Performance analysis of significant aircraft at different CS-23 levels and study of electrification potential

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ABSTRACT

This study investigates the performance and electrification potential of representative aircraft within the CS-23 certification levels, focusing on the Cirrus SR-22 and the Cessna 208B Grand Caravan EX. Employing the FAST-OAD software for preliminary aircraft design and performance analysis, various electric and hybrid powertrain configurations were modeled and evaluated through the metric of fuel consumption mainly. The study highlights the trade-offs between battery load, wing design, and thrust distribution, emphasizing that although electrification can bring aerodynamic benefits, current technology limits its advantages in larger CS-23 aircraft.

I. INTRODUCTION

Aviation is in the spotlight of current eco-transition initiatives. A re-thinking of mobility patterns is being encouraged while novel architectures and greener powerplants are being proposed[1] [2]. Regarding the latter, hydrogen and electric propulsions are currently the object of a remarkable amount of studies[3] . Although long-haul flights are out of electric propulsion's reach, its interest for general aviation has been proved by the Slovenian Pipistrel Velis Electro[1]. Purchase and flight-hour costs have been dramatically reduced. Besides, noise regulations hinder fuel-powered aircraft from flying at given times and locations, which would not restrain the more silent electric aircraft. The Pipistrel Velis is a CS-23 aircraft, i.e. general aviation. Within it, it belongs to the lowest level, that of twin-seaters.

This article aims to explore the electrification potential of larger CS-23 aircraft. First, the Cirrus SR-22 (4-seater) was tackled, followed by the Cessna 208B Grand Caravan EX (14-seater). Both aircraft are recent, robust and widely used models, thus becoming representative examples of their own CS-23 level. The main parameter aimed at in this paper is fuel consumption, whose reduction was sought with novel powering configurations. Hence, fuel saving was deemed the main criterion for considering the interest of any of the proposed architectures from this paper. The main limitation for attaining it is the battery's poor energy density[4] [5]. Current batteries offer low energy at high weight, which highly restrains electric aircraft capabilities if compared to fuel-powered aircraft. Still, the lightness and simplicity of electric motors allow to benefit from further design synergies than conventional aircraft. Thus, electric solutions are only made feasible by a range reduction according to the mean profile of the aircraft's missions. Many of them are below the design range of the vehicle so a shorter-haul electric version may be economically convenient.

For a given mission, the electric aircraft was sized and its main performance parameters were compared to the original version's. In addition, hybrid motorization was been tested, both in parallel and series configurations. Thus, this paper also aims to shed light on such configurations.

II. METHODOLOGY

The goal of this paper is to compare the electric and hybrid aircrafts' performances to the original ones'. Namely, fuel consumption is the main criterion to determine whether a version is more advantageous than another. This was achieved using the FAST-OAD software developed by ISAE-SUPAERO, specifically the General Aviation version. FAST-OAD models aircraft from a preliminary design standpoint, calculating its main characteristics out from geometric inputs and Top Level Aircraft Requirements (TLARs). A full sizing of the proposed aircraft was performed, meaning a whole new airplane was dimensioned even if it started from the base of the original aircraft.

FAST also has the aircraft's powertrain as an input. The software models the energy source, the engine, the propeller and their connections. Hence, several electric, thermal or hybrid configurations can be defined. Such software has been chosen since it does not require to code at user level and it yields quite robust results. Indeed, the base, fuel-powered aircraft employed in this study were modeled in FAST and their performances matched the actual ones. Mission data was retrieved from Opensky's website[2]. Other tools such as FLARM or FlightRadar24 are useful as well since they sort flights by aircraft type, but the free-version does not allow to access past data.

So far, electric propulsion has mainly been applied to low level CS-23 aircraft[3] [4]. Indeed, the only one finding commercial viability so far has been the Pipistrel Velis. Bigger General Aviation electric aircraft start-ups have been launched, leading many of them to economic failure[5] [6].

Still, the advance of all-electric aircraft remains relentless, foreseeing economic advantage within its range of capabilities. The first all-electric commercial flight was completed in 2025[7].

