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Preliminary Sizing of Airport Infrastructures for Refuelling Hydrogen-Powered Aircraft

Lorenzo Trainelli[1,a*], Gabriele Sirtori[2,b], Carlo E.D. Riboldi[1,c], Giorgio Filippoli[1,d], Stefano Cacciola[1,e]

[1]Department of Aerospace Science and Technology (DAER), Politecnico di Milano, Milan, Italy

[2]Fédération ENAC ISAE-SUPAERO ONERA, Université de Toulouse, Toulouse, France

[a]lorenzo.trainelli@polimi.it, [b]gabriele.sirtori@polimi.it, [c]carlo.riboldi@polimi.it, [d]giorgio.filippoli@polimi.it, [e]stefano.cacciola@polimi.it

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Abstract. This paper illustrates a general methodology 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 methodology 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". A sensitivity analysis shows how the system performs in off-design conditions, with the price of the various components needing to be shared by a smaller hydrogen production.

Introduction

A revolution in future civil aviation is currently being envisaged through the switching of the current jetliner fleet to hydrogen-powered aircraft, seeking a significant reduction of the environmental impact of commercial air transport. While the technology of hydrogen propulsive systems is currently undergoing research and initial development, making the implementation of suitable airframes reasonably likely in the next decades, another significant hurdle for the entry-into-service of such a fleet is posed by the need to provide the required quantity of hydrogen at airports. Therefore, a methodology to estimate the infrastructural needs is essential to support feasibility analysis and scenario studies towards the fleet switching from kerosene- to hydrogen-powered airliners. Similarly to what was accomplished for the preliminary sizing of a battery-recharging airport equipment[1], this paper introduces a methodology to preliminarily size an infrastructure devoted to the on-site production, storage and delivery of liquid hydrogen.

The sizing is based on an optimal procedure that, based on the flight scheduling at a given airport, computes the need for hydrogen generation, liquefaction, storage and just-in-time distribution to each aircraft, by minimizing the total cost of acquisition and operation of the hydrogen plant and thus of the fuel. Grid electricity cost day variations are considered, as well as other factors impacting costs and operations. The hydrogen needs for each aircraft model are computed by using a dedicated preliminary sizing methodology that allows substituting current aircraft models with performance-equivalent hydrogen-powered ones [2].The process not only delivers the overall sizing of the hydrogen generator, liquefier, cryogenic tank and of the set of dispensing units, but also provides the optimal time scheduling of hydrogen mass flows across the various components of the infrastructure.

A similar approach is shown in [3], which identifies that hydrogen can be delivered as a liquid or a gas to the airport, or produced on-site, with the last two instances requiring on-site liquefaction. After being stored as a liquid at the airports, the cryogenic fuel can be delivered via LH2 tank trucks or an airport pipeline infrastructure, with aircraft serviced by dispensing trucks.

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The former is more flexible and economical for airports with annual demands below 125 kt of LH2. In contrast, the latter is economically viable for airports with higher demands, offering faster and safer refueling. The expected hydrogen price will be between 2.6 and 3.9 $/kgH2 for a 2050 time horizon, depending on the airport size and refueling layout. For a large airport, 69 % of the hydrogen cost at refueling is represented by the GH2 supply, followed by 25 % for the liquefaction. The remainder is represented by storage, dispenser and pipeline costs.

Besides the methodology description, presented in ch. 2, an example application and sensitivity studies referred to existing international airports with actual aircraft movements are discussed in ch. 3.

Methodology

The objective of the work presented here is to size the main elements of an airport hydrogen refueling facility in support to hydrogen-powered airliners. This allows to quantify the required electricity supply, with a view to the foreseen adoption of this fuel in place of jet-fuel for commercial aircraft operations. The developed methodology is called Airport Hydrogen Refueling Equipment Sizing (AHRES). The airport refueling station includes three main elements:

• The generator, consisting of an electrolyzer, a buffer tank, and a liquefier, where, starting from liquid water, hydrogen is obtained through an electrolysis process powered by electric energy from the grid or from a local renewable electricity plant; the gas is then cooled to cryogenic temperatures for storage in liquid form;

• The storage tank which accumulates the hydrogen produced earlier than it is required, e.g., during a time slot when electricity is cheaper, so that there is enough of it stored to refuel departing aircraft;

• Dispensing units that pump liquid hydrogen from the storage tank to the aircraft tank.

Details on the cost of the components implemented within AHRES can be found in *[4] [5]*.

The preliminary sizing of an airport's hydrogen refueling infrastructure, characterized by a large number of variables and parameters, is approached as an optimization problem. Thus, a cost function, representing the daily cost of the system as the sum of the costs of its components and cost of electricity and power, is defined. The cost function is minimized while all relevant constraints are satisfied. The constraints of the optimizer aim to ensure that the problem properly reflect real-world operations: maximum capacity of the ground and aircraft tanks is respected, there is enough availability of hydrogen and dispensing units for each departure, the electrolyzer is always running at least at its minimum production rate.

The solution of the problem, based on the daily schedule of the busiest day of operations at the selected airport, details the nominal production rate of the hydrogen generator and liquefier, the size of the cryogenic ground tank, the number of required dispensing units and the detailed refueling time history over the considered time frame. The selection of the busiest day ensures that the refueling system is properly sized for the traffic received at the airport. The ultimate output is the cost of 1 kg of hydrogen.

