STUDY OF HYBRIDISATION SCENARIOS FOR TURBOPROP AIRCRAFT IN THE GENERAL AVIATION SEGMENT

Florent Lutz[1], Joël Jézégou[1], Marc Budinger[2] & Aurélien Reysset[2]

[1]ISAE-SUPAERO - Université de Toulouse, 31055 Toulouse, France
[2]INSA Toulouse, 31400 Toulouse, France

Abstract

In order to reach the goals set as part of the Paris Agreement, and to limit the effect on climate, there is a pressing imperative to reduce the impact of the aviation industry. Among the gases released by the production of fuel and the use of aircraft, green house gases which include CO_2 have been identified as one of the main contributor. Because of the long residency time of CO_2 in the atmosphere and in order to reduce the cumulative emissions, aircraft designs presenting less ambitious gains but with rapid entry into service should be investigated. While the light aircraft segment seems the most promising candidate for total electrification, hybridisation of turboprop aircraft in the CS-23 category appears achievable considering the compatibility between their most commonly flown routes and the ranges achievable with state of the art electric components. This paper presents the study of the hybridisation of two turboprop aircraft, the TBM 900 and the Kodiak 100. The performances of these design, assessed using an extension of the FAST-OAD-GA framework, are then compared to their conventional counterpart to assess potential gains in terms of CO_2 emissions.

Keywords: Overall Aircraft Design, FAST-OAD, MDAO, CO_2 emissions

Nomenclature

D(E)P	Distributed (Electric) Propulsion
EF	Emission Factor
EIS	Entry-Into-Service
FAST-OAD	Future Aircraft Sizing Tool - Overall Aircraft Design
FAST-OAD-GA	Future Aircraft Sizing Tool - Overall Aircraft Design - General Aviation
FT	Fischer–Tropsch
GA	General Aviation
GHG	Green House Gases
HEFA	Hydroprocessed Esters and Fatty Acids
ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
OAD	Overall Aircraft Design
POH	Pilot Operating Handbook
SAF	Sustainable Aviation Fuel
SFC	Specific Fuel Consumption
TRL	Technology Readiness Level
TTW	Tank-To-Wake
WTT	Well-To-Tank

1. General Introduction

Aviation emissions make up for a significant share of man-made emissions contributing to global warming with recent studies estimating that contribution to around 5% of the net anthropogenic forcing [1]. Among those emissions, Green House Gases (GHG) which include CO_2, CH_4 and N_2O have been identified as one of the greatest contributor to global warming and is directly linked to the combustion and production of fuel for aviation. In addition to that, the life-time of CO_2 which is orders of magnitude above that of non-CO_2 species is very high. This entails that the earliest emissions are cut back, the smallest the cumulative impact [2]. Despite technological advances which have led to annual gains in terms of fuel efficiency of between 0.4 and 2.6% [3], the rapid growth in air traffic, forecasted at an annual growth of around 3% in the coming years [4], more than offsets these improvements. As a result, the aviation sector is turning towards disruptive solutions and new energy carriers to reach its climate targets. Solutions include the development of Sustainable Aviation Fuel (SAF), the utilisation of electric or hybrid propulsion and new architecture utilising synergies between disciplines such as blended wing bodies or Distributed Propulsion (DP) aircraft [4].

These innovative solutions, in spite of their potential to bring significant gains in terms of emissions reduction [5, 6], come with additional challenges that are likely to delay their Entry-Into-Service (EIS) on commercial aircraft. One of such challenges is the gap in terms of means of compliance to assess the certifiability of innovative configurations [7, 8]. In addition to its low maturity, various questions regarding the required infrastructure changes to accommodate hydrogen propulsion are also raised [9] such as its storage, its refuelling and its manufacturing pathways. Additionally, full electric propulsion is also met with questions regarding its technical feasibility. Indeed, current battery energy densities have been identified as a strong bottleneck for the deployment on commercial aircraft [8, 10], not to mention issues linked to thermal management, new design constraints or technological readiness level of electric motors in the MW range. Another consideration when assessing the environmental impact of the introduction of electric or hydrogen propulsion is their method and location of production. In regions of the world where the electricity is produced with carbon intense means, flying electric aircraft might emit more CO_2 than their kerosene counter part [11]. All things considered, and because they account for less emissions when considered on their entire life cycle [12], SAFs seem to be the most mature and plausible choice [9] in the short term. Not unlike hydrogen and electricity, however, there are discussions regarding the pathway used for production. This comes in addition to today's low volume of production forcing arbitration to be made between transportation sectors.

Nevertheless, electrification of small aircraft in the General Aviation (GA) segment was proven to be feasible with the certification of the Velis Electro [13] and the retrofit of existing airframe such as the Cessna Grand Caravan modified by Ampaire [14]. In addition to proving the viability of this technology for specific applications, it cements the role of the GA segment as an early adopter of electric propulsion [15]. This observation, added to the considerations mentioned earlier, tend to favour the quick introduction, on smaller segments, of aircraft with low hybridisation ratio to minimise CO_2 emissions as soon as possible while mitigating the drawbacks stemming from battery usage. Within this context, manufacturers, such as Aura Aero [16] or Daher [17] have started announcing their plans to launch hybrid electric aircraft within the next 5 years.

The use of full or partial electric propulsion however imposes severe constraints on achievable ranges and performances as illustrated by the comparison between the thermal version of the aforementioned aircraft and their electric retrofit. This may impose to rethink the mission requirements imposed on the electric aircraft [15] and will likely mean that those novel designs will be less flexible.

This paper aims at studying the feasibility of the hybridisation of two aircraft of the General Aviation segment conventionally fitted with turboprop as well as assess their most common route for a potential reduction of performance targets. Two designs were retained. The first one will employ an electric branch to boost the conventional turboprop and allow its downsizing for a design tailored for cruise conditions. In the second one, a turbo-electric powertrain will be used to power an array of distributed propulsive elements with goal of utilising aero-propulsive interactions to reduce the wing area.

In the first section, the methodology retained for the assessment of the performances of a hybrid aircraft will be presented. This will be followed by a discussion on the selection of the aircraft under study along with a presentation of the methodology used to select the reduced range of their hybridised version. In the second section, the models added to the selected Overall Aircraft Design (OAD) framework will be presented. Finally, the results of the study on the hybridisation of the selected aircraft will be discussed.

2. Methodology

2.1 Selection of the framework

For this paper, the FAST-OAD framework [18], and more specifically, its plugin containing models tailored for the sizing of GA aircraft [19] was selected. This open-source framework, co-developed by ISAE-SUPAERO and ONERA is based on the OpenMDAO framework. Its features allow the quick integration of new models and an easy customisation of the analysis process which enable to evaluate both the performances of a retrofit aircraft as well as a sizing from scratch. The general aviation plugin contains by default models for the computation of the aerodynamics of an aircraft, its mass breakdown, its performances and can model fuel based propulsion chain with Internal Combustion Engine (ICE) and turboprops [20]. This software was validated on three low wing aircraft in the GA segment: the Cirrus SR22, the Beechcraft Duchess and the TBM900. In addition to that, recent release of the open-source part of the code have expanded the model base to allow for the sizing of high-wing aircraft and permit the computation of lateral aerodynamic derivatives. This framework was also the subject of a rework of the performances estimation to allow more complex powertrain to be modelled [20].