1 https://www.pipistrel.fr/velis-electro-easa-tc/
2 https://opensky-network.org/data/aircraft
3 https://www.airport-technology.com/projects/extra-330le-electric-aircraft/
4 https://www.diamondaircraft.com/en/flight-school-solution/aircraft/eda40/overview/
5 https://www.reuters.com/legal/litigation/boeing-convinces-us-judge-overturn-72-mln-trade-secrets-verdict-2024-08-14/
6 https://techcrunch.com/2024/10/24/lilium-shuts-down-electric-aircraft-germany-startup/
7 https://beta.team/aircraft

Projects of CS-25 aircraft require agressive assumptions of future battery development[6] [7]. Thus, existing technologies seem to work only for less than 19-seater aircraft.

III. AIRCRAFT

A. Cirrus SR-22

The Cirrus SR-22 is a composite aircraft from 2001, constituting the best-sold CS-23 aircraft since 2003 with its 8000 units[1].

1. Real and modeled reference aircraft

The aircraft was modeled in FAST-OAD by introducing its main parameters and having the software size the resulting aircraft, whose characteristics do match with the real aircraft[2] [3]. Table 1 summarizes its main geometrical characteristics and Top-Level-Requirements (TLARs).

Length (m)	Wingspan (m)	MTOW (kg)	W_{PL} (kg)	Max speed (km/h)	Range (km)	Max ceiling (ft)
7,9	11,6	1633	602	333	2164	17500

Table 1: Main parameters of the original Cirrus SR-22

2. Mission range

As shown in Fig. 1, a range over 250km is beyond electric aircrafts' reach[8]. This would make the Cirrus' design range unattainable for any electric project.

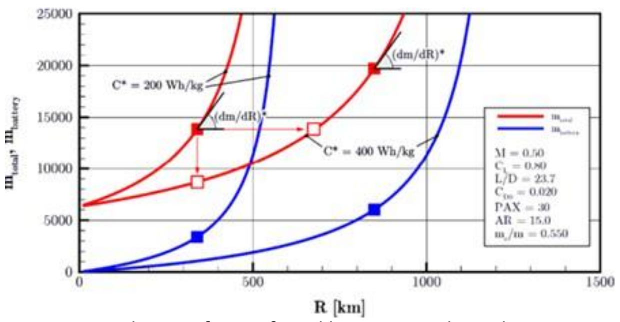

Figure 1: Evolution of aircraft and battery weight with range. Note how they tend to infinite beyond R=500km

Nevertheless, it was shown that the majority of this aircraft's missions actually cover much lower distances. Fig. 2 illustrates such phenomenon. Namely, 55% of flights are below 100NM. Thus, for almost all missions accomplished by the SR-22, electric propulsion is theoretically feasible. Such data was computed by processing the information from OpenSky.

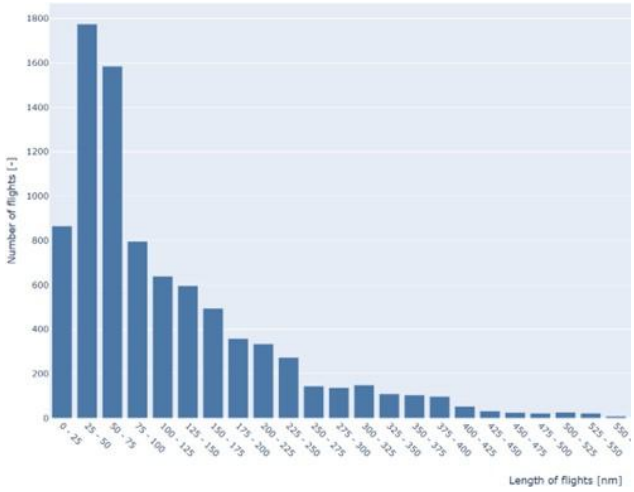

Figure 2: Range distribution per mission for Cirrus SR-22

3. All-electric

A twin-motor configuration was chosen for it induces slipstream effect. In other words, it increases the dynamic pressure of airflow over the wing by accelerating it, which in turn enhances lift at low-speeds[9]. Its powerplant is represented in Fig. 3.

