The impact of propulsive architecture on the design of a 19-passenger hybrid-electric aircraft

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Abstract. The electrification of aircraft is an on-going endeavor, currently examined intensively in the general aviation class. However, for the commuter class, the proper selection of the hybrid-electric propulsive architecture is instrumental, to fully exploit the electrification benefit. Within this work, a comparison of two 19-seater aircraft with different hybrid-electric propulsive components is made, using an in-house aircraft conceptual design tool. The first aircraft is based on a twin-turboprop parallel-hybrid configuration that cruises at low Mach number speeds and altitude. On the other hand, the second aircraft variant is based on a tri-fan series/parallel-hybrid configuration with an aft Boundary Layer Ingestion system that operates at both higher altitude and Mach numbers. A design space exploration is performed where different degrees of hybridization and batteries specific energy are considered, to define the technological requirements for each architecture. The evaluation of the propulsive architectures is based on block fuel reduction, overall mission duration, direct operating costs and total environmental impact. The results aim to quantify the benefits of each configuration and determine the one with the closest entry into service. Finally, it is observed that the overall environmental impact reduces by 26 % and 17 % for the turboprop and turbofan variants respectively.

1. Introduction

The environmental goals that are announced for future aviation applications act as a catalyst towards the transition to alternative propulsion configurations and significant effort is put from the industry to that direction. According to the Advisory Council of Aviation Research in Europe – ACARE, the goals for emission reduction in aircraft operation by 2020, accounted for a 50 % reduction in carbon dioxide emissions, 80 % reduction for nitrogen oxides (Landing and Take-Off – LTO and cruise) and an overall noise emission reduction of 50 %, compared to aircraft and engines with Entry-Into-Service- EIS technologies of 2000 [1]. Furthermore, when considering the future goals of the year 2050, the goals become even stricter, according to Darecki et al., [2]. This means that radical technological improvements are required to attain such ambitious environmental goals. One such potential solution is the electrification of the propulsion system of aircraft. However, when examining the current technological maturity and estimating the potential for future advancements in the field of batteries for the upcoming decade, indications show a great obstacle in the delivery of high-energy and high-power battery cells [3]. According to Epstein et al. [3], the possibility of having batteries able to power long-haul distances are quite slim. This makes the short-haul, small-passenger aircraft, the ideal candidate for electrification.

By analyzing the world market, it is observed that the small passenger aircraft class covers only the 7 % of the global aviation fuel consumption [3]. In addition, only 2 % is for aircraft with less than 30 passengers. That is because both the single- and twin- aisle aircraft are the most
versatile and cost-efficient and can operate for a variety of mission distances, both short- and long-haul. However, considering the work of Schäfer et al., [4], there is an increased need for aircraft servicing routes of less than 600 nautical miles (nmi), in three different markets, namely, North America, Europe and Eastern Asia. This observation generates a motive to study the potential for deploying electrification concepts onto small aircraft of 19 passengers that adhere to CS-23 / FAR-23 airworthiness standards [5],[6].

According to the work of Wall et al., [7], the next aircraft class that is an ideal candidate for electrification is the commuter class, as it operates short-haul distances and offers greater margin for improvement, than long-haul. For this reason, the scope of the current research is to perform a feasibility study for small aircraft with novel electrified propulsion system and to identify the Technology Readiness Level – TRL before the concept becomes viable. Two propulsive architectures are examined: a parallel hybrid twin-turboprop aircraft and a series/parallel hybrid aircraft with a tri-fan configuration with an aft Boundary Layer Ingestion – BLI system. The Top-Level Aircraft Requirements are defined for each architecture and an in-house aircraft sizing tool is used to perform the first three levels of conceptual design. Then, a design space exploration is performed to determine the technological requirements for each architecture and the mission performance is evaluated for both cases. Finally, both the Direct Operating Cost and Environmental Impact for each aircraft are assessed, using adapted methodologies from the literature, tailored for the hybrid-electric archetype.

