work is the reference aircraft D239, widely used within DLR studies and in particular in the EXACT project [10]. The D239 was designed with similar Top Level Aircraft Requirements (TLARs) as the A321neo, and it could be defined as a DLR interpretation of it. Some of the key features of the aircraft are listed in Table 1. The geomerty of the D239 is shown in Figure 2.

Parameter	Value	Unit
Fuselage Length	44.51	m
Fuselage Diameter	4.045	m
Wingspan	35.8	m
MTOM	94227	kg
OEM	51114	kg
Max Payload Mass	25000	kg
Fuel Capacity	18642	kg
Fuel Type	Kerosene	-
Design Range	2500	NM
Number of Engines	2	-
Engine Type	Turbofan	-

TAB 1. Reference aircraft data

3.2. Baseline Aircraft

The main parameters of the baseline aircraft D239B are listed in Table 2. The geometry views of the concept are shown in Figure 3.

Parameter	Value	Unit
Fuselage Length	43.41	m
Fuselage Diameter	4.045	m
Wingspan	42	m
MTOM	84110	kg
OEM	47306	kg
Max Payload Mass	25000	kg
Fuel Capacity	18968	kg
Fuel Type	SAF	-
Design Range	2500	NM
Number of Engines	2	-
Engine Type	Turbofan	-

TAB 2. Baseline aircraft data

The design process that lead to the D239B with EIS in 2040 can be described as divided in three types of modifications applied to the reference aircraft in order to adapt it to the future technology. Regarding the evaluation of the magnitude of the impact of technology improvement, it is essential to estimate the technology status of the starting product, which is that of the D239: from a general point of view, the most relevant (and easily available) information to be retrieved is the manufacturing year of the aircraft, that reflects its technology status. For the A321neo, this corresponds to 2014. This information allows to understand the level of advancement of the technology used for the production, and hence estimate the extent of the gap that has to be filled in order to reach the desired level, tightly bound to the chosen EIS year. In the following paragraphs, the modifications applied, as well as the logic behind them, will be analized. The study will then result in a new aircraft, the D239B (Baseline), which represents the projection of the D239 in 2040.

3.2.1. Weight Reduction

One of the main figures affecting aircraft performance is its weight. Weight can be subjected to a remarkable reduction if traditional metallic materials like aluminum and titanium are replaced by composite materials. Taking into account the technology status of the reference aircraft, the starting point is already including a small presence of composite materials (around 15%). When calculating the final percentage of composite materials used in the production of an aircraft for EIS in 2040, the initial value has to be considered, so that the choice of the final percentage does not lead to an overestimation. For this study, it was assumed that by 2040, a presence of 60% of composite materials for the whole aircraft [11].
The weight reduction was applied to wings, fuselage and tail-planes. Each one of these components has a different structure, so the substitution of traditional metal alloys with composites can lead to a heteroge-

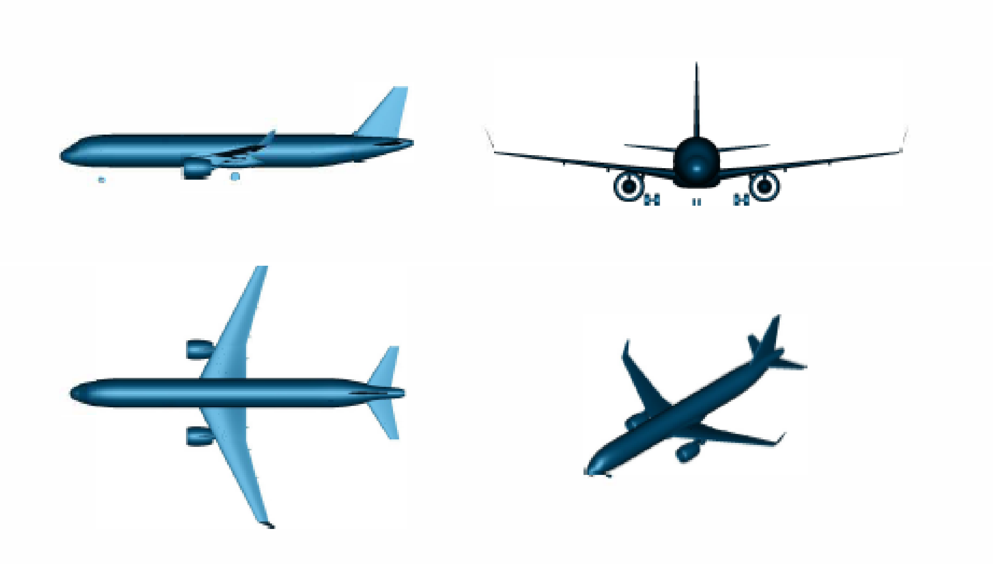

FIG 2. Left, front, top and axonometric views of the D239

neous weight reduction. For a switch from 100% alloys to 100% composite materials for each component, the weight reduction factors in Table 3 were identified [11].