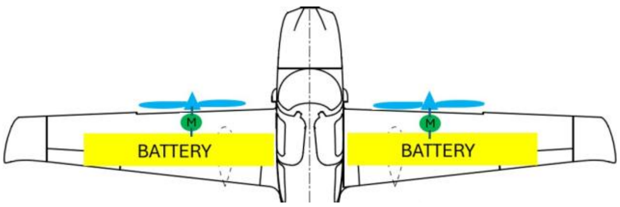

Figure 3: All-electric Cirrus SR-22 powertrain

It is not possible to achieve an all-electric Cirrus at the established 100NM range keeping positive State-of-Charge (SOC) of the battery. The maximum range for which FAST achieves the SOC=20% threshold is 31NM. Such a case requires 40 thousand cells, meaning an MTOW of 5340kg (331% of the original SR-22). Since there are only 15% of Cirrus' missions below the 30NM threshold, the all-electric option is deemed unsatisfactory.

4. Parallel-hybrid

Given the insufficiency of the full electric powertrain, the thermal engine was kept and the electric powerplant was used as a reinforcement at low speed. First, a parallel hybrid configuration was tackled. A parallel-hybrid configuration implies thermal and electrical systems are independent, each having their own source, motor and propeller without being connected at any point on the aircraft. Its layout is shown in Fig. 4.

1 https://www.aopa.org/news-and-media/all-news/2024/february/21/aviation-industry-growth-robust-yet-at-risk
2 https://cirrusaircraft.com/aircraft/sr-series/models
3 https://jasonblair.net/wp-content/uploads/2015/06/Cirrus-SR22-POH.pdf

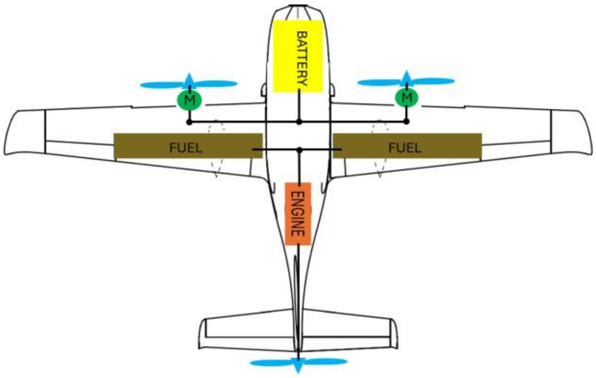

Figure 4: Parallel-hybrid Cirrus SR-22 powertrain

The pusher propeller was chosen to benefit from design synergies enabled by electric configuration, which also allows to employ distributed propulsion. Table 2 summarizes them and how they have been accounted for:

Benefit	FAST-OAD benefit modelling
Boundary Layer Ingestion (aft propeller)	6% total drag reduction
Slip-stream effect	Already accounted for by FAST's model
Wing-tip propeller for induced drag countering	10% wing drag reduction

Table 2: Summary of the synergies enabled by electric propulsion[10] [11]

Once the aircraft's characteristics have been laid out, some parameters can be modified to seek its best performance. Table 3 summarizes them, showing the criteria leading to their choice:

Parameter	Choice criterion
Battery cells in series	Minimum to guarantee, if possible, $V_{input\ motor} = V_{nominal\ motor}$
Battery modules in parallel	Minimum to guarantee $SOC_{final} = 20\%$ with given cells in series [1]
Thermal engine power share [2]	Minimum to guarantee $SOC_{final} = 20\%$
Wing area	It increases weight but also the effect of air suction on extrados

Table 3: Parameters to select for hybrid aircraft and their choice criteria

For an aircraft of Cirrus' size, electric reinforcement allows the reduction of the engine's size until suitable power for a ROTAX engine is reached, a small, light and efficient engine. Namely, it yields 25% less fuel consumption than FAST's by-default Lycoming engine[4]. Its benefits are modeled by setting FAST's specific fuel consumption constant at $k_{sfc} = 0.75$.

