
# HYDROGEN TANKERING: TOOLS FOR ECONOMIC AND ENVIRONMENTAL IMPACT SCENARIO STUDIES

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## Abstract

Hydrogen-powered aircraft operations will be constrained by a slow roll-out of hydrogen refueling infrastructure across airports. Hydrogen tankering will enable flights to airports that have no hydrogen refueling capabilities, as long as the destination is within half of the operational range of the selected aircraft, at the cost of a slight increase in fuel burn. The proposed methodology aims to assess said increase, while minimizing the expenditure for hydrogen, and the coverage of a reference network, achievable considering aircraft performance and assumptions on the availability and cost of hydrogen at various airports. The results of such analysis can be used to determine whether a reduction of the design range of a given aircraft is acceptable. Such a reduction would mitigate the impact that the hydrogen tank has on the sizing of the aircraft.

**Keywords:** Hydrogen tankering, hydrogen-powered aircraft, aircraft preliminary sizing

## 1. Introduction

Environmental sustainability is the big challenge that commercial aviation is facing and will be facing in the next decades. In fact, aviation accounts for about 2% of man-made greenhouse emissions and for 12% of transport-related emissions [1]. A technological revolution is necessary, in order to allow the sector to comply with the Paris Agreement requirements by 2050. In this context, hydrogen is deemed as one of the best solutions to decarbonize air transport, specifically for short [2, 3] and long-range aircraft [4, 5], which would use hydrogen via direct combustion. Regional aircraft could also use hydrogen recurring to hybrid-electric architectures, in which hydrogen would be used by fuel cells to be converted into electricity [6]; this aircraft category could also recur to thermal hybrid-electric configurations, which could come to market sooner because of a higher TRL [6]. Besides research projects, there is also an emerging industrial interest in hydrogen-powered commercial aviation, such as Airbus ZeroE [7] and Universal Hydrogen [8]. Nonetheless, most of the research develops useful tools for the preliminary sizing of innovative, hydrogen-powered aircraft, without questioning much about whether the Top Level Aircraft Requirements (TLARs) should evolve from the current status quo, in order to minimize the impact of the energy carrier switch. In fact, parallel results [9] show that the switch to hydrogen causes an increase in the Energy Intensity (EI, that is the energy used to transport one passenger over a distance of 1 NM, measured in MJ/ASNM) by approximately 9% showing the need to reduce the negative impact. The energy increase is due to the elongation of the fuselage required to accommodate the cryogenic hydrogen tank (greater wetted surface) and of sub-optimal temperatures in the combustion chamber to maintain a suitable Turbine Entry Temperature, both causing an increase in the Thrust Specific Energy Consumption and thus on the overall mission energy.

The objective of the work introduced in this paper is to assess the impact of hydrogen tankering on economics and in terms of the extra consumption linked to this practice. Tankering is currently mainly practiced because of economic reasons, as there could be occasions in which taking more fuel at an airport where its price is low might cause savings to the airline, despite an increased fuel consumption because of a higher gross mass. Other instances of application of tankering might be

linked to strikes of refueling personnel or limited supply of jet fuel because of pipeline failures; such cases are extraordinary and not considered here.
Similarly, hydrogen tankering may offer economic savings, but, more importantly, could enable the operation of hydrogen-fuelled flights to destinations that do not have a hydrogen refueling infrastructure. In fact, the airline fleet turnover will cause concurrent operation of airliners using either kerosene or hydrogen, with hydrogen refueling infrastructure likely to be introduced initially at the largest hubs. Smaller airports would probably be involved at a later stage. Furthermore, the presented methodology allows to asses complete operational scenarios consisting in short and medium-haul flights out of a reference airport. The analysis gives interesting results in terms of the repartition into operable (eventually with partial tankering for economic reasons), operable with full tankering and not operable routes within the scenario, mostly depending on the Design Range (DR) of the aircraft.
Ch. 2 describes the context in which the presented work is developed, with a detailed formulation of the methodology presented in ch. 3. Ch. 4 shows the results of the methodology applied to different scenarios, with varying schedules, reference airports and hydrogen infrastructure availability.

## 2. Setting the Picture

Given a reference airport equipped with a hydrogen refueling infrastructure, there are five possible operational cases, which depend on the presence of hydrogen refueling infrastructure at the destination airport and on the design range of the aircraft that operates that particular flight. A short route is here defined as a route whose covered distance is less than half of the aircraft's operational range, meaning that the tank has enough capacity to contain hydrogen for both the outbound and inbound flights, with enough capacity for the regulatory reserves for both flights. The two-flight mission profile is shown in fig. 1, detailing the altitude and tank level as a function of time. Instead, a long route

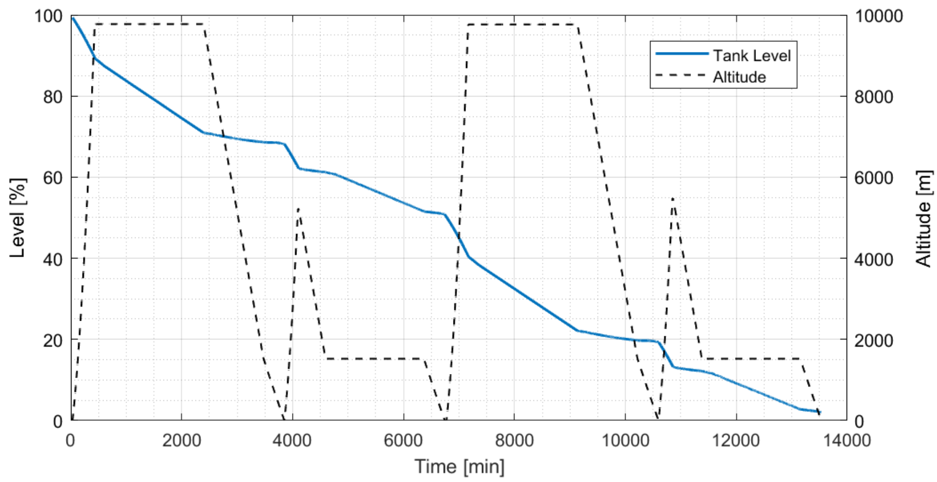



Figure 1 – Mission profile for the two-segment short route, with refueling only at the origin.

