AEGATS2018_28

DESIGN OF AIRPORT INFRASTRUCTURES IN SUPPORT OF THE TRANSITION TO A HYBRID-ELECTRIC FLEET

Federico Bigoni, Alejandro Moreno-Perez, Francesco Salucci,
Carlo E. D. Riboldi, Alberto Rolando, Lorenzo Trainelli(1)
Department of Aerospace Science and Technology, Politecnico di Milano, Milano, Italy
(1) Corresponding author, lorenzo.trainelli@polimi.it, +39.02.2399.8387

KEYWORDS: hybrid-electric propulsion, airport infrastructures, optimal sizing, battery swapping station, plug-in chargers.

ABSTRACT

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. Two alternative charging strategies were identified and compared: plug-in recharge and battery swapping. The sizing is driven by the fleet flight schedule and by the technological properties of aircraft, batteries and chargers. This method was applied on Bresso city airport (Milano, Italy), to assess the infrastructures required in case the current fleet is replaced with hybrid-electric aircraft. Results were employed to carry out a cost analysis. The fleet renewal with hybrid-electric aircraft was compared with the purchase of new conventional aircraft.

1. INTRODUCTION

Aeronautics is a vital sector of European society and economy and is now directly concerned by new challenges regarding its competitiveness, performance and sustainability. European Commission invited key stakeholders of European aviation to come together in a high level group to develop a vision for Europe's aviation system and industry: Flightpath 2050 [1]. It includes several goals: 90 % of travellers 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.

In this vision, protecting the environment and the energy supply is a key element: in 2050, technologies and procedures will allow a 75% reduction in CO_2 emissions per passenger kilometre and a 90% reduction in NOx emissions. The perceived noise emission of flying aircraft will be also reduced by 65% with respect to the capabilities of typical new aircraft in 2000. The EU targets are considered as being on an equal footing with those announced by International Civil Aviation Organization (ICAO), International Air Transport Association (IATA), National Aeronautics and Space Administration (NASA). [2, 3, 4]. To fulfil these long-term emission goals, it is not possible to rely on conventional thermal propulsion: current technology has already been pushed to the edge. Indeed, a radical innovation is required.

Among new applicable concepts and systems, pure-electric or hybrid-electric (HE) aircraft have the capability to significantly lower chemical emissions and noise pollution. A recent effort in HE propulsion development is the MAHEPA project, an activity aimed to bridging the gap between the research and product stages of this technology for aviation. This project includes the complete development and flight testing of two serial HE General Aviation (GA) airplanes, one equipped with a thermal engine and the other with a fuel-cell system. This will provide a comprehensive knowledge base useful to validate performance, efficiency, and the emission reduction potential of HE propulsion. In addition, investigation of HE aircraft design and analysis methodologies, powertrain model scalability, and impact prediction is ongoing, including a study concerning the fleet switching from conventional to HE aircraft and its overall impact on aviation.

Among the most interesting topics connected to this scenario concerns airport infrastructures. Indeed, the existing airport framework was not designed for operating HE types of aircraft. Infrastructural enhancements will be necessary to support operations of full-electric and/or HE aircraft. In particular, a modification of the current airport electric network will be necessary to provide adequate energy supply to the aircraft, as well as ground storage and distribution. Indeed, aircraft batteries will need to be recharged and an appropriate sizing of the recharging facility must be addressed to estimate the number and type of charging points, their electrical consumption in terms of energy and power, and the economics involved. The present contribution delves on this topic, which does not seem to have been dealt with to date.

The problem is being studied for the increasingly popular terrestrial electric vehicles (EVs). However, the biggest obstacle to wider adoption of EVs is (im)maturity of battery technology [5]. Recharging the batteries takes more time than refuelling, which might be inconvenient. Various plug-in fast charging schemes are being developed and implemented, in order to reduce waiting times at public charging stations [6, 7, 8]. An alternative to plug-in chargers is represented by Battery Swapping Stations (BSSs), where discharged EV batteries can be quickly swapped for fully charged ones, thus eliminating long waiting times normally needed for recharge [9, 10, 11]. Unfortunately, the adoption of this new technology involves large investments [12].

This work aims to investigate airport infrastructural needs in support of a HE fleet. In particular, attention is focused on the requirements related to battery charging. Two alternative charging strategies were identified and compared: plug-in recharge and battery swapping. In the first case, aircraft are connected to the grid directly from the apron; in the second case, depleted batteries are exchanged with fully-charged ones provided by a dedicated facility.

The paper organization is as follows: we first introduce the technological framework involving new aircraft types, batteries, and battery charging options; then, we briefly present the optimal sizing method; finally, we show the results of the application of the method to the Bresso city airport (Milano, Italy), home to *Aero Club Milano*, which operates a GA aircraft fleet for training and recreational flight. A fleet switching from current conventional airplanes to HE ones was considered, in order to assess the infrastructures required.

