Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: Gabriele Sirtori *et al* 2024 *J. Phys.: Conf. Ser.* **2716** 012015

Prediction of environmental benefits introducing hybrid-electric propulsion on regional aircraft

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Abstract. The objective of this paper is to assess the environmental benefits arising from the introduction of hybrid-electric propulsion on regional and commuter turboprop aircraft. A great focus is put on the propulsion based on a turbine engine coupled with batteries, combining mature technologies. The introduction of novel propulsion architectures on aircraft deployed on regional and commuter networks allows a substantial reduction of the fuel needed by airlines. In this work, scenarios based on real airline networks are presented, in order to quantify the reduction of greenhouse gas emissions possible considering the expected technological advancement for 2035 and 2050. This analysis is conducted by retrofitting the hybrid-electric propulsive system onto existing aircraft that can carry 19 passengers (Dornier DO228) or 70 passengers (ATR72-600). For the 19-seat class, a clean sheet design is also considered to overcome some limitations of the reference aircraft. A precise assessment of the peculiarities linked to the chosen propulsive configuration shows that networks that have shorter flights are better suited to the introduction of this technology, as the restriction on the design payload is less stringent. The proposed propulsive architecture allows a reduction of the operators' yearly fuel budget of up to 50% in 2035 and 80% in 2050. At last, the taxi phase is of particular importance for regional aircraft that perform several rotations a day, therefore a further analysis of this phase is carried out. The result shows that the considered aircraft are capable of completing a full Landing & Take-Off (LTO) cycle without resorting to the thermal part of the propulsive system, reducing considerably the impact of the aircraft on the airport area.

1. Introduction

Environmental sustainability is the big challenge that the aeronautical industry has to face. In fact, aviation accounts for about 2% [1] of man-made greenhouse emissions and 12% of transport-related emissions. This is the reason why recently some countries, such as France and Austria [2, 3], have begun to put in place legislative limitations to flights, especially if ground-based alternatives are viable. Besides, an industry-wide effort is being carried out on current aircraft technologies to reduce the operational impact on the environment. The use of SAF (Sustainable Aviation Fuel), carbon offsetting and the introduction of flight efficiency programs allow to mitigate the environmental footprint of airline operations, but a leap forward is needed to put aviation on par with the general societal effort needed to achieve carbon neutrality.

This technological advancement can be achieved with innovative propulsive configurations, based on the different energy sources suitable for aeronautical applications, which are electricity, kerosene and hydrogen. This paper aims to assess the reduction of the environmental impact of the operation of small turboprop aircraft possible thanks to the introduction of Thermal Hybrid-Electric (THE) propulsive architectures, comparing the emissions of the baseline aircraft with those of the innovative configuration. In this work, the design mission is fine-tuned, thanks to a thorough exploration of the operation of regional and commuter aircraft in Europe.

The work is based on the output of an in-house preliminary sizing methodology HYPERION [4] and aims to assess the operations of aircraft whose requirements are fine-tuned to satisfy the commercial requirements while mitigating the mass increase linked to THE propulsive configuration. In particular, scenarios based on current airline networks are developed considering the expected technological levels for 2035 and 2050. The reference aircraft are the ATR72 (70 passengers) for the regional class and the Dornier DO228NG (19 passengers) for the commuter class, whose (i.e. Maximum Take-Off Mass (MTOM) and wing area remain unchanged) are called R70THE and R19THE respectively.

1.1. State of the art

Previous projects, such as MAHEPA [5] and UNIFIER19 [6], and industrial developments, such as the Pipistrel Velis Electric, which was the world-first certified electric airplane, have demonstrated that innovative propulsive configurations can be successfully applied to general aviation and commuter aircraft, paving the way for the development of environmentally sustainable solutions for larger airplanes, studied within the CS2 SIENA project.