4.1 Trend analysis on electrification

Knowing the aircraft will embark both fuel and batteries, the effect of increasing the number of batteries for reducing the thermal engine's preponderance must be clarified. Such a case proposed the trade-off of reducing the importance of fuel against increasing battery weight. Such weight growth is linear as seen in Fig. 5:

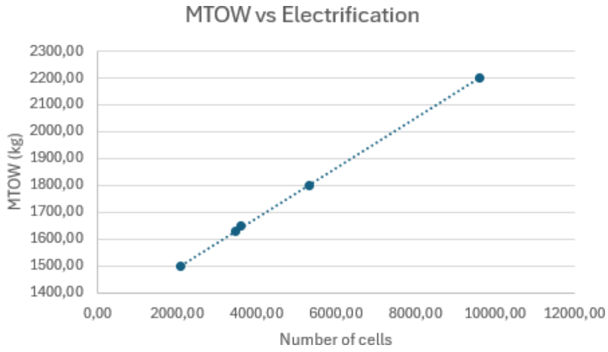

Figure 5: Evolution of aircraft's MTOW with the on-board battery load

Yet, such battery weight increase is negative in terms of fuel consumption, which is regarded as the main parameter of interest.

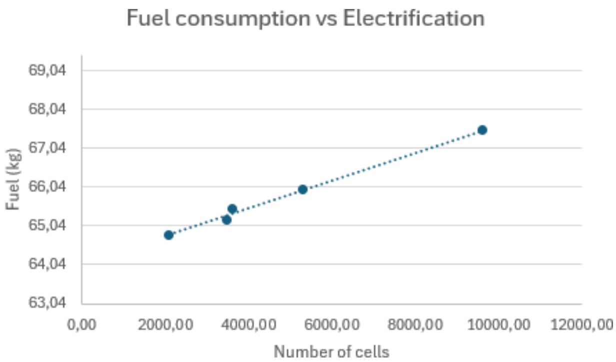

Figure 6: Evolution of the fuel consumption with the on-board battery load

Thus, the whole energy on-board increases as more battery cells are added. Therefore, including additional battery for increasing the electric energy available is actually detrimental, since it increases weight drastically.

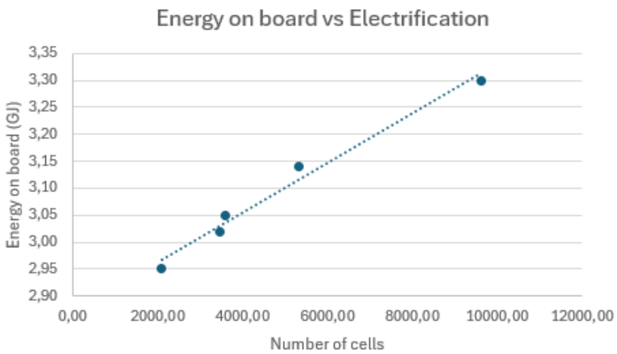

Figure 7: Evolution of the embarked energy ob board with the on-board battery load

[1] SOC stands for State of Charge of the battery
[2] Power share represents the amount of the aircraft's power relying on the thermal engine
[3] The electric motor is assumed to be an EMRAX, the same as in the Pipistrel Velis, and is selected from EMRAX's catalog: https://emrax.com/
[4]https://www.flyrotax.com/p/service/technical-documentation

4.2 Parametrical study

Having established that minimizing the amount of batteries is in our interest, the case converging with the minimal number of batteries was selected for the performance of a parametric study. The effect of the electric motor's RPM and the disposition of batteries in series/parallel was also studied. Yet, they yield no change as long as they stay within a range ensuring appropriate torque and motor input current. Modifying the motor's voltage does not induce any change either. Finally, wing area was selected as a parameter, having its lower bound in the minimum surface for low-speed equilibrium. All other parameters have been selected so that SOC=20%. Fig. 8 shows the interest of increasing wing area up until a certain limit, where the benefit becomes assymptotic.

