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Executive Summary of the Thesis

Preliminary sizing of an airport facility for refueling liquid hydrogen-powered aircraft

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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1. Introduction

The aviation industry contributes approximately 2.5% of all human-made CO_2 emissions. To reduce the environmental impact of the sector, hydrogen has emerged as a potential alternative to current aircraft fuels. The use of hydrogen can completely eliminate CO_2 emissions and substantially reduce NO_x and particulate emissions. This thesis aims to evaluate the feasibility, both technically and economically, of establishing an airport hydrogen refueling facility for hydrogen-powered aircraft. The study will explore different technical and technological options for producing, storing, and distributing hydrogen to refueling stations located at airports. Concrete results on the initial investment and operational expenses associated with such a facility will be provided, along with potential solutions to enhance the affordability of the investment.

2. AHRES methodology

This study utilized the AHRES (Airport Hydrogen Refueling Equipment Sizing) methodology, which employs an optimization code to identify the most cost-effective solution that meets the specified performance requirements. The methodology ensures that the desired performance is achieved while minimizing the overall plant cost.

2.1. The airport facility

In order to achieve meaningful results it was essential to establish a simplified model of the system. The advantage of the software design tool developed is its high level of flexibility. All parameters can be easily modulated, allowing for easy correction of results in case of updated estimates. The plant considered consists mainly of three elements presented in detail below: the generator (GNR), storage tank (ST) and dispensing units (DU).

Generator

The generator includes an electrolyzer, a buffer tank and a liquefier. Its job is to produce hydrogen gas by electrolyzing water, the gas is then cooled to cryogenic temperatures, turning it into liquid form. Water electrolysis is the most environmentally sustainable method of producing hydrogen, but it is an extremely energy-intensive process: 50 kWh of energy is required to produce one kilogram of hydrogen, and a further 10-12 kWh is needed for its liquefaction. The element cost estimate is based on the projection made in a report by Clean Hydrogen [6], and depends on the amount of hydrogen produced daily. Specifically, a value of 1 250 €/(kg d) is used. O&M costs of 10% per year over the first 10 years of use were added to this cost, as well as those of all other elements.

Storage Tank

To ensure a reliable hydrogen supply and meet variations in hydrogen demand, a storage system is required between the central production plant and the refueling stations. To prevent evaporation, the liquid hydrogen must be kept at a temperature of -253°C, which requires the ground tank to have highly effective insulation from the external environment. While there are various insulation techniques available, the most reliable and established technology involves vacuum-insulated, double-wall tanks with perlite in the annulus. Despite this insulation, some of the hydrogen will inevitably evaporate due to heat ingress caused by the strong temperature gradient between the tank and its surroundings, a phenomenon known as boil-off. While it is difficult to accurately estimate the magnitude of boil-off, a value of 1% of the maximum stored mass was chosen based on research by Brewer [2]. This value would be somewhat overestimated considering only the tank, but the boil-off phenomenon occurs along the entire hydrogen pathway, so using this estimate, all losses are concentrated in one element of the system, in order to have a leaner model. The cost of the tank is heavily influenced by its size, and an average cost estimate of 200,€/kg was selected from the estimates provided by Amos [1].

Dispensing Units

Dispensing unit refers to the part of the facility required to transfer hydrogen from the storage site to the refueling station and to actually refuel the aircraft. The main methods of hydrogen distribution at the airport are by pipeline or by tanker trucks. Although the former method is more effective especially for larger airports, a tanker dispensing system is considered in this study because it is more flexible and because the technology regarding cryogenically insulated piping is not yet sufficiently mature. The number of dispensing units needed depends on the distribution of flights in the airport. To the number of dispensing units needed are added a few safety units in case of malfunction or maintenance of the others. The cost estimate, derived from [6], is € 3 200 000 each.

2.2. Electricity pricing

As energy represents the primary cost of the entire system, the obtained results will be highly sensitive to the electricity tariff selected. Two tariffs were examined in this study: a simple tariff, where the price of energy remains constant regardless of the time of day, and a bi-hourly tariff that offers discounted prices during nighttime hours (from 7pm to 8am) and elevated prices during daytime hours. The tariff data, presented in Table 1, were obtained from the official website of ARERA (Italian regulator of electricity, gas, and water markets) [4] and correspond to the energy price in the first quarter of 2021, which predates the recent energy crisis, thus ensuring that the final results are not affected by temporary conditions. Another cost related to the price of energy is the amount to be paid in proportion to the committed power, even in the absence of energy consumption. This parameter assumes a value of 30 €/(kW·year) in the case of non-household users according to ARERA [3].