Particularly, there are several possible innovative propulsive configurations, detailed in [7, 8], based upon the combination of different energy sources (hydrogen, jet fuel, electricity stored in batteries) and the consequent propulsive components (fuel cell, turbine or Electric Motors (EMs)). The work shown in this paper focuses on the serial THE configuration, in which the propellers are powered by EMs, whose power either comes from a kerosene-fed turbine (Power Generation System, PGS) or batteries. The THE configuration has been chosen over hydrogen-based solutions for its technological readiness level, as it is based on the combination of more mature technologies. The considered architecture has been assessed in two time scenarios, reflecting the expected technological advancement for 2035 and 2050. Current battery technology is in fact too limiting on the overall aircraft performance. The assumed values of specific power for EM, batteries and PGS, and the specific energy for batteries are shown in table 1 and have been obtained via extrapolation of data presented by [9–12].

Year		2035	2050
Battery Type		Li-Ion	Li-Air
Specific energy - battery	[Wh/kg]	350	1690
Specific power - battery	[W/kg]	2270	5070
Specific power - PGS (ICE)	[W/kg]	4120	4910
Specific power - EM	[W/kg]	11100	16540

Table 1: Energy and power density for battery, EM and PGS at 2035 and 2050 time horizons.

Besides, the introduction of a hybrid propulsive configuration enables different power management strategies [13], which impact the sizing of the propulsive components. A metric selected to minimize the impact on local air quality and noise around airports is to enable all-electric operations below a certain altitude, defined as hybrid transition altitude. This requires that the batteries carry enough energy to complete the taxi out, take off and climb. The PGS is therefore sized to provide the final climb power. Batteries are recharged in cruise, to allow powering an eventual go around. Batteries are sized considering that their recharge level is limited between 25% and 85% to increase the useful lifetime [14]. Other possible figures of merit could be the CO_2 emission minimization, a target hybridization level, the minimization of the direct operating cost and others [13]: each objective function leads to a different result for the preliminary aircraft sizing.

The increased electrification introduced by the THE configuration calls for a Thermal Management System (TMS), which is currently not sized within HYPERION. [15] proposes several possible system layouts, which use RAM air and fuel as heat sinks. The different layouts are assessed in terms of mass, required power (marginal compared with the power required for flight) and impact on drag. [15] can be used as a reference to model the TMS within HYPERION, to improve the quality of the results.

1.2. Structure of the paper

This paper is divided into three subsections. The first details how the current operations of commuter and regional aircraft are used to develop scenarios that allow to compute the baseline fuel consumption and emissions. The second section details the effect of the introduction of hybrid-electric propulsion onto aircraft operating in the modeled scenarios, with a focus on the constraints at the preliminary aircraft design level. Furthermore, there is a section that details the overall results in terms of the reduction of fuel budget and emissions thanks to the introduction of THE aircraft.

2. Airline Network and Fuel Budget Modelling

To develop a realistic scenario for the sizing of the retrofitted aircraft, a thorough assessment of Europe's main users of the ATR72 and of different commuter aircraft (namely, the Let 410 and the Beechcraft BD1900D) has been carried out, to obtain a solid understanding of how the operators use regional and commuter aircraft. For this task, data has been collected on Flighradar24 "Airline routes and destinations" page, referring to the specific pages of the selected airlines and to the flights operated by the selected fleets. In particular, the following ATR72 operators have been considered: Air Corsica (5), Binter Canarias (23), Finnair (12), Iberia (11) and TAP (8). Furthermore, also Olympic Air has been assessed, even if its fleet is more diverse, including 3 ATR42 and 8 Bombardier DHC-8-Q400. The obtained data for weekly flights, referring to the last week of July 2021, has been elaborated to obtain three Key Performance Indicators (KPI), needed to effectively compare the operators to select the most interesting for the development of the scenario. These KPIs, presented in fig. 1, are the amount of weekly flights, the average flight duration and the daily aircraft utilization, including half an hour of turnaround for each rotation. The optimal network for the application of the THE