2. TECHNOLOGY FRAMEWORK

2.1 Hybrid-electric aircraft

Hybrid-electric aircraft are able to use both electric motors and conventional thermal engines or fuel cells for propulsion. Against continuous increasing of energy demand and rising fuel price, hybrid electric propulsion has the potential to reduce fuel consumption in the aviation industry, particularly in the lighter sectors.

A saving up to 20% for a typical transfer mission and up to 30% for a training mission is stated to be possible in [13] for a light aircraft. According to [14], a 10% to 39% fuel reduction is achievable by 2030 for a commuter aircraft, while a 15% reduction is expected for a narrow body liner. The largest reduction in fuel burned is expected by using the available electric energy during cruise, since usually it is the longest flight phase. Using the electric motor could have a significant benefit on the gas-turbine performance and it would help to increase the life cycle of the combustion engine. In addition, electric taxiing and other potential benefits make the electric propulsion appealing [15]. Moreover, HE propulsion systems provide not only a fuel saving, but also a reduction in take-off noise and emissions.

Currently, multiple examples of HE or pure electric aircraft projects are burgeoning, including the E-Fan X program [16] (Airbus, Rolls-Royce and Siemens), Zunum startup [17] (Boeing and BlueJet), EasyJet is working with Wright Electric [18] and Pipistrel, who marketed the first commercial all-electric trainer, the Alpha Electro [19].

2.2 Batteries

Energy storage is the first aspect to consider while analysing the differences of HE airplanes with conventional airplanes. Lithium-ion (LIB) and Lithium-polymers batteries are the most common type of batteries due to very high performance compared to other technologies available on the market. Current energy density of LIBs is around 200-250 Wh/kg, but many studies report that this value may increase up in the near future, allowing batteries to become lighter and electrically-powered flights to be longer. Current electric aircraft are typically powered by LIBs due to their lower cost and greater diffusion. Other types of Lithium-based batteries are being studied to achieve higher energy and power densities. Among the various battery technologies under development, all-Solid-State Batteries (SSBs), Lithium-Sulphur Batteries (LSBs) and Lithium-Air Batteries (LABs) are found. A synthetic review of battery technologies is shown in Table 1.

2.3 Plug-in chargers

Battery charging technologies have recently spread for automotive applications. However, the aviation sector faced the problem of delivering energy at high power rates well before the automotive field. For instance, typical electrical connections for aviation today are capable of handling up to 90 kVA. Bigger aircraft could require even more power. ISO 461 contains the specifications for aircraft plugs. It features 3 connectors, with different output voltage [20]. Nowadays, other players are approaching the problem and new standards and connectors are being designed, specifically for the automotive field.

According to the present technological development, Direct Current (DC) charging systems are the ones that can be employed in fast charging and can be used on the apron without altering the turnaround times, while Alternate

Table 1: Battery technology review

	Battery technology			
	LIB	SSB	LSB	LAB
Cathode composition	NMC with Carbon black	NMC with Carbon black	S + porous Carbon	Gas Diffusion Layer + Co_2O_3
Anode composition	Graphite	Li-C	Lithium-metal	Lithium-metal
Electrolyte composition	LiPF6 in ethylene carbonate	LiPON	LiTSFI	LiClO4 in TEGME
Specific energy [Wh/kg]	~ 250	~ 250	~ 400	~ 800

Current (AC) charging systems could be used only during overnight charging. CHAdeMO standard is the most common charging system for EVs with a total 51% market share, and the only one used for fast charging operations. These chargers are known to be very efficient with a charging efficiency up to 96% and can charge with less overcharging increasing the battery efficiency. Due to the limited number of pure-electric or HE aircraft currently on the market, examples of aircraft charging operations are confined to few models. Pipistrel Alpha electro is one example. The operation requires an external 60kW charger, that could be either fixed or movable. The 20 kWh capacity (13 kWh per an hour of flight, plus reserves) can be easily removed to be replaced with fully charged ones, but plug-in charge is also an available option.

2.4 Battery swapping stations

Another strategy to charge batteries is represented by BSSs. Swapping allows to replace depleted batteries with fully recharged ones without plugging the aircraft to the grid between two flights. In this case, a BSS responsible for battery charging, is present on ground. This method might be an appealing options for commercial aviation: aircraft will be equipped with high capacity batteries that, with the current charging technology, would not make possible to perform the charge within the turnaround time, as the conventional refuelling is. For instance, a hybrid version of the popular Boeing 737-800 would require a 3.5÷7.0 MWh battery [21].

Within an airport, a BSS facility could serve multiple airlines and make different deals with airlines. An option is a battery ownership from the operator that leases batteries to airlines for a fee. In this case the airline does not own the battery and it transfers the costs over the battery, the battery life, maintenance, capital costs, quality, technology and warranty to the BSS company. In this way, the airline could purchase the aircraft at a lower price, since the battery cost is not involved. Batteries in BSS could participate to Vehicle-to-Grid (V2G) storage and are actually charged when the energy cost is lower and in slow charging mode to extend their lifetime [22].