Results

Here results considering the Milan Malpensa short-haul flights are presented, as both the airport operator [6] and one of the main airlines [7] have shown particular interest in developing climate-neutral flight technologies. In particular, the busiest day of operations (Most Demanding Day – MDD) in 2022 showed 239 short-haul flights, all considered in the following analysis. Namely, two pricing models for electricity have been introduced, enabling the comparison of the sizing with a fixed electricity rate or with cheaper prices at night. Table 1 details the results. The main differences between the mono- and dual-rate electricity cost simulations are the operation and sizing of the hydrogen generator and the size of the tank. The overall daily costs to support the hydrogen production plant, including the cost of the components, the peak power, and the electricity, increase by 7.7% going from a mono- to a dual-rate electricity cost. The lower electricity costs permitted by the dual-rate scenario (-4.9%) are outbalanced by an increased maximum power (+81.4%), generator (+85.3%), and tank (+125.6%) costs. The hydrogen cost increases by 7.3%, going from 4.104 €/kg to 4.405 €/kg.

Table 1: Comparison of the results for Milan Malpensa considering mono- and dual-rate

Indicator	Mono-rate	Dual-Rate	Change[%]
Cost function [€/day]	$1.70 \cdot 10^{+6}$	$1.83 \cdot 10^{+6}$	7.7
Consumed energy [kWh/day]	$2.57 \cdot 10^{+7}$	$2.58 \cdot 10^{+7}$	0.3
Electricity cost [€/day]	$1.45 \cdot 10^{+6}$	$1.38 \cdot 10^{+6}$	-4.9
Max. power [kW]	$1.07 \cdot 10^{+6}$	$1.94 \cdot 10^{+6}$	81.4
Power cost [€/day]	$8.94 \cdot 10^{+4}$	$1.62 \cdot 10^{+5}$	81.4
H2 production [kg/day]	$4.14 \cdot 10^{+5}$	$4.16 \cdot 10^{+5}$	0.3
GNR cost [€/day]	$1.42 \cdot 10^{+5}$	$2.63 \cdot 10^{+5}$	85.3
Max mass in ST [kg]	$1.14 \cdot 10^{+5}$	$2.58 \cdot 10^{+5}$	125.6
Boil-off mass [kg]	$1.14 \cdot 10^{+3}$	$2.58 \cdot 10^{+3}$	125.6
ST cost [€/day]	$6.26 \cdot 10^{+3}$	$1.41 \cdot 10^{+4}$	125.6
Number of DU [-]	9	9	–
DU cost [€/day]	$9.47 \cdot 10^{+3}$	$9.47 \cdot 10^{+3}$	0.0
Cost of 1 kg of LH2 [€/kg]	4.104	4.405	7.3

The lowest obtained hydrogen pricing (4.10 €/kg for the Malpensa mono-rate scenario) is in line with the information presented by McKinsey in their 2021 Hydrogen Insight Report [8], which shows the price of 1 kg of green hydrogen in the range of 3.5-4.8 $/kg (3.2-4.3 €/kg) for 2023. The cost of energy is also coherent across the two models, with ours considering 0.0565 €/kWh and [8] a range of 25-73 $/MWh (0.023-0.067 €/kWh).

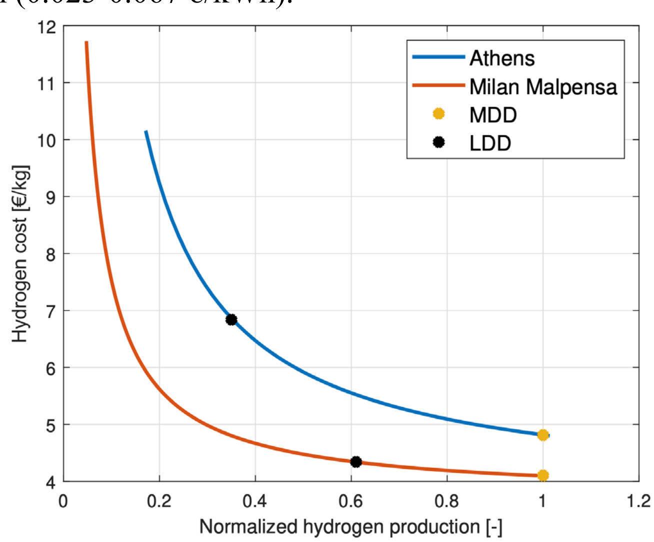

Figure 1: Variation of the cost of 1 kg of hydrogen as a function of the normalized production level.

Since the refueling system has been sized considering the busiest day, it is relevant to assess the impact on the hydrogen price on off-design conditions, with a lower required production. Figure 1 shows how the price of 1 kg of hydrogen for the considered scenario and for a smaller airport sized for regional hydrogen-powered operations only. The Least Demanding Day (LDD) is also shown, indicating the day with the least operations. It is acceptable that larger plants work at 30% of their nominal capacity, with the cost of 1 kg of hydrogen rising to 5 €/kg. For smaller plants, the price is already high at the nominal production level, therefore an oversizing will make innovative aircraft not competitive with conventional ones in terms of fuel cost.

conclusion

This paper presents the AHRES methodology, whose objective is to optimize the sizing of a hydrogen production plant at airports, developed with the objective of supporting hydrogen-powered aircraft. A proper assessment of the impact on supporting infrastructures for hydrogen flights is important, in order to facilitate a smooth entry into service of novel aircraft. In fact, all the aviation stakeholders have the common objective of reducing the environmental impact of air transport: to achieve this, parallel development of hydrogen aircraft and of the refuelling infrastructures at airports is necessary, as the introduction of hydrogen as the main energy carrier onboard aircraft will represent a complete revolution for the aeronautical sector. The presented methodology is capable of sizing the generator, tank and amount of dispensing units necessary to support a given schedule while optimizing the overall cost. Particularly, the explication of the mathematical modeling and constraints and the application to selected scenarios are introduced. The results, with the cost of 1 kg of hydrogen being the ultimate indicator, are comparable with scenarios presented in the literature.

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