2. Methodology

2.1. Top-Level Aircraft Requirements

The Top-Level Aircraft Requirements for the series/parallel turbofan configuration are extracted from the work of Gkoutzamanis et al., [8]. The turbofan aircraft has a service ceiling of 35,000 ft and cruises at 410 KTAS (0.7 M), whereas the parallel hybrid turboprop, operates at 10,000 ft and cruises at 195 KTAS (0.3 M). Both aircraft are compared to their respective conventional architecture, with EIS technologies of 2014. The TLAR for the parallel hybrid turboprop architecture are selected to be similar to those in the work of Romano et al. [9].

2.2. Aircraft Sizing

The aircraft sizing methodology followed in this work, is based on the proposition of Raymer [10] and is modified to account for the hybrid-electric configuration. An in-house software tool is developed for that purpose, that has a modular form and offers robust preliminary design. The tool implements a weight-based approach on the aircraft sizing and reaches up to a 3rd level of conceptual design, meaning that the weight of each component is estimated according to its dimensions. The overall aircraft weight is implicitly calculated, whereas the mission range is estimated using a modified version of the Breguet range equation, that considers the degree of hybridization of the configuration. It is also linked to OpenVSP [11], that is a parametric geometry generation tool, to produce a conceptual sketch of the aircraft. This sketch enables exploring additional disciplines, i.e., the positioning of components, the stability, and the control of the aircraft. In addition, a basic aerodynamic evaluation is performed, including the parasite drag estimation and drag polar. Finally, the sizing tool is coupled with two additional modules that are responsible for the evaluation of the Direct Operating Cost and Environmental Impact of each produced design.

2.3. Powertrain modeling

Two aircraft variants are examined in this study, a twin-turboprop hybrid-electric with a parallel hybrid architecture and a tri-fan aircraft with two wing-mounted turbofan engines and one aft BLI system, forming a series/parallel hybrid-electric architecture, as shown in Figure 1. The parallel hybrid makes an ideal candidate for a configuration with a closer EIS date, as it is a simple configuration with the fewer number of components. On the other hand, the series/parallel is a more advanced architecture, that can benefit from novel concepts such as BLI
and Distributed Electric Propulsion, that will increase the total propulsive efficiency. Though, since it is a more complex system, it has a later EIS date than the parallel hybrid.

| Table 1. Degree of Hybridization for each variant |
|-----------------------------------------------|
| Parallel Hybrid                              | $H_{P_{\text{load}}} = \frac{P_{\text{EM}}}{P_{\text{EM}} + P_{\text{GT}}} = 0$ and $H_{P_{\text{source}}} = \frac{P_{\text{BAT}}}{P_{\text{BAT}} + P_{\text{GT}}} = \text{constant}$ |
| Series/Parallel Hybrid                        | $H_{P_{\text{load}}} = \frac{P_{\text{EM}}}{P_{\text{EM}} + P_{\text{GT}}} = \text{variable}$ and $H_{P_{\text{source}}} = \frac{P_{\text{BAT}}}{P_{\text{BAT}} + P_{\text{GT}}} = \text{variable}$ |

For each variant the Degree of Hybridization - DoH is defined appropriately, as presented in Table 1. Two DoH factors are defined; one that determines the amount of electric thrust provided by the system and another that controls the amount of electric power provided by the system. For the parallel hybrid configuration, the first DoH factor is zero, as the Electrical Motors - EM act as boosters to the Gas Turbines – GT, whereas the second DoH factor is considered constant, as it dictates the amount of battery power available for the mission. On the other hand, for the series/parallel variant, both DoH factors are non-zero, with the former depending on the aft EM power, whereas the latter on the available batteries power of the system.