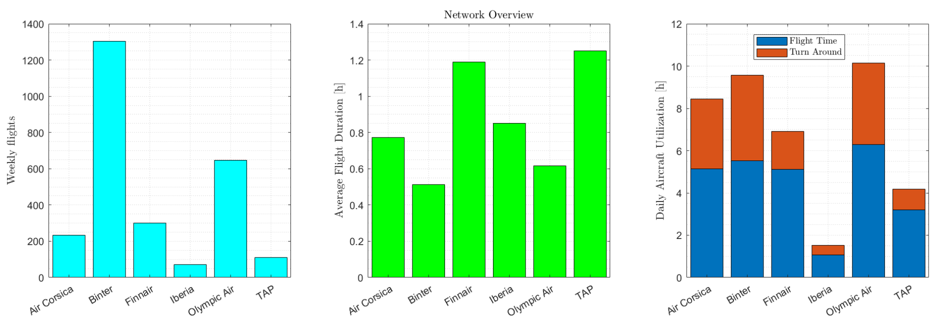


Figure 1: Network Overview KPIs.

propulsion needs specific characteristics. First, a larger amount of weekly flights maximizes the benefit achieved with the introduction of the new technology. Then, a high aircraft utilization guarantees a fast return on investment. Short average flights are better suited to be operated by THE aircraft, as the hybrid-electric configuration is constrained in terms of design range, as further detailed in section 3. Looking at the data presented in fig. 1, it is clear that Binter and Olympic Air are the optimal networks to take as reference for the development of the scenario. Instead, commuter aircraft are not that common in Europe, therefore the entire operations of TwinJet from France, with a fleet of 12 Beechcraft 1900D, and Silver Air, operating a single Let L410 Turbolet out of Elba island, Italy, have been considered, without any further assessment of their operation.

The next necessary step is the modeling of the fuel consumption of the reference aircraft: for commuter aircraft, the fuel consumption is simply obtained by multiplying the hourly fuel flow by the duration of the considered flights, for lack of more precise information. For the ATR72 instead, it is possible to derive a fuel consumption model, called Mission model, based on Eq. 1, which divides the flight into different phases (taxi out, climb, descent and cruise):

$$F_{Trip} = F_{TaxiOut} + F_{Climb} + F_{Descent} + \frac{D - \frac{D_{Climb}+D_{Descent}}{2}}{v_{TA}} \dot{W}_f \ N_{Eng} \tag{1}$$

The parameters presented in Eq. 1 are derived from the ATR72 FCOM [16] and are dependent on the cruise altitude, which is directly associated with the route length. The developed model has been validated with a comparison with the output of the EEA Master Emission Calculator [17]. This tool, developed by the European Environment Agency, evaluates aviation fuel consumption and consequent emissions, using a 3A Tier Method [18], based on precise information about the network and operating aircraft. It is possible to obtain a comparison between the Mission and EEA models by applying them to the same set of missions, identified by the operating aircraft and flight distance. The amount of fuel computed by EEA, which is a linear function of the flight distance, acts as an asymptote for the output of the Mission model for longer flights, validating the proposed approach. On the other hand, the developed Mission model is more precise for shorter missions, of particular interest for the aircraft categories considered in this work, as it allows us to account for the effect of lower cruise altitudes, namely less fuel required for the climb but a higher fuel flow during the short cruise phase. A similar approach also computes the fuel consumption of the Q400 and ATR42.

The developed fuel consumption model is used to assess the yearly fuel budget of the considered carriers. Particularly, the information regarding the number of flights has been collected for a peak week of July and has been extended to the full year, via the computation of a seasonal corrective factor s, to model the winter schedule. This factor is computed by assessing the monthly movements at each operating base of the considered airlines, M_i, thanks to data obtained in [19], taking as reference the movements of july at that base, M_7, and scaling the final airline factor considering the frequencies operated out of each base f_b over the total frequencies f_{Tot}, as in Eq. 2. The total yearly flights are computed as the product of s times 52 (weeks in one year) times the number of sampled flights.

$$s = \frac{1}{f_{Tot}} \sum_{b=1}^{B} \left(\frac{\sum_{i=1}^{12} M_i}{12 \ M_7} \right)_b f_b \tag{2}$$

The obtained results, in terms of yearly flights, fuel consumption and consequent emissions are shown in table 2. The emissions have been evaluated considering the EEA Emission Inventory [18], which gives the mass of emitted CO_2, NO_x, SO_x and CO per kilogram of burnt fuel.