Component	Weight Reduction
Wing	-20%
Htp	-25%
Vtp	-25%
Fuselage	-25%

TAB 3. Weight reduction due to composite materials usage for wings, horizontal tailplane, vertical tailplane and fuselage

At this point, the EIS year becomes relevant. These factors refer to a complete substitution with composites, but as previously mentioned, the reference aircraft already includes a small amount of composite materials, and also the final value aimed is not 100%, but 60% of composites usage. To account for both these two factors, the following formula was developed:

$$F = (1 - 0.6) + 0.15 + ((0.6 - 0.15) * f) \tag{1}$$

Where F is the total mass reduction factor applied to the corresponding component mass estimation method, and f is the component mass reduction identified in Table 3 (e.g. for the wing, that has a mass reduction of -20%, f = 0.8). The formula is written so that the different contributions stand out: the first term (1-0.6) indicates the percentage of the aircraft that will not be substituted with composites by the EIS year, the second term (0.15) refers to the amount already included for the reference aircraft, and the third term (0.6-0.15) accounts for the effective modification made for the baseline. The final total mass reduction factors applied to each component are summarized in Table 4.

Component	Weight Reduction Factor
Wing	0.91
Htp	0.8875
Vtp	0.8875
Fuselage	0.8875

TAB 4. Weight reduction factors applied to each component

3.2.2. Wing Modifications

Another important change that has been applied to the reference aircraft is in the wing span: it has been increased from a starting value of 35.8 to 42 meters. The wing span increase leads to an improvement in the aerodynamic efficiency. However, to make sure the aircraft is still compliant to the same airport category, a wing folding mechanism was also included. However, since this increases the complexity of the wing structure, the winglets have been removed to balance this effect.

3.2.3. Fuel, Gas Turbine Efficiency and Skin Friction

The propulsive system has also been subjected to modifications. First of all, the fuel type has ben changed from conventional kerosene (Jet-A1) to SAF (Sustainable Aviation Fuel), mainly for a reduction of CO_2 emissions. Moreover, by assuming that the technology level will raise by 2040, but also as a consequence of the choice of a different fuel, the efficiency of the gas turbine has been increased of 5%.
Still talking about improvements due to reasonably supposed future advancements, an enhancement in production technologies, combined with the use of composite materials that don't need rivets and bolts, a reduction of the skin friction drag has been

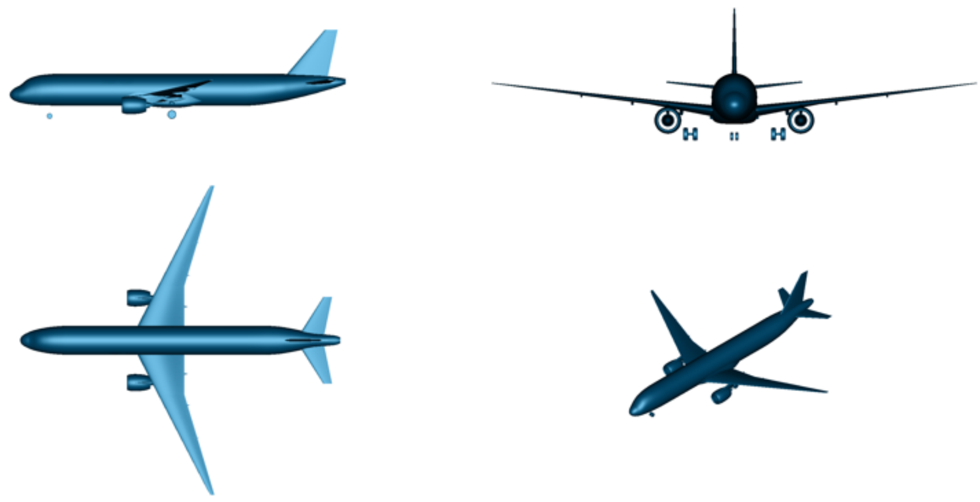

FIG 3. Left, front, top and axonometric views of the D239B

included, by applying a factor of -2% to the zero-lift drag coefficient (C_{D0}).

3.3. Liquid hydrogen powered aircraft

The pure LH_2 concept D239B-LH2 has been designed starting from the baseline aircraft. Again, several modifications have been applied in order to achieve the final design of an aircraft that relies on liquid hydrogen as energy carrier.

