METHODOLOGIES FOR THE PRELIMINARY SIZING OF HYDROGEN-POWERED AIRCRAFT AND SUPPORTING AIRPORT INFRASTRUCTURES

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Abstract

This paper illustrates two general methodologies aimed at coping with the need to preliminarily assess the feasibility, cost and performance of a future commercial aviation system based on hydrogen as the in-flight energy source. The first concerns the preliminary sizing of a hydrogen-powered aircraft based on mission and certification requirements, which takes into due account the numerous modeling and operational prescriptions departing from consolidated procedures used when sizing conventionally-powered aircraft. The second is devoted to the preliminary sizing of the complex airport infrastructure needed to service hydrogen-powered airliners, namely on-site generator and liquefier, storage tank, and dispensing units, providing an optimal solution in terms of acquisition and operating costs, and eventually hydrogen cost “at the pump”. These two methods can help identify hurdles and enabling factors that determine the pathway to the entry into service of hydrogen-powered aircraft.

Keywords: hydrogen-powered aircraft, aircraft preliminary sizing, hydrogen-burning turbofan, airport infrastructure, environmental impact of aviation

1. Introduction

Commercial air transportation, as well as aviation at large, is facing radical technological challenges toward a drastic reduction of its environmental impact, accounting for about 2% of man-made greenhouse emissions and for 12% of transport-related emissions [1]. This has led to considering the possibility of switching from hydrocarbon-powered to hydrogen-powered aircraft. One propulsive architecture uses H_2 as a mean to produce electric energy via fuel cells, while another relies on H_2 as a fuel to be burnt. The former option applies to propeller-driven aircraft, and thus is of high interest in General Aviation (GA) and regional air transport, while the latter applies to jet aircraft, with a possible dramatic impact on mid- and long-haul commercial flights.

Multiple initiatives involving the development and feasibility demonstration of such new propulsion systems are currently ongoing, with some of the most notable being Airbus ZeroE [2], for large commercial aircraft, and Universal Hydrogen [3], targeting the retrofit of the ATR72. However, the implications on the thorough redesign of many aspects of the civil aviation system are far from being clearly solved, due to the lack of any previous experience related to large-scale implementation of the various systems involved. Therefore, new preliminary design methodologies with sufficient generality to be fit for feasibility and future scenario studies are needed. The present contribution reports on the recent development of two of such methodologies, dedicated to the most fundamental elements at play: the hydrogen-powered aircraft and the airport hydrogen infrastructure.

A conceptual design and preliminary sizing methodology for hydrogen-powered aircraft is summarized, providing applications and study cases stemming from research efforts concerned with innovation in aeronautical propulsion, including the EU-funded projects MAHEPA [4], UNIFIER19 [5], and SIENA [6]. This is complemented by the presentation of a preliminary sizing methodology for airport infrastructures in support of H_2-powered commercial fleets, including on-site hydrogen production, storage, and just-in-time delivery to aircraft. Study cases have been carried out within the SIENA project. The availability of tools providing the preliminary sizing of both the aircraft platform and the airport equipment generates an ideal ground for scenario studies, such as the investigation on H_2 tankering discussed in a companion paper [7].

This paper is divided into three chapters, detailing respectively the preliminary sizing of hydrogen-powered aircraft, the preliminary sizing of hydrogen airport infrastructure and overall results that outline the main barriers to a smooth entry into service of hydrogen-powered aircraft.

2. Hydrogen-powered aircraft preliminary sizing

This chapter details the methodology developed for the conceptual design of hydrogen-burning jet aircraft, showing the preliminary results obtained for short-range aircraft, based on the Airbus A320 TLARs, and a long-range one, based on the Airbus A350-900.

2.1 Methodology outline

The methodology developed for the conceptual design of hydrogen-powered fixed-wing aircraft has been implemented in a suite of tools providing a preliminary sizing of the airplane, including a preliminary geometry description, lofting, and performance analysis. At the heart of this approach lies the initial sizing procedure coded in the HYPERION (HYbrid PERformance simulatION) methodology. At the beginning, this has been developed for pure (battery) electric and hybrid electric propeller-driven aircraft, subsequently encompassing fuel-cell powered aircraft [8] and, finally, H_2-burning jets [9]. In HYPERION, the preliminary sizing process is performed by estimating the fuel, engines, and airframe masses required to perform an assigned design mission with a prescribed payload, taking into account all relevant market, operational, and certification requirements. The design mission is simulated, allowing to retrieve the time history of the main flight mechanics quantities during all phases of flight, including loiter and diversion. For this reason, the tool requires an adequate modelling of the aerodynamic, structural and propulsive characteristics of the aircraft. Several approaches are considered for the modelling of such characteristics, including historical-statistical regressions, quasi-analytical formulae, and fully physics-based models. The inputs needed by HYPERION to perform the initial sizing procedure are specific information regarding the aircraft (payload, crew), its aerodynamics (lift coefficients in different configurations and drag penalties due to landing gears and flaps), specific characteristics for the Electric Motors (EM), Fuel Cells (FC) and batteries, jet engine configuration (two or three spools, Turbine Entry Temperature (TET)), wing sweep angle and other characteristics.