2.2 Selection of the aircraft under study

For this study, the two aircraft from the French manufacturer DAHER, the Kodiak and the TBM were chosen as reference cases.

The TBM 900 is a high-performance single engine turboprop business aircraft with a low-wing and conventional tail configuration. The reasons behind the choice of this aircraft are twofold, the first one being the data available regarding its design. Indeed, because this aircraft has already been validated as a reference case in the conventional version of the FAST-OAD-GA code, results are available making the study of a retrofit version of the aircraft easier. The second motivation behind this choice is the fact that the TBM 900 was chosen as a demonstrator platform for the EcoPulse project [21]. The goal of this project, co-lead with Airbus and Safran, was to explore the potential benefits of Distributed Electric Propulsion (DEP) and to increase the maturity of key technological bricks. Regarding the choice of the powertrain architecture, it was decided, for safety reasons, to decouple the electric propulsion part from the original turboprop [22]. While this ensures a functional separation of the two sides of the powertrain, allowing to physically segregate the electric part during in-flight testing, this means that the architecture is far from being optimal. Additionally, with the EcoPulse being a retrofit of a TBM900, keeping mostly the same wing, the slipstream effect coming from the use of DEP are not optimally used as would be the case with a redesign of the wing [15]. The evaluation of the EcoPulse with a design "from scratch" thus appears as a worthwhile case study. Regardless, it is worth noting that the TBM 900 has very high performances and achievable ranges which is incompatible with heavy hybridisation with the maturity of today's electric technologies [23]. Consequently, aggressive range and speed reduction, whose study is the subject of section 2.3, are to be expected for a feasible design.

As for the Kodiak, the reasons motivating its choice are largely based on the characteristics of the aircraft which makes it a reasonable candidate for hybridisation. It has similar performances as other aircraft used as test benches such as the Cessna Grand Caravan modified by Ampaire [14] or the full electric De Havilland Beaver operated by the Harbour Air [24]. Additionally, the aircraft has a very versatile cabin with lots of room to accommodate large batteries and flies at relatively low speeds. It also flies at low altitude removing the need to pressurise the cabin. This has the additional benefit of reducing the risk of the potential partial discharges of a high voltage electric powertrain as they are more likely to occur when air density is low [25].

2.3 Selection of a hybrid range

Because of the technological maturity of today's electric components, range and performance reduction, when compared to their conventional counterpart, might be required for a feasible design of a hybrid aircraft. However, to set commercially realistic targets, the practical uses of the selected fuel-burning aircraft will be studied. To do so, data from the OpenSky network [26] will be used. The OpenSky network is a community based receiver network which continuously collect data for air traffic research. Through this network, various database containing flight data are made available. Two databases are of particular interest to us: a database including a list of flight, with a location of origin, a destination and the type of aircraft used to perform this specific flight and a database which contains a list of all known registered aircraft and their type. While the latter is fairly complete, the former heavily relies on volunteers installing receivers, making the coverage very poor in regions other than Europe, North America and Japan.

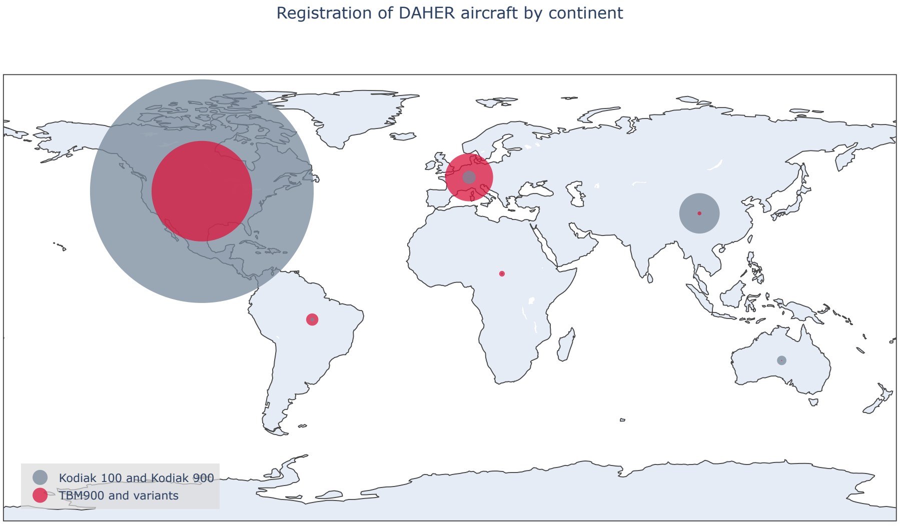

Figure 1 – Distribution of the countries of registration of the TBM 900 and the Kodiak 100/900

Fortunately, the vast majority of DAHER aircraft are registered in countries were coverage is extensive as can be seen in Figure 1. Based on this observation, we will consider the OpenSky database representative. The other conclusion that can be drawn from this map is the choice for the value of emission factor, the amount of CO_2 released for the production of a given quantity of electricity. Indeed this value is highly dependent on each country's method of production for the electricity so knowing the value for the main markets of the aircraft is paramount to minimise the emissions of an aircraft storing electricity in batteries.

For the study of the most frequent use of the aircraft, a modified version of the 2019 OpenSky database, which has been developed as part of the creation of the AeroSCOPE tool [27], will be used. In this modified database, more than 12200 TBM 900 flights have been registered while for the Kodiak, this number is around 2200. Out of those flights, a certain number was filtered out when the route distance could not be computed, was equal to zero (local flights and flights for which the destination or the origin was unknown) or was above the maximum range of the aircraft. In the end, slightly less than 7000 TBM flights and more than 1300 Kodiak flights were considered. Their distribution, as a function of the distance of the flight, is represented in Figure 2.
As can be seen in Figure 2, more than half of the flights considered for the TBM 900 have a range of 250 nm or less which is compatible with the range achievable with today's electric technologies [23]. A similar conclusion can be reached for the Kodiak, with two thirds of the flights being 100 nm or less. Nonetheless, a range of 200 nm will be selected for the case of the hybridised Kodiak. While this is above the most frequently flown range, for a mission of 100 nm and considering a cruise at 10000ft, only half would be flown in cruise conditions according to the reference aircraft's Pilot Operating Handbook (POH). These two ranges will serve as targets for the hybridised version of the studied aircraft. Caution must however be taken with the data. As previously mentioned, nearly half

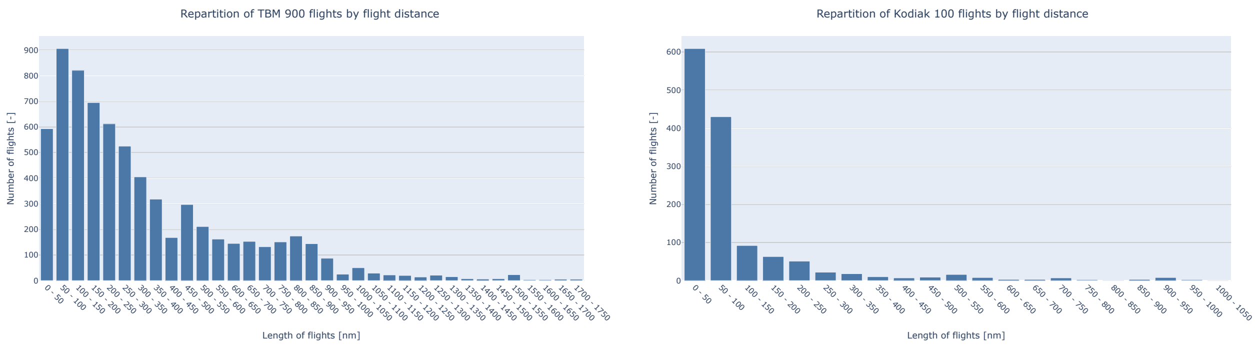

Figure 2 – Distribution of flight as a function of distance for the TBM 900 and variants (left) and the Kodiak 100 (right)

of the fights were discarded because either the origin or the destination of the flight were unknown.