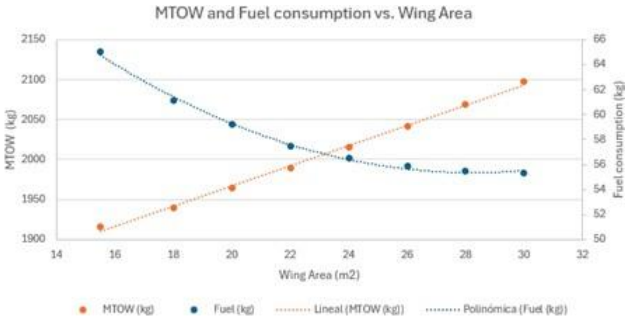

Figure 8: Evolution of the aircraft's MTOW and fuel consumption with wing area. The fuel gain is assymptotic

Hence, the optimal Parallel-Hybrid Cirrus case is characterized by Table 4. Since its fuel consumption is greater than the original Cirrus', the former is retained less interesting than the latter:

Number of battery modules	MTOW (kg)	Fuel consumption (kg)	Wing Area (m^2)
3000	1741	50	30

Table 4: Main characteristics of the optimal series-parallel hybrid Cirrus

5. Series-parallel hybrid

Next, a series hybrid configuration was tackled, meaning the electric and thermal systems are coupled by a planetary gear box which feeds a single propeller.

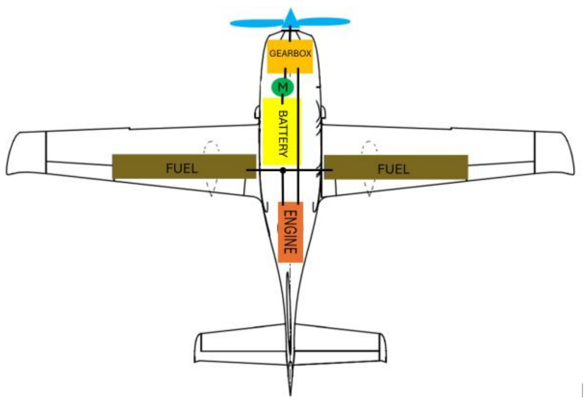

Figure 9: series-parallel hybrid powertrain layout

Retaining the same logic as for the parallel-hybrid, the optimal case was found for the minimum battery-load. Instead, wing area plays no role here since there is no air suction over the extrados. Table 5 resumes its main characteristics.

Number of cells	MTOW (kg)	Fuel consumption (kg)	Wing Area (m^2)
2025	1926	77	15

Table 5: Main characteristics of the optimal series-parallel hybrid Cirrus

Therefore, the series-parallel hybrid configuration proves to be less interesting than the parallel hybrid one. This seems reasonable since this option retains the height battery weight, yet losing the high efficiency and design synergies of electric motors.

6. Turboelectric

In the current configuration, fuel supplies power to a turboshaft, which in turn can drive either directly a propeller or an electric generator supplying several electric motors. This way, battery weight is saved up whilst air suction over the wing is retained. Another important factor is that this configuration, not depending upon batteries, can be used for longer distances without such weight penalization. This was tested for two different propeller configurations.

6.1 Six electric propellers

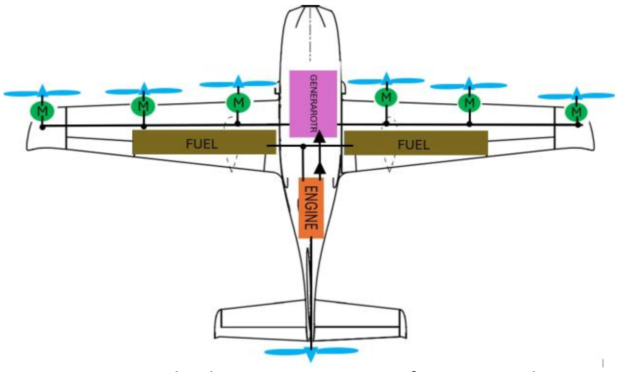

Figure 10: Turboelectric powertrain configuration with six propellers

A parametric study on the effect of giving certain importance to the thermal or electric propellers was performed. This is accounted by a parameter named "Thrust Distribution" which assigns a given share of thrust to each propeller. The unit being the standard amount, increasing it gives more importance to one propeller over the others.