covers a distance that is longer than half of the operational range, meaning that the aircraft cannot operate the round trip with fuel only coming from the origin airport. The operational range is obtained from HYPERION [10] for each aircraft that operates a route in the considered scenario. The five operational scenarios are defined as the following five possible types:

1. **Short route with hydrogen refueling infrastructure at destination:** the aircraft can be refueled both at the reference airport and at the destination airport. The quantity of fuel bought at the destination airport is computed minimizing the overall expenditure for hydrogen for the return trip, with an eventual constraint on the additional hydrogen consumption caused by tankering on the outbound trip.

2. **Short route with no hydrogen refueling infrastructure at destination:** the return flight can be operated; all of the hydrogen required to operate the return trip is uplifted at the reference airport.

3. **Long route with hydrogen refueling infrastructure at destination:** the aircraft does not have the capability to operate the return trip only with hydrogen bought at the reference airport. Partial tankering can still happen, should the hydrogen price at the destination airport be significantly higher than that at the reference airport. In any case, it will be necessary to buy some hydrogen at the destination airport.

4. **Long route with no hydrogen refueling infrastructure at destination:** this city pair cannot be operated by the selected aircraft, as it cannot be refueled to operate the return flight.

5. **Destination further than the aircraft maximum range:** The reduction of the design range will prevent the operation of certain flights, whether the destination airport has hydrogen infrastructure or not.

These five possible cases are represented in Figure 2, highlighting that airports that have no hydrogen refueling infrastructure and are further than half of the operational range of the selected aircraft cannot be served with nonstop flights. The developed methodology has the objective of quantifying

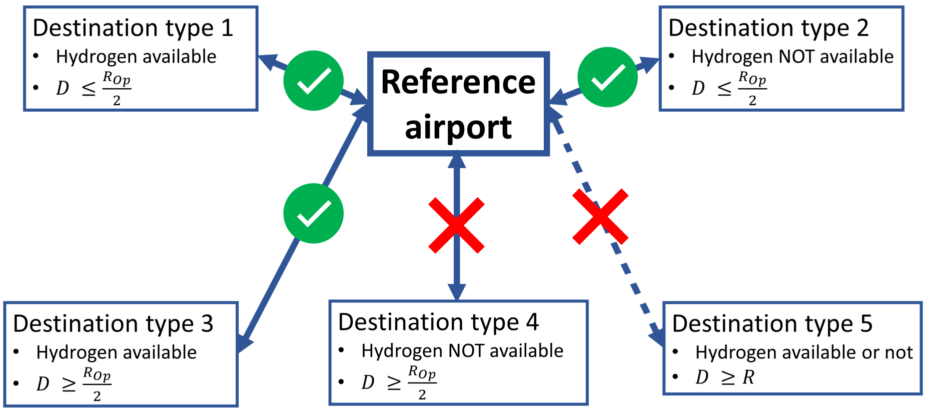



Figure 2 – Representation of operational scenarios.

the impact of hydrogen tankering, in terms of increased fuel consumption, but more importantly in terms of improved versatility for the operation of hydrogen-powered aircraft, which can be used to partially serve airports that have no hydrogen refueling infrastructure.

## 3. Methodology

Fuel tankering is a practice whereby an aircraft carries more fuel than required for its flight to reduce or avoid refueling at the destination airport, as defined by EUROCONTROL [11]. This practice is currently carried out to reduce the airlines' expenditure for fuel, despite the greater environmental impact caused by increased fuel consumption due to flights being operated with more than the strict necessary fuel amount. For future hydrogen-powered aircraft, the practice of tankering can also enable operations in airports not equipped with refueling infrastructure, depending on the performance of the aircraft and the distance between the departure and destination airport.

The proposed methodology takes as input aircraft performance, in terms of hydrogen consumption and DR, and hydrogen availability and cost at different airports. Given a series of flights departing from the reference airport, operated by different aircraft with different performance, the code matches each flight with its corresponding operational case, out of the five presented in Section 1. For routes of types 2 and 4, the solution is trivial: all of the refueling happens at the reference airport and the city pair cannot be served with the selected aircraft, respectively. For destinations of types 1 and 3, the optimization is based on the minimization of the round trip hydrogen cost, eventually subject to constraints on the maximum percent extra hydrogen burn in case of tankering, and others. Routes of type 5 can only appear if the scenario is run considering aircraft with a reduced design range compared to the real Top Level Aircraft Requirement (TLAR).

The output shows the total expense for hydrogen at the reference and destination airports, the extra hydrogen consumed because of tankering and how many flights of the considered scenario can be operated considering the hydrogen availability constraint. It is possible to study different hydrogen refueling infrastructure distribution scenarios and the corresponding route coverage, to assess whether it is possible to reduce the DR of the aircraft, allowing for a smaller hydrogen tank to be installed.