3. Models

3.1 Addition of models for high wing aircraft

A review of existing models inside the selected aircraft design framework was conducted to identify any lack regarding the ability to model the selected aircraft. As previously mentioned and as the TBM 900 is a reference case for the FAST-OAD-GA framework [20], no specific models needed to be added. The modelling of high wing aircraft was however not possible so additions were made. The effect of high wing configuration was identified as having 2 main impacts: one on the mass of the aircraft and one on the aerodynamic characteristics. The effect on mass was implemented through the use of statistical formula and can be found on the mass of the wing itself as well as an added mass for the landing gears [28, 29]. As for the aerodynamics, the main impacts can be found in the computation of lateral characteristics which are done through the use of handbook formula [30].

3.2 Models for the sizing of hybrid aircraft

The original version of the framework selected for this study only contains models for the sizing of fuel based powertrains and the extension of its capabilities to assess electric and hybrid-electric aircraft has been previously identified as key point for further development. This led to the creation of the open-source FAST-OAD-CS23-HE framework [1]. It retains the original aircraft design model but adds a new approach to enable the sizing of electrified powertrains. This approach combines the flexibility of a load flow analysis method [31] with medium fidelity models to study the aircraft level impacts of novel power train architecture. In addition to that, the FAST-OAD-CS23-HE framework implements a pseudo user-interface that allows the description of propulsion chains in the forms of a simplified input file where users specify which components are to be used and how they are connected. This provides an easy way to represent a wide variety of powertrains without requiring users to modify scripts in the original code. Additionally, because this approach relies on OpenMDAO's capability to solve implicit equations, the extension to other disciplines, namely thermal analysis, is possible and will be the subject of future developments. However, the number of variables involved as well as the strong coupling between them makes the use of gradient based solver mandatory [32]. This in turns has an impact on the selected models because models which can be analytical differentiated needs to be favoured.

The default delivery of the FAST-OAD-CS23-HE framework is bundled with model for propellers, electric motors, power electronics, wiring systems, batteries, generators and ICE. The following sections discusses the addition of models for turboshaft and gearboxes to allow for the evaluation of turboprop and hybridised turboprop aircraft.

3.2.1 Turboshaft

As part of the FAST-OAD-GA-HE framework, components of the powertrain are categorised according to the role they fulfill and models for each type of components are expected to provide certain

[1] https://github.com/florentLutz/FAST-OAD-CS23-HE

value. Within this context, turboshaft are considered sources and implemented models are expected to provide a way to compute fuel consumption throughout the flight but also the limit power depending on the flight conditions. The residual thrust of the exhaust must also be modelled as it can account for a significant part of the total thrust in cruise conditions. These considerations were taken into account for the choice of the models to implement.
The estimation of the performances of gas turbines is extensively covered in literature, and, beyond a modelling through a simple fixed specific fuel consumption (SFC) and power density [33, 34], it is mostly done using thermodynamic cycles [20, 35, 36, 37]. Further breakdown on this type of method can be made on the level of details taken for the modelling of rotating parts. While fixed efficiencies can be taken for the compressors, turbines and fans with decent level of accuracy [20], in practice they highly depend on the operating conditions. Theses efficiencies are often computed using maps. High level of details concerning the design of rotating parts is however necessary to estimate those maps, making them hard to use.
Another approach commonly found is the use of specialised software or frameworks like GasTurb [38, 39, 40] or PyCycle [41]. While this approach enable high level of fidelity and, to a certain degree, the study of future gas turbine performances, it won't be retained. The reason is that this type of approach typically has long runtimes and, unless the interfacing can be automated, these method requires the intervention of human in the optimisation process. Another remark that can be made about the usage of high-fidelity tools in conceptual design is the fact that they lead to more point of failure, from a numerical standpoint, which will cause the code to be less robust [42]. To overcome those issues, surrogate models are frequently used [43, 44]. In addition to replacing computationally expensive simulations by lightweight approximate functions [45], an explicit form can be requested for the approximate which allows analytical differentiation.
The choice was however made to not reuse existing surrogate but rather to build an existing one based on the method in the original FAST-OAD-GA framework as it proved to yield good results on the TBM900 use case [20]. This choice was also motivated by the fact that, although analytical differentiation of the original model could be possible, runtime would be prohibitively high. Finally building a submodel from scratch would allow to include the effect of exhaust thrust and to compute the operating parameters of the the engine. This is important because it enables the implementation of detailed emissions models, some of which relies on the pressure and temperature at the entry of the combustion chamber like the P3T3 method [46].

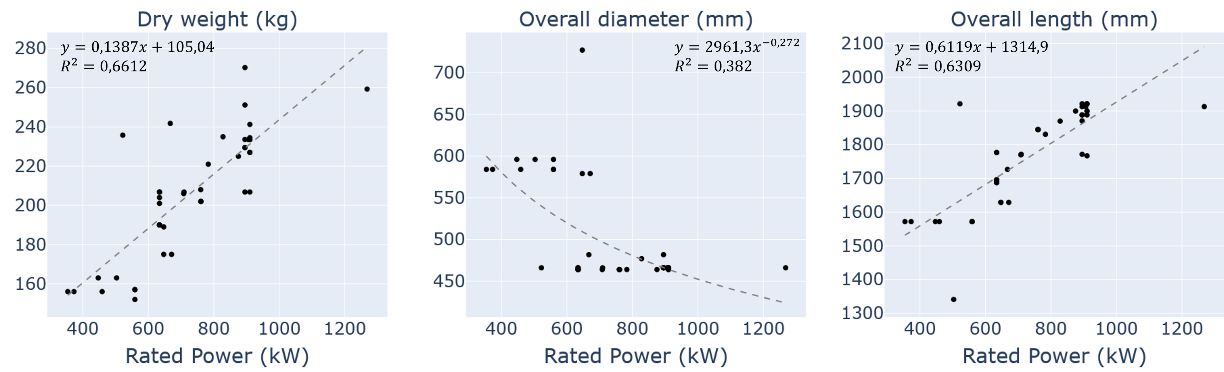

Figure 3 – Statistical analysis on the characteristics of the PT6A turboshaft family

The mass and dimensions of the turboshaft must also be evaluated to enable the evaluation of all its aircraft levels impacts. To do so, the choice was made to perform a statistical analysis and devise regressions based on data from existing turboshaft. A focus was set on the PT6A family as it is a popular choice for CS-23 category aircraft and the type of engine which is installed on the aircraft under study. Data were found in the engine's TCDS, Pratt & Whitney's website and in Jane's Aero Engines. It is worth noting that those data already include the weight and dimensions of a power turbine module that brings rotation speed down to 1700-2000 rpm. The result of this statistical analysis is presented in Figure 3. This analysis was also used to define realistic bounds for the data to be

used to construct the surrogate. Simplifying assumptions were made to reduce the complexity of the surrogate models, namely: the component efficiencies and pressure drop were assumed constant across engines, the ratio of offtake bleed to engine mass flow is constant and the design point will always be static at sea level. The selected inputs are: the engine design parameters (design OPR OPR_{des}, design turbine entry temperature TET_{des} and design power P_{des}); the engine operating conditions (Mach number M, air density ratio σ and power required P_{req}) as well as its components limits (limit OPR OPR_{limit}, limit inter turbine temperature ITT_{limit} and shaft power limit P_{limit}).
A dataset of 5000 points was generated with values for the inputs parameters covering the range of values presented in Table 2