3. Introduction of the Hybrid-Electric Propulsion on the Modeled Networks

3.1. Preliminary sizing of THE Aircraft

This section aims to evaluate the effect of the introduction of aircraft with a novel propulsive configuration onto the modeled networks. Existing aircraft, specifically the ATR72-600 and

Airline	Yearly flights	Fuel [t]	CO_2 [t]	NO_x [t]	SO_x [t]	CO [t]
Binter	63116	27229.7	85773.6	337.6	22.9	11518.2
Olympic	28929	16215.9	51080.2	201.1	13.6	6859.3
Silver Air	880	209.0	658.4	2.6	0.2	88.4
TwinJet	4360	2915.6	9184.1	36.2	2.4	1233.3

Table 2: Yearly emissions for the analyzed carriers.

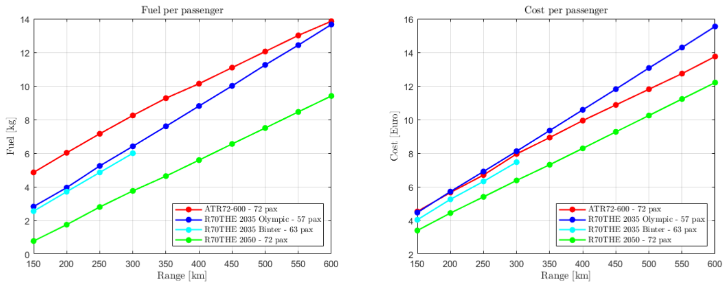
Dornier DO228, are retrofitted with a THE propulsive configuration, considering a fine-tuning of the design point (range and payload) with respect to the network scenarios developed in Section 2, to assess the achievable environmental benefits. A clean sheet aircraft is also designed for the commuter category, in order to offer a more suitable replacement for current aircraft. As detailed in section 1, the selected innovative propulsive architecture is the serial hybrid-electric layout, which sees the propellers connected to EMs, whose power either comes from a PGS or from batteries. The preliminary sizing of such innovative aircraft is carried out using the HYPERION methodology, thoroughly described in [4], which also enables retrofit studies, in which the MTOM and wing area remain unchanged from that of the reference aircraft. HYPERION, which relies on aircraft design methodologies proposed by the likes of Roskam and Raymer [20, 21], has been thoroughly validated in previous work. Given the higher complexity, thus higher mass, of the proposed THE propulsive configuration in comparison to that of conventional aircraft, in order to satisfy the MTOM constraint imposed by the retrofit, it is necessary to reduce the design point of the aircraft, either acting on the design range, payload or a combination of the two.

Looking at the network characteristics for Binter and Olympic Air, the chosen design ranges are 300 km and 600 km respectively. These values introduce a 10% margin on the longest missions of the networks to account for wind, aircraft deterioration over time and the fact that routes are not flown as straight lines, with the flown distance longer than the nominal distance between the airports. The fact that the MTOM remains unchanged across the version tailored for Binter and Olympic means that the propulsive components (EM and PGS) maintain their mass, whereas the trade-off is between the payload and the energy storage (battery and fuel). The maximum allowable payload comes as a result of the energy storage mass (battery and fuel), sized from the design mission analysis, and the constraint on the MTOM, imposed by the retrofit strategy. Table 3 shows the results for the sizing of the retrofitted regional aircraft, in terms of mass breakdown.