The methodology introduced here is built based on previous research efforts, most notably in the context of the Clean Sky 2 project SIENA [12], which have led to the development of novel methodologies dedicated to the most fundamental elements at play: the hydrogen-powered aircraft and the airport hydrogen infrastructure sizings.

The first, mainly implemented in the HYPERION tool, provides a procedure for the preliminary sizing of innovative aircraft, including fuel-cell propeller-driven airplanes and hydrogen-burning jetliners. HYPERION has been extensively validated and then used to size hydrogen-powered airliners, whose Top-Level Aircraft Requirements are the same as those of existing aircraft. The second, implemented in the AHRES tool, allows to preliminarily size the hydrogen production, storage and refueling infrastructure at an airport, given a defined flight schedule. A greater utilization of AHRES could allow an expansion of the presented work, most notably in terms of analyses concerning the transient linked to the entry into service of novel hydrogen-powered aircraft. Both methodologies are illustrated in a companion paper submitted at ICAS 2024 [9].

The present contribution represents an example of the investigations allowed by coupling the above-mentioned tools. Here, HYPERION results are fed into AHRES, to obtain the required hydrogen uplift for each flight of the scenario. In fact, once the preliminary sizing of the aircraft is achieved, HYPERION allows to simulate any off-mission, given specific initial conditions. These results are used to compute the hydrogen required to perform a given flight and the extra consumption linked to tankering.

## 3.1 Implementation and Mathematical Formulation

The solution is set as a minimization problem, where the cost function is represented by the sum of the hydrogen expense for each return trip $i$ of the analyzed scenario. Thus, the minimum cost for the entire assessed operational scenario comes as the sum of the optima for each round trip. The tool first associates each destination and operating aircraft to the corresponding category, out of the five presented in the previous section. The methodology takes as main input the scenario schedule, consisting of the list of flights detailing the destination, the distance from the reference airport and the operating aircraft. An aleatory Load Factor (LF) between 55% and 100% is also associated to each flight. The considered schedules cover the busiest day of the year 2023, as shown by Eurocontrol data [13] at some large European airports: Paris C. de Gaulle on 23/08/2023, Amsterdam Schipol on 05/10/2023, Milan Malpensa on 18/09/23 and Lisbon on 17/05/2024. Amsterdam and Paris have been selected as they are the largest airports in the EU. Milan Malpensa has been selected as two important stakeholders, the airport operator, SEA [14], and one of the most present airlines, easyJet [15], have shown significant interest in adopting sustainable hydrogen-based solutions to make air transport greener. The Portuguese scenario has been included to assess a case study that could expose the weakness of the proposed methodology when applied to decentralized airports. Precise information regarding the schedule, including frequency and operating aircraft, was obtained from the API Flight Labs [16].

### Aircraft hydrogen consumption

Only short- and medium-haul flights are considered in this study. The most common aircraft that operate such missions have been modeled on HYPERION [12, 9], considering the original TLARs: the Airbus A320 family, including the A319, A320, A321, the Airbus A220-300, the Boeing 737-800 and the Embraer 190. HYPERION gives various information regarding the aircraft layout, performance, and thrust, but the sized aircraft can be deployed on a mission simulator, which allows computing its performance on off-design missions. This feature has been used to obtain look-up tables for the

| Tank Level [%] | 17.1 | 22.5 | 33.4 | 44.5 | 56.72 | 67.1 | 78.54 | 90.4 | 100 |
|---|---|---|---|---|---|---|---|---|---|
| Distance [km] | | | | | Fuel [kg] | | | | |
| 200 | 406 | 408 | 414 | 420 | 427 | 431 | 437 | 444 | 448 |
| 500 | | 717 | 722 | 728 | 734 | 740 | 746 | 752 | 756 |
| 1000 | | | 1356 | 1367 | 1377 | 1386 | 1397 | 1407 | 1417 |
| 1500 | | | | 2001 | 2018 | 2031 | 2046 | 2060 | 2074 |
| 2000 | | | | | 2654 | 2673 | 2692 | 2711 | 2728 |
| 2500 | | | | | | 3313 | 3333 | 3360 | 3379 |
| 3000 | | | | | | | 3976 | 4003 | 4029 |
| 3500 | | | | | | | | 4648 | 4677 |
| 4000 | | | | | | | | | 5323 |

Table 1 – Hydrogen consumption as a function of flight distance and initial tank level for the A320H with 100% payload.

fuel consumption of the aircraft, given a route length and an initial tank level equal to or more than the minimum level, including reserves, needed to complete the mission. Table 1 shows the hydrogen consumed to perform a flight of a given distance with different initial tank levels, considering a hydrogen-powered aircraft sized according to TLARs matching the performance of the Airbus A320. The values reported on the diagonal of the matrix show the amount of hydrogen required to perform the mission with an initial filling equal to the amount of fuel needed for the mission and 5% of the reserves, whereas by moving to the right, the required hydrogen increases with the initial filling of the tank.
Such tables have been obtained for each aircraft type, with different payload levels (100%, 85%, 70% and 55%). A linear interpolation across them is performed to obtain the fuel consumption table associated with the payload level of each route. Then, a proper Non-Linear Least Squares Method [17] allows to estimate the fuel consumption for flight distances longer than 500 km. For shorter flights, linear interpolation is used.