Table 2 – Range of values for the input parameters covered in the dataset

Input parameter	σ	M	P_{des}(kW)	OPR_{des}	TET_{des}(°K)	P_{req}(kW)	OPR_{lim}	ITT_{lim}(°K)
Minimal value	0.31	0.04	864	7.0	990.0	100.0	8.37	958.15
Maximum value	1.0	0.6	2890	19.5	1420.0	1280.0	22.5	1273.15

To perform the regression, the pyVPLM package [47] was used. The choice for the order and number of terms in the surrogate was made to ensure that the mean error and standard deviation were both below 5%, which led to the results in Figure 4.

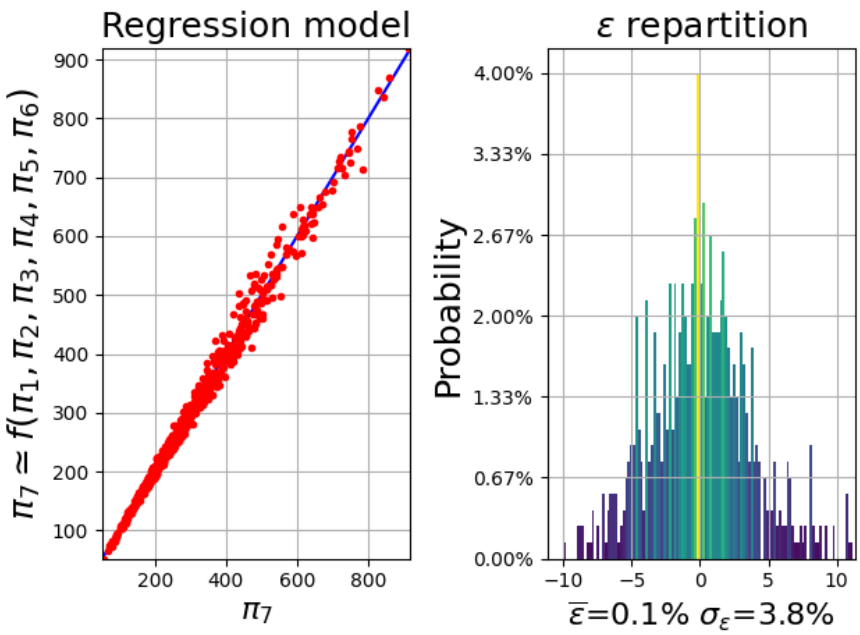

Figure 4 – Results of the surrogate modelling for the turboshaft performances

3.2.2 Gearbox

Models for two types of gearboxes were implemented. The first type, which will be called speed reducers, serves as a way to reduced shaft rotation speed. This allows, for instance, to connect propellers who typically have rotation speed of around 2000-3000 rpm to electric motors who benefit from running at higher rotation speed [43]. The other type will serve as a way to sum the power of two shafts as can be seen on some parallel hybrid powertrains like the on the H3PS project [2].
Both gearbox will however be based on the planetary gearbox architecture as it can be used in both case [48, 43]. Consequently, most models will be common. For the estimation of the performances, a constant efficiency of 0.98, representative of current technologies, will be assumed [43, 49]. The gearbox will also be characterised by the gear ratio [43], left as an user input. To estimate the dimensions of the gearboxes, scaling laws will be used [50]. The choice for the reference component

[2] https://h3ps.eu/

will be a range of existing inline planetary speed reducer [3]. Even though the specifications of that range of gearbox is on the lower end of the power range for hybrid aircraft, the availability of technical data motivated that choice.
The estimation of the weight will be done using a method developed at NASA based on a survey of existing gearboxes [51]. In addition to a dependency on the gear's ratio and output torque, this method also uses a technology factor to scale results. Judging from the results displayed in the original paper and the application of that method on the selected reference gearbox, that factor highly depends on the power output and technology of the gearbox. It was left as an user input but it's default value will be taken at 6.16.

3.3 Estimation of CO_2 emissions

As part of this study, only the GHG emissions of the different design will be evaluated even though, as mentioned in section 1, these emissions represent only one of the contributors to the impact of aviation on global warming. When considering the GHG emissions of an energy carrier on aircraft, the scope must go beyond simply its use by the aircraft, often called the Tank-To-Wake (TTW) pathway [37]. Indeed, a significant part of the emissions occur upstream of the life-cycle [2], in the extraction and production phase, also called the Well-To-Tank pathway (WTT). Both are then combined in the Well-To-Wake (WTW) pathway which represents all the steps from the extraction of the energy to its use. Values for the equivalent CO_2 impact of each of the retained energy carriers have been accurately calculated [52] for the WTW pathway and will be used to compare the retained designs. A common way to evaluate the impact of GHG is to use the warming potential of CO_2 as a reference value for other gases such as CH_4 and N_2O.

For the CO_2 impact of conventional jet fuel, and because the process is well developed there is only a slight variation on the values reported for the whole cycle of the fuel, with values ranging from 81.1 to 94.8 $gCO_{2,eq}$/MJ. Rather than doing a study for both value for the carbon intensity of jet fuel, we will use a weighted average of 88.7 $gCO_{2,eq}$/MJ [2]. As part of this study, we will also compare the hybrid electric design with a conventional design using SAFs. The designation SAF is however very wide covering a great variety of feedstock and pathways. Consequently, we will only focus on two biofuel pathway for which the Technology Readiness Level (TRL) is compatible with a rapid EIS: Hydroprocessed Esters and Fatty Acids (HEFA) and Fischer–Tropsch (FT) [2]. Even with a choice made for the process, uncertainties on the carbon intensity of the resulting fuel remain because of the choice of feedstock and on the estimation of induced land use. For biofuel from the FT pathway, we will use median values assuming the use of lignocellulosic crop and forest and agricultural residues, resulting in an average of 7.7 $gCO_{2,eq}$/MJ [2]. For biofuel produced through the HEFA pathway, we will choose cooking oil as a feedstock even if it raises the question of availability. This results in an average carbon intensity of 21.6 $gCO_{2,eq}$/MJ. It is however worth noting that there is a significant dispersion in carbon intensity for this pathway with other feedstock with an upper bound reaching up to more than 120 $gCO_{2,eq}$/MJ which is even higher than jet fuel.