Year	Current	2035		2050	
Aircraft	ATR72-600	R70THE O.	R70THE B.	R70THE O.	R70THE B.
MTOM [kg]	23000	23000	23000	23000	23000
NP Airframe [kg]	12158	12158	12158	12158	12158
Payload [kg]	7900	6110	6888	7553	8134
EM [kg]	-	338	338	228	228
Battery [kg]	-	1854	1852	832	832
PGS [kg]	1025	968	967	812	812
Fuel [kg]	1925	1574	996	1419	837

Table 3: Mass breakdown for regional aircraft sized considering two technological scenarios and two operational networks.

It is possible to see the remarkable impact on the payload and crew in the 2035 scenario, with a drop of 24% and 13% for Olympic Air and Binter respectively, going from the original 7500 kg. The 2050 scenario instead enables the original payload for Olyimpic's scenario and even an increase for Binter (+8%). Because of this, it is necessary to assess whether the fuel and operating cost *per passenger* in 2035 are actually reduced with the THE configuration. The costs are assessed with a simple model that accounts for energy and crew costs.

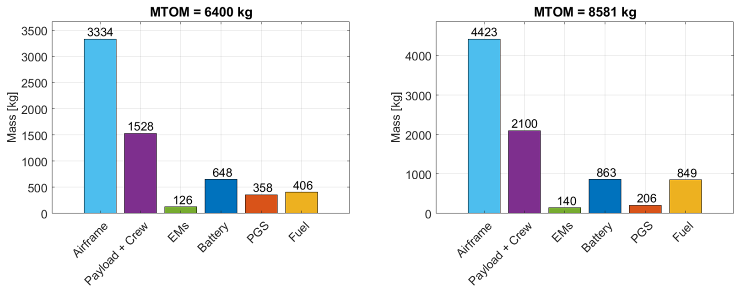


(a) Fuel per passenger. (b) Cost per passenger.

Figure 2: Fuel and cost per passenger for regional aircraft.

Figure 2 shows fuel and cost per passenger as a function of flight distance. The network of Binter, which includes routes shorter than 300 km, is well suited to the introduction of the hybrid propulsive system: both the fuel and cost per passenger are consistently lower than those of the baseline, already in 2035. In fact, the shorter design range allows a lower reduction of the design payload, making the benefits in terms of fuel and cost per passenger already possible throughout the network in 2035. This is not the case for the longer routes of Olympic Air, for which a similar analysis shows that routes longer than 450 km operated by the 2035 version of R70THE require a similar amount of fuel per passenger when compared to the baseline aircraft. Given that the crew cost per passenger increases as there are fewer passengers onto which it is shared and the fuel cost per passenger remains unchanged as the fuel per passenger is comparable, these longer routes show a higher cost per passenger in 2035 compared to the baseline aircraft. The 2050 scenario instead shows a reduction of both fuel and cost per passenger, with respect to those of the baseline aircraft.

For commuter aircraft, a compromise on range for retrofits based on the DO228 is not possible, as its design range is already very limited, 396 km. A reduction of the payload is instead possible, but it would push the aircraft away from its already niche market. Therefore, the retrofit solution, called R19THE, is assessed, together with a clean sheet design, called C19THE, which takes full advantage of the MTOM limit for CS23 commuter aircraft (8618 kg) to limit the negative impact of the heavier THE propulsive architecture. Top Level Aircraft Requirements (TLARs) for the clean sheet aircraft have been derived from UNIFIER19 requirements [6]. Figure 3 shows the comparison between the retrofit of the DO228, which sees the payload drop from 1960 kg to 1328 kg, and the clean sheet design, which has a higher airframe mass, which enables to take the full 19-passenger payload on a longer design range, despite the heavier propulsive architecture. A compromise on the speed had to be taken, in order to lower the fuel mass to comply with the CS23 Commuter aircraft MTOM: the cruise speed was reduced by 15%, which might seem significant, but it is not extremely impacting on such short routes, in which the cruise phase represents a minimal portion of the total flight time. The analysis of the fuel and cost per passenger shows that the retrofit is comparable to the reference aircraft for both indicators in the 2035 scenario, because of its ability to only take 14 passengers rather than 19. The clean sheet design is more fuel and cost-effective than both the reference aircraft and the retrofit, despite the lower cruise speed that causes an increase in crew-related costs. The 2050 scenario sees the C19THE again as the optimum aircraft, but in this situation, also the R19THE is better than the reference aircraft in terms of fuel and cost per passenger.