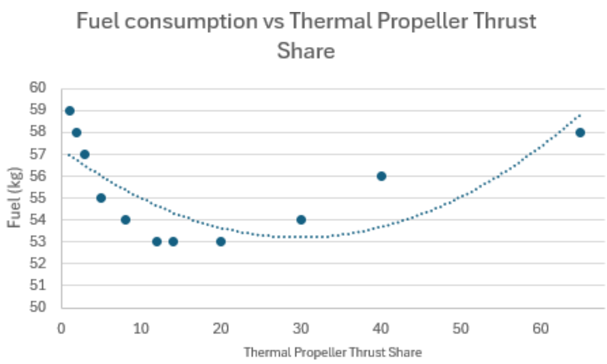

Figure 11: Evolution of fuel consumption with respect to the thrust share granted to the thermal propeller. Note the existance of an optimum in the repartition of thrust

Fig. 11 shows the existence of an optimal balance between electric and thermal thrust distribution. It shows how the main thermal propeller is required, while it does benefit from the electric propeller's reinforcement. Since range extension is possible for this case, another parametric study has been performed on this variable. Yet, no effect has been remarked as it can be seen in Fig. 12:

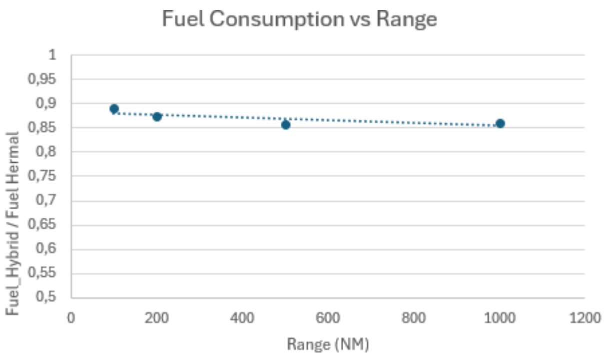

Figure 12: Evolution of fuel consumption for different ranges. No effect was remarked

Hence, the optimum case for this configuration yields the characteristics shown in Table 6:

MTOW (kg)	Fuel consumption (kg)	Wing Area (m^2)
1570	49	30

Table 6: Main characteristics of the optimal six-propeller hybrid Cirrus

6.2 Two electric propellers

Only two wing tip propellers have been kept in this case. They have been selected to remain since they reduce induced drag. The trade-off here is the weight reduction coupled to an air suction at low-speed loss.

MTOW (kg)	Fuel consumption (kg)	Wing Area (m^2)
1460	49	30

Figure 13: Main characteristics of the optimal hybrid Cirrus

The data for its optimal case are presented in Table 7:

MTOW (kg)	Fuel consumption (kg)	Wing Area (m^2)
1600	49	15

Table 7: Main characteristics of the optimal hybrid Cirrus

B. Cessna 208B Grand Caravan EX

The Cessna 208B Grand Caravan EX belongs to the biggest CS-23 level, that ranging from 14 to 19 passengers. The Grand Caravan EX is a 2012 version of the 1982 original C208, being an updated, yet well proven aircraft [1] [2]. . More than 3000 C208s have been manufactured and employed for diverse uses such as training, humanitarian missions and freight or passenger transport[3].

1. Real and modeled reference aircraft

The Caravan's main geometric parameters and TLARs are presented in table 5.

Length (m)	Wingspan (m)	MTOW (kg)	W_{PL} (kg)	Max speed (km/h)	Range (km)	Max ceiling (ft)
12,7	15,9	3995	1447	343	1689	25000

Table 8: Main characteristics of the origianl C208B

2. Mission range

Similarly to the SR-22, average mission range is much lower than the design one, as seen in Fig. 14. Thus, a standard range of 100NM is selected.