### Minimization problem

The minimization function is shown in eq. (1):

$$C = \sum_{i=1}^{N} (C_{H2,Origin} F_{Origin} + C_{H2,Dest} F_{Dest})_i \tag{1}$$

The objective function is subject to some constraints that vary from case to case. The most interesting are the ones for case 3, presented in eq. 2.

$$\begin{cases} F_{Req} + F_{Div} R_{Div} \leq F_{Origin} \leq T_{aircraft} \\ 0 \leq F_{Dest} \leq F_{Req} + F_{Div} R_{Div} \\ 2F_{Req} + 2F_{Div} R_{Div} \leq F_{Origin} + F_{Dest} \\ F_{Origin} - F_c(D, F_{Origin}) + F_{Dest} - F_c(D, F_{Origin} - F_c(D, F_{Origin})) + F_{Dest}) = 2F_{Div} R_{Div} \\ \dfrac{F_c(D, F_{Origin}) - F_{Req}}{F_{Req}} \times 100 \leq T \end{cases}$$
(2)

where:

- $C$ : is the total fuel price for the scenario and represents the objective function [€].
- $C_{H2,Origin}$ : is the fuel price at the airport of origin [€].
- $C_{H2,Dest}$ : is the fuel price at the destination airport [€].

- $F_{Origin}$ : is the fuel amount carried from the airport of origin [kg].
- $F_{Dest}$ : is the fuel amount carried from the destination airport [kg].
- $F_{Req}$ : is the minimum (i.e. no tankering) required fuel amount to fly each leg of the round-trip. It is computed by interpolating the diagonal of table 1.[kg].
- $F_{Div}$ : is the fuel amount required to perform one diversion [kg].
- $R_{Div}$ : is the diversion rate. This is a surrogate to account for the reserve fuel. Rather than accounting for $R_{Div}$% of flights using the full reserve fuel, all flights are considered to use $R_{Div}$% of the reserve fuel. This factor is equal to 5% for the considered scenario [%].
- $T_{aircraft}$ : is the aircraft maximum tank capacity [kg].
- $T$ : is the limit threshold set on the extra fuel burn [%].

The first and second equations of system 2 represent the lower and upper bounds on $F_{Origin}$ and $F_{Dest}$, whose satisfaction automatically satisfies the third equation. The fourth and fifth equations introduce the nonlinearity linked to the fuel consumption as a function of distance and initial tank level. In the equality constraint, the remaining fuel at the end of the round-trip is imposed equal to the quantity $2F_{Div}R_{Div}$. This constraint is used to compute the optimal fuel weights to be carried from the airports, while accounting for the diversion fuel amount as well. The last inequality constraint ensures that in case the first flight of the round trip carries more fuel than the required amount, the extra fuel burn due to the increase in fuel weight is limited by the factor $T$, set equal to 1% for the presented results.

**Hydrogen pricing model**

The hydrogen pricing model for the different airports used in this work is explained in detail in both [18, 19]. The first paper thoroughly analyses different ways of supplying hydrogen to airports, namely on-site production, considering various energy sources, and off-site production, with transport via LH2 or GH2 pipelines. The on-site production was identified as the most convenient at least for larger airports, validating the approach and results of AHRES, presented in the parallel paper [9]. The second paper presents, among other things, a list of airports and relative expected hydrogen prices and supply methods. The short- and medium-haul destinations out of Milan Malpensa are shown in fig. 3: the circles represent airports that are equipped with a hydrogen infrastructure according to [19], with the color representing the price of 1 kg of hydrogen, spanning between 1.97 €/kg at Dublin and 2.97 €/kg at Krakow; the black asterisks represent the destinations that are not expected to have hydrogen available. A different hydrogen distribution scenario has also been analyzed, considering only the airports with more than 10M passengers in 2019, marked by pink circles in fig. 3. This analysis is a preview of a broader assessment of the transient linked to the introduction of novel aircraft, which will see a growing number of airports be equipped with hydrogen refueling infrastructure and a larger percentage of hydrogen-powered aircraft as the time advances.

## 4. Results

This chapter details the results obtained from the application of the methodology to different scenarios, with the objective of assessing the extra fuel burn linked to tankering and the coverage of a given route network, given aircraft with different DRs.

### 4.1 Definition of the scenarios

The methodology has been applied to various scenarios in which all flights have been considered to be operated by the Airbus A320 various hydrogen-powered counterparts, sized with HYPERION. Particularly, all the TLARs remained unchanged, except for the design range at maximum payload, which changed from the original 3770 km to 4000 km, 3000 km and 2000 km. A further version, based on a DR equal to 2450 km, has also been considered, as it corresponds to the maximum round trip range of 981 km, value that represents the average stage length for European flights in 2020, as pointed out by Eurocontrol [20]. An objective design range of 2000-km has also been identified for