In some of the hybridised designs that will be investigated in further sections, batteries will be used to complement conventional fuel burning powertrain. We must thus investigate the carbon intensity of electricity, which, as was previously mentioned, highly depends on the method of production of the country where the aircraft is charged. For this study and with the goal of having a rapid EIS in mind, we will only look at today's value for the emission factor, rather than using prospective value corresponding to future years. As part of this paper, and considering the main market for DAHER aircraft some conclusion can be immediately reached. Indeed, given today's electric mix in the US and assuming that no dedicated renewable source of energy will be put into place in the near future, the emission factor of the US is equal to 105 $gCO_{2,eq}$/MJ [2] which is greater than that of jet fuel for the same energy efficiency. We will thus consider the value for the second greatest market for DAHER aircraft which is Europe, where the carbon intensity of the average electric mix is equal to 72.7 $gCO_{2,eq}$/MJ [2]. A point of caution that needs to be raised regarding the electricity as an energy carrier, and one which will not be further investigated in this paper, is the environmental cost of

[3] `https://www.ato.com/inline-planetary-speed-reducer-gearbox`

producing batteries. Even if, when designing commercial aircraft, the biggest impact comes from its usage, it might be different for smaller scale aircraft. In the case of drones, for instance, the production and renewal of battery has a significant contribution on the climate impact [53]. Additionally, the small aircraft are used less intensively than commercial one, making the use part less predominant.

4. Results

The framework and models described in earlier sections will be used in this part to assess the design of the aircraft chosen for this study as well as their hybridised version.
The complete list of inputs necessary for the sizing of those aircraft and their values being available on the FAST-OAD-CS23-HE repository [4], only the most relevant ones will be presented below.

4.1 Reference case: the Kodiak 100

The Kodiak 100 is a single engine turboprop utility aircraft with a high-wing and conventional tail configuration. It is versatile aircraft powered by a PT6A-34 engine. Combined with a four-bladed propeller, the aircraft has Short Take Off and Landing capabilities and can carry payload of more than 1100 kg. The data that have been used as inputs are either extracted from Jane's All the World's Aircraft, from commercial materials or they are taken from the aircraft's POH. For the powertrain file, which is used to describe the powertrain to size, a simple chain consisting of a propeller, turboshaft, fuel system and tanks was considered. The weight of the aircraft's systems was also directly used as inputs because they were readily available in the POH. A summary of the main inputs is presented in Table 3.

Table 3 – Main input parameters for the sizing process of the Kodiak 100.

Parameter	Value
Number of passengers	4.0
Design range (nm)	1144.0
Design mission speed (KTAS)	120
Design mission altitude (ft)	10000
Approach speed (KTAS)	78
Wing aspect ratio	8.41
Number of engine	1
Engine rated power (kW)	551.0

The outputs of the sizing process are presented in table 4. Most of the results show very good agreement for preliminary design. The results of the fuel consumption models were compared outside the sizing loop to known data. This resulted in the addition of a 1.05 correction factor. Even so, there is a slight difference on the fuel consumed. The post-processing tools available in the FAST-OAD-CS23-HE framework as well as performance data available in the POH were used to further investigate that difference.

Table 4 – Main outputs for the Kodiak 100 run.

Parameter	Output value	Reference value	Diff. (%)
MTOW (kg)	3280	3290	0.3
OWE (kg)	1727	1712	0.8
Fuel mission (kg)	933	960	3.1
Wing area (m^2)	23.04	22.3	3.1
HTP area (m^2)	6.43	6.21	3.5
VTP area (m^2)	2.83	2.92 [5]	3.1
Aircraft length (m)	10.3	10.3	0 [6]

[4] https://github.com/florentLutz/FAST-OAD-CS23-HE
[5] Measured on 3 view drawings
[6] Aircraft length was used as an input for this run

The main source of error comes from the estimation of the fuel consumed during the reserve and cruise phases. The former is mainly due to the fact the target height and speed set for the reserve phase were taken equal to that of a cruise at 10000 ft in maximum range profile. These, however, corresponds to the performances of a fully loaded aircraft while the framework considers that the aircraft has already consumed fuel for the climb, cruise and descent phase. This lead to an error of around 7 kg which equates to around 10% of reserve fuel. For cruise, while the relative error is much smaller (around 2%), it still accounts for 15 kg on the overall mission. As the hourly fuel consumption gave a good match, this difference was not looked into further.
The post-processing tools were also used to analyse the evolution of the power the turboshaft is required to provide in order to better guide the choice for hybridising the aircraft. A required cruise power of 200kW was computed which showed good agreement with cruise performances indicated in the POH. Surprisingly however, the power required to reach target descent performances was found to be greater than the power required for cruise. While the aircraft thrust is indeed lower, the fact that the descent airspeed was set at 160 KEAS results in a greater power required. This yields descent power decreasing from 230 to 200 kW. Results were still considered valid as the fuel consumed during descent seemed to closely match the data from the POH. The choice was however made to consider a descent speed of 140 KEAS for further computation.

Table 5 – Computed Kodiak 100 performances on the operational mission

Parameter	Value
Operational range (nm)	200.0
Operational payload (kg)	1140.0
Cruise speed (KTAS)	120
Cruise altitude (ft)	10000
Descent speed (KEAS)	140
Takeoff weight (kg)	3113
Start of cruise power (kW)	180
Fuel consumed (kg)	246
Emissions (kg$CO_{2,eq}$)	938
Emission factor (g$CO_{2,eq}$/kg$_{PAX}$/km)	2.22

The performances of the Kodiak 100 were also evaluated on a shorter operational mission with a range corresponding to the range selected in section 2.3For that mission, a payload corresponding to the Kodiak 100 max payload was selected. The conditions for climb, reserve and cruise were selected equal to that of the design mission. The main results of the operational mission are presented in Table 5 and its flight profile is presented in Figure 5. These results will serve as the baseline to study the potential gain of hybridising the aircraft.

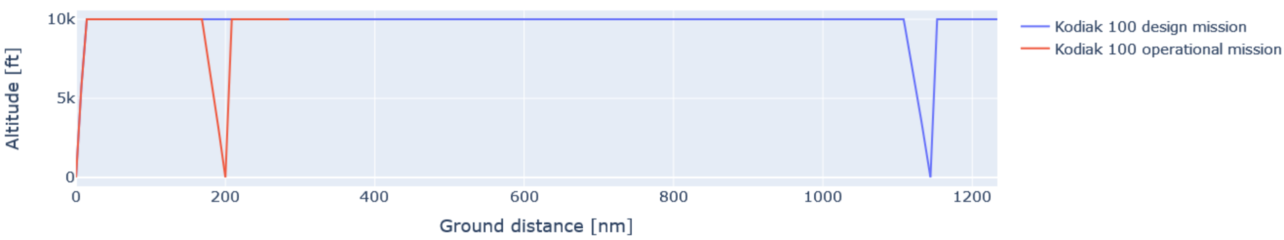

Figure 5 – Comparison of Kodiak 100 design mission and operational mission

4.2 Hybridisation of the Kodiak 100

For the hybridisation of the Kodiak, a parallel hybrid powertrain where the batteries would be used to boost a turboshaft in power intensive phases was selected. The reason behind this choice is that it would allow the turboshaft to be sized for cruise power and thus operate closer to its optimal point, consequently reducing emissions with only mild hybridisation levels [54, 15]. To accelerate a potential

EIS of the hybridised Kodiak and to reduce time to certification, no redesign of the airframe will be made. This will be modelled as a constant geometry and a constant airframe weight. Additionally, the payload will be adjusted in order to ensure that the MTOW of the hybridised Kodiak is equal to or below that of the reference aircraft. The powertrain which we will consider is presented in Figure 6.