![Flowchart](image1.png)

**Figure 1.** Parallel hybrid (left) and series/parallel (right) hybrid-electric configurations

### 2.4. Direct Operating Cost

The Direct Operating Cost analysis is a common discipline in conceptual aircraft design. Even though plenty of methodologies exist regarding cost analysis [10], [15], [16], there is a lack of methods employed in the case of hybrid-electric small aircraft. The analysis presented in this work is based on a modified methodology provided by Hoelzen et al. [12], to account for changes in commuter aircraft case. Four costs are included, namely, (i) Energy Costs, (ii) Crew costs assumed constant including 1 pilot, 1 crew member with 4 crew compliments, (iii) Maintenance and (iv) Fees (landing, ground, navigation). Additionally, the capital costs have been included. Also, the fuel prices are based on conservative value predictions for the year 2035.

### 2.5. Environmental Impact

For the environmental impact assessment an adapted method of the work of Johanning et al. [13] is used. Appropriate modifications have been made to account for hybrid-electric aircraft, as the method presented in the work of Johanning et al. is applied to fully electric or conventional architectures only. The inventory analysis of the aircraft includes all four major phases of its life, namely (i) Design and Development, (ii) Production, (iii) Operation, (iv) End-of-life. The
level of details for each of the life phases is limited by the availability of open-source databases. The non-dimensional number that has been used to define the single score is the unit of impact per passenger per kilometer. In addition, the ReCiPe [14] method is used to convert gaseous emissions to midpoint categories, such as climate change, ozone depletion etc. Furthermore, it is also used for the endpoint categories, i.e., human health, ecosystem diversity and resource availability. For the impact assessment, there are three approaches for the calculation: (i) the Individualist, when a short-term impact is considered, (ii) Hierarchist for medium-term impact and (iii) Egalitarian for long-term impact. For this work, the Hierarchist version including world normalization and average weighting set is used.

3. Results

3.1. Airport Network Study in European Countries

To justify the selection of maximum range in the TLAR, the mutual distance for various airports is calculated for three European countries: Greece, Sweden, and Switzerland. The selection of countries is made to consider several country profiles. With the global coordinates of the aerodromes, the mutual distance between airports is extracted, using the haversine formula. Then, the average airport mutual distance is calculated, along with coverage rates for various mission range limits. The results are presented in Table 2.

| Country | ≤ 300 nmi (555 km) | ≤ 400 nmi (740 km) | ≤ 600 nmi (1111 km) | Avg. mutual distance, nmi (km) |
|---------|------------------|--------------------|---------------------|-------------------------------|
| GR      | 87.55%           | 99.16%             | 100%                | 183 (338)                     |
| SE      | 72.15%           | 85.35%             | 97.59%              | 232 (430)                     |
| CH      | 100%             | 100%               | 100%                | 58 (107)                      |

It is observed that the maximum average mutual distance appears in the case of Sweden, as it is the country with the greater surface area. In addition, Greece shows a great mutual distance as well, due to the airports being scattered in the island complexes, even though it has almost one third of the surface area of Sweden. By evaluating the coverage rates for each country, the selection of 600 nmi as maximum mission range offers the greatest coverage rate for all three examples. In the case of Sweden, almost 97.6% of the airports are less than 600 nmi apart, which means that a hybrid-electric small aircraft with the same maximum range can cover almost every distance in Sweden, without the need to refuel. Furthermore, when focusing on mission ranges of 300 and 400 nmi, the coverage rates remain within acceptable limits, with the case of 300 nmi offering a coverage of 72.15% for the case of Sweden and 87.55% for Greece.

3.2. Design Space Exploration for selected propulsive technologies

The design space exploration for this study was performed using the in-house aircraft sizing tool, for both propulsion architectures. The design space for the 600 nmi maximum mission range case is shown in the surface graphs of Figure 2, for both turbofan and turboprop hybrid-electric aircraft. As expected, the current State of the Art – SoA batteries technology (approximately 500 Wh/kg [17]) is not sufficient to store enough energy to power a hybridized aircraft of this class, with a DoH greater than 10%, for the 600 nmi case. For this reason, the design space shown in Figure 2 includes batteries with energy density greater than 750 Wh/kg. In addition, a hybrid-electric design with 40% DoH and 600 nmi maximum mission range, requires almost triple than the current SoA batteries specific energy (Esb), in order to comply with the CS-23 airworthiness certification Maximum Take-Off Mass limitation of 8618 kg [5]. Finally, it is evident that there is a trade-off between maximum mission range and battery TRL. If the mileage is reduced, the feasible region of the design space expands, leading to configurations with closer EIS date. Some indicative design cases are presented in Table 3.
3.3. Aircraft Mission Evaluation