HYPERION computes the mass of the aircraft as the sum of the masses of the main components on board the aircraft. The main remark lies in the fact that what is traditionally considered as OEM (Operative Empty Mass) is here divided into non-propulsive airframe, including the fuselage, wing, tail and systems, and the propulsive system, which includes the engines, whose type depends on the chosen propulsive architecture. The energy storage, consisting in hydrogen and its tank, and eventually in batteries, is also considered separately. This approach allows the use of regressions based on existing aircraft, adapted to account for the specifics of the selected architecture, and to model more in detail the elements that are most modified, the propulsive components. The Maximum Take-Off Mass (MTOM) of jet and propeller aircraft is expressed as the sum of the mass of each subcomponent, as presented respectively in Equations 1 and 2:

$$M_{MTO,Jet} = M_A + M_{Pl} + M_E + M_F + M_T \tag{1}$$

$$M_{MTOProp} = M_A + M_{Pl} + M_{EM} + M_B + M_G + M_F + M_T \tag{2}$$

with M_{MTO} representing the MTOM, M_A the mass of the airframe, M_{Pl} the mass of the payload, M_E the mass of the engines, M_{EM} the mass of the electric motors, M_B the mass of the battery, M_G the mass of the generator (a fuel cell for hydrogen-powered hybrid-electric configurations, otherwise a gas turbine), M_F the mass of the fuel and M_T the mass of the tank, which is zero for jet-fuel aircraft. Results for propeller-powered aircraft, sized considering eq. (2) with the legacy version of HYPERION, can be found in [10, 9]. These equations are mathematically trivial, but they hide the inherent complexity of the aircraft sizing discipline as all of the components are coupled. M_E (or M_G

and M_{EM}) , M_F and M_T directly depend on the performance requirements. M_E (or M_G and M_{EM}) is linked to the magnitude of thrust (or power) needed to comply with the prescribed field length for take-off, with the target cruise speed and with regulations. M_F and M_T depend on the mission range and on the fuel flow of the engines.

For H_2-powered aircraft, both gaseous and liquid hydrogen storage tanks have been considered. The results show the liquid solution to be more promising because of a more compact tank volume. In the case of fuel-cell propulsion systems, a first-principle fuel cell model has been implemented and validated [10]. In the case of jets, a relatively refined turbofan thermodynamics model was introduced. This is able to simulate both two-spool and three-spool configurations and has been validated by comparing the simulated cruise Thrust-Specific Fuel Consumption (TSFC) with the values retrieved from multiple references over a sample of seven turbofan engines in current use for airliners [11], as shown in table 1. The low difference between the modeled TSFC and the data available in the literature validates the implemented engine model. The conversion to hydrogen-burning jet engines is obtained by changing the thermodynamic properties of the fuel and the TET, from 1280 K to 1480 K [12]. The obtained reduction of TSFC by 60-65% depending on the considered engine is coherent with the 3-times higher specific energy in hydrogen compared with jet fuel. Furthermore, it is also supported by some literature, such as [13, 14].

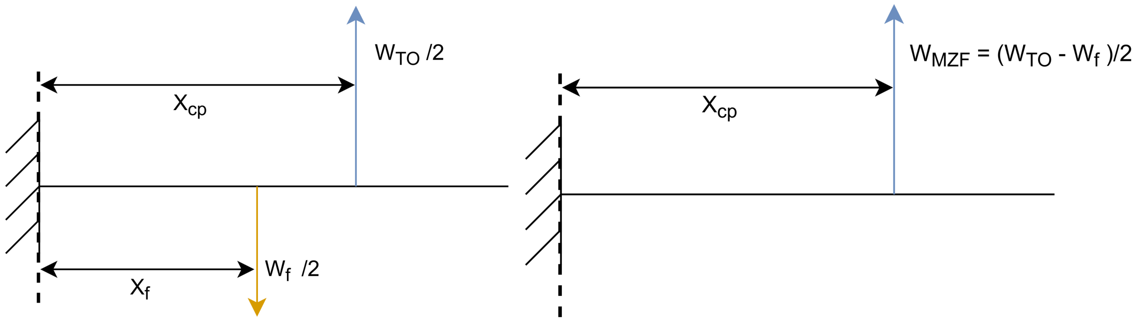
Engine	**Aircraft**	**Mod. TSFC [kg/(N h)]**	**Lit. TSFC [kg/(N h)]**	**Difference [%]**
CFM56-5AI	Airbus A320	0.0579	0.0577	+0.35
GE90-85B	Boeing 777-200ER	0.0502	0.0526	+4.56
Trent 700	Airbus A330	0.0585	0.0589	-0.68

Table 1 – Modeled (Mod.) TSFC compared with literature (Lit.) [15].