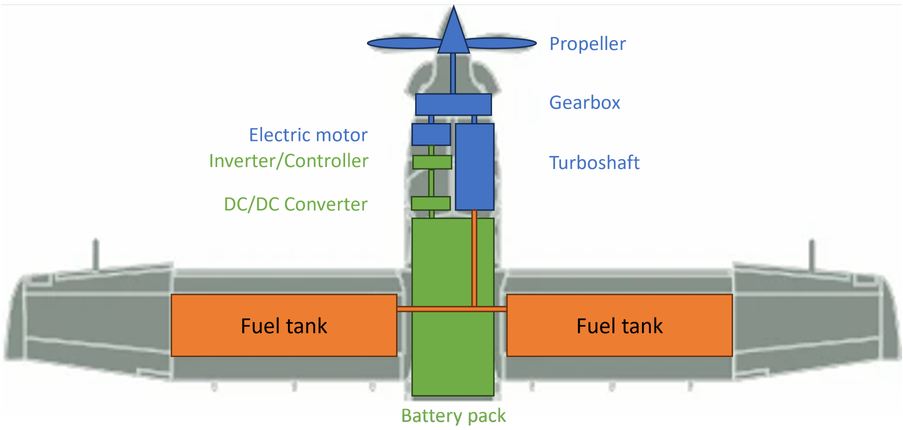

Figure 6 – Powertrain considered for the hybridisation of the Kodiak 100

For the choice of the turboshaft, given the 200kW power requirement on the reference sizing mission, limited options were available. In particular, most turboshafts from the PT6 family have rated power way above that target. As for the remaining ones, the PT6A "Small" engines [7], SFC values seemed to indicate that they would not bring any significant gains. A review of other engines in that power range was thus conducted which led to the choice of another turboshaft from Pratt & Whitney, the PW206B. It is originally a helicopter engine and has a flat rating at 321 kW. Because its design power is lower than the bounds for the training data for the surrogate, the outputs of the model were compared to reference values found in Jane's Aero Engines to assess the accuracy. This resulted in the addition of a correction factor of 1.11 to estimate the fuel consumption of the selected engine.

Table 6 – Main input parameters for the sizing process of the hybridised Kodiak 100.

Parameter	Value
Design range (nm)	200.0
Design mission speed (KTAS)	120
Design mission altitude (ft)	10000
Approach speed (KTAS)	78
Network Voltage (V)	800
Battery reference cell	Samsung INR18650-25R
Battery cell weight fraction	0.768
Battery min SOC (%)	20
Engine rated power (kW)	321

The estimation of the performances of the battery pack is computed based on the performances of a reference cell. The original cell has a decent capacity for its weight but it is fairly limited in terms of maximum C-rate, which might prove to be problematic given the power intensive use envisioned for the pack. For this reason, it was elected to instead use the Samsung INR18650-25R as a reference because it trades energy for a greater maximum current output. For the cell weight fraction of the pack, it was taken equal to 0.768 which is the value used for the Pipistrel Velis Electro reference case in the framework. Finally, for the choice of the electric network voltage, a value of 800 Vdc was selected based on the voltage of the battery pack in the EcoPulse demonstrator [8].

[7] https://www.prattwhitney.com/en/products/general-aviation-engines/pt6a

[8] https://www.airbus.com/en/newsroom/news/2022-03-airbus-high-voltage-battery-technology-prepares-for-ecopulse-flight-test

Similarly to what is done for the reference aircraft, only key inputs will be discussed in Table 6 with the full list of inputs being available on the FAST-OAD-CS23-HE repository. The power profile resulting from our choice of hybridisation is presented in Figure 7.

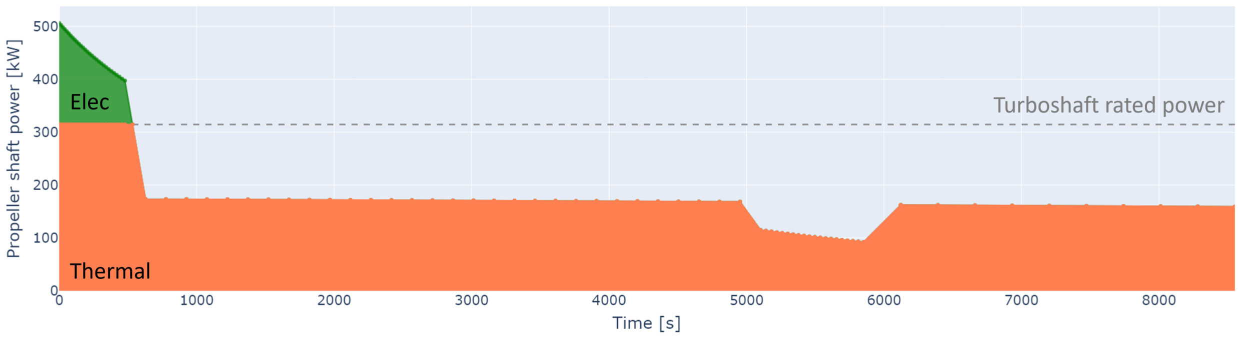

Figure 7 – Propeller shaft power profile with each contributing source

The results of the FAST-OAD-CS23-HE run on the hybridised Kodiak shows a fuel consumption of 210 kg and an electricity consumption of 24.8 kWh. This is a 15% improvement when compared to the fuel consumption of the reference Kodiak on the operational mission. While a part of that reduction is due to the fact that climb is partially done with electric power (7 kg reduction), the majority is due to the reduced fuel consumed during cruise (14 kg reduction) and reserve (9 kg reduction). In term of specific fuel consumption, having a smaller, more efficient turboshaft working closer to its optimal point allowed a reduction from 0.488 kg/h/kW to 0.382 kg/h/kW. This reduced fuel consumption is however offset by the fact that the aircraft is heavier due to the more complex propulsion chain. The OWE has indeed increased by 12%, going from 1727 kg in the reference case to 1939 kg. This in turns means that the max payload of the original aircraft, 1140 kg, cannot be flown without exceeding the MTOW, resulting in a marginal decrease to 1130 kg.
In addition to using battery cells that are available on the market rather than prospective ones, consistency with current technologies was also ensured by comparing sizing parameters of the electric components and technological figures of merit with what is currently available. While the rpm and voltage on the electric motor show good agreement with a high voltage EMRAX348 [9], the torque required at the beginning of climb, 538 Nm, is slightly above the 500 Nm continuous torque from the datasheet but still way below the 1100 Nm peak torque. The weight of power electronics (inverter, DC/DC converter, rectifiers, ...) is computed, inside the chosen framework, based on the converter architecture and the sum of the weights of its sub-components: IGBT modules, heat sinks, control card and connectors [55]. Based on that weight, the power density of the converter were computed for comparison. While those value are high, 57 kW/kg for the inverter and 70 kW/kg for the DC/DC converter, they are not far from an existing prototype [56]. This, however, is retained as a point of caution.

Table 7 – Comparisons of emissions of the reference aircraft and hybrid aircraft

	Jet fuel, EU mix		FT biofuel, EU mix		HEFA biofuel, EU mix	
Aircraft	Ref K100	HE K100	Ref K100	HE K100	Ref K100	HE K100
Emissions (kg_{CO2})	938	809	81.5	76.2	228.6	202
Difference (%)	-	13.75%	-	6.5%	-	11.6%
EF ($g_{CO2}/kg_{PAX}/km$)	2.22	1.93	0.193	0.182	0.542	0.483
Difference (%)	-	13.06%	-	5.7%	-	10.9%

Finally, the emissions of the two aircraft variants were computed using the fuels introduced in section 3.3 both in terms of total emissions but also in terms of emission factor (EF) which represents the

[9] https://emrax.com/e-motors/emrax-348/

emissions per kg of payload per km. A synthesis of the results is available in Table 7. The results show that, regardless of the type of fuel used, the emissions and emission factor are better in the hybrid case. Another observation that can be made is the fact that the lower the carbon intensity of the fuel the lower the gain compared to the baseline aircraft. This stems from the fact that for climb, some electric energy is used. One final observation that can be made is that the reduction of total emissions is not equal to the reduction in terms of emission factor. This is a direct result from the required reduction in payload in order to not exceed the MTOW. However, even accounting for that reduction, the results show that reductions of emission factor can be achieved.