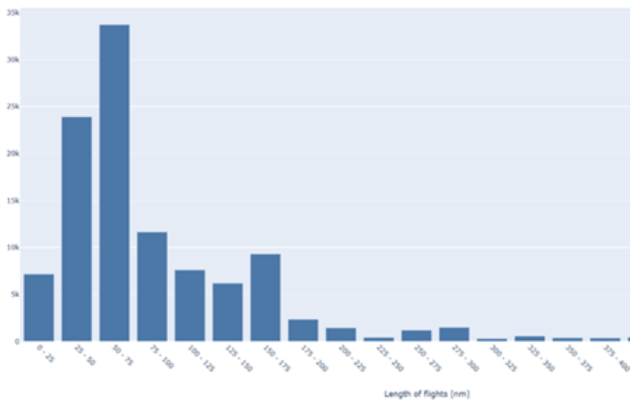

Figure 14: Distribution of C208B missions by range

3. All-electric

First, a full-electric C208B was modelled as a 6 propeller electric airplane with engines mounted along its wings. Its benefits are discussed in the *Parallel-Hybrid* Section. The resulting aircraft is shown in Fig. 15:

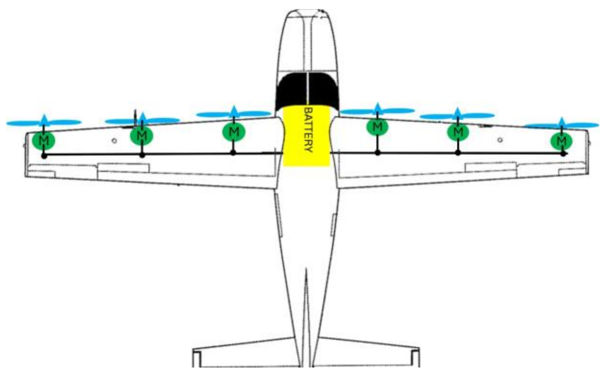

Figure 15: Full electric C208B powertrain, with 6 propellers

Before any simulations are computed, an analytical approach may be advisable in order to have a range of magnitudes on the battery's mass. From standard battery data, the battery weight for matching the energy yielded by the fuel and the power from the engine were computed and shown in Table 9:

1 https://cessna.txtav.com/en/turboprop/grand-caravan-ex
2 https://caravannation.com/208BG1000POH.pdf
3 https://media.txtav.com/

$Mass_{fuel}$ (kg)	$Power_{engine}$ (kW)	$Mass_{battery}$ (energy) (kg)	$Mass_{battery}$ (power) (kg)
202	647	2930	7800

Table 9: Energetic data from C208B and required battery mass of the all-electric C208B for equling the original's power and on-board energy. $Mass_{fuel}$ corresponds to a 100NM flight consumption for thermal model

A battery mass 3 times superior to the aircraft's OEW must call for caution. Indeed, FAST-OAD does not converge for the C208B's full-electric case no matter its range.

4. Parallel-hybrid

Since the series hybrid configuration was unsatisfactory, design synergies enabled by electric propulsion were combined with hybrid propulsion using a parallel configuration. The 6 electric propellers have been preserved and the thermal propeller has been placed at the aft position. This yields the scheme represented by Fig. 16:

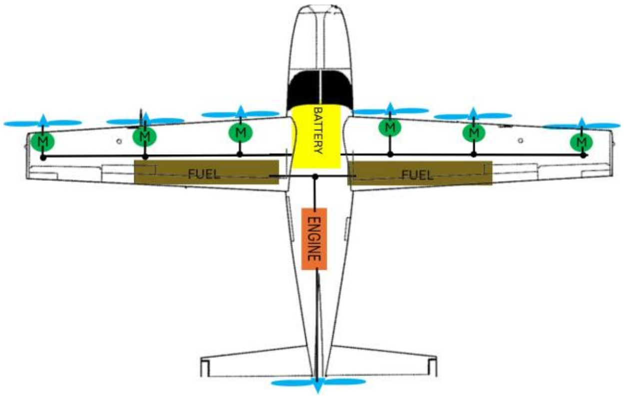

Figure 16: Parallel-hybrid Caravan scheme

The trend in terms of MTOW, fuel consumption and on-board energy with respect to the degree of electrification remains the same as for the Cirrus. Thus, the case with least-battery possible was studied. Table 10 summarizes its main characteristics. Since it consumes more fuel than the original C208B it is deemed less interesting than it, the same behavior shown by the Cirrus.