Special care has been placed in solving the crucial problem of estimating the aircraft's operational empty mass fraction. Indeed, an approach relying on historical regressions based on the Maximum Take-Off Mass (MTOM) cannot be employed, due to the obvious lack of data. Therefore, a build-up method has been developed and validated, where the masses of each structural component are computed separately, relying on quasi-analytical and regression-based methods. The wing mass is computed considering the area required to deliver the required performance. Furthermore, it is necessary to analyze the effect of the missing load alleviation provided by the jet fuel, stored in the wing, to verify if a wng structural reinforcement is necessary. In fact, in hydrogen-powered aircraft, tanks and fuel can be thought as an additional structural payload, summing to cargo and passengers The most critical load conditions are two for conventional aircraft [16]. The first one is given by the aircraft flying at MTOM, carrying its maximum structural payload, which is given by the difference between the MTOM and OEM. The lift reaches its maximum value, but wing loads are alleviated by the wet wing. The other critical load condition is given by the aircraft flying with no fuel at its MZFW. Lift is not at its peak, but there is no load alleviation. An analysis of these two load conditions, based on a simplified cantilever model, as shown in fig. 1, shows that the second condition is less limiting than the first. This allows the corresponding hydrogen-powered aircraft to have a higher maximum structural payload.

The fuselage mass is estimated considering a total length able to accommodate both a cabin of the required length and the hydrogen tank. The mass of the other subsystems, such as landing gear, avionics, hydraulics, cabin furnishings, are computed using regressions that are based on historical data and depend on various factors such as MTOM, number of passengers and wing area. In this way, the effects of the substantial lengthening of the fuselage to accommodate the bulky cryogenic H_2 tank can be taken into account. This, together with *ad-hoc* recipes for the estimation of the aircraft's drag polar, including the increased parasite contribution for the larger wetted area, as well as compressibility effects, allow to provide a reliable conceptual design solution, capable of accounting for the the impact of the hydrogen tank.

It is interesting to look more closely at how the mission requirements are expressed to characterise each mission phase: information regarding the desired payload and range, by definition of the corner



(a) Take off at MTOW, carrying maximum structural payload and with wet wing.

(b) Dry wing and gross weight equal to MZFW.

Figure 1 – Limit wing loading conditions. The engine concentrated load is not shown as its effect is constant for both loading conditions.

point in the payload-range diagram; the diversion range; the desired cruise altitude and speed; the loiter time and altitude. Particularly, the modeling of the diversion and of the loiter is necessary to show that the aircraft is capable of carrying out a specific mission while having sufficient reserves to comply with regulations applicable to fuel planning, contained in Annex IV - Part CAT of Air Op.

2.2 Application studies

After a thorough validation process concerning existing conventional aircraft across all civil transport categories, see table 2 for a subset of validation cases, two sets of studies have been accomplished involving H_2-powered aircraft.

Aircraft	MTOM		Thrust to weight		Wing loading	
	[kg]	$\Delta\%$	[-]	$\Delta\%$	[N/m^2]	$\Delta\%$
Embraer 190	46 849	-2.0	0.3251	-1.5	5 056.1	-0.2
Airbus A320	77 217	-1.0	0.3008	+3.4	6 209.6	+0.6
Airbus A350-900	279 271	-0.3	0.2698	-1.1	5 279.3	+1.0

Table 2 – Validation of HYPERION results for some conventional aircraft, spanning from regional to long-range jets.

First, the conversion of existing airframes to the use of hydrogen as the energy carrier was considered. In this case, the airframe is maintained unchanged (and therefore the fuselage length and wing area, as well as the non propulsive airframe mass, are kept the same as those of the original aircraft) and H_2 tanks and H_2-burning turbofan engines are considered. Furthermore, the TLARs, most notably detailing performance elements such as the take off and landing distance, the range, the cruise and climb speeds, are maintained unchanged, to enable a fair comparison. An example of such studies concerned with popular airliners such as the Airbus A320 shows that guaranteeing zero CO_2 emissions thanks to the H_2 propulsion comes with some inefficiencies in energy utilization. Indeed, operational key performance indicators, such as Revenue Work per Energy (RWE, i.e. the ratio between the work to carry the design payload over the design range and the energy from all sources on board) and Energy Intensity (EI, i.e. the ratio between the liberated energy and the available seat nautical mile (ASNM)) appear worse than for the conventional-propulsion counterparts (whose performance is accurately computed considering their HYPERION model).

Parameter	Jet-fuel Aircraft	Fixed-airframe retrofit	Relative Difference	Extended-airframe retrofit	Relative difference
RWE	1.155	0.788	-31.8%	0.907	-21.5%
Energy intensity [MJ/ASNM]	1.726	3.083	+78.6%	2.128	23.3%

Table 3 – Energy performance indicators for A320 H_2-burning retrofit solutions on the design mission.