3. OPTIMAL SIZING

An adequate charging facility is needed to ensure smooth operations of a pure-electric or HE fleet. A sizing framework was implemented, where, throughout an optimization process, infrastructural costs and operational expenses are minimized. The sizing of the recharging equipment is driven by the fleet type composition, which involves the properties of aircraft, batteries, and chargers, and by flight scheduling.

The goal is to design an infrastructure that can satisfy the charging requests, minimizing the investment and operational costs of the recharging facility through an optimization. The optimization process includes the selection of the charging strategy, plug-in or Battery Swapping Station (BSS), that best suits the case under analysis. It provides the optimum battery charging schedule, the number of spare batteries needed, and the minimum number of aircraft needed for the planned missions. Energy price variation during the day is considered.

The optimization model is described in Figure 1. It consists of a Mixed Integer Linear Programming (MILP) formulation inspired by the one presented in [9], which refers to a BSS for ground EVs. A major overhaul was necessary, however, to allow a similar analysis for electric aircraft. Input data includes technology properties of BSS, plug-in chargers, batteries, expected electricity price and airport traffic requirements. These inputs are then employed to trigger the optimization of an objective function, composed by all the costs related to airport sizing and operation, as seen in Figure 2.

The aim of the optimization is to select the solution with the lower cost. Thus, the objective function ω

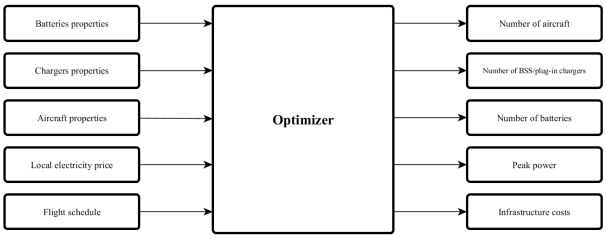


Figure 1: Optimizer architecture

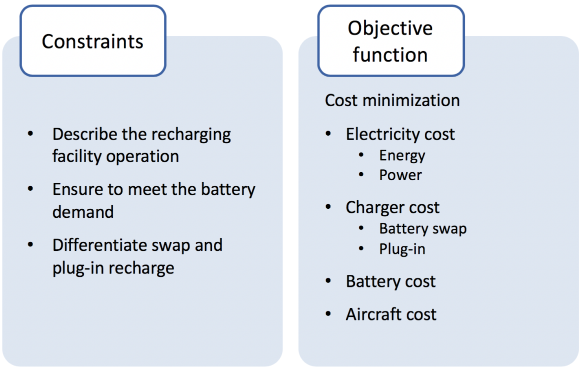


Figure 2: Objective function and constraints

contains a collection of costs to be minimized:

$$\omega = \underbrace{C_e + C_p}_{\text{electricity cost}} + \overbrace{C_{\mathrm{BSS}} + C_{\mathrm{pi}}}^{\text{chargers cost}} + \underbrace{C_b}_{\text{batteries cost}} + \overbrace{C_{a/c}}^{\text{aircraft cost}} \qquad \text{(Eq. 1)}$$

The main components of the objective function are costs related to electricity consumption: namely, the energy cost and the power cost. The energy cost, C_e, is the cost related to the amount of consumed energy, while the power cost, C_p depends on the peak power required from the electric grid. Then, C_{BSS} is the BSS chargers cost and C_{pi} is the plug-in chargers cost. Finally, there is C_b, the cost of a all necessary batteries.

Constraints are then added to trigger the optimization process: they oversee the physics and the coherence of the system, such as limits on energy state-of-charge of each battery at every time instant, maximum charging (or discharging) power limit and schedule limitations.

In order to consider both BSS and plug-in chargers, penalties were added:

- when a battery is charged in the BSS, it is unavailable for the time needed to perform the swap. During this time, the battery cannot be charged nor be used to fly.
- when a plug-in charger is used, it requires the aircraft to stay on ground to perform the recharge.

Detailed explanation of imposed constraints is given in [23]. Under this set of problem-specific constraints, the model is able to determine the minimum number of aircraft to employ for the scheduled timetable, infrastructural needs like the number of batteries, the number of BSS/plug-in chargers, the peak electric power and infrastructural and operational costs. An optimum battery recharging time schedule is also provided.

4. CASE STUDY

The proposed method was applied on the *Aero Club Milano* fleet, consisting in 21 GA aircraft based in Bresso city airport, to assess the infrastructures required in case the current fleet is replaced with HE aircraft. To perform the sizing, actual movements occurred during 2017 have been considered. The results were employed to carry out a cost analysis. The fleet renewal with HE aircraft was compared with the purchase of new conventional aircraft.

4.1 The airport

Bresso airport is an aerodrome located in the northern suburbs of Milan, Italy. Its technical data are given in Table 2. This airport is home of of *Aero Club Milano*, whose fleet realized approximately 80% of the movements in this airport in 2017. To apply the infrastructural sizing method described in [23], it has been supposed to replace the current fleet with HE aircraft.