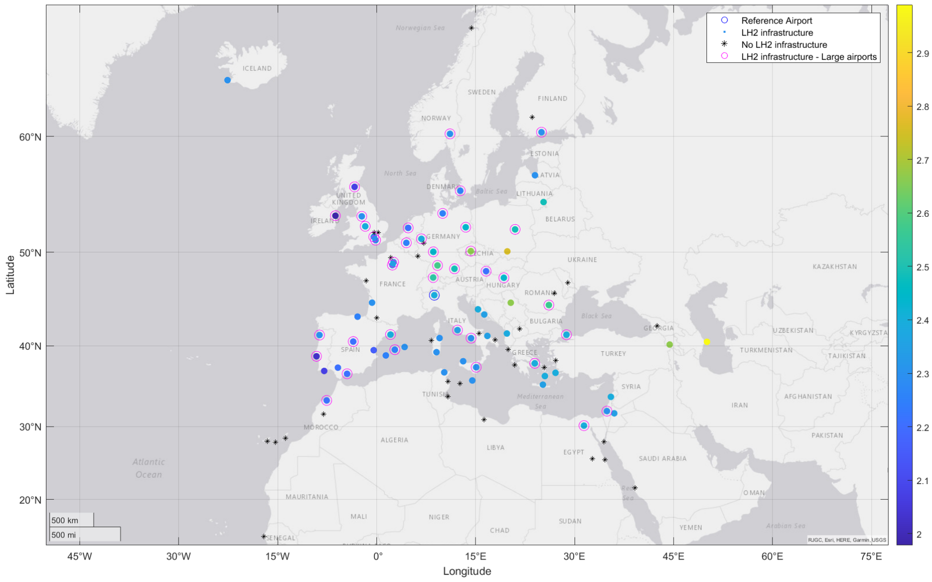



Figure 3 – Hydrogen infrastructure availability and price for the short-medium range network out of Milan Malpensa.

the Horizon Europe EFACA project [21], which, among others, aims to develop a 150-seat hydrogen-powered aircraft, showing how a reduction of the design range compared to current levels is a valid pathway. Note that the mentioned ranges are the true ranges, as a 150-km diversion and 30 minutes of loiter are also considered. Information resulting from the preliminary sizing of the different aircraft and relevant for the current analysis are shown in table 2.

| **Aircraft** | **Real TLARs** | **DR4000** | **DR3000** | **DR2450** | **DR2000** |
|---|---|---|---|---|---|
| **Design Range [km]** | 3770 | 4000 | 3000 | 2450 | 2000 |
| **Max RT Range [km]** | 1650 | 1720 | 1250 | 981 | 760 |
| **Tank capacity [kg]** | 5726 | 6131 | 4512 | 3706 | 3074 |
| **Reserve hydrogen* [kg]** | 544 | 551 | 535 | 528 | 522 |
| **Reserve hydrogen [%]** | 9.5 | 9.0 | 11.9 | 14.2 | 17.0 |

* Reserve including 150 km to alternate airport and 30 minutes of loiter.

Table 2 – Data for aircraft with modified DR.

The methodology has first been applied to Milan Malpensa for the schedule of 18/09/2023 (busiest day of the year 2023), consisting in 260 short and medium-haul flights. Figure 4 shows the design range and the maximum round trip range out of Milan Malpensa for aircraft sized with a 2000-km, 3000-km and 4000-km DRs. The curves corresponding to real aircraft and the 2450-km design range are not shown here for better clarity, as the former almost coalesces with the green curves and the latter is halfway in between the blue and red circles, in a region in which the Mercator distortion is not yet very pronounced. Looking at the curves, it is clear that a 3000-km DR aircraft (red circle) covers all of Europe from a very central airport as Milan Malpensa, making such a DR sufficient for European operations, assuming a good availability of hydrogen refueling infrastructures. The maximum range for single refueling return trips associated to the 3000-km design range also offers a decent coverage of continental Europe, with the exception of Scandinavia, Portugal, Ireland and Greece.
This initial overlook shows how the location of the reference airport impacts how limiting the chosen DR and associated maximum range for single refueling return trips are. For this reason, it was decided to assess how the same preliminary-sized aircraft behave when deployed on other scenarios, namely the short and medium-range flights of Amsterdam Schipol (schedule of 05/10/2023, 566 flights), Paris Charles de Gaulle (23/08/2023, 473 flights) and a more decentralized airport such as

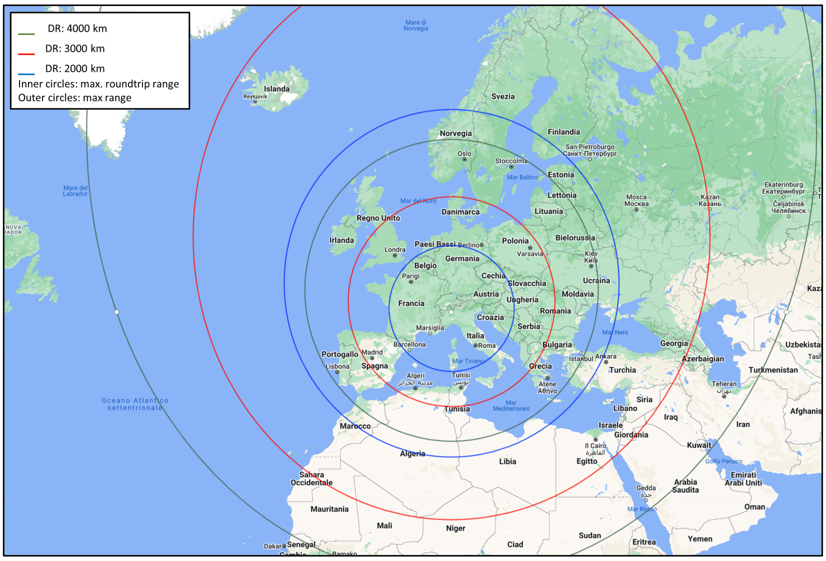



Figure 4 – Design range (outer circles) and maximum range for single refueling return trips (inner circles) for aircraft with a 2000 km (blue), 3000 km (red) or 4000 km (green) design range.

Lisbon (17/05/2024, 223 flights).