Table 3 illustrates such results in two cases. The first is for a pure retrofit, where the fuselage geometry is untouched, leading to a loss of 78 out of 180 passenger seats (–43%) due to the need to house the 8.4 m long cryogenic tank. The second originates from the introduction of a suitable fuselage elongation to preserve passenger capacity. As apparent, in both cases, the RWE is lower and the EI higher (albeit a clear improvement is seen when the fuselage is elongated because of the payload returning to the original amount).
A second, more ambitious, option is based on clean-sheet design solutions instead of retrofitting existing airframes. An initial study, involving some simplifying assumptions such as fuselage width, wingspan and other parameters equal or close to the existing aircraft, provides interesting results. Nonetheless, future further analyses on some of these parameters could help identify a different set of optimal parameters for hydrogen-powered aircraft. Table 4 shows the MTOM and its breakdown for the HYPERION solutions to the sizing of an aircraft exactly matching the A320 performance. As seen, the differences between the conventional and the H_2-powered versions are strikingly limited and even favorable for the H_2 version in terms of MTOM. The results include the A320H sized considering both a 6 and 9.6 BPR. The higher BPR version reflects the current state of the art for jet engines, which improves the overall aircraft performance, because of better engine efficiency, which in turn reduces the fuselage mass because of the snowball effect [17]. The overall reduction of the MTOM is made possible by the 3-times higher specific energy of hydrogen compared to kerosene. The gain in energy mass is almost balanced by the tank mass and by the increase of the airframe mass required to accommodate the tank in the fuselage for the 6-BPR case. The high BPR version allows instead for a significant reduction of the MTOM, as the quantity of required hydrogen drops, reducing also the tank mass and the increase of the airframe mass.

		Jet-fuel aircraft	H_2-burning aircraft (BPR6)	Relative difference	H_2-burning aircraft (BPR9.6)	Relative difference
Mass [kg]	MTOM	78,217	76,753	-1.8%	73,874	-5.6%
	OEM	43,143	49,733	+15.3%	48,166	+12.8%
	N. P. Airframe	38,738	41,628	+7.5%	40,810	+5.3%
	Payload	19,700	19,700	-	19,700	-
	Engines	4,409	4,746	+7.6%	4,521	+2.5%
	Fuel	15,371	7,321	-52.4%	6,008	-60.9%
	Tank	-	3,359	-	2,835	-

Table 4 – Comparison between conventional and H_2-burning solutions for a A320-like aircraft.

Parameter	Jet-fuel aircraft	H_2-burning aircraft (BPR6)	Relative difference	H_2-burning aircraft (BPR9.6)	Relative difference
RWE	1.155	0.868	-24.9%	1.059	-8.3%
Energy intensity [MJ/ASNM]	1.726	2.288	+32.6%	1.878	+8.8%

Table 5 – Energy performance indicators for A320 H_2-burning clean-sheet solutions.

It is important to notice that, due to the 11.43 m long H_2 tank, the hydrogen-powered version has a much longer fuselage than the real A320 and thus a significantly lower L/D ratio by 15%. This translates again into a lower energy performance compared to the conventional aircraft, as seen in Table 5. Interestingly, in the case of larger airliners, a similar study taking the Airbus A350 as a reference shows that the differences in both indicators, while substantial in the case of a fixed-airframe retrofit solution, decay to only 2-4% for elongated-fuselage retrofit and the clean-sheet design solutions. Results for the sizing and energy indicators for a hydrogen-burning A350-like aircraft are shown in table 6. Also for the long-haul case, a reduction of the MTOM is achieved thanks to the switch to hydrogen as the main energy source on-board and is more marked than in the short-haul case, given the higher fuel mass fraction in the baseline aircraft. It is also interesting to notice how the airframe mass remains virtually unchanged, despite the elongation required to accommodate the tank. In fact, the significant reduction of the fuel mass allows a smaller wing to be sufficient to obtain the same required performance as that of the baseline aircraft.

		Jet-fuel aircraft	H_2-burning aircraft	Relative difference
Mass [kg]	MTOM	282,769	240,587	-14.9%
	OEM	142,724	140,712	-1.4%
	N. P. Airframe	128,480	128,317	-0.1%
	Payload	53,800	53,800	-
	Engines	14,244	12,395	-13.0%
	Fuel	86,245	32,089	-52.4%
	Tank	-	13,986	-
	RWE [-]	1.565	1.508	-3.7%

Table 6 – Comparison between conventional and H_2-burning solutions for a A350-like aircraft.

3. Hydrogen airport infrastructure preliminary sizing

This chapter details the methodology used to perform the preliminary sizing of the hydrogen refueling infrastructure at airports, given the flight schedule and the electricity price. The ultimate output of the methodology, here applied to the Milan Malpensa scenario, is the price of 1 kg of hydrogen.

3.1 Methodology outline

The methodology developed for the preliminary sizing of airport infrastructures in support of H_2-powered commercial fleets completes the framework already including an analogous methodology for the preliminary sizing of airport battery recharging equipment presented in [18]. In the present case, the AHRES (Airport Hydrogen Refueling Equipment Sizing) methodology provides an estimate of the required infrastructural needs based on the knowledge of the airport's flight schedule and the characteristics of the operating aircraft. The latter are retrieved by applying the preliminary sizing methodology described above, to provide performance-equivalent substitutes to current airliners. This delivers the corresponding hydrogen quantities to be loaded on board for any mission of interest. With these data, an optimal solution is computed to specify the need for hydrogen generation, liquefaction, storage and just-in-time distribution to each aircraft, by minimizing the total cost of acquisition and operation. Grid electricity cost hourly variations are taken into account, as well as other factors impacting costs and operations. The process not only delivers the overall sizing of the refueling infrastructure, but also provides the optimal time scheduling of hydrogen mass flows across the various components of the infrastructure. This eventually generates the cost of H_2 per unit mass "at the pump".