3.3.1. Modifications

The first thing that comes into mind when thinking of moving to a new type of fuel, is the storage of it, and how it can affect the whole design process. Given that, in order to have redundancy for safety reasons, the tanks have to be two, for a short-medium range aircraft the best choice for the integration of the LH2 tanks is that of having them in the rear section of the fuselage. This configuration is much easier to integrate, compared to that of having one tank in the frontal section and one in the back, for multiple reasons. Firstly, having tanks close together allows for simpler fuel lines, valves, and pressure management systems, which reduces weight and system complexity compared to running cryogenic lines across the aircraft. Secondly, the rear fuselage is typically further away from passengers and crew, which is ideal for storing cryogenic hydrogen. It makes it easier to contain and manage in case of a leak or failure. Finally, if one of the two tanks is integrated in the front part of the fuselage, the cockpit position could likely change in order to fit the tank, and this could come along with the need of a more complex pressurization system.
Since the fuel is not stored in wings as for kerosene aircraft, there will be no wing bending relief due to the weight of the fuel in wing fuel tanks. For this reason, more structural weight has to be added to the wings: a wing mass penalty of +5% with respect to the baseline aircraft due to fuel absence has been considered.
When it comes to the propulsive system, the choice of burning hydrogen instead of kerosene leads to several consequences. First of all, the specific energy of hydrogen is much higher than kerosene's, which means that for the same thrust output, less mass is needed. The combustion of hydrogen leads to a more complete burn, no CO_2 emissions and water vapor as the only emission product. Another key aspect is the flame speed: hydrogen has a higher flame speed, that allows for faster and more complete combustion [12]. These features have been accounted for in the aircraft model by increasing the efficiency of the gas turbine by +5% with respect to the baseline.
Going back to the integration of the tanks, their presence has led to an increase in fuselage length, while the fuselage diameter was kept fixed. Moreover, in order to simplify the integration in the rear section of the fuselage, the tailplane configuration has been changed from a conventional configuration to a T-tail, which moves the interface of the horizontal tailplane at the tip of the vertical tailplane, avoiding additional structural complexity in the fuselage tail cone due to the interfaces.
As far as performance is concerned, the range of the LH_2 concept has been reduced to 1500 NM. Keeping the range consistent with D239B (2500 NM) would have led to a further increase in fuselage length and weight, as it will be shown for the LH_2 tankering concepts.

3.3.2. LH2 Concept Results

The main parameters of the D239B-LH2 are shown in Table 5, coupled with a percentage variation with respect to the baseline aircraft.

Parameter	Value	Unit	Δ
Fuselage Length	50.3178	m	+ 16 %
Fuselage Diameter	4.045	m	+ 0 %
Wingspan	42	m	+ 0 %
MTOM	83128	kg	- 1.2 %
OEM	56696	kg	+ 19.9 %
Max Payload Mass	25000	kg	+ 0 %
Fuel Capacity	3756.7	kg	- 80.2 %
Fuel Type	LH2	-	-
Design Range	1500	NM	- 40 %
Number of Engines	2	-	-
Engine Type	Turbofan	-	-

TAB 5. LH_2 **aircraft data (Δ% w.r.t. Baseline)**

It can be seen that, even with a 40% design range reduction, the fuselage has to be longer for tanks integration and the MTOM is still comparable to that of the baseline. The weight of the tanks and of the different fuel system can be seen in the change in OEM, where the LH_2 concept appears to be about 20% heavier than the baseline. The views of the resulting model are shown in Figure 4.

3.4. Dual-Fuel Concepts

The design strategy for the Dual-Fuel aircraft concepts can be described as follows. The basic principle is to design the aircraft as a pure LH_2 model, with its LH_2 fuel system and tanks. Then a secondary fuel system for SAF is included, as well as wing tanks to contain the desired fuel mass. The result is an aircraft that has two separate fuel systems and storage tanks. The purpose of carrying such an additional mass is not to have an extended mission range, and so include an in-flight fuel switch, but to allow the possibility to use a different fuel, performing missions using SAF when for example hydrogen is not available at the airport. Following this logic, the amount of secondary fuel should be sized in order to have the possibility to reach a new destination, where the LH_2 tanks can be filled-up again. As previously mentioned, this scenario aims to depict a transition-to-hydrogen phase, where hydrogen is available to fly, but not all the airport facilities are ready to operate it yet.
The secondary fuel mass is described as simple additional mass in the sizing phase, and then allocated as fuel just in the post-processing mission calculation phase. When it comes to this step, for the way the secondary fuel is intended to be used, the hydrogen mission has already been executed, so there is a fraction of the maximum hydrogen mass that has been consumed.
Once again, the design workflow is capable of sizing a liquid hydrogen powered aircraft starting from a certain set of TLARs, including its design range. When it came to modify the workflow to allow the design for dual-fuel aircraft, it was decided to follow the same approach. Simply, after the LH_2 aircraft is sized, one could swap the hydrogen on board with the SAF, recalculate the mission performance due to the different fuel properties, and obtain as a result the *secondary* range capabilities for the secondary fuel. However, it was noted that due to the very different properties, using an amount of SAF equal in mass to the LH_2 would lead to very scarse range performance. Therefore, it was decided to introduce in the sizing of the dual-fuel concepts a certain delta, indicating the additional mass of SAF (w.r.t. the total mass of LH_2), so that the aircraft would be sized in order to be able to carry that additional mass when needed (during SAF powered missions). The mission range achievable with SAF is still an output in this case. Should be noted however that the theoretical max SAF mass is in practice never achieved as it is assumed that 30% of LH_2 remains in the tanks (which are never fully emptied).
To evaluate the potential of the dual-fuel concepts, and to identify a suitable value for the secondary fuel mass a trade study was set-up. Three aircraft concepts have been developed, differing just for this fixed additional SAF capacity value: 5, 7.5 and 10 tons of SAF have been used respectively for the three models. The nomenclature of the three concepts is based on the additional sizing mass of secondary fuel: DFS for the 5 tons models, DFM for 7.5 tons and DFL for the 10 tons one, standing for *Dual-Fuel Small, Medium, Large*.
Returning to the mission calculation for the SAF missions, since LH_2 can be considered partially consumed, a mass of SAF equivalent to that of consumed LH_2 has been added, in such a way that the total take-off mass (TOM) remains unchanged between the start of a LH_2 mission and that of a SAF mission, but the capabilities in terms of range of the second one are not limited to those prescribed by the initial fixed sizing mass value.
Geometry-wise, the dual-fuel concepts have been designed the same way as the hydrogen tankering concepts. With the LH_2 concept as starting point, what effectively changes from a model to the other is the mass of additional fuel. Additional fuel mass means additional weight, and hence more primary fuel needed (LH_2) for the design mission range and so larger tanks. This snowball-effect leads again to an increase of fuselage length, while the diameter remains fixed. However, the order of the weight addition occurred for the dual-fuel concepts leads to an increase in primary fuel mass that is quite low with respect to that caused by the increase of design range in hydrogen tankering concepts. The percentage increase of fuselage length with respect to that of LH_2 concept is +0.8%, +1.2% and +1.7% respectively for DFS, DFM and DFL concepts.