## 4.2 Milan Malpensa

The international Milan Malpensa Airport (LIMC), Italy, is taken as the reference airport for the results presented here, with a reference hydrogen price set equal to 2.39 €/kg. The route network, including 260 return trips has been simulated considering the Airbus A320-like hydrogen aircraft with the original design range and with four other design ranges. Furthermore, the aircraft with a 2450-km design range, and a corresponding maximum range for single refueling return trips equal to the average length of European sectors, has been deployed also on a different hydrogen distribution scenario, which sees only airports with more than 10M yearly passengers having hydrogen refueling capabilities. The resulting route categorization for each assessed scenario is presented in fig. 5. Routes in yellow (dark and light) are the ones that cannot be operated given the particular coupling

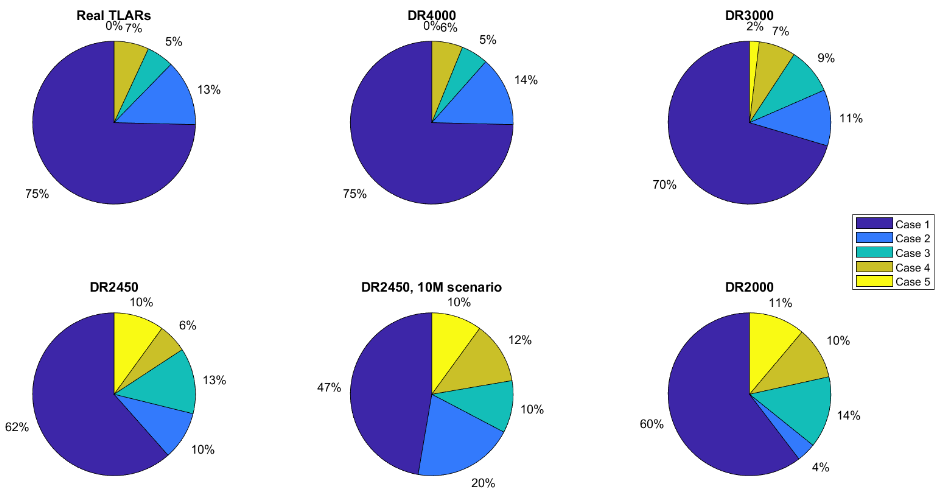
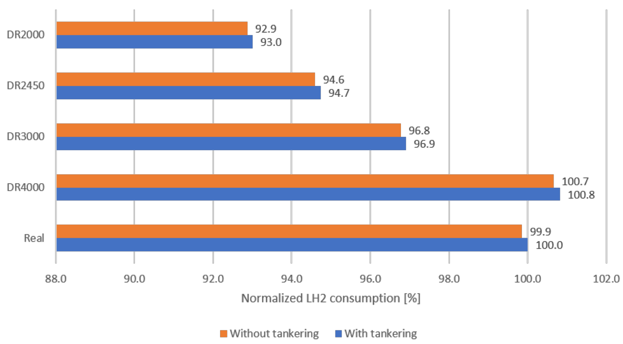


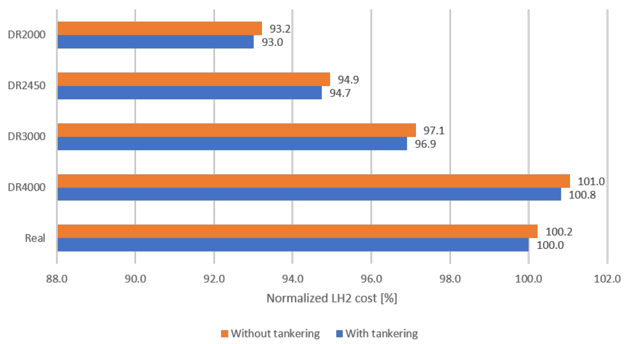

Figure 5 – Route categorization at Milan Malpensa with aircraft with different design ranges.

of aircraft performance and hydrogen distribution scenarios. There is almost no difference between the real TLAR and the 4000-km DR scenarios with 7% and 6% of not operable flights, as the latter sees aircraft with a slightly larger DR, making a few flights move from category 4 to category 2. The

reduction of the DR to 3000 km, 2450 km and 2000 km causes, as expected, the insurgence of flights belonging to category 5 and an overall increase of flights that cannot be operated, adding up to 9%, 16% and 21% respectively. It is also interesting to notice the important impact of having only large airports (>10M passengers per year) being equipped with hydrogen refueling infrastructure; in this case, up to 22% of flights are not operated. Given these results, it might seem that the reduction of the design range of hydrogen-aircraft might be too constraining for real-world operations, given that between 6% and 22% of flights need to be canceled. Nonetheless, this analysis concerns the first generation of hydrogen-burning jet aircraft, which will be operating side by side with current kerosene airplanes, such as the Airbus A320NEO and Boeing 737 MAX families, able to take up those missions that novel hydrogen-planes cannot operate. In fact, as suggested by [22], planes have a 30-year long lifespan; historically, the plane retirement age has not been affected by more stringent air quality and noise regulations, but only, by a sudden increase of fuel prices. It will be necessary to evaluate if the change of energy source affects the fleet turnover dynamics.
Tankering in itself is more of an operational aspect, rather than something usually considered in the pre-design phase; nonetheless, the results of this analysis, in terms of design range associated to the operable percentage of the existing flights of the considered schedule, could be used as an input to perform an educated reduction of the DR, before the aircraft project is finalized. This is extremely relevant, as the design range of a hydrogen aircraft is strongly coupled with the sizing of the aircraft itself. In fact, a longer design range causes a longer hydrogen tank, which in turn causes a further elongation of the fuselage, deteriorating the aerodynamic performance of the aircraft and thus its energy efficiency. Instead, the coupling between aircraft sizing and design range is not nearly as strong for conventional jet-fuel-powered aircraft, as generally speaking, the wing is sized to guarantee a certain level of low speed performance, making enough volume for the fuel tank available. A clear evidence of this can be found in fig. 6a, which represents the normalized hydrogen consumption for all and only the flights that can be operated by DR2000 (79% of the flights), considering a case in which tankering is applied (blue bars) or not (orange bars, this assumes that hydrogen is available everywhere). The reference fuel consumption is the one of the operations of the aircraft with the real range TLAR, with tankering. Similarly, fig. 6b shows the normalized hydrogen cost, again considering tankering and no tankering, for all and only routes operated by DR2000 and using the aircraft with real TLARs as a reference. The normalized hydrogen consumption and cost for the scenario that only considers large airports to be equipped with hydrogen refueling infrastructures is not shown in these plots, as its results are not comparable, as both the aircraft performance and the hydrogen accessibility vary in this case study.