In a simplified way, the airport refueling station can be imagined as consisting of three main elements: the **generator** (consisting of an electrolyzer, a buffer tank, and a liquefier) where, starting from water, hydrogen is obtained through an electrolysis process using a large amount of energy; the gas is then cooled to cryogenic temperatures so that it is liquefied; the **storage tank** whose job is to store the hydrogen produced in advance, e.g., during a time slot when the cost of energy is lower, and then use it as needed to refuel aircraft; and **dispensing units** that pump hydrogen from the storage tank and transfer it to the aircraft tank. Only electrolysis is considered to produce hydrogen as it has the potential of being completely carbon-free, depending on the used energy mix. In particular, the electrolysis and liquefaction to obtain 1 kg of hydrogen require 50 kWh and 12 kWh respectively. The total cost function eq. (3) is defined as the sum of all involved costs over a single day as:

$$J = C_e + C_p + C_{GNR} + C_{ST} + C_{DU}, \tag{3}$$

where C_e represents the cost of the electric energy purchased from the grid, C_p the cost of the corresponding peak power, and C_{GNR}, C_{ST} and C_{DU} are the cost of the generator, storage tank, and dispensing unit, respectively. The methodology aims to minimize J, while at the same time satisfying the constraints imposed by the assessed scenario. The optimization is based on a single day, divided into 10-minute timesteps i. The problem is subject to constraints, which ensure that the optimization is coherent with its actual context, that is airline operations. The mathematical constraints imposed on the model thus are:

- The hydrogen stored in the ground tank is always between 5% and 100% of the tank capacity, to ensure thermal stability;
- The fuel required by an aircraft at timestep i depends on the aircraft type and on the length of the mission to be operated. The modeling of the various considered aircraft is based on HYPERION;
- A given aircraft is refueled in the timestep(s) that precedes the take-off;
- The dispensing unit remains coupled with the aircraft from the beginning of the refueling operations until the aircraft's take-off;
- The generator has a minimum flow, to avoid the transient liked to switch off and restart in case of a dual-rate electricity cost;
- The number of available dispensing units must always meet the schedule's demand;
- At each time step, the mass of the hydrogen stored in the ground tank is updated, to account for the mass entering from the generator, the mass delivered to aircraft and the mass lost because of boil-off.

In fact, liquid hydrogen is stored at -253℃, with the tank being inserted in normal conditions, with temperatures spanning between -20℃ and 40℃, making an inward heat flow inevitable. This heat causes the evaporation of a portion of the hydrogen, causing an increase of the pressure within the tank. Once the maximum pressure is reached, gaseous hydrogen needs to be released into the atmosphere, to avoid the structural failure of the tank. The amount of daily boil off considered in AHRES is equal to 1% of the tank capacity [19]. For ground-based systems, it is possible to re-liquefy the boiled-off hydrogen, as the mass linked to the extra pipings is not constraining.

3.2 Application studies

As an illustration of the AHRES operation and results, the case of the Malpensa International Airport (LIMC) is considered since both the airport operator, SEA, and one of the most prominent airlines, easyJet, are highly invested in the decarbonization of commercial aviation [20, 21]. All short- and medium-haul flights are assumed to be entirely carried out by a variety of H_2-powered airliners substituting the existing ones. The flight schedule corresponds to the most demanding day in 2022 (September 5^{th}), with 239 flights.

The first graph in fig. 2 illustrates the on-site production time history (in blue), i.e. the H_2 mass flow in the generator and liquefier (GNR), together with the dual-rate electricity tariff (in red). As apparent, the optimal solution forces electricity consumption during nighttime, when the tariff is lower. The second graph shows the H_2 mass flow in the cryogenic Storage Tank (ST), accounting for concurrent input from the liquefier and output to the dispensing units, which subsequently deliver it to the aircraft. The third graph shows the H_2 mass delivered by the dispensing units, which are related to the fight schedule shown at the bottom of the figure.

The solution discussed above corresponds to the sizing reported in table 7, which also shows the case of a constant electricity tariff and the difference between that and the dual-rate solution.