3.5. LH_2 Tankering Concepts

The Dual-Fuel concepts discussed in the previous section are designed to have the capability to run two separate missions, one using LH_2 and one using SAF. This was done in order to overcome the problem of limited availability of hydrogen at smaller airport

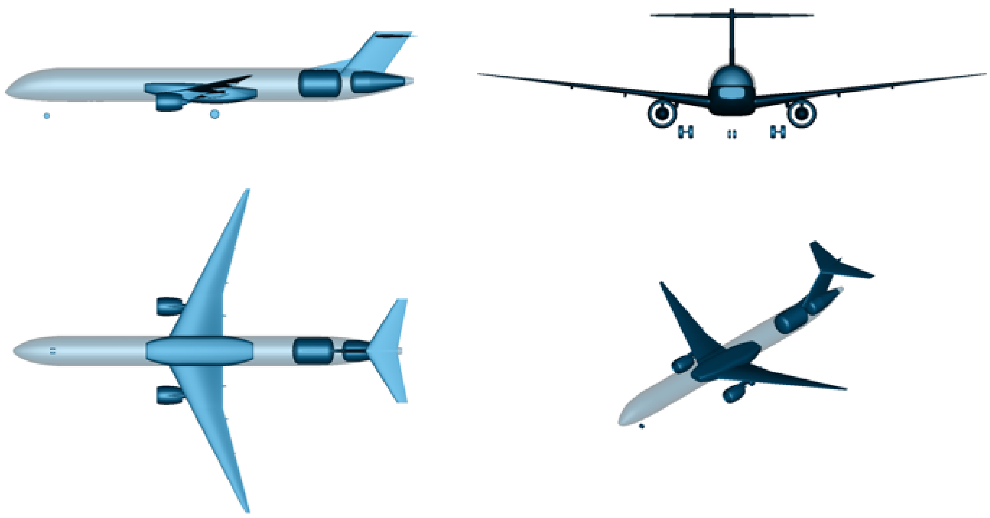

FIG 4. Left, front, top, and axionometric views of the LH2 concept

during the transition phase to full hydrogen based aviation.
In such a scenario, a pure LH_2 concept could not be operated, or at least not in full, due to the impossibility of refueling at certain locations. Therefore, in order to establish a fair comparison to evaluate the performance of a dual-fuel aircraft, some LH_2 tankering concepts needed to be designed. In aviation, for *tankering*, it is intended the loading of more fuel than the one required for the current mission, in order to perform later a second mission. In this case, we defined a tankering aircraft concept, as a pure LH_2 concept that is designed for a larger amount of fuel, in order to be able to perform two subsequent missions, each of length comparable to one typical short-medium range mission: 1000 - 1500 NM.
In particular, it was decided to design two models starting from the D239B-LH2, with no major modifications to the concept, but with an increased design range, set to 2000 NM and 2500 NM, respectively. This choice allows to compare the dual-fuel concepts on double missions, evaluating both fuel performances at once, against tankering concepts that can perform the double mission on LH_2 without refueling. The two tankering concepts will be addressed from this point on as *TM* (Tankering Medium, 2000 NM design range) and *TL* (Tankering Large, 2500 NM design range) while the D239B-LH2 will also be referred to as LH_2 concept for simplicity.