(a) Normalized $LH_2$ consumption.




(b) Normalized $LH_2$ cost.

Figure 6 – Comparison of fuel consumption and cost considering different aircraft with different design ranges for the Milan Malpensa scenario.

There is a few key messages shown by fig. 6:

- Tankering causes an increased fuel consumption by 0.1% on the complete scenario for all DRs, but reduces the cost linked to fuel acquisition by 0.2%; these results include a hard 1% limit on extra fuel consumption for those routes for which tankering is only an economic mean and not the enabler of the route.

- The reduction of the DR can reduce by up to 7% the hydrogen consumption and the associated cost.
- Even a marginal range increase, for example, going from 3770 km to 4000 km, causes a 0.8% increase in cost and fuel consumption.

The percentile reductions might seem trivial and not worth the limited flexibility of the aircraft, but reducing the design range from the real value to 2450 km allows saving up 27.3 t of hydrogen daily (less on not peak days of traffic) only for short and medium-range flights in and out of Milan Malpensa, resulting in savings of 64 k€, as shown by the data presented in table 3.

| Aircraft | Hydrogen consumption [t] | | Hydrogen cost [M€] | | PREE |
|---|---|---|---|---|---|
| | Tankering | No tankering | Tankering | No tankering | |
| **Real TLARs** | 518.8 | 518.1 | 1.215 | 1.218 | 1.1730 |
| **DR4000** | 523.0 | 522.2 | 1.225 | 1.228 | 1.1617 |
| **DR3000** | 502.8 | 502.1 | 1.178 | 1.180 | 1.2139 |
| **DR2450** | 491.5 | 490.8 | 1.151 | 1.154 | 1.2377 |
| **DR2000** | 482.5 | 481.8 | 1.130 | 1.133 | 1.2590 |
| **Airbus A320** | - | - | - | - | 1.4647 |

Table 3 – Daily hydrogen consumption and cost for Milan Malpensa; PREE on a 981-km mission by different aircraft.

Furthermore, the reduction of the design range allows for a decrease in the difference between the PREE of the conventional Airbus A320 and those of the various hydrogen-powered counterparts. The Payload-Range Energy Efficiency (PREE), computed on a 981-km mission, is defined as follows in eq. 3:

$$PREE = \frac{m_{pl} R g}{m_{Fuel} e_{Sp}} \tag{3}$$

where $m_{pl}$ represents the payload mass, $R$ the range, $m_{Fuel}$ the fuel mass and $e_{Sp}$ the fuel lower heating value. The PREE increases by 5.5% lowering the PREE from the real value to 2450 km. However, it still remains 15.5% lower than that of the conventional aircraft, showing the difficulty of integrating hydrogen into aircraft.

## 4.3 Other Airports

The same methodology has also been applied to different study cases, to assess whether the reduction of the design range is too impacting on other scenarios. Paris C. de Gaulle on 23/08/2023 with 472 flights, Amsterdam Schipol on 05/10/2023 with 566 flights and Lisbon on 17/05/2024 with 223 flights have been considered. Figure 7 shows the results of the three scenarios, in comparison with Milan Malpensa, in terms of route categorization considering the DR2450 aircraft, therefore the one sized considering the average length of European flights as the maximum flyable return distance. Amsterdam and Paris see a route categorization distribution similar to that of Milan Malpensa, with approximately 60% of flights belonging to Category 1 and 11% of flights that cannot be operated, compared to 16% for Milan Malpensa. A completely different situation appears for the Lisbon scenario, in which only 36% of flights are "short" (cat. 1 and 2) and 19% of flights cannot be operated. This result shows that less central airports have fewer "short" routes and more routes that cannot be operated, either because of the lack of hydrogen refueling infrastructures or because of the more limited aircraft performance.