It is interesting to notice how the dual rate case shows 7.7% higher total costs, resulting in an increase of the hydrogen cost per kg by 7.3%, going from 4.104 €/kg to 4.305 €/kg. In fact, despite reduced energy costs, which represent between 73% to 85% of the total cost in the single rate scenario as shown, in fig. 3, the higher-rate production causes higher power costs (+81.4%). Furthermore, since most of the H_2 production happens at night, with the fuel still being used during the day, the tank size, consequent boil off and cost are more than doubled, balancing out the savings linked to profiting off the dual electricity price. The real advantage of the infrastructure sized considering a dual electricity

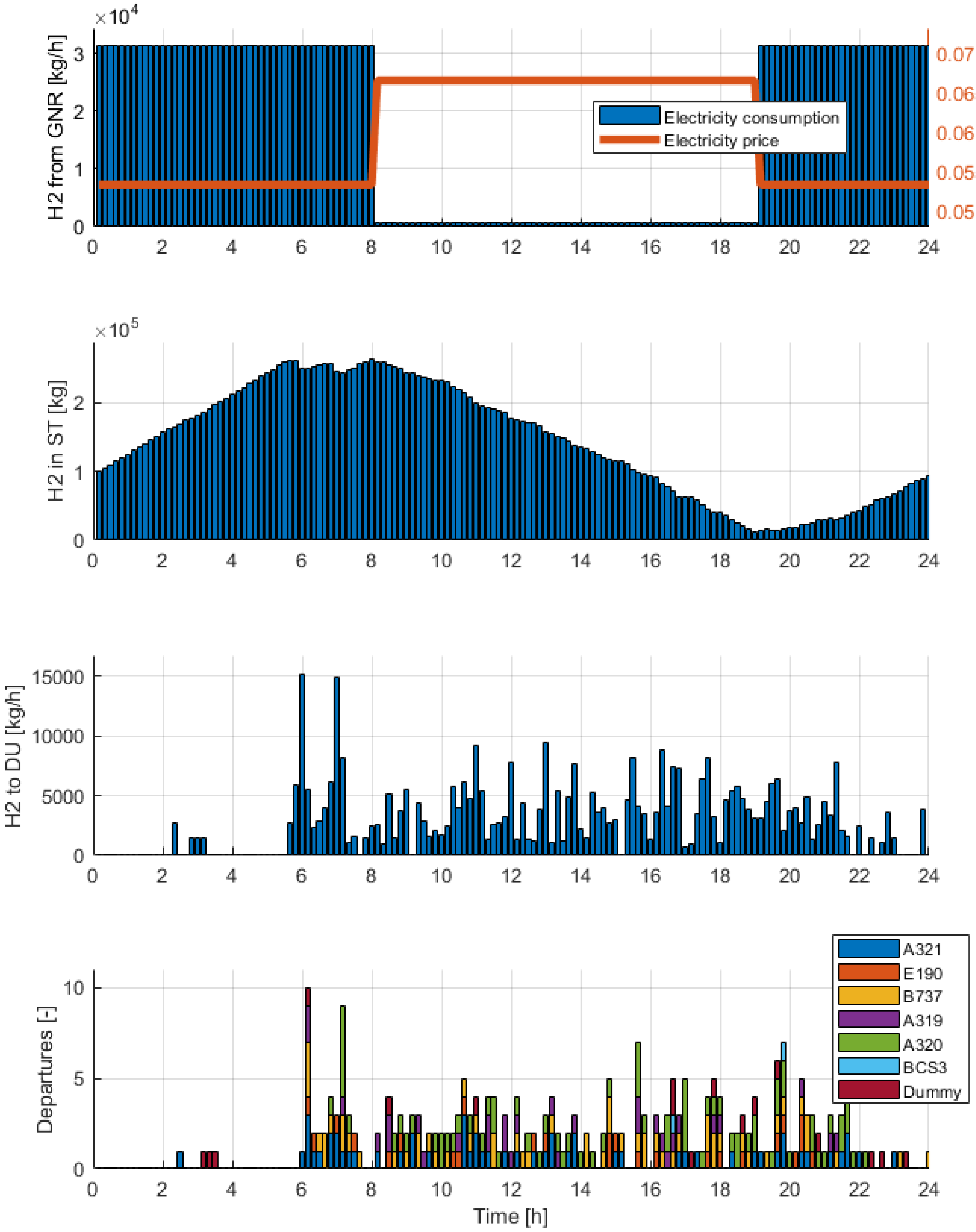


Figure 2 – AHRES time histories for Malpensa International Airport.

price lies in the fact that said infrastructure is already ready to accommodate an increase in the level of traffic by simply increasing the production rate during the expensive hours, whereas the infrastructure sized with the monorate electricity price is already used at its fullest by the input scenario. Simply said, the by-hourly scenario is more expensive as a bigger ground tank and generator are installed. A broader insight on the potential of the methodology is offered by fig. 3, which details the cost distribution of a regional (Athens airport, only considering regional turboprop-operated flights, top row) and large airport (Milan Malpensa, considering only short and medium range flights, bottom row), with both a constant (left side) and dual-rate electricity price (right side). Athens, that given the

Indicator	**Mono-rate**	**Dual-Rate**	**Change[%]**
Cost function [€/day]	1.70 e+06	1.83 e+06	7.7
Energy consumed [kWh/day]	2.57 e+07	2.58 e+07	0.3
Electricity cost [€/day]	1.45 e+06	1.38 e+06	-4.9
Max Power [kW]	1.07 e+06	1.94 e+06	81.4
Power cost [€/day]	8.94 e+04	1.62 e+05	81.4
H_2 production [kg/day]	4.14 e+05	4.16 e+05	0.3
GNR cost [€/day]	1.42 e+05	2.63 e+05	85.3
Max mass in ST [kg]	1.14 e+05	2.58 e+05	125.6
Boil-off mass [kg]	1.14 e+03	2.58 e+03	125.6
ST cost [€/day]	6.26 e+03	1.41 e+04	125.6
Number of DU [-]	9	9	–
DU cost [€/day]	9.47 e+03	9.47 e+03	0.0
Cost for 1kg of H_2 [€/kg]	4.104	4.405	7.3

Table 7 – AHRES sizing results for Malpensa International Airport.