4.2 The aircraft

For the present application, the hybrid version of the Pipistrel Panthera was considered as the reference GA aircraft. The Panthera is a modern four-seat, single-engine aircraft designed and developed by Pipistrel to be CS/FAR-23 certified (Figure 3). Its hybrid version is one of the two aircraft models currently under development within the MAHEPA project.

It is a serial HE airplane provided with a four-stroke Internal Combustion Engine (ICE) for in-flight electric power generation. It is intended as a bridging achievement towards the mass production of HE GA airplanes. Technical data about the Panthera Hybrid and its battery pack are reported in Table 3.

4.3 Infrastructural sizing

This airport is open to Visual Flight Rules (VFR) traffic only, and operations take place from 08:00 local time to 30 minutes past sunset [24]. Due to these reasons, the number of departures varies

Table 2: Bresso airport technical data

Bresso airport	
ICAO airport code	LIMB
Aerodrome reference code	2B
Airport type	Public
Location	Bresso (Milano, Italy)
Coordinates	$045°32'29''$N, $009°12'08''$E
Elevation	484 ft AMSL
Runway	18/36, 3,543 ft, asphalt

Figure 3: Pipistrel Panthera

during the year. For sizing purposes, movements occurred in November 2017 have been considered, since it turned out that it is the most demanding month in terms of infrastructural needs. In fact, because of fewer daylight hours available, operations are packed in 8 hours and the number of take-offs per hour increases. Thus, recharged batteries must be provided with a higher rate. Other months with even fewer daylight hours (December, January) are less demanding because of Christmas holidays. In addition, the number of flights increases during the weekend, since there are more people willing to fly in those days.

The flight schedule used to perform the sizing is reported in Table 4. To increase accuracy, daylight hours have been divided in 15-minute time periods. Initially, the infrastructural sizing procedure has been applied on the most demanding day (Saturday) only; aftewards, it has been extended to the entire week. Results in terms of infrastructural needs are reported in Table 5 and the optimum recharge schedule is shown in Figure 4. In particular, subfigure (a) reports the scheduling for Saturday only, while subfigure (b) shows it for the entire week. In both subfigures, in the upper graph blue bars represent bought electric energy necessary to recharge the batteries and orange line shows electricity price variation during the day. In the lower graph, bars represent the demanded number of batteries during the day.

Table 3: Panthera Hybrid technical data

No. pax	4
Rated power	200 kW
MTOW	1,315 kg
Cruising speed	177 KTAS
Range	>1,000 NM
Battery nominal capacity	13.8 kWh
Battery life @100% DOD	500 cycles
Battery life @75% DOD	800 cycles
Charging efficiency	93%
Discharging efficiency	85%
Charging Power	60 KW

Table 4: Average Bresso departures (November 2017)

h	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
M	0	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0
T	0	0	0	0	2	1	3	1	3	2	2	1	0	0	0	0
W	0	0	0	2	2	4	3	2	2	3	2	0	0	0	0	0
T	0	0	0	2	2	4	2	1	3	3	2	0	0	0	0	0
F	0	0	0	1	2	3	3	3	4	5	3	0	0	0	0	0
S	0	0	0	6	6	7	4	3	7	8	3	0	0	0	0	0
S	0	0	0	3	7	6	3	4	4	6	4	0	0	0	0	0

It can be observed that night hours, with lower energy price, are exploited to charge the batteries. Indeed, since 2007 the conventional electricity pricing scheme in Italy is based on three time slots with decreasing electricity price, as shown in Figure 5:

- F1 (Peak): from Monday to Friday, from 8 AM to 7 PM;
- F2 (Mid-level): from Monday to Friday, from 7 AM to 8 AM and from 7 PM to 11 PM. Saturday, from 7 AM to 11 PM;
- F3 (Off-peak): every night from 11 PM to 7 AM, plus the whole Sunday.