## 4.4 Sensitivity studies

It is also interesting to perform a sensitivity analysis on the hydrogen price difference between the reference and destination airport. The hydrogen price at the reference airport is set equal to 2.39 €/kg. Considering that hydrogen is available at both destinations, a maximum of 2% extra hydrogen consumption over the round trip is set, to mitigate the environmental impact. This threshold is twice as large as that used to assess the complete scenarios, to obtain more insightful results. Figure 8

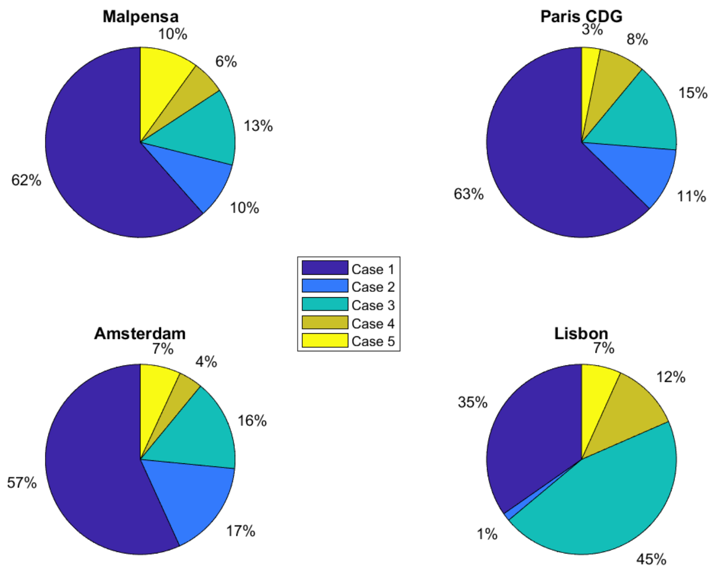



Figure 7 – Route categorization at various airports with aircraft with a 2450-km design range.

shows the results in terms of net savings, tankering percentage, extra fuel burn, as a function of flown distance and considerining a price difference spanning from 1% to 5%.

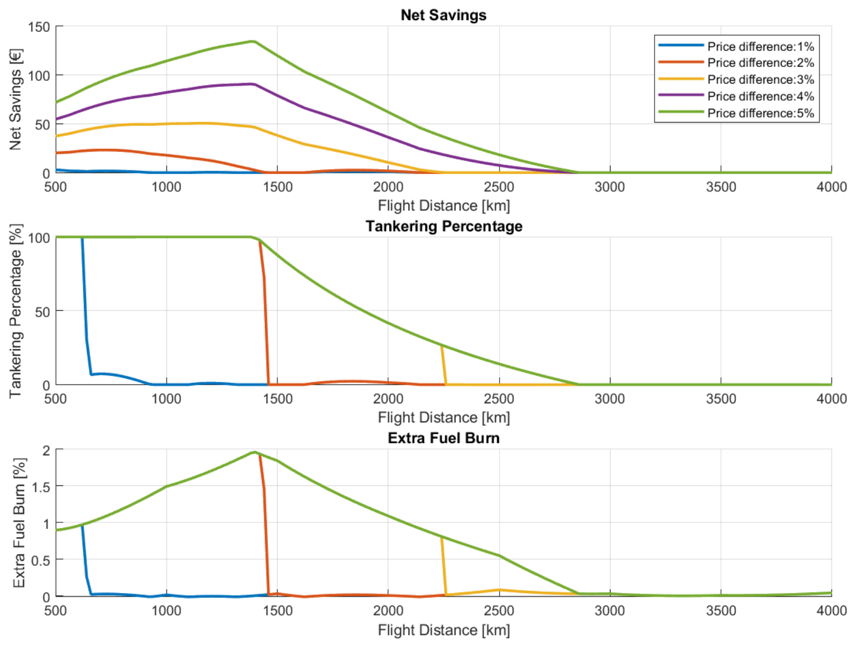



Figure 8 – Net savings, tankering percentage and extra fuel burn for the 4000-km range aircraft, as a function of flight distance for various price differences between the reference and destination airports.

No minimum net saving has been imposed for the sensitivity studies. If the threshold used in the complete scenario simulations (30€ on each return trip) is considered, it is clear that a 1% or 2% price difference does not warrant tankering, if only for economical reasons. The tankering percentage stays equal to 100% up until the maximum round trip range for higher price differences. It decreases slowly because of the tank size limit, but drops to zero as soon as the net savings would become negative, meaning that the increased fuel consumption would cost more than the saving enabled by the cheaper fuel. Intuitively, higher price differences enable higher economical savings. The distance corresponding to the maximum saving increases with the hydrogen price difference.

## 5. Conclusion

The work presented here introduces the formulation of a minimization problem which aims to assess the impact of hydrogen tankering on a given airline network scenario considering different hydrogen refueling infrastructure availability and aircraft with varying design ranges. The interesting concept of maximum range for single refueling return trips is introduced: this represents the maximum return distance that the considered aircraft can fly refueling only at its departure airport, including two reserves. This enables the operations of hydrogen aircraft even at airports that have no hydrogen refueling capabilities, provided that the distance from the reference, hydrogen-equipped airport, is short enough. The analysis of the design range of a hydrogen aircraft, based on the TLARs of the Airbus A320, shows that, for the short haul network of Milan Malpensa, its reduction from 4000 km to 2000 km causes an increase of flights that cannot be operated from 7% to 21%. A sweet spot for the design range, 2450 km, has been selected so that the maximum range for single refueling is equal to the average flight length in Europe. Such an aircraft enables the reduction of the used hydrogen and its corresponding acquisition cost by 5.3%. Furthermore, the aircraft with such DR can cover between 11% and 19% of short and medium-haul flights at four different European airports.

The presented methodology has the potential of enabling a thorough assessment of the transition of commercial aviation from kerosene to hydrogen, in which not only the fleet turnover but also different hydrogen infrastructure availability levels need to be taken into account to ensure that the novel aircraft that are delivered can effectively fly as many hours as the ones they are replacing, despite a more challenging operational environment.

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## Copyright statement



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