4.3 Reference case: the TBM900

The TBM 900 was also sized using the FAST-OAD-CS23-HE. This case will serve as a check to ensure consistency of results with the previous framework but also to get the data for the study of the hybridised version. A comparison of results with the reference case [20] is presented in Table 8.

Table 8 – Main outputs for the Daher TBM 900 run compared with original results [20].

Parameter	Out. FAST-OAD-GA	Out. FAST-OAD-CS23-HE	Ref.	Diff. with ref. (%)
MTOW (kg)	3358	3378	3370	<1
OWE (kg)	2114	2088	2109	1
Fuel mission (kg)	763	802	774	3.6
Wing area (m^2)	18.07	18.06	18.0	<1
HTP area (m^2)	4.94	4.61	4.76	3.2
VTP area (m^2)	2.85	2.81	$\approx$ 3.00	6.3
Aircraft length (m)	10.736	10.736	10.736	0.0 [10]

The main difference lies in the estimation of the fuel consumption and the empty weight. The results however remain within acceptable range for preliminary design. They will thus be used to study the hybridisation of the TBM900.

As was done in Section 4.1 the performances of the TBM900 will also be evaluated on an operational mission whose range will be taken equal to the value discussed in 2.3 For the climb and reserve, the same target performances will be selected. In addition to that, and while the design mission was chosen as a max power mission, the operational mission will be performed with the long range cruise setting. Finally, even though the descent phase of the sizing mission was performed assuming a constant equivalent airspeed of 230 KEAS, for the operational mission, it will be done with an equivalent airspeed of 160 KEAS. A summary of the main data is given in Table 9.

Table 9 – Computed TBM 900 performances on the operational mission

Parameter	Value
Operational range (nm)	250.0
Operational payload (kg)	650.0
Cruise speed (KTAS)	244
Cruise altitude (ft)	28000
Descent speed (KEAS)	160
Takeoff weight (kg)	3012
Start of cruise power (kW)	354
Fuel consumed (kg)	273
Emissions ($kgCO_{2,eq}$)	1042

4.4 Hybridisation of the EcoPulse

In this section, and as discussed in section 2.2 two versions of the EcoPulse, a demonstrator plane derived from the TBM 900, will be studied. First, we will investigate the EcoPulse as a retrofit of the TBM 900 without doing any changes on the airframe. As for the hybridisation of the Kodiak, this means the geometry and aerodynamics will be kept constant and so will the mass of the airframe, systems and furniture. The payload will also be adjusted so that the MTOW of the reference aircraft is not exceeded and so that it is below the original max payload value. A different propulsion chain as the EcoPulse demonstrator will however be considered. In this study a turbo-electric powertrain will be considered. It will include 6 electric motors and wing-mounted propellers as on the demonstrator. An additional propeller in the nose will also be kept but we will consider that it does not produce any thrust. For the on-board power generation, the same engine as the TBM900, a Pratt and Whitney PT6A-66D, will be used. The result of those design choices lead to the powertrain presented in Figure 8.

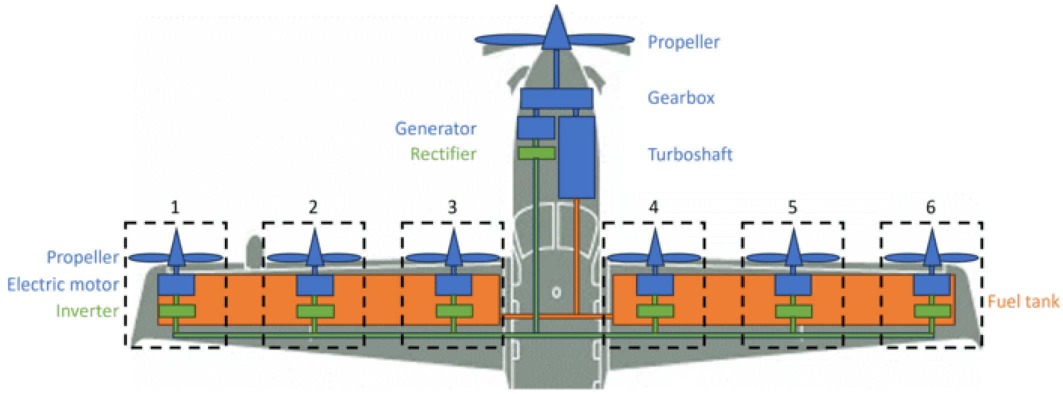

Figure 8 – Powertrain considered for the study of EcoPulse as a retrofit

To assess the benefits of DEP, a second design of the EcoPulse will also be investigated. This design, which will be referred to as "from scratch", will have a reduced wing area as a result from the additional lift generated by DEP in low speed conditions. In the FAST-OAD-CS23-HE framework this wing area is computed by finding the minimal wing surface for which it is possible to maintain the equilibrium on the longitudinal axis considering slipstream effects. An additional constraint will be added for the computation of the geometry of the wing in that the span will be kept constant. The wing aspect ratio will thus change based on the value taken by the wing are during the iterations of the solver. The rest of the airframe will however be kept constant. This means that only the wing weight will be recomputed. This will allow is an evaluation of the structural synergies brought by DEP [57]. An additional difference with the retrofit design is that the nose propeller will be removed and all the thrust will be produced by the wing-mounted propeller. The resulting powertrain is presented in Figure 9.

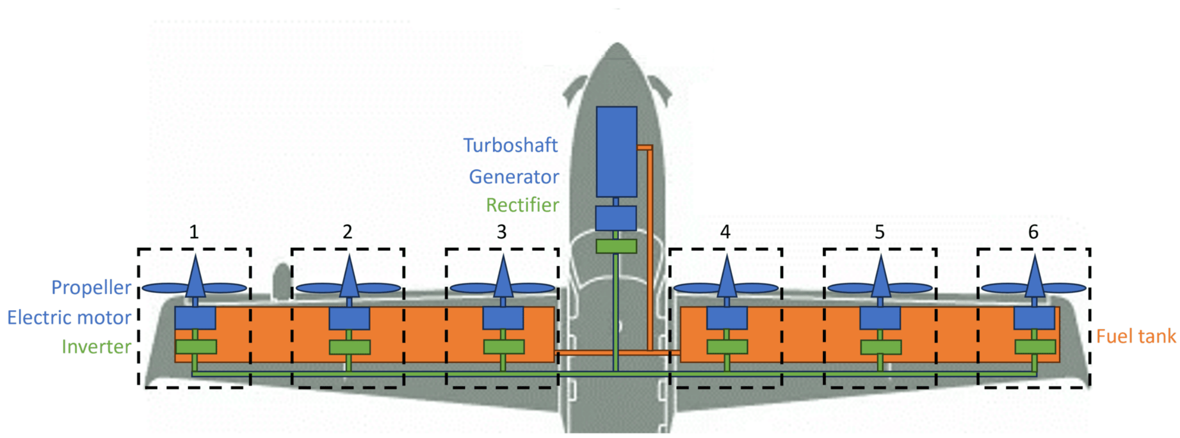

Figure 9 – Powertrain considered for the study of EcoPulse with a design from scratch

The complete list of inputs used for the sizing of both version of the EcoPulse is freely available on the FAST-OAD-CS23-HE repository, the main ones will however by summed up in Table 10. As it was decided to keep on the two hybrid variants the same turboshaft as the original TBM900 design, its characteristic inputs will be kept constant. The diameter of wing mounted propeller and their position was estimated based on pictures of the demonstrator.