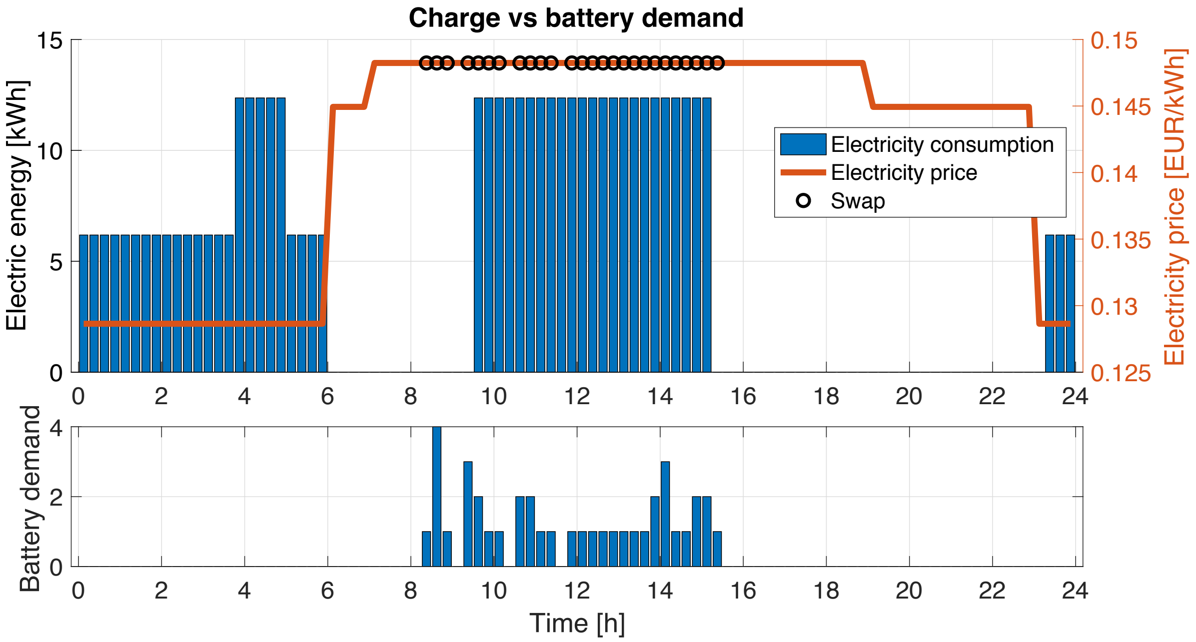
The mean energy price for 2017 was taken from [25].

Charging terminates when the electricity price rises in the morning. Then, batteries are used and, when there are no more fully-charged batteries available, depleted ones are recharged. Once the last charged battery is delivered, and no more flights are scheduled, depleted batteries are no longer recharged until the electricity price decreases, to take advantage of off-peak fares.

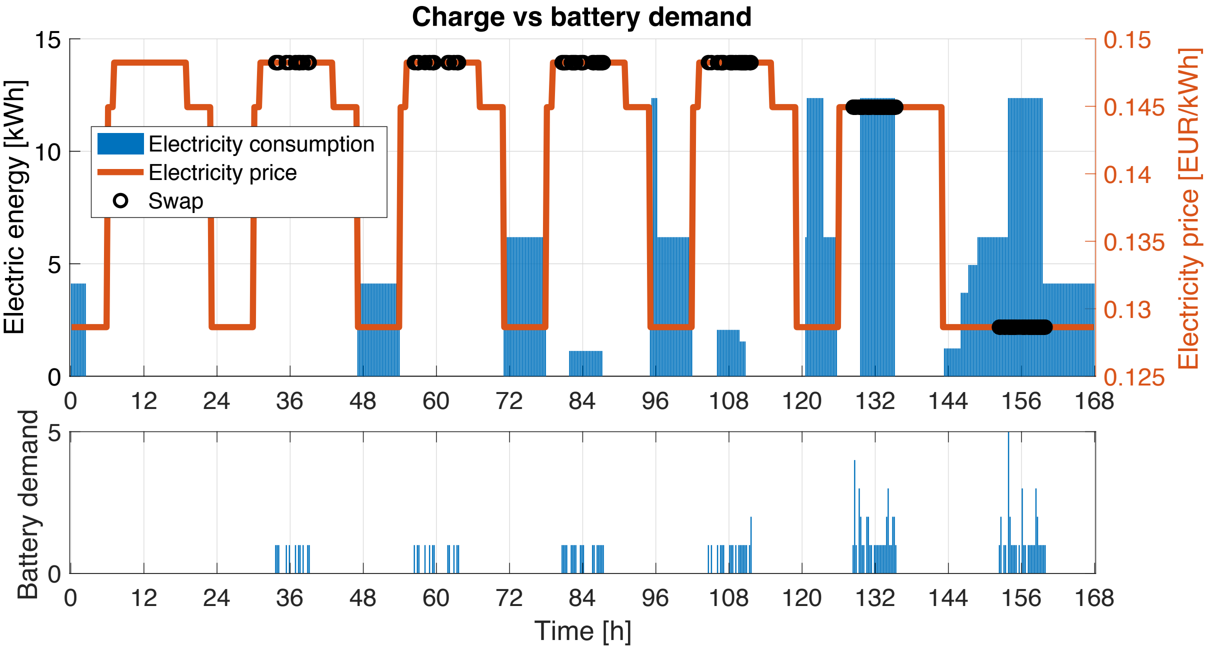
In this airport, no difference has been identified between the two charging methods, BSS and plug-in stations. In each case, a single charger is sufficient for the airport needs, and peek power, energy consumption and battery number are not affected by the charging method. This is mainly due to the short charging time: the Panthera Hybrid batteries can be recharged in less than 15 minutes. Therefore, they can be charged during the turnaround phase

Table 5: Bresso infrastructural sizing output

Property	Unit	Value	
		Saturday	Week
Charged Batteries		39	136
Energy consumption	kWh	410	1430
Peak power	kW	60	60
Losses (heat)	MJ	103	361
Battery number		16	16
Chargers		1	1
Aircraft		10	10



(a) Sizing for Bresso airport - Saturday only



(b) Sizing for Bresso airport - entire week

Figure 4: Infrastructural sizing for Bresso airport.

