An Optimization Model for Airport Infrastructures in Support to Electric Aircraft

Francesco Salucci, Lorenzo Trainelli
Dept. of Aerospace Science and Technology
Politecnico di Milano
Milan, Italy
francesco.salucci@polimi.it

Roberto Faranda, Michela Longo
Dept. of Energy
Politecnico di Milano
Milan, Italy
michela.longo@polimi.it

Abstract—**This paper investigates the airport infrastructural needs in support of hybrid-electric fleet operations. Attention is focused on the battery-charging related requirements. The recharging facility sizing problem concerns the identification of the number and type of charging points and their related electrical consumption in terms of energy and power, as well as the number of spare batteries needed to guarantee smooth operations, in case of battery swapping. The aim is to design an infrastructure that can satisfy the charging requests while minimizing the investment and operational costs of the recharging facility through an optimization approach. The developed algorithm includes the selection of the charging strategy that best suits the case under analysis, which is strongly affected by battery capacity and charging power. In addition to the sizing of the charging devices, the method allows finding the best battery charging schedule, and the minimum number of aircraft needed for the planned missions.**

Index Terms —**Airport infrastructures sizing, Battery recharge, Emissions, Green aviation, Hybrid-electric aircraft.**

I. INTRODUCTION

Flightpath 2050 is an ambitious vision for aviation promoted by the European Commission which includes several ambitious goals. Among these, 90% of travelers within Europe will be able to complete their journey, door-to-door, within 4 hours, flights will arrive within 1 minute of the planned arrival time regardless of weather conditions and the number of accidents will be reduced by 80% compared to 2000 taking into account increasing traffic [1-3]. In this vision, protecting the environment and the energy supply is a key element [4,5]. In 2050 technologies and procedures available will allow a 75% reduction in CO_2 emissions per passenger kilometer and a 90% reduction in NO_x emissions and the perceived noise emission of flying aircraft will be also reduced by 65% with respect to the capabilities of typical new aircraft in 2000 [6].

Such goals are not likely to be achieved with an incremental innovation, i.e. the continuous improvement of conventional means: the current technology has already been pushed to the edge. Indeed, a radical innovation is required. Among new aircraft concepts or systems, the electric aircraft promises to lower emissions and noise pollution, while offering adequate performance and safety levels [7]. Pure-electric concepts are being considered for smaller size and shorter-range General Aviation applications, while hybrid-electric designs may be employed for commercial air transportation in the regional segment [8].

However, the existing airport framework was not designed for this aircraft. Infrastructural enhancements will be necessary for the operations of pure-electric or hybrid-electric aircraft [9-111]. In particular, airports are not ready to deal with large quantities of batteries and their recharge [12]. An upgrade of the current grid is necessary. This paper addresses the issue of ground infrastructure needs of a regional hybrid-electric fleet, aiming to remedy to a lack in the literature regarding this topic. Indeed, compared to automotive industry, where electric-driven vehicles are a reality, aviation is lagging, and scenario studies are scarce [13-15].

The adoption of this new technology is bounded to its cost-effectiveness. The transition of the current regional aviation to hybrid-electric aircraft is subject to the price of the new elements: batteries, chargers and electricity. If their cost is paid back by the lower fuel consumption, the aircraft owner shall obtain a profit. This, combined with a reduced environmental impact, would open the door to the spread of such an aircraft. This may reflect into benefits immediately appreciable at airport level, that could facilitate the acceptance of this new technology: lower pollutant emissions and, in case landing and take-off are performed using electric motors only, also lower noise.

This work investigates the airport infrastructural needs in support of a hybrid-electric fleet. In particular, attention is focused on the battery-charging related requirements [16]. This method has been applied on the “Aero Club Milano” fleet, consisting in 20 General Aviation aircraft based in Bresso city airport (Milano, Italy) [17]. In the present contribution, the application to a large airport with a huge regional traffic, Athens Airport, is considered.

II. BATTERY CHARGING

In this section, the infrastructural sizing methodology is discussed where, throughout an optimization, infrastructural costs and operational expenses are minimized.

A. Model Architecture

The architecture of the model developed is given in Figure 1. The starting point consists in the definition of the properties of chargers and batteries. For convenience, the charger properties are split in two files, one for regular chargers and another for fast chargers. Charger property files include, for each charger: name, power, voltage, current, method (AC od DC), charger location (on-board or off-board) and cost. For fast chargers, a dedicated script estimates the cost for the charging power. Battery property files contains name, technology, specific energy, energy density and life cycles. There is another property file, for aircraft. Some of their properties depends on the battery and are recalled for the battery definition file: once the user specifies technology and capacity, other parameters are computed accordingly and stored in the aircraft file. The aircraft property file contains name, battery properties (capacity, energy density, specific energy, technology, cost, efficiency, life, charging power), cost, passengers and technology (electric or hybrid-electric).