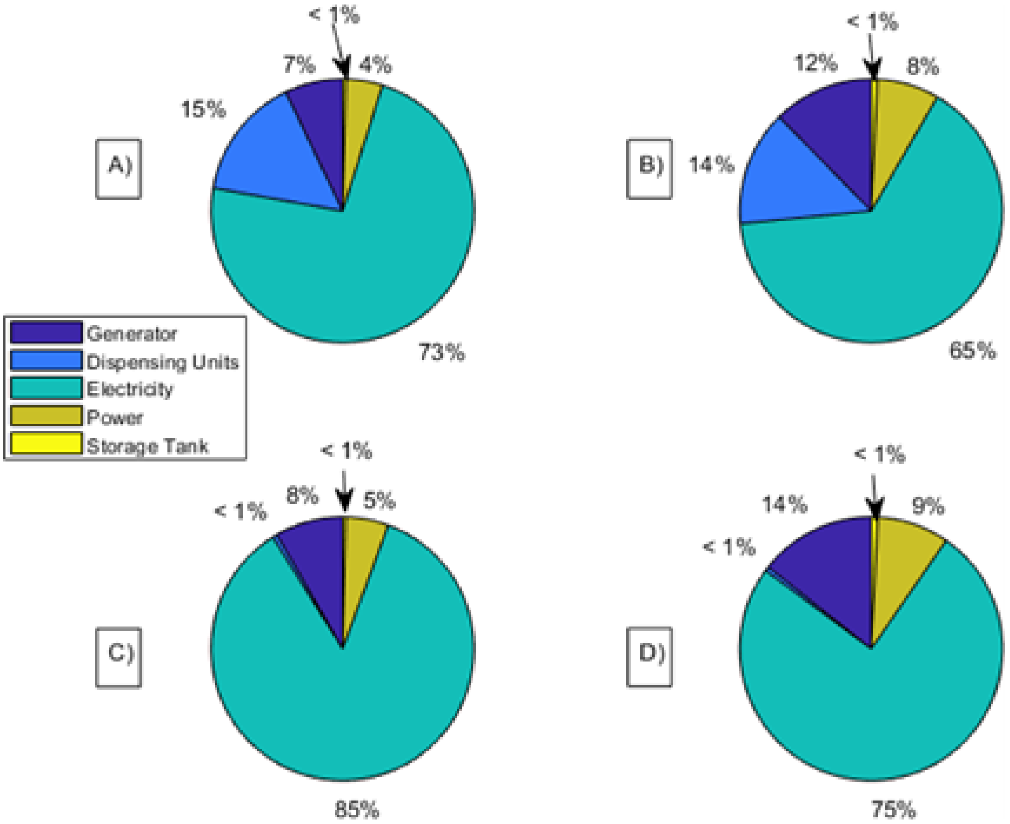


Figure 3 – Cost distribution:
(A) Athens with a constant fee. (B) Athens with a dual-rate fee.
(C) Malpensa with a constant fee. (D) Malpensa with a dual-rate fee. .

low frequency of regional flights only has a single dispensing units, shows a negligible cost for them. Ultimately, it is possible to see the highest cost share for energy in the constant case scenario.
It is also interesting to see how the infrastructure, sized for the busiest day, behaves in off-sizing conditions, i.e. in days that are not those of the peak of flights. The results, for regional and medium-large airports are shown in fig. 4. This picture shows two interesting results: larger airports achieve the economy of scale making hydrogen cheaper at larger airports and hydrogen price increases quadratically as the level of production decreases.