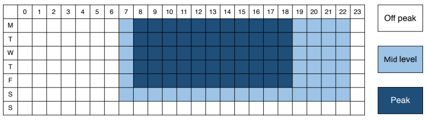


Figure 5: Italian current electricity pricing policy

connecting the aircraft to the grid, without affecting flight scheduling.

4.4 Fleet renewal cost analysis

The cost of a fleet renewal with the Pipistrel Panthera was evaluated. The analysis was performed comparing the purchase of new HE aircraft with the conventional-engine model of the same airplane. In this way, it is possible to evaluate whether a HE aircraft, besides being less noisy and polluting, is also economically convenient.

The sizing performed in Section 4.3 provides data for the cost analysis. A single charger has a 60 kW power demand from the grid. Although the power is high, due to an electricity consumption of approximately 60 MWh/year, the airport is considered a non-energy-intensive user (according to [26], energy-intensive users consume more than 300 MWh/year). Electricity providers do not usually apply special fares for users in this segment. Contracts are based on standardized commercial offers. For a new contract, a 69.57€/kW grid-connection fee is requested. Each 60 kW charger costs 39.8 k€, with an expected life of 10 years. Every year, maintenance cost is approximately 10% the purchase cost. The transformer cost is 35 k€ and the grid reinforcement requests 15 k€[6].

As a side result, the sizing showed that it is possible to perform the operations owning only 10 aircraft, half the magnitude of the current fleet. However, there are different reasons for buying more aircraft than the requested ones: for example, it may happen that some of them are forced on ground for maintenance. Considering the more numerous aircraft models currently belonging to the fleet, 2017 movements show that, as the number of aircraft of a specific model in the fleet increases, the average number of movements per aircraft increases as well. Values are shown in Figure 6.

For instance, every *Aero Club Milano*'s C172 flew on average 356 times in 2017, and the most used aircraft was I-ALEW, with 569 flights. By increasing the number of aircraft in the fleet, the number of spare aircraft necessary to cover the ones on ground for maintenance or to meet demand above the average decreases. In fact, a single failure affects the schedule in a less relevant way. By assuming as a safe value that every new aircraft will be able to perform no more than 356 flights in a year (as the C172) and neglecting any possible improvement in the maintenance schedule, a higher aircraft reliability or a shorter repair, it is found that the new fleet requires 14 aircraft.

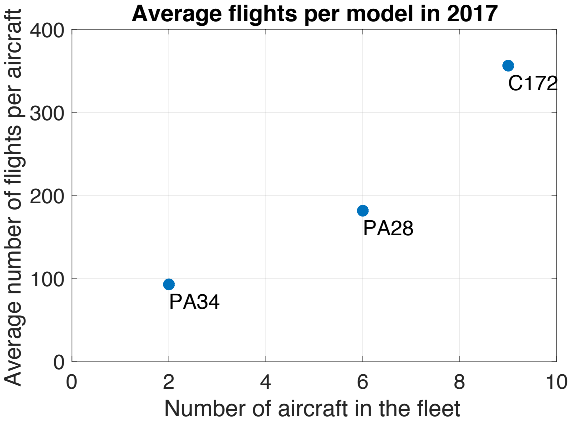


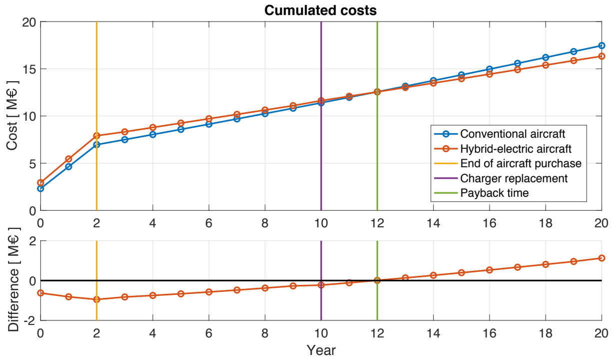
Figure 6: Average number of flights per model

The Avgas price has been set to 2.70 €, according to the early 2018 prices published in two GA aerodromes: Ozzano Dell'Emilia (Bologna) and Venezia-Lido. The annual fuel price rise considered in the analysis is 1%/year [27]. Also electricity price is assumed to rise, by 3.5%/year [28]. Battery prices, instead, are expected to decrease, with a 8%/year rate. This rate is the one expected for HE vehicles, while industry-wide cost declined by approximately 14% annually between 2007 and 2014 [29].