Number of cells	MTOW (kg)	Fuel consumption (kg)	Wing Area (m²)
5000	4700	302	35

Table 10: Parallel hybrid Caravan geometrical and performance data

4.1 Range assessment

The effect of range on the aircraft's performance was considered. The fuel consumed by the hybrid version was compared to that of the thermal version for the same mission. Yet, no remarkable changes were noted, as seen in Figure 17:

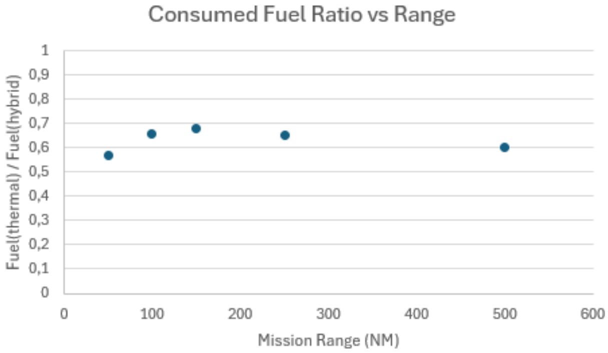

Figure 17: Evolution of relative fuel consumption of the hybrid aircraft against its range. No effect is remarked

However, an extended range requires a greater on-board battery load. Hence, it must be recalled that for a greater range (i.e. heavier battery) the MTOW increases at equal payload. Thus, longer-range aircraft are equally efficient in terms of fuel, but show poorer performance in terms of relative useful load.

5. Turboelectric

Since this configuration yielded the best results for the Cirrus, it was tried again for the Caravan. Its powertrain scheme is identical to the former's. Let us recall that for a 912NM range the original Caravan consumes 951kg of fuel.

5.2 Six motors

The six motor version performs less well than the original Caravan since its fuel consumption exceeds the Caravan's one, even accounting for the aerodynamic benefits proposed by electrification. This is shown by Table 11.

MTOW (kg)	Range (NM)	Fuel consumption (kg)	Wing Area (m²)
4320	912	1320	35

Table 11: Performance parameters of the six-motor, turboelectric Caravan.

5.2 Twin-motor

As with the Cirrus, the twin-motor aircraft performs better than the six motor, although it still consumes more than the original Caravan.

MTOW (kg)	Range (NM)	Fuel consumption (kg)	Wing Area (m²)
4320	912	1068	35

Table 12: Main performance parameters of the twin-motor version

The only way to lower the consumption with respect to the original thermal Caravan is by compromising on some TLARs, such as the climb rate and thus the altitude attained by the aircraft. If sacrificing such parameter, it becomes possible to lower the fuel consumption with respect to the original Caravan.

Max ceiling (ft)	Climb rate (ft/min)	Fuel consumption (kg)
4320	912	775

Table 13: Performance parameters of the twin-motor version with lower ceiling. Only the parameters which have been modified respect to the previous version are shown

IV. DISCUSSION

Several trends were identified. First of all, it was shown that full-electric aircraft propulsion is not viable beyond the CS-23 first level (twin-seaters). Next, the incorporation of batteries along with the thermal powerplant deteriorates all parameters: MTOW, fuel consumption and energy on board. There increase is linear with the number of battery cells added. Next, both wing area and thrust distribution to the thermal propeller improve the aircraft's performance but have an optimal point beyond which there is no interesting in still increasing the parameter. Finally, results showed that the least consuming hybrid option is the one without batteries (i.e. being fuel powered and electrically propelled, AKA ”turboelectric”). However, no hybrid configuration improves the consumption of the original aircraft, in spite of their aerodynamic advantages. This means that given the current technology it is not possible to power aircraft of higher CS-23 levels than the first one.

In addition, there is another trend to be identified. Turboelectric models have not yielded satisfactory results, and there is no technological improvement expected in that area. However, parallel-hybrid consumption remains fairly close to the original one (around 10% for the Cirrus) and it is expected to have some techonological leverage on the battery energy density over the next years[12]. This could boost the interest of sourcing some of the aircraft's energy from electrical (and hopefully green) energy, particularly for the 2nd CS-23 level -10% fuel offset for the Cirrus vs 30% for the Caravan. Hence, current results do not favour electric or hybrid propulsion for higher CS-23 levels. Nevertheless, they do pave the way for a more-electric and sustainable aviation.

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