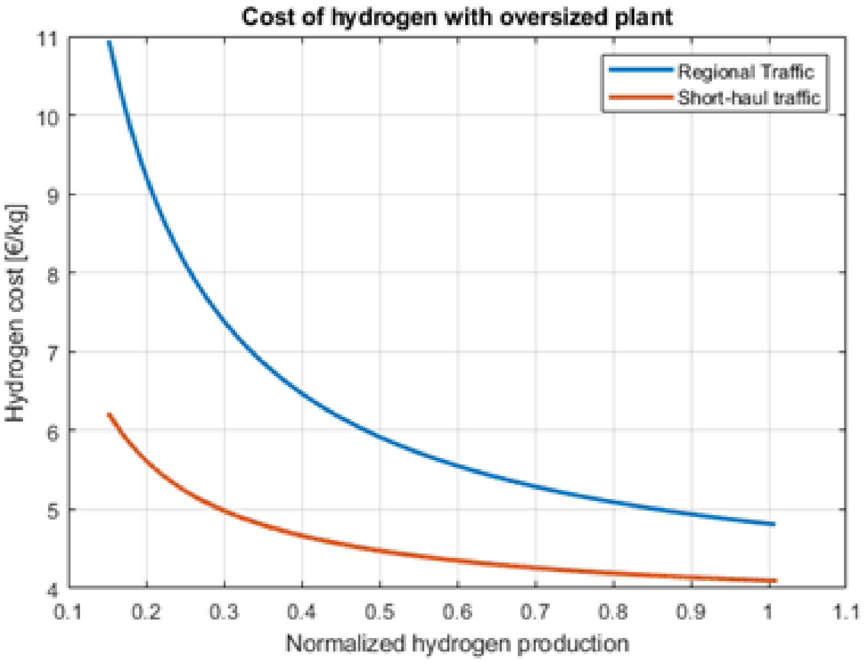


Figure 4 – Cost of hydrogen with oversized plants - Regional (blue) and short-haul scenario.

4. Pathway for hydrogen aircraft

The present paper introduces two methodologies and the respective results, developed with the objective of assessing the preliminary sizing and entry into service of hydrogen-burning jet aircraft, from a pre-design and operational point of view. The main impacts lie in the aircraft development, including changes in the design process and in the certification, and in operations, mostly for what concerns hydrogen refueling, in terms of procedures and availability. In fact, the development of hydrogen-powered aircraft will need to overcome the following:

- Low TRL for hydrogen tank, hydrogen fuel system and combustion chamber/turbine of hydrogen-burning jet engines.
- Lack of a clear certification context, both in terms of applicable regulation items (CS25 does not account for hydrogen-powered aircraft as of now) and of acceptable means of compliance. This would cause an extended duration of the certification period as the interaction between the authority (EASA for European applicants) and the applicant (that is the aircraft constructor) would need to define novel procedures to ensure that the novel aircraft are at least as safe as the ones they are set to replace.
- A successful EIS can only happen if the aircraft can be serviced at the airports it is set to operate at. That means that hydrogen must be available at these airports, at a cost that allows operations to be economically viable. This aspect is developed thoroughly in the following chapter.

Aircraft design and certification The integration of hydrogen as the main energy source onboard jet aircraft is feasible, as broadly shown in section 2. The main challenge is to account for the hydrogen tank, which is placed at the back of the fuselage. This requires the fuselage to be elongated, causing an increase in the structural mass. The hydrogen tank also adds extra mass to the OEM. An elongated fuselage ultimately causes an increase in the drag coefficient, which in the end causes an increase of the required thrust and thus of energy required to carry out the mission. This effect is particularly remarkable for short-haul aircraft, as the fuel represents a lower mass fraction in jet fuel aircraft, if compared with long-range jets. These aircraft are therefore less sensitive to switching to a higher specific-energy fuel than long-haul aircraft, for which the overall energy consumption does not change significantly. In both cases, the replacement of jet fuel with hydrogen zeroes out CO_2

emissions at the aircraft level and reduces NO_x by approximately 70% [22], reducing significantly the environmental impact of aircraft operations. A broad analysis of the Certification Specifications applicable to jet aircraft, notably CS-25 [23], CS-E [24] and CS-APU [25], in the context of the SIENA project [26], showed how the current versions of the CSs require a significant effort to close the gaps to allow the certification of hydrogen-powered aircraft, particularly for what concerns hydrogen tanks and less so for the electrical systems needed to support innovative system architectures. Regarding hydrogen-burning jet engines, the designers will mostly take up the effort, as it is only necessary to ensure that the combustion chamber and the turbine can face the higher temperature linked to hydrogen utilization.

Operations and infrastructure The considered aircraft architecture is still based on the traditional tube+wing layout, therefore, the ground servicing vehicles will not be impacted. The only significant impact is linked to the refueling. Hydrogen refueling infrastructures will need to be available at least partially on a given network, as broadly discussed in the companion paper [7], and the refueling trucks or hydrogen airport pipeline will need to be cryogenic and to account for the recovery of the boiled off hydrogen [27]. The optimal choice between a proper number of refueling trucks and a LH2 airport pipeline system depends on the level of traffic at the airport, in terms of the presence of long-range flights and the number of overall flights, just like it currently happens for kerosene, with pipelines available at larger airports and fuel trucks used at smaller ones.

5. Conclusion

The present contribution highlights two original methodologies that can be of use in the investigation of the foreseen “Hydrogen Revolution” in commercial aviation. Both allow us to derive quantitative results on the impact of H_2-based aeronautical propulsion systems through the ability to preliminary size future airliners starting from mission and certification requirements and the corresponding supporting airport infrastructure. Results from the application of these methodologies represent core outcomes in recent EU-funded projects on environmental sustainability in aviation and are included also in a companion paper submitted at ICAS 2024.

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