3.5.1. First Tankering Concept - 2000 NM Design Range

Since the tankering concepts are nothing else than the LH_2 concept with an increase of design range, Table 6 shows just the parameters that change from one concept to the other. The values for the tankering concept are reported, with a percentage variation with respect to the hydrogen baseline.

Parameter	Value	Unit	Δ
Fuselage Length	52.8025	m	+ 4.9 %
Fuselage Diameter	4.045	m	+ 0 %
MTOM	86496	kg	+ 4 %
OEM	59013	kg	+ 4 %
Fuel Capacity	4807.2	kg	+ 28 %
Design Range	2000	NM	+ 33.3 %

TAB 6. TM aircraft data (Δ% w.r.t. LH_2 concept)

The value of the fuselage diameter is reported to highlight the way the design is made: the aircraft geometry is kept fixed, except for the fuselage length, for which the 4.9% increase is due to the increase of hydrogen tanks length, due to the increased fuel capacity. The left view of both TM and LH_2 concept is shown in Figure 5 to highlight the fuselage length increase.

3.5.2. Second Tankering Concept - 2500 NM Design Range

The same is done for the TL concept. The relevant data is summarized in Table 7. The side view of the TL is also visible in Figure 5.

Parameter	Value	Unit	Δ
Fuselage Length	55.6327	m	+ 10.5 %
Fuselage Diameter	4.045	m	+ 0 %
MTOM	90820	kg	+ 9.3 %
OEM	62153	kg	+ 9.6 %
Fuel Capacity	5997.8	kg	+ 59.7 %
Design Range	2500	NM	+ 66.7 %

TAB 7. TL aircraft data (Δ% w.r.t. LH_2 concept)

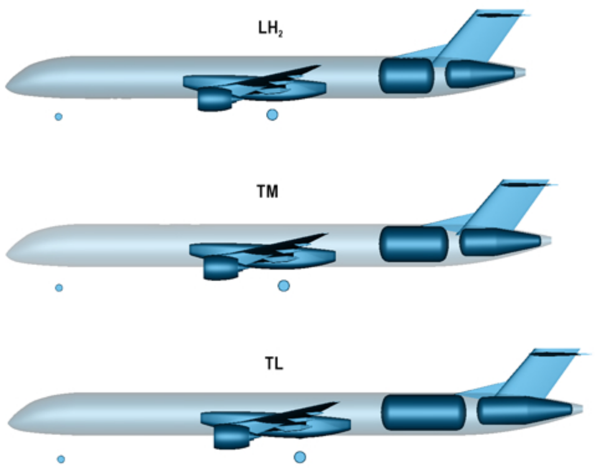

FIG 5. LH_2, TM and TL left views

4. RESULTS

In this sections the main results of the studies carried out on the dual-fuel concepts, as well as the comparisons with all the other concepts, are presented. The main KPI used for the results is the energy consumed over several calculated missions. This value will be addressed as specific energy or specific block energy, as described by the following formulas.

(2) $$E = m_{\text{fuel}}\, LHV$$

(3) $$SE = \frac{E}{m_{\text{Payload}}}$$

(4) $$SBE = \frac{E}{m_{\text{Payload}}\, R_{\text{B}}}$$

Since the purpose of the dual-fuel concepts is to operate in a transition-to-hydrogen phase, two main studies have been carried out: one on single missions (one way), and one on double missions, in which the possibility of an unavailable LH_2 refueling is highlighted. As for the single missions, all the concepts have been compared to the baseline aircraft concept for a general overview, but the most relevant studies to evaluate the performance of the dual-fuel option are those presented in the second part. There, the main mean of comparison for dual-fuel an tankering concepts is the LH_2 model, since the context of the study is that of the advent of hydrogen aviation.

4.1. Single Missions

Starting with the analysis of the specific block energy in single missions, the results have been retrieved by making a comparison between baseline aircraft, LH_2 concept, hydrogen tankering concepts and dual-fuel concepts. The mission calculation for the three dual-fuel concepts has been performed for both primary (LH_2) and secondary (SAF) fuel. The missions using hydrogen as energy carrier have been calculated considering two cases: when no SAF mass is carried during the mission (E, empty), and when a certain amount of secondary fuel mass is carried on board (not used), equal to the reserve fuel mass (R, reserve). This choice was done to higlith the differences between a scenario in which after flying a SAF mission the wing tanks could be emeptied to optimize performance of the LH_2 mission, and a second scenario where the reserve SAF is left in the tank after a mission, and therefore stays there during LH_2 missions.
In order to increase the forcefulness of the results, the results for every concept have been grouped in a single plot, and every value has been represented as percentage deviation with respect to the baseline aircraft in Figure 6.