Table 1: Electricity price

Simple tariff [€/kWh]	Bi-hourly [€/kWh]	
	day	night
0.05657	0.06662	0.05336

2.3. Mathematical formalization

Since the problem involves a large number of variables and parameters, it is treated as an optimization problem. An objective function, in this specific case, the daily cost of the system, is defined and the aim is to determine the solution that will minimize this function while satisfying all relevant constraints. This is applied to a given time frame for which a detailed flight schedule is known. The solution is provided as optimal values of the hydrogen generator production capacity, the size of the ground storage tank, the number of necessary dispensing units, the maximum power absorbed by the system, and the detailed time scheduling of the refueling process.

The cost function J is defined as the sum of all involved costs over the time duration L as

$$J = C^{e} + C^{p} + C^{\mathrm{GNR}} + C^{\mathrm{ST}} + C^{\mathrm{DU}}; \quad (1)$$

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 depreciation cost of the generator, storage tank, and dispensing units, respectively. The components of the cost function are subject to various constraints, which are expressed mathematically and take into account both technological limitations and models of the refueling processes. Some of the primary restrictions that must be satisfied include:

- Maintaining the ground tank and aircraft's replenishment level within a designated range of minimum and maximum values.
- Ensuring that the aircraft has a sufficient amount of hydrogen for the mission before takeoff.
- Prohibiting the refueling of aircraft earlier than 30 minutes before takeoff, as operational considerations at busy commercial airports are taken into account.
- Guaranteeing that an adequate number of dispensing units are available to meet the flight demand.

The problem was implemented in MATLAB and solved using the Gurobi Optimizer solver.

3. Applications scenarios

The methodology presented was applied to real case studies. In particular, the focus was on regional transport at Athens Airport (ATH) and short-haul flights at Milan Malpensa Airport (MXP). These two types of traffic were found to benefit the most from a switch to hydrogen-powered aircraft in the near future [5]. Turboprop aircraft, such as ATR42, ATR72, and Dash 8, are commonly used for regional transport, and a fuel cell can be used as a power source for these aircraft. This method is considered the most eco-friendly option available, but it has limitations, primarily related to the low power density of hydrogen, which currently makes it impossible to use this technology for larger-sized aircraft or longer flights. When it comes to jet aircraft, such as those used for short-haul transport, fuel cells cannot be used as a power source. In these cases, the only option is to burn the hydrogen. The Boeing 737, Airbus A320 family, and Embraer E-Jet family are among the most frequently used short-range airliners. The hydrogen consumption of the models in the simulations is depicted in Figures 1 and 2. These were estimated using HYPERION, a tool developed in the Department of Aeronautical Science and Technology at the Politecnico di Milano for sizing innovative hydrogen-powered aircraft.

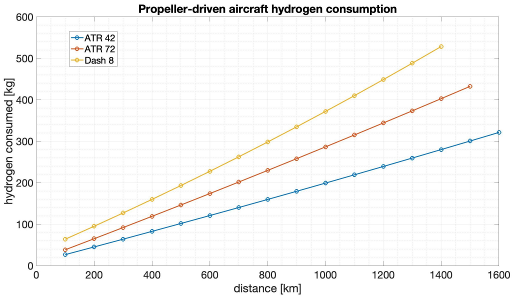

Figure 1: Graph of propeller-driven aircraft hydrogen consumption

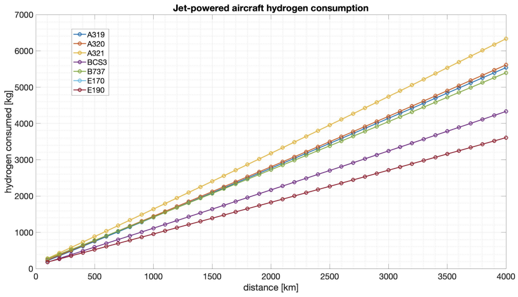

Figure 2: Graph of jet-powered aircraft hydrogen consumption

When analyzing the movement trends of selected airports in 2022, the busiest and the least busy days were identified and referred to as the Most Demanding Day (MDD) and Least Demanding Day (LDD), respectively.