Considering the mission time per variant, the overall mission duration for 600 nmi range and additional 30 minutes of loiter time is 158 minutes for the turbofan, whereas 225 min for the turboprop. As the turbofan is 67 min faster, it can operate more frequently and become more profitable. However, this is subject to additional maintenance and repair cost analysis. By examining the design cases of Table 3, which are compared to their respective conventional ones, it can be observed that for the same DoH and mission range, the turboprop variant has a greater potential for block fuel reduction. However, this does not eliminate the turbofan architecture, as it has a greater profit margin, due to its faster operation. Furthermore, if the SoA in batteries specific energy doubles, the block fuel reduction benefit will triple. Finally, by comparing all cases of Table 3, the TP 2 case has both closer EIS date and higher block fuel reduction simultaneously.

Table 3. Electrification benefit for different aircraft requirements

| Case               | DoH | Esb   | MTOM  | Range | Block fuel reduction |
|--------------------|-----|-------|-------|-------|----------------------|
| Turbofan 1 (TF1)  | 0.41| 1094  | 7905  | 200   | 4.78 %               |
| Turbofan 3 (TF3)  | 0.31| 1026  | 7994  | 300   | 4.2 %                |
| Turbofan (TF)     | 0.4 | 1550  | 8646  | 600   | 13.0 %               |
| Turboprop 2 (TP2) | 0.41| 747   | 8153  | 200   | 10.79 %              |
| Turboprop 4 (TP4) | 0.31| 657   | 8573  | 300   | 7.84 %               |
| Turboprop (TP)    | 0.4 | 1550  | 8583  | 600   | 28.39 %              |

3.4. Direct Operating Cost

For the DOC evaluation, the various costs are presented in the pie charts shown in Figure 3. It can be observed that the capital cost increases when advancing from conventional to hybrid technologies, that is also linked with the uncertainties introduced by the new technologies, such as the electrical propulsion system. Preliminary results presented in Table 4 indicate that advancing to hybrid technologies is economically feasible. Furthermore, the turboprop case results in lower cost increase when advancing to hybrid solutions, as compared to the turbofan case. However, this is not the rule, as it has been observed that there is a switch point which is energy intense, after which it is not feasible to advance to hybrid-electric technologies.
Lastly, further trade-off identification of costs must be conducted such as maintenance and manufacturing, if novel materials are employed, and electrical propulsion costs for novel technologies and operations, if crew is reduced to 1 person, a scenario that is allowable by the CS-23 airworthiness certification.

Table 4. Annual direct operating costs for the examined aircraft

|            | Turbofan | Hybrid | Difference | Conventional | Hybrid | Difference |
|------------|----------|--------|------------|--------------|--------|------------|
| Fees (%)   | 22.2%    | 21%    | -1.2%      | 17%          | 16.5%  | -0.5%      |
| Energy (%) | 22.2%    | 18%    | -4.2%      | 25%          | 20%    | -5%        |
| Capital Cost (%) | 25%    | 33%    | 8%         | 29%          | 34%    | 5%         |
| Crew (%)   | 8.4%     | 7%     | -1.4%      | 8%           | 7.5%   | -0.5%      |
| Maintenance (%) | 22.2% | 21%    | -1.2%      | 21%          | 22%    | 1%         |
| Total Annual Cost [M] | 5.66  | 6.65   | 17.5%      | 6.11         | 6.45   | 5.6%       |

3.5. Environmental Impact

To assess the environmental impact, six different test cases are examined in total. A conventional (inner ring) and a hybrid-electric configuration with 40 % DoH are tested for each variant. Especially for the hybrid-electric configurations, both EU electricity mix (intermediate ring) and renewable sources (outer ring) are considered, as presented in Figures 4, 5. An 85 % average flight distance is selected, compared to the maximum range, as well as a 90 % passenger load factor, as shown in Table 5. For the turboprop variant, aircraft electrification improves the overall environmental impact as described by the single score results in Table 5. The same applies for the turbofan case, however, when implementing hybridization with EU electricity mix, the benefit is only marginally present. The difference of the two aircraft configurations is detected to be driven by the cruise altitude, which asymmetrically affects the kerosene emission contribution. The higher the flight altitude, the higher the contribution of a given volume of emissions to the environmental impact.