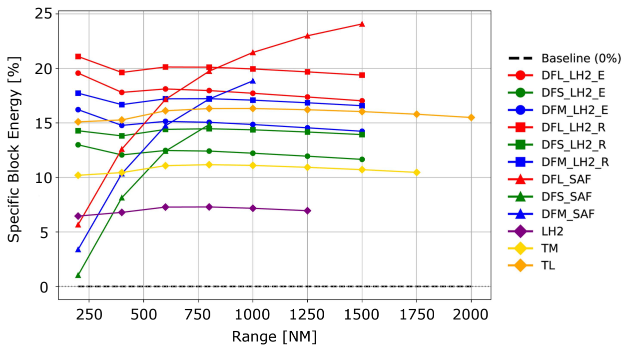

FIG 6. Δ_{SBE} [% w.r.t. Baseline] vs Range

Before making the effective comparisons, it is important to identify the couples to be compared: if the OEM is examined as an indicator of the size of the aircraft, DFS and DFL models can be respectively compared to TM and TL models, since the mass value is quite close, while the DFM concept is in between the two hydrogen tankering. Given this, it can be seen from the graphs above that as for single missions dual-fuel concepts have worse performance than tankering concepts.
Looking at the comparison couples identified, the energy efficiency of the dual-fuel concepts is about 5% worse than the tankering concepts one in the reserve-carrying case (values normalized to baseline energy). As for the 0% SAF carried case, dual-fuel energy efficiency is still worse than tankering, but the difference drops to a 2%, which might make it still a feasible option. Obviously, the pure LH_2 aircraft would be the best alternative, since it has no additional mass to be carried during the nominal mission, still being 7% less energy efficient than the SAF baseline for the mission ranges analized.

4.2. Double Missions

The single mission scenario offers, however, a limited comparison only, as the real benefit of the dual-fuel concepts (the possibility of operating on LH_2 even when this might not be available for refueling at the destination airport) is not captured. Here are then an-

alyzed several double-mission combinations, where pure LH_2 might not be able to operate due to the impossibility of refueling at the first destination airport, and the tankering concepts need to be loaded with enough fuel to perform both missions already at the first departure airport. Note that each double mission is intended as two separate complete missions.
With regards to the dual-fuel concepts, they have the advantage of relying on already available infrastructures, and will then only have the penalty to carry the reserve SAF during the first mission, in which primary fuel is consumed (LH_2). The rest of the secondary fuel, needed for the second mission (SAF driven), will be refueled at the first destination airport, at the end of the first mission. Note that for simplicity only the more realistic scenario in which the reserve SAF needs to be carried during LH2 missions is analysed here.
The results of the ideal case of using the pure LH_2 concept with the possibility to refuel hydrogen in the first destination airport will also be shown for reference, despite the practical impossibility for the pure LH_2 concept to perform such double missions in this scenario.
The first results take into account a fixed length of 750 NM for the first mission, while the range of the second mission is progressively increased. Starting with a 500 NM second leg, in Figure 7 it is represented the energy consumed per kg of payload over the distance. In Figure 8, these values are summed up to a total specific energy consumption over the two missions, for each concept.

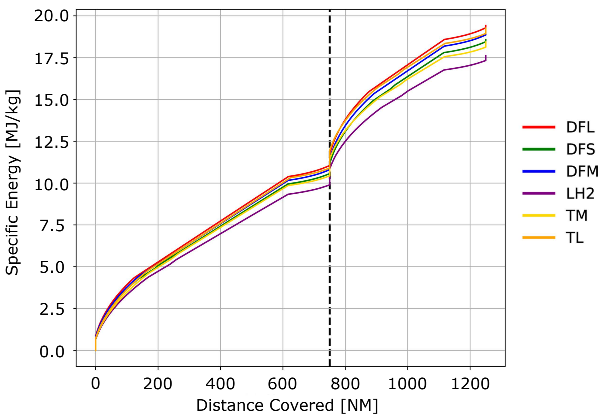

FIG 7. Specific Energy vs Distance Covered for 750 NM + 500 NM Mission

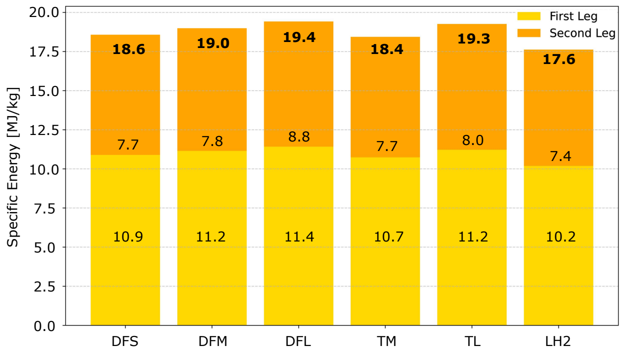

FIG 8. Total Energy per mission (750 NM + 500 NM)

As could be already seen for single SAF missions, SAF is more energy efficient for short ranges. In fact, as it can be seen in the detailed breakdown of the total specific energy consumption for each leg in Figure 8, the first 750 NM leg shows a small advantage of the tankering concepts, while in the second leg (500 NM) dual-fuel and tankering concepts have almost the same energy consumption. All in all, the total energy consumed for the double mission shows only roughly 1% worsening in dual-fuel energy efficiency with respect to the tankering concepts, calculated by normalizing the values to LH_2 concept energy consumption.
By increasing the range of the second mission to 750 NM two effects can be noticed: the worsening of SAF performance and the absence of the medium tankering concept (TM). In Figure 9 and Figure 10, it can be seen that the energy efficiency of SAF driven missions is lower when the range is increased. For this reason, the total energy difference between dual-fuel and tankering raises to circa 2%, making the dual-fuel concepts less efficient when compared to the tankering concepts according to the couples identified earlier. On the other hand, the smaller tankering concept is missing from the graphs, which means it is not capable of executing such a long double mission. It results that the tankering concepts are more negatively affected by range extensions under this point of view.