4. Results

4.1. Athens Airport

In order to size the Athens Airport plant, the schedule of the MDD was considered. In fact, if the plant can meet the hydrogen demand on that day, it can handle the lower demand throughout the rest of the year. If the plant sizing was only based on the real flight schedule, it would be underestimated and unable to provide to any increases in hydrogen demand from the system.

Hence, in all simulations, to ensure a safety margin in the plant component sizing, an extra 5% of dummy flights were added to the schedule, randomly distributed throughout the day. These flights are operated by aircraft that have average fuel consumption compared to those used in the simulations and cover a distance equal to the daily average of all flights.

In the first graph in Figure 3, the amount of hydrogen produced by the generator is displayed. Each blue bar represents the value of the hourly production every 10 minutes, while the red line represents the energy pricing. The second graph displays the amount of hydrogen stored in the ground tank, the third graph shows the flow rate of hydrogen through dispensing units, and the last graph displays the distribution of takeoffs throughout the day.

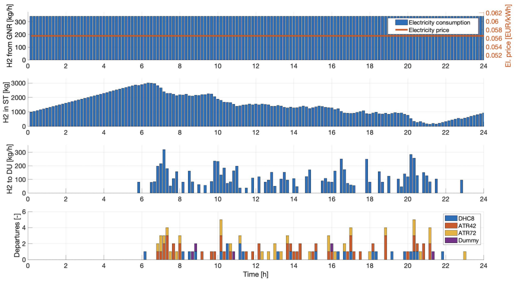

Figure 3: Results on MDD at ATH Airport with a simple electricity tariff

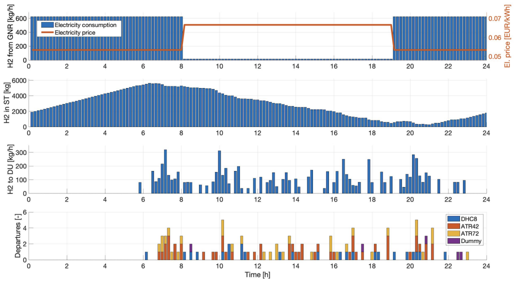

Figure 4: Results on MDD at ATH Airport with a bi-hourly electricity tariff

It can be observed that in the case of simple pricing, hydrogen production is evenly distributed over 24 hours. Since there is no penalty for electricity usage during daytime hours, this allows for minimizing the absorbed power. On the other hand, in the case of bi-hourly pricing, the substantial difference is that production is concentrated during nighttime hours to take advantage of the discount on energy tariffs. This results in a slightly lower energy cost, however, it increases the cost of peak power and the ground storage tank size. The tank, indeed, must store a larger amount of hydrogen even though daily production in both cases is almost the same, as it needs to satisfy the demand for the following 10 hours after 8 am, when the production reaches its minimum. It is necessary to specify that a periodicity constraint is set in the code, so the schedule considered in the simulation repeats every day. Therefore, after the last flight has taken off, the plant starts producing hydrogen again to supply to the aircraft that will take off the next day. The main numerical results are detailed in Table 2.

Table 2: Athens Airport on MDD: results

Tariff	**Simple**	**Bi-hourly**	**Change**
Ele. consumption	512 510 kWh	514 140 kWh	
Ele. cost	€ 28 993	€ 27 576	-5.1%
Power absorbed	21 420 kW	38 734 kW	
Power cost	€ 1 786	€ 3 238	44.8%
LH2 production	8 266 kg/d	8 292 kg/d	
GNR cost	€ 2 831	€ 2 840	0.3%
Max mass in ST	3 017 kg	5 647 kg	
ST cost	€ 165	€ 309	46.6%
No. of DU	5	5	
DU cost	€ 5 260	€ 5 260	0.0%
Total cost	€ 39 035	€ 39 223	0.5%
Cost/kg of LH2	€ 4.72	€ 4.73	0.2%

The methodology was also used to conduct further analysis on the airports taken as examples. The off-design analysis allows for estimating what is the cost increase that occurs when the plant operates on a schedule for which it is not optimized. Initially, in Case A, the plant is optimized according to the LDD schedule, while in Case B, a plant sized for the MDD schedule - with significantly larger components than required - is employed and operates with the LDD schedule. The results reveal that the cost per kilogram of hydrogen rises significantly in Case B due to the volume disparity between high and low seasons for regional flights at Athens Airport. Specifically, the total distance covered by all aircraft during the MDD is three times greater than during the LDD.