By examining Figures 4, 5, it is observed that while LTO, cruise and kerosene productions remain prominent, electricity production seems to be present when conventional power units are used for its production (17.82 % for the turboprop and 13.34 % for the turbofan respectively).
However, when renewables are used the impact of the electricity production is reduced below 1 %. This difference affects the single score per passenger per kilometer index as well, as it is 17 % less in the renewables case, compared to the EU mix, for the turboprop variant. Finally, another interesting finding is that the overall impact of the batteries production is less than 1 %. Overall, approximately 95 % of the total environmental impact comes from the operation phase, i.e., cruise, Landing and Take-Off - LTO and kerosene production for the conventional turboprop configuration, as shown in Figure 4. The same trend applies to the turbofan configuration, for which the cruise phase becomes more critical. For turbofan, the cruise flight has a share of 52.84 %, the LTO cycle a share of 7.66 % and the kerosene production a share of 29.57 %, as presented in Figure 5.

| Table 5. Environmental impact analysis report |
|---------------------------------------------|
| Annual Flight Cycles | Turboprop (TP): 1640 | Turbofan (TF): 2053 |
| Maximum Range [nmi] (avg.) | 600 (510) | 600 (510) |
| Degree of hybridization [-] | 40% (100) | 0% | 40% (100) | 0% |
| Fuel consumption per flight [kg] (avg.) | 860 (731) | 1200 (1020) | 890 (757) | 1023 (870) |
| Electric power consumption [kWh] | 1178 | 0 | 1401 | 0 |
| Empty weight (without batteries) [kg] | 4963 | 4540 | 4851 | 4051 |
| Batteries weight [kg] | 650 | 0 | 904 | 0 |
| Battery life cycles [-] | 1500 | - | 1500 | - |
| Average number of passengers [-] | 17/19 | 17/19 |
| Flight altitude [ft] | 10.000 | 35.000 |
| Impact per passenger per km single score | EU mix | Renewables | Conventional EU mix | Renewables | Conventional |
| | 0.0164 | 0.0136 | 0.0184 | 0.0261 | 0.0228 | 0.0263 |

4. Conclusions
Two 19-passenger small aircraft variants were conceptually sized and examined in this work, a parallel hybrid twin-turboprop aircraft and a series/parallel tri-fan with an aft Boundary Layer Ingestion system. The variants were sized using an in-house software tool, that also performed the design space exploration of both aircraft. A trade-off between mission range and Entry Into Service date was observed, with reduced range leading to more feasible designs. Between the two variants, the turboprop showed a greater potential for block fuel reduction, for the same Degree of Hybridization and range, whereas the turbofan indicated a more profitable operation. In addition, strong indications existed that by doubling the batteries specific energy, the block fuel reduction benefit would triple. Moreover, the Direct Operating Cost was examined for both
aircraft, revealing 17.5 % and 5.6 % increase in the total annual cost for the hybrid turbofan and hybrid turboprop variants respectively. Finally, the environmental impact of the variants was assessed, revealing a 26 % reduction in the passenger per kilometer environmental impact index for the turboprop and a 17 % reduction for the turbofan.

Acknowledgments
Part of the work described in this article was done within the project HECARRUS, which has received funding from Clean Sky 2 Joint Undertaking (JU), under the European Union’s Horizon 2020 Research and Innovation Programme, under Grant Agreement number 865089. Furthermore, the authors would like to thank the project’s Technical Advisory Board members, for their support and guidance.

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