The data are then used to model the airport. This is done in two steps. Since this procedure could be applied to airports that already have a recharging facility for electric or hybrid-electric aircraft, a file containing the chargers and aircraft already in an airport is created. A special empty airport is created, in case the recharging facility is not present already. Afterwards, the airport under analysis is modeled. In this step, a file containing existing infrastructure and aircraft models already there, new aircraft that will operate in the airport and chargers' type to be installed is created. In this way the airport model can be easily loaded from the simulation script. What is already in the airport is separated from new items, not to be included in the cost analysis of new infrastructures.

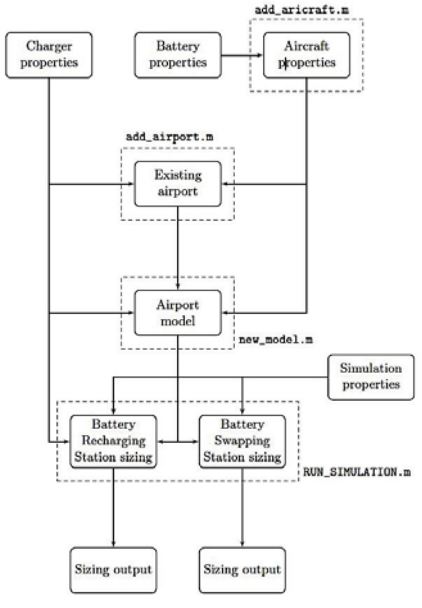


Figure 1. Model architecture.

In the core simulation script, implemented in MATLAB, two sizing are performed: Battery Swapping Station (BSS) sizing, to determine the battery number, operational cost and peak power, and the Recharging Station (RS) sizing, to obtain charger number, cost and peak power. Simulation properties includes the flight schedule, electricity pricing and solver options.

B. Battery Swapping

The BSS sizing problem requires to tune different parameters. Quantities like the number of batteries in the BSS, the number of chargers, the BSS peak power request and others design output are coupled and the variation of one of them affects the others. For example, to face a battery demand above the average at a particular time, it is possible to increase the number of chargers, or to increase the number of spare batteries and charge some of them during off-peak time. Both methods allow to have fully charged batteries when requested, but each solution has a cost. Furthermore, they affect the other parameters of the problem, like the electricity peak power request, in a different way. This algorithm has been implemented in MATLAB and tested for simple instances.

C. Battery Swapping and Plug-in charge comparison

The code described so far is intended to size a BSS. The model also includes a RS sizing. However, until now, the two procedures have not been compared. In fact, the two sizing are performed separately, and there is no indication about the best charging method. In addition, the optimal charging infrastructure could employ both methods. To have a fair comparison, the two charging strategies are now evaluated together.

The charging method is selected by the solver adding the capability to choose the best one in the BSS sizing algorithm. The new model is described in Figure 2.

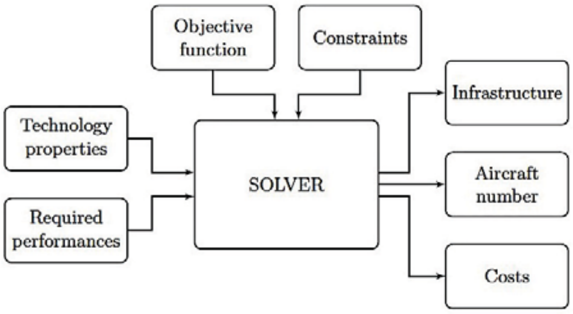


Figure 2. Model architecture of BSS sizing algorithm.

III. INFRASTRUCTURAL SIZING APPLICATION: ATHENS AIRPORT

Athens International Airport Eleftherios Venizelos (ICAO code: LGAV) is the primary international airport that serves the city of Athens and the region of Attica. It is Greece's busiest airport and it serves as the hub and main base of Aegean Airlines, as well as other Greek airlines. It has been selected as a test airport for the sizing procedure, since in 2016 it was the

European airport with the highest number of propeller-driven regional aircraft movements. Concerning regional aircraft, Athens has been the busiest airport from 2014, with the number of movements constantly increasing from that year [13]. Regional aircraft are widely used to connect Greek islands to the mainland; thus, Athens airport makes a good test case to assess the infrastructural needs of regional aircraft operation.

Figure 3. View of Athens International airport.

Publicly available data [14] has been used to estimate the movements and to build up an average daily flight schedule. During a typical day, there are approximately 30 departures relevant for the analysis: 14 flights performed with a Bombardier Dash 8 Q400 and it carries 78 passengers, 12 with an ATR 42 and it carries 48 passengers, and 6 with an ATR 72 and it carries 70 passengers.