Table 3: ATH off-design analysis: results

	Case A	**Case B**	**Change**
Ele. consumption	176 090 kWh	177 000 kWh	
Ele. cost	€9 960	€10 010	0.5%
Power absorbed	7 362 kW	7 400 kW	
Power cost	€613	€617	0.5%
LH2 production	2 840 kg/d	2 854 kg/d	
GNR cost	€973	€2 831	65.6%
Max mass in ST	1 549 kg	1 551 kg	
ST cost	€85	€165	48.6%
No. of DU	2	5	
DU cost	€2 104	€5 260	60.0%
Total cost	€14 263	€18 886	24.5%
Cost per kg of LH2	€5.02	€6.61	24.1%

Finally, a sensitivity analysis was also carried out to estimate the influence of the various inputs on the final results, from which it was found that the only parameters that could result in a substantial alteration of the final solution are the energy parameters.

4.2. Milan Malpensa Airport

The analyses conducted for Athens Airport were replicated for Malpensa Airport, revealing a notable contrast in hydrogen demand due to a greater number of flights, longer distances traveled, and higher aircraft fuel consumption. While the operation of the plant under simple or bi-hourly pricing resembled what was studied in Section 4.1, Table 4 shows a substantial increase in plant size.

Switching to a bi-hourly energy pricing was found to result in similar savings in energy costs and an increase in power costs as observed in the Athens Airport case. However, the tank size increased more substantially.

Performing the off-design analysis again, here the cost per kg of hydrogen shows only a 5.4% increase between the two cases, which is much smaller compared to the 24.1% increase observed for Athens Airport. This is because Malpensa Airport experiences a smaller variation in flights between high and low seasons, resulting in a smaller reduction in the total number of flights compared to ATH. More specifically, while MXP Airport records a 40% decrease, ATH Airport experiences a much more significant reduction of 67%.

Table 4: Malpensa Airport on MDD: results

Tariff	**Simple**	**Bi-hourly**	**Change**
Ele. consumption	25 228 000 kWh	25 311 000 kWh	0.3%
Ele. cost	€1 427 200	€1 357 600	-5.1%
Power absorbed	1 054 560kW	1 906 700 kW	
Power cost	€87 880	€159 400	44.9%
LH2 production	406 901 kg/d	408 250 kg/d	
GNR cost	€139 350	€139 810	0.3%
Max mass in ST	123 950 kg	257 740 kg	
ST cost	€6 792	€14 123	51.9%
No. of DU	9	9	
DU cost	€9 468	€9 468	0.0%
Total cost	€1 670 648	€1 680 500	0.6%
Cost per kg of LH2	€4.10	€4.12	0.5%

5. Conclusion

Some of the main conclusions drawn from the study can be summarized as follows:

- Energy is the biggest cost in all considered cases.
- The plant's elements require greater performance than currently available, highlighting the need for rapid technological development to meet the necessary ground facility performance for large-scale adoption of hydrogen-powered aircraft.
- The cost per kilogram of hydrogen decreases as production increases up to a certain point, but after that, the energy cost is the only factor that significantly influences the final results.
- To reduce the production cost per kilogram of hydrogen and reach the expected value of $1/kg in one decade, it is necessary to lower energy costs by reducing energy requirements or producing part of the energy on-site with renewable systems.
- The adoption of bi-hourly pricing does not offer significant benefits, and a discount at nighttime below a certain proportion (20-15%) would provide no advantage at all.

This work could be improved in the future by using more accurate input data, particularly regarding airport requirements and cost estimation.

The goal of this study is not to offer definitive and certain data, but to provide a first approximation of the scale of such a facility and, more importantly, a practical tool that can be customized to specific requirements due to its remarkable adaptability and versatility, which allows it to go beyond civil airports to include also private airfields or military bases.

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