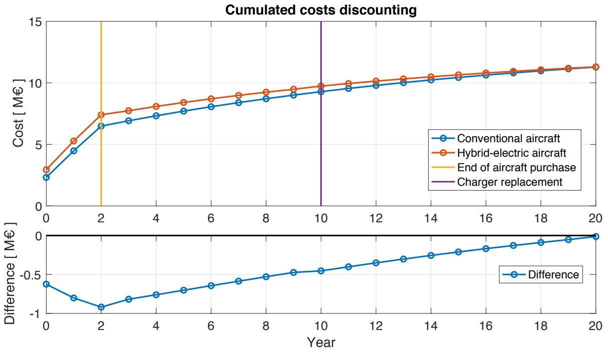
Another assumption is that customers will pay the same amount per flight hour, and in case the operational costs are lower, the infrastructure manager (*i.e. Aero Club Milano*) will be saving money. No variation in traffic from the 2017 values has been considered. A fuel consumption of 37 litres per mission for the conventional-engine aircraft has been considered and the reduction in fuel consumption, for the HE version employed on a standard training mission, has been estimated to be 30% of the conventional version [13]. The price tag difference between the conventional model and the HE one is 60 k€. The aircraft purchase is spread over 3 years. Each battery, with a 11.5 kWh useful capacity, costs 15 k€. The 16 requested batteries for the single charger strategy last 2.5 years with the current usage, the 11 requested batteries for the two chargers strategy must be replaced every 1.72 years. No enhancements on the current refuelling station has been considered.

Using these values, the cost analysis gives the results shown in Figure 7. The 20 years life span used is the one suggested by the Federal Aviation Administration (FAA) for major airport infrastructure projects, although longer life spans may be used if justified. [30]

Year 0 represents *time now*, when the investment starts, with the purchase of the chargers and the first aircraft. Operations with the new fleet start on year 1. During the transition to the new fleet, the share of flights performed with the new fleet corresponds to the share of aircraft purchased so far, while the other flights are performed with the old fleet. This may be a conservative approach, since the fleet owner could



(a) *Aero Club Milano* fleet renewal costs



(b) *Aero Club Milano* fleet renewal costs discounting

Figure 7: Cumulated costs for *Aero Club Milano* fleet renewal

enforce customers to use the new fleet as much as possible, with lower fuel consumption, and save more. With the current flight schedule, every year 6.4 new batteries must be purchased.

On year 12, the cumulated costs to run a HE fleet become lower than the ones to operate the conventional model of the same aircraft if the airport relies on a single charger. With two chargers, the higher purchase cost, maintenance cost, and electricity cost (due to the higher power) make the payback time occur on year 15. The cost difference between the two strategies, after 20 years, is 320 k€.

Most airport investments involve the expenditure of large blocks of resources at the outset of the project in return for an annual (usually rising) flow of benefits to be realized in the future. The cost analysis must take into account the fact that money paid out or earned in the near-term is worth more in “present value” than in the far-term. The process of converting future cash flows into present value is called *discounting* [30]. The present value v of a single cash flow c in the year y is obtained as:

$$v\left(0\right) = \frac{c\left(y\right)}{\left(1+r_{\%}\right)^{y}}. \qquad \text{(Eq. 2)}$$

The FAA recommends the use of constant money cash streams, and the discount rate should be net of inflation. This net-of-inflation rate is called the *real discount rate*. The *real discount rate* used in this analysis has been the one relevant to all airport projects to be funded with FAA grant funds, equal to 7% [30].

Considering the costs of the reference infrastructural cost analysis (Figure 7b), it is possible to see how the interest rate affects the profitability of the transition to a HE fleet. Using this rate, investments turn out not to be profitable before 20 years relying on fuel saving only. The positive slope of the line suggests that more years are requested to buy back the transition to a HE fleet. However, in 20 years, the aircraft useful life is not ended and the investment keeps guaranteeing a lower operative cost. Nevertheless, an anticipated aircraft purchase, will bring more savings but anticipating the cash out may increase the corresponding discount rate.

5. CONCLUSION

A model able to size the required airport infrastructure in support of a hybrid-electric fleet has been developed. It is based on the battery, charger and aircraft properties and flight schedule. An optimization is performed in order to find the infrastructural needs to perform smooth operations, while minimizing the cost.

The model has been tested on Bresso airport, identifying the infrastructural requirements needed to switch the current GA fleet to a hybrid-electric one. To date, a hybrid-electric aircraft in this category appears to be cost-effective with respect to a conventional one. Infrastructural costs of the recharging facility and operational expenditure are compensated by fuel saving.

In fact, a GA aircraft fleet requires a moderate initial expense and can benefit from a higher fuel saving. The Bresso case study, shows that the the biggest expense corresponds to the purchase of new aircraft, followed by battery and electricity costs. The charger cost and power charge are less relevant, but are the ones that make a difference in the sizing.

For instance, increasing by one the number of the chargers, its purchase, grid reinforcement and maintenance cost, combined with the higher power charge, leads to an extra 320 k€ expenditure in 20 years. Even if the number of batteries required for the operations decreases with an extra charger, as the charging schedule can be improved, no saving is achieved in the far-term because a more frequent battery replacement is necessary.

6. ACKNOWLEDGEMENTS

The research has been partially funded by the European Union’s Horizon 2020 research and innovation programme under Grant Agreement N. 723368 (project MAHEPA – Modular Approach to Hybrid-Electric Propulsion Architecture).