(a)

(b)

(c)

Figure 4. Regional liners operating at LGAV: (a) Bombardier Dash 8 Q400, (b) ATR 42 and (c) ATR 72.

A conceptual design of hybrid electric regional airplanes corresponding to the aforementioned models was first carried out using dedicated tools [15], and subsequently employed to replace the conventional fleet of aircraft. Resulting data is shown in Table 1.

TABLE I. AIRCRAFT CHARACTERISTICS.

Type of Aircraft	**Pax**	**Price [M€]**	**Estimated battery capacity [kWh] for HE variant**
DH8D	78	21.9	1,400
ATR42	48	12.2	1,000
ATR72	70	15.4	1,300

In Athens, flights are distributed during the day as reported in [16]. No operation takes place before 06:00 local time. For what concerns costs, a price tag for these hybrid-electric regional aircraft should be introduced in the model. As scope of this work is to provide a proof of concept and a presentation of capabilities of the described approach, the current price of the conventional versions of Bombardier Dash 8 Q400, ATR 42 and ATR 72 planes has been considered. Current electricity prices in Greece are reported in Table 2. Daytime charge refers to weekdays, from 7 AM to 23 PM. The particularity of Greek electricity fares lies in the power component pricing. It depends on the maximum power demand during *daytime* (daytime power charge).

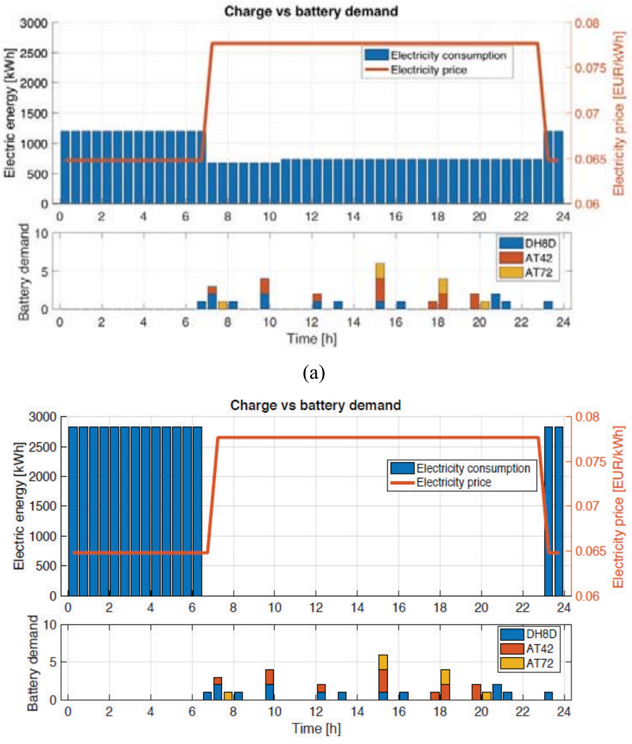
TABLE II. GREEK ELECTRICITY PRICES

Description	**Unit**	**Value**
Constant fee Fixed charge	€/month	9.7085
Daytime energy charge	€/kWh	0.05903
Nighttime energy charge	€/kWh	0.04614
Daytime power charge	€/kW/mo	8
Transport power charge	€/kW/mo	1.329
Distribution energy charge	€/kWh	0.0029
Distribution power charge	€/kW/mo	1.179
Other energy charge	€/kWh	0.01576

IV. ANALYSIS AND DISCUSSION OF RESULTS

Figure 4 shows the optimum recharging schedule considering 200 kW chargers. Two cases have been investigated. The Daytime Power Charge (DPC) and the

Nighttime Discount Power Charge (NDPC). The NDPC is obtained forcing the solver to charge batteries during the night to avoid paying for the daylight power component. In this case, the nightly discount in the power price makes it convenient to charge almost all the batteries during the night, as displayed in Fig. 5 (bottom). In the Fig. 5, each Bar represents 30 minutes. The upper graph displays the electric energy consumed to recharge the batteries. The lower graph shows the number of batteries requested during the day for each airplane model.



(a)

(b)

Figure 5. Athens airport charging schedule with 200kW chargers (a) Daytime Power Charge case and (b) Nighttime Discount Power Charge case

However, recharging all the batteries during the night is not the cheapest option, since it requires to increase the number of chargers and batteries (Table III).

TABLE III. INFRASTRUCTURAL SIZING WITH 200 KW CHARGERS – DPC AND NDPC

Description	**Unit**	**DPC**	**NDPC**
Total Batteries		26	31
Chargers		10	26
Aircraft		12	12
Peak Power	MW	2.0	5.2
Chargers total cost	M€	0.57	1.49
Battery replacement	Years	1.78	2.12

In fact, each charger would cost approximately 57 k€, and their expected life of 10 years corresponds to pay 157 €/day for 10 chargers and 409 €/day for 26 chargers. However, this power pricing policy makes the power price equal to 488 €/day for the night charge strategy, against 700 €/day for 10 chargers used all day long.