Table 10 – Main input parameters for the sizing process of the EcoPulse.

Parameter	Value
Design range (nm)	250.0
Design mission speed (KTAS)	244
Design mission altitude (ft)	28000
Approach speed (KTAS)	85
Network Voltage (V)	800
Engine rated power (kW)	634
Propeller diameter (m)	1.5
Propeller rpm (-)	3000

The comparison of the hybrid design obtained with those choices are compared with the results of the evaluation of the reference TBM900 in Table 11.

Table 11 – Main outputs for sizing of the differnt version of the EcoPulse

Parameter	Ref. TBM900	Retrofit EcoPulse	EcoPulse from scratch
TOW (kg)	3012	3378	3378
OWE (kg)	2088	2570	3473
Payload (kg)	650	473	585
Propulsion chain mass (kg)	357.4	830	725
Wing mass (kg)	360	360	375
Wing area (m^2)	18.06	18.06	16.52
Fuel mission (kg)	273	334	320
Emissions ($kgCO_{2,eq}$)	1042	1277	1218
EF ($g_{CO2}/kg_{PAX}/km$)	3.46	5.82	4.49

One notable results from the comparison of the investigated designs is that a reduction of the wing surface area of more than 1.5 m^2 could be achieved on the design from scratch. This leads to a reduced profile drag. In addition to that and because of the assumed constant wing span, this reduction in wing area is also associated with an increased in aspect ratio, with a value going from 8.22 to around 9.00. This, in turns, is associated with a decrease in lift induced drag. The combination of those two effects results in a lift-to-drag ratio in cruise conditions increasing from 13.06 in the original design to 14.79.

The investigated hybrid designs however perform worse in almost every other aspect. The fuel consumed during the mission is significantly above that of the reference aircraft with an increase of 17% for the design from scratch and an increase of more than 22% for the retrofit design. For the retrofit design, the results could have been expected given the fact that we only introduce inefficiencies in the powertrain without taking advantages of the better aerodynamics from a resized wing. For the design from scratch however, the result is more telling. Further investigation into the efficiencies of the powertrain components reveals that the efficiency from propulsive power to turboshaft required power varies from 77% in the original design to 64% in the design from scratch. This decreased efficiency and the added aircraft mass outweighs the gains in terms of aerodynamics. Those gains in terms of aerodynamics were evaluated by comparing the design from scratch to the retrofit one which showed a reduction of less than 5% of the fuel consumed. It is worth noting that the losses in terms of efficiency is not only due to the losses in the electric components but also to the efficiency of the wing mounted propeller which is smaller due to a smaller radius.

The increase in aircraft empty mass was also investigated. Beyond the increase due to the electric components, for which the computed breakdown is presented in Figure 10, a slight contribution can be imparted to the wing weight. Thanks to the physics based method implemented in the FAST-OAD-GA framework and used in the FAST-OAD-CS23-HE framework [57], supplementary analysis on the reasons for those increase could be conducted. The main contributor to that increase is the skin mass which increased because of the increased aspect ratio and reduced chord lengths. For the rest of the primary structure, the gains stemming from the structural synergies from DEP were offset by the reduced fuel mass which previously acted as a relief force.

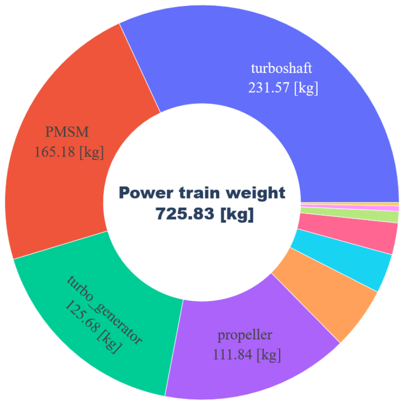

Figure 10 – Mass breakdown of the powertrain for the design of the EcoPulse from scratch

In conclusion, the investigated designs for the hybridisation of the EcoPulse don't seem promising with current technologies. While a significant gain in terms of lift-to-drag ratio could be observed, the losses stemming from the use of electric propulsion to provide thrust in cruise and the added power train mass completely outweighs those gains. Two avenues for improvements can however be identified. The first comes from the fact that it was decided to keep the same positioning and same diameters for the propulsive elements as on the demonstrator. This resulted in only 75% of the span being blown but more importantly in only using propulsive elements with fairly large diameter. More gains could be achieved by using a greater number of smaller propeller as the strength of slipstream effects seem to increase with a decreasing propeller diameter [58]. This would allow to increase the lift coefficient in approach conditions and thus further decrease the wing area. This would however come at the cost of a reduced propeller efficiency.

Another avenue would be to increase the efficiency of the propulsion chain to reduce the fuel consumption. While little work can be done on the efficiency of the component themselves, it could be worth investigating a more complex power management scheme. For instance and similarly to what was envisioned for the X-57, only a single nose mounted propeller could be used in cruise conditions to attain the same powertrain efficiencies as in the original design while wing mounter propeller could be used in low speed conditions. This would allow to utilise the aerodynamics efficiency gains stemming from DEP without having the efficiency penalty from the electric components. The weight penalty, however, would remain.

5. Conclusion

This paper presents a study on the feasibility and the potential benefits of hybridisation of turboprop aircraft. The motivation behind this study arose from the observation that, to reduce the cumulative emission of CO_2, a green house gas with an extended lifetime, new designs with a rapid EIS could be desirable. The modification of two designs from the french manufacturer DAHER were retained and investigated: the TBM 900 and the Kodiak 100. Based on the observation on the range of viability of electric propulsion, the practical use of these aircraft was also investigated in order to have realistic targets compatible with a hybrid aircraft. This study was conducted using an extension of the FAST-OAD-GA framework with the addition of models allowing for the sizing of high wing aircraft and a methodology to assess the performances and sizing of a hybrid electric aircraft. Results show that a gain of almost 14% could be obtained in terms of total emissions by retrofitting an existing aircraft with a turboshaft boosted by an electric motor and battery pack. While this is slightly mitigated by the reduction of payload due to the added weight of the powertrain, reduction in terms of emissions per weight of payload could still be attained with current technologies. Two prospective design for the EcoPulse demonstrator were also studied, but, while improvements on the aerodynamic were observed, the added weight and losses induced a greater fuel consumption.

6. Contact Author Email Address

mailto: Florent.LUTZ2@isae-supaero.fr

7. Supplementary materials

FAST-OAD-GA is available online at https://github.com/supaero-aircraft-design/FAST-GA, FAST-OAD-CS-23 is available online at https://github.com/florentLutz/FAST-OAD-CS23-HE.

8. Copyright Statement

9. Fundings

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