7. REFERENCES

1. Siim Kallas, Máire Geoghegan-Quinn, M Darecki, C Edelstenne, T Enders, E Fernandez, and P Hartman. Flightpath 2050 europe's vision for aviation. *Report of the High Level Group on Aviation Research, European Commission, Brussels, Belgium, Report No. EUR*, 98, 2011.
2. ICAO. Environmental report 2016. *Aviation and climate change*, 2016, 2016.
3. International Air Transport Association et al. A global approach to reducing aviation emissions. *First stop: carbon-neutral growth from*, 2020, 2009.
4. Aaron Drake. Nasa environmentally responsible aviation (era) n+ 2 advanced vehicle study. In *50th AIAA Aerospace Sciences Meeting*, 2012.
5. Vedran Bobanac and Hrvoje Pandzic. Lithium-ion batteries: Experimental research and application to battery swapping stations. In *2018 IEEE International Energy Conference (ENERGYCON)*. IEEE, 2018.
6. Andreas Schroeder and Thure Traber. The economics of fast charging infrastructure for electric vehicles. *Energy Policy*, 43:136–144, 2012.
7. Nthirai Sujitha and Subramanian Krithiga. Res based ev battery charging system: A review. 75, 11 2016.
8. https://www.tesla.com.
9. Mushfiqur R Sarker, Hrvoje Pandžić, and Miguel A Ortega-Vazquez. Optimal operation and services scheduling for an electric vehicle battery swapping station. *IEEE transactions on power systems*, 30(2):901–910, 2015.
10. Vedran Bobanac, Hrvoje Pandzic, and Tomislav Capuder. Survey on electric vehicles and battery swapping stations: Expectations of existing and future ev owners. In *2018 IEEE International Energy Conference (ENERGYCON)*. IEEE, 2018.
11. Carlos Adrian Correa-Florez, Alexis Gerossier, Andrea Michiorri, and Georges Kariniotakis. Stochastic operation of home energy management systems including battery cycling. *Applied Energy*, 225:1205–1218, 2018.
12. Kay O Ploetner, Marcia Urban, Arne Roth, Gilbert Tay, and Antoine Habersetzer. Fulfilling long-term emission reduction goals in aviation by alternative fuel options: An evolutionary approach. In *2018 Aviation Technology, Integration, and Operations Conference*, page 3990, 2018.
13. Emma Frosina, Carmine Caputo, Gianluca Marinaro, Adolfo Senatore, Ciro Pascarella, and Giuseppe Di Lorenzo. Modelling of a hybrid-electric light aircraft. *Energy Procedia*, 126:1155–1162, 2017.
14. Yann Fefermann, Christophe Maury, Clélia Level, Khaled Zarati, Jean-Philippe Salanne, Clément Pornet, Bruno Thoraval, and Askin T Isikveren. Hybrid-electric motive power systems for commuter transport applications. In *Proceedings of the 30th Congress of the International Council of the Aeronautical Sciences, Daejeon, Korea*, pages 25–30, 2016.
15. Clément Pornet, Corin Gologan, Patrick C Vratny, Arne Seitz, Oliver Schmitz, Askin T Isikveren, and Mirko Hornung. Methodology for sizing and performance assessment of hybrid energy aircraft. *Journal of Aircraft*, 52(1):341–352, 2014.
16. https://www.airbus.com/newsroom/press-releases/en/2017/11/airbus–rolls-royce–and-siemens-team-up-for-electric-future-par.html.
17. https://zunum.aero.
18. https://www.bbc.com/news/business-41404039.
19. https://www.pipistrel.si/plane/alpha-electro/overview.
20. Aerospace Standards Committee. *Aircraft — Connectors for ground electrical supplies Part 2: Dimensions*. British Standards Institution, 2011.
21. Christian Friedrich and Paul A Robertson. Hybrid-electric propulsion for aircraft. *Journal of Aircraft*, 52(1):176–189, 2014.
22. Yu Zheng, Zhao Yang Dong, Yan Xu, Ke Meng, Jun Hua Zhao, and Jing Qiu. Electric vehicle battery charging/swap stations in distribution systems: comparison study and optimal planning. *IEEE Transactions on Power Systems*, 29(1):221–229, 2014.
23. Bigoni F. Impact of hybrid-electric aircraft operations. *Politecnico di Milano - Master thesis*, 2018.
24. http://www.aeroclubmilano.it/it.
25. https://www.servizioelettriconazionale.it/it-it.
26. https://www.cn.camcom.gov.it/sites/default/files/uploads/documents/prezzi/tasp/rapporto%20costi%20energia%20elettrica.pdf.
27. U.S. Energy Information Administration. Annual energy outlook 2017 with projections to 2050, 2017.

28. https://www.theguardian.com/environment/2014/jul/10/price-electricity-double-next-20-years-national-grid.

29. Björn Nykvist and Måns Nilsson. Rapidly falling costs of battery packs for electric vehicles. *nature climate change*, 5(4):329, 2015.

30. FAA. *Airport Benefit-Cost Analysis Guidance*. 1999.