In both cases, the solver computed the same number of aircraft requested for the operations (assuming an aircraft performs a flight to another airport and comes back in 2.5 hours), but this number actually depends on how the airlines manages the fleet, and if all the aircraft departing from Athens are based in this airport.

In the DPC case, it is required to replace a battery pack every 1 year and 9 months, while, in the NDPC case, the higher amount of batteries has to be substituted every 2 years and 2 months. Nevertheless, in the long run, the amount of purchased batteries will be the same, since what really matters is the number of charging cycles a battery can bear.

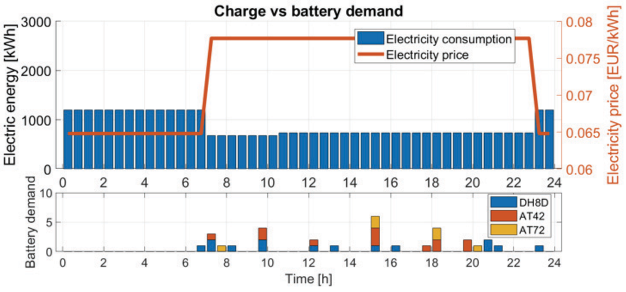
To investigate the robustness of the solution, we tried to vary the daily traffic volume with respect to the baseline day schedule described in [16]. Table IV displays the subsequent changes in the solution, calculated considering the DPC case.

TABLE IV. INFRASTRUCTURAL SIZING WITH 200 KW CHARGERS CONSIDERING TRAFFIC VOLUME VARIATIONS – DPC

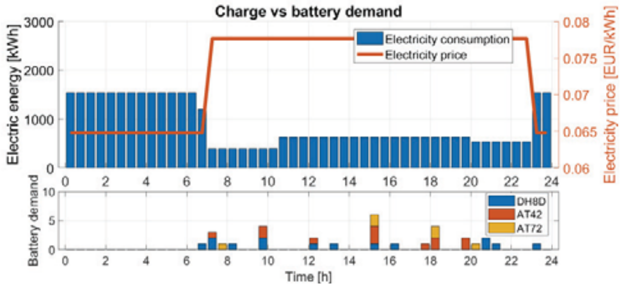
		Variation on baseline traffic volume			
Item	**Unit**	**-10 %**	**0**	**+10 % peak**	**+10% off-peak**
Total Batteries		24	26	29	28
Chargers		9	10	11	11
Aircraft		11	12	12	12
Peak Power	MW	1.8	2	2.2	1.1
Chargers total cost	M€	0.51	0.57	0.63	0.63
Battery replacement	Years	1.81	1.78	1.82	1.77

The number of batteries, and chargers decreases and increases respectively to fulfill the lower and higher number of flights. Also, the peak power and the charger's cost are affected accordingly. It is interesting to notice that, the variation in the number of total batteries is lower in case the increase in traffic takes place during off-peak hours.

Increasing the charging power to 400 kW and 800 kW, results are illustrated in Figure 5 and Table V.



(a)



(b)

Figure 6. Athens airport charging schedule with 400 kW and 800 kW chargers (a) 400 kW charger and (b) 800 kW chargers

TABLE V. INFRASTRUCTURAL SIZING WITH 400 KW AND 800 KW CHARGERS

Item	**Unit**	**400 kW chargers**	**800 kW chargers**
Total Batteries		21	21
Chargers		6	4
Aircraft		12	12
Peak Power	MW	2.4	3.2
Chargers total cost	M€	0.41	0.31
Battery replacement	Years	1.51	1.51

The 400 kW and 800 kW charging schedules are similar to the 200 kW case, with higher power peaks. While the number of chargers and their cost are strongly affected by the higher charging power, the variation of other parameters is less relevant.

V. CONCLUSIONS

An optimization algorithm able to size the airport infrastructure in support of a hybrid-electric fleet has been developed. Starting from battery, charger, aircraft properties and flight schedule the optimization finds infrastructural needs to perform smooth operations, minimizing the cost. Two charging strategies have been identified: BCS and BSS. This procedure has been tested on Athens international airport since it was the European airport with the highest number of propeller-driven regional aircraft movements in 2016 and because propeller-driven regional aircraft are considered the first step for the scalability of hybrid-electric propulsion from general aviation to airliners. Infrastructural requirements such as the number of necessary chargers, batteries, the number of aircraft required to operate current flight schedule and electric peak power have been identified. An optimum recharge scheduled has also been assessed.

In the Athens case study, the plug-in solution was not deemed suitable for the big batteries required by regional airplanes. 200 kW, 400 kW and 800 kW chargers were considered. Greek electricity fares showed different optimum solutions involving a varying number of chargers/batteries.

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