(a) R19THE 2035. (b) C19THE 2035.

Figure 3: 2035 Mass breakdown for retrofit R19THE (a) and the clean sheet C19THE (b).

3.2. LTO Cycle and Complete Fuel Budget

The introduction of a THE propulsive configuration gives the chance to carry out the ground phase and LTO cycle without using the PGS. The power required to carry out the taxi phase, not directly computed by HYPERION, has been evaluated as a percentage of the power required for take-off, in accordance with ICAO's Default LTO cycle [18]: from this, it is possible to assess the battery discharge rate, which allows the computation of the energy required for taxi to and from the runway, given the average taxi time at a considered airport.

The analysis of the complete mission enables the computation of the fuel budgets of the THE aircraft on the networks detailed in section 2: the results are presented in table 4. Note that for commuter operators, the considered THE aircraft is the clean sheet one, C19THE.

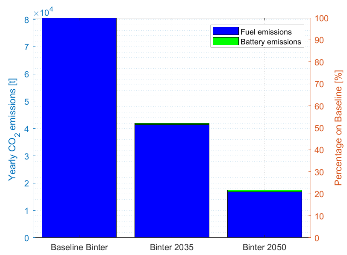


Figure 4: CO_2 emissions (current, 2035 and 250 scenario) for Binter.

Aircraft	Baseline	2035		2050	
Scenario	Fuel [t]	Fuel [t]		Fuel [t]	
Olympic	16501	8611	-48%	5652	-66%
Binter	27868	14505	-48%	8090	-71%
Silver Air	213.9	92.5	-57%	48.3	-77%
TwinJet	2984.1	1430.1	-52%	715.1	-76%

Table 4: Complete fuel budget comparison.

The significant fuel savings enabled by the innovative aircraft, up to -57% in 2035 and -77% in 2050, also cause a significant reduction of CO_2 emissions, even considering the emissions related to the production of the electricity required to recharge the batteries, as shown in fig. 4. It is also possible to notice how negligible the emissions linked to the battery recharge are compared to those emitted by the fuel consumption, considering the average expected electricity carbon intensity, extrapolated from [22].

It is possible to conclude that the retrofits introduce a significant improvement to the fuel budget and consequent emissions, both for regional and commuter aircraft, without being an economic burden for the operators.

4. Conclusion

This work allows appreciating how the future introduction of a THE propulsive configuration may improve the environmental sustainability of aircraft operations on regional networks. Specifically, the foreseen reduction of fuel budget and consequent emissions is considerable, with no noteworthy impact on operational costs that would be cascaded down to the passengers. The assessed propulsive configuration allows to perform complete LTO cycles powered by batteries only, thus considerably reducing local emissions (gases, particulates and noise) at airports. The following results may be highlighted:

- **Fuel budget reduction:** for regional turboprop up to 50% in 2035 and more than 70% in 2035, depending on the characteristics of the considered network; for commuter aircraft, a reduction of about 50% in 2035 and up to 80% in 2050;
- **Optimal network characteristics for hybrid-electric propulsion application:** the introduction of the new propulsive technology increases the complexity and mass of the propulsive system, limiting either the design payload or range, to satisfy the retrofit constraint; networks that have shorter routes incur in less stringent limitations and have a higher degree of energy hybridization, maximizing the benefits of the THE technology;
- **Emission free LTO cycles:** the sized aircraft have batteries that allow to perform taxi out, take off, climb up to 3000 ft, approach, landing and taxi in only using energy from the batteries; this allows to significantly reduce the environmental impact on the area surrounding the airports.

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