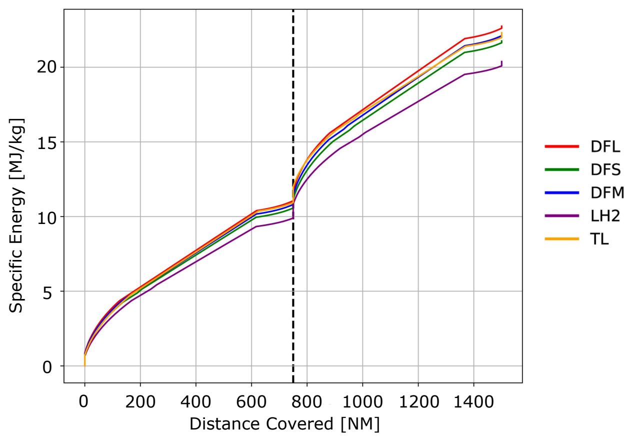

FIG 9. Specific Energy vs Distance Covered for 750 NM + 750 NM Mission

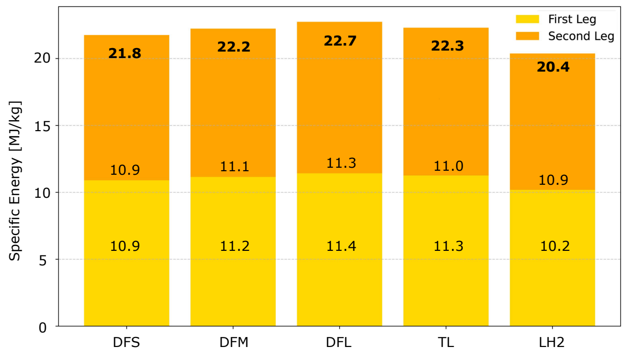

FIG 10. Total Energy per mission (750 NM + 750 NM)

By further extending the range of the second mission, the results in Figure 11 and Figure 12 are obtained. The two trends already seen for the previous case can be confirmed: a further increase in range for the second leg reveals further worsening of SAF based mission performance of the dual-fuel concepts w.r.t the tankering concepts. Secondly, the increased range is a limiting factor for the tankering options, and in fact the larger tankering (TL) could not tolerate any further range increase. Must be noted that at this longer range also the small dual-fuel concept (DFS) is not capable of mission execution.

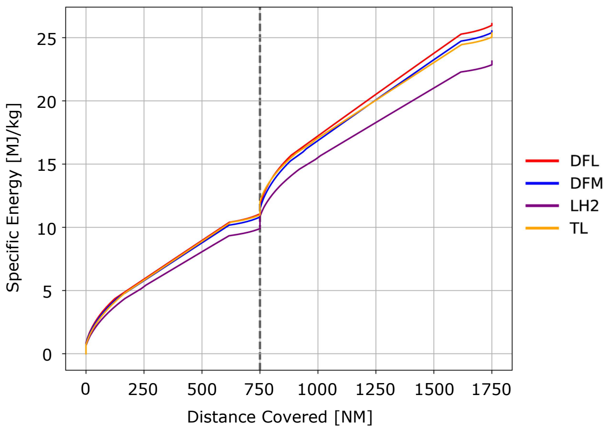

FIG 11. Specific Energy vs Distance Covered for 750 NM + 1000 NM Mission

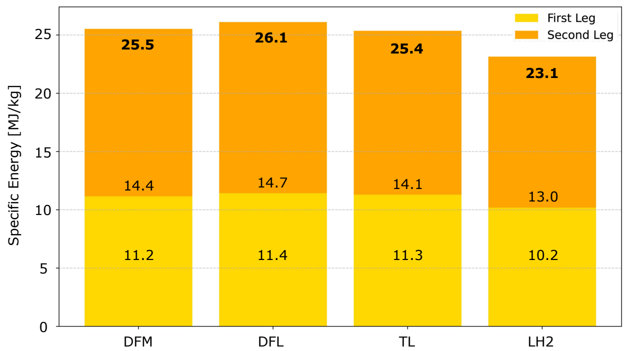

FIG 12. Total Energy per mission (750 NM + 1000 NM)

A second study provides the analysis of the total specific energy for the two summed missions, but this time the range of the first leg is varied from 500 to 1500 NM to capture the effects of range variation on the LH2 powered mission of the dual-fuel concepts. The results are also plotted for three different second mission ranges, respectively 500, 750 and 1000 NM to capture possible correlations.

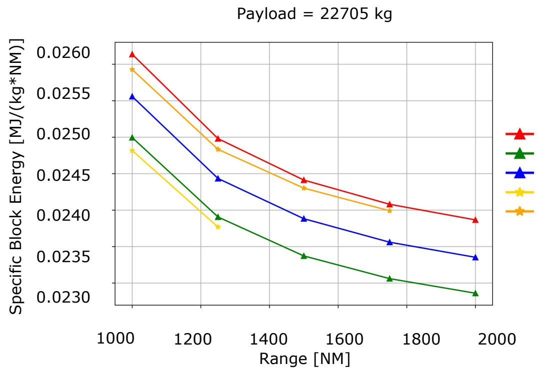

FIG 13. SBE vs Range, II leg 500 NM

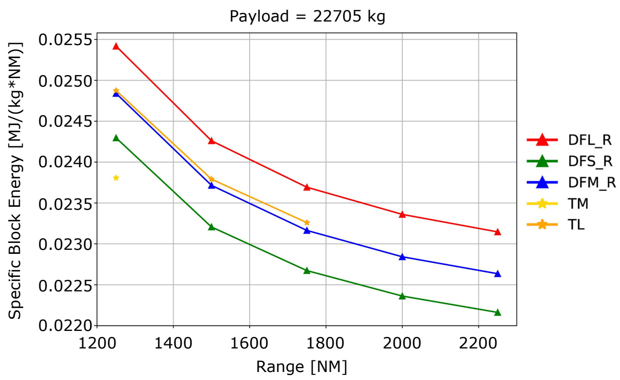

FIG 14. SBE vs Range, II leg 750 NM

FIG 15. SBE vs Range, II leg 1000 NM

The results in Figure 13, Figure 14, and Figure 15, show the clear range limitation faced by the tankering concepts. The limit for the TM concept is to have a total range below 1500 NM, while for the larger concept, TL, the limit is below 1800 NM. In contrast, dual-fuel concepts have wider range capabilities, since the energy consumption of the first mission is nearly not affected at all by the fuel needed for the second leg.

If higher ranges are to be reached with a tankering configuration, a much larger tankering aircraft would be needed, which would then not be as convenient as the dual-fuel concepts for this study. Furthermore, regulations should be kept in mind when analysing such scenarios. As for kerosene/SAF driven aircraft, the tankering option is limited by current regulation [13], because of the increased emissions it causes. No regulation has been presented yet for hydrogen aviation, but the possibility to have rules limiting hydrogen tankering must be considered. If this will be the case, in a transition-to-hydrogen phase, with the hydrogen tankering forbidden by hypothetical regulations, dual-fuel would be the only available option to operate in a transition scenario.

5. CONCLUSION

In this work the performance of a dual-fuel option for a future transition to hydrogen aviation has been evaluated. In order to provide an alternative solution to be compared with the dual-fuel concepts, two differently sized hydrogen tankering concepts have been developed.

The analysis has been carried out across mission profiles of differing ranges, both for single nominal missions and for double missions. In particular, for every mission the specific energy consumed by each concept has been evaluated, in order to retrieve comparison results in terms of energy efficiency.

The results indicate that hydrogen tankering could be the most energy-efficient alternative between the two for short-range missions, but its performance quickly worsen when the mission range is increased. For medium-ranged missions, dual-fuel configurations offer a mor suitable balance, providing operational flexibility and extending the achievable range for secondary missions when required by the impossibility to refuel hydrogen.

Overall, both the examined configurations demonstrate energy efficiencies with a worsening of around 10% with respect to the liquid hydrogen ideal case, which might be one of the key values to consider in the assessment of the viability of dual-fuel and hydrogen tankering solutions. While the present study provides a comprehensive initial assessment of dual-fuel and hydrogen tankering concepts, several areas remain open for further development and refinement.

5.1. Future work

A natural continuation of this work would be to design more optimized and accurately dimensioned hydrogen tankering aircraft. The current tankering models were developed with simplified assumptions for comparative purposes; however, a dedicated design loop that optimizes the tankering configuration specifically for extended reserve capability could provide more robust reference points for future comparisons.

In parallel, the dual-fuel aircraft design strategy could be revisited and refined. In the current implementation, the dual-fuel system is treated as a static backup option, with separate sizing phases for each mission. Introducing the possibility of an in-flight switch between LH_2 and SAF would significantly increase operational flexibility, enabling dynamic fuel management based on mission needs, unexpected diversions, or performance optimization. Implementing such a feature would require additional studies on propulsion system compatibility, fuel system integration, and flight control strategies under hybrid operation.

These future developments would provide a more complete understanding of the trade-offs between the proposed concepts and enhance the fidelity of the assessment. Additionally, they would contribute valuable insights for both aircraft designers and policymakers engaged in planning for a sustainable transition to hydrogen-powered aviation.

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