TECHNICAL ARTICLE

The Potential of Structural Batteries for Commuter Aircraft Hybridization

Gennaro Di Mauro (ID)*, Salvatore Corcione, Vincenzo Cusati, Valerio Marciello, Michele Guida,* and *Fabrizio Nicolosi*

Electric or hybrid electric propulsion systems have received a great deal of attention in recent years in various branches of transportation including aviation. Europe is committed to the ambitious goals of reducing CO_2 emissions by 75%, NOx emissions by 90% and perceived noise by two-thirds by the year 2050 compared to the average new aircraft of the year 2000. The main barrier of the electric propulsion is bound to the battery limits in terms of energy and power densities, thus determining a relevant negative impact on payload or aircraft size. It is possible to design and fly an electrically propelled aircraft, as testified by some existing examples, both prototypical and production models, in the categories of ultralight and general aviation aircraft. A novel technology, which allows the electrification process toward heavier categories of aircraft, is constituted by structural batteries. These are similar in structure to carbon fiber composites, where the matrix features dielectric characteristics, making the structure capable of storing electric energy while retaining the capability to withstand mechanical loads. Despite that, it raises relevant issues concerning aircraft sizing procedures that need to be conceived considering the specific characteristics of such multifunctional technology. This research work aims to evaluate the potential benefits the structural batteries have on the fuel burn for a 11-seater commuter aircraft. According to the envisaged technologies (structural batteries), this work will focus on the determination of the best hybridization factors determining the energy requirements for the typical mission of a commuter aircraft.

1. Introduction

Aviation is nowadays demanded to unite environmental sustainability and economic growth (Ref 1). These needs resulted in policy roadmaps in Europe and led to consistent long-term research efforts. In 2019, the European Green Deal (Ref 2) set the ambitious goal of achieving climate neutrality in all sectors of the EU economy, including air transport, by 2050, raising the bar significantly above the previous environmental targets. One of the main strategies to limit in-flight emissions of Green-House Gases (GHG) and pollutants is the increased use of electrical energy onboard aircraft for both non-propulsive (e.g., secondary systems) and propulsive purposes, leading to

Gennaro Di Mauro, Salvatore Corcione, Vincenzo Cusati, Valerio Marciello, Michele Guida, and **Fabrizio Nicolosi**, Industrial Engineering Department of University of Naples Federico II, 80125 Naples, Italy. Contact e-mail: gennaro.dimauro@unina.it.

the concepts of "More Electric Aircraft" (MEA), "Hybrid Electric Aircraft" (HEA) and "All-Electric Aircraft" (AEA).

HEA solutions provide several benefits (Ref 3, 4): low- or even zero-emission flight, new potential air transportation missions, safer flights and enhanced design flexibility thanks to innovative design solutions like the Distributed Electric Propulsion (DEP) (Ref 5). However, there are also some drawbacks hindering the trend to HEA propulsion. Examples are low weight performance of energy storage devices, lack of regulation for future mobility concepts and uncertainty on future market demand.

These new concepts have been investigated for all aviation sectors, from twin-aisle aircraft to urban air transport with vertical take-off and landing capabilities.

As of today, some all-electric aircraft have been designed and flown; a short list of models is provided by Riboldi (Ref 6). Those models are electrified versions of existing gliders, like the Lange Aviation Antares 20E and 23E or the Pipistrel Taurus Electro G2, or very light machines, inspired by a corresponding conventionally powered aircraft in the Light Sport Aircraft (LSA) category like the Yuneec International E43 or the Pipistrel Alpha Electro.

Concerning hybrid electric propulsion, even fewer specimens exist, and currently, there are no designs available on the market. However, today research is active in this field.

Although modern electric motor (EM) drives are more efficient in converting stored energy into mechanical power with respect to conventional Internal Combustion Engines (ICE), the main limit to electric propulsion is represented by the limits of energy storage systems, i.e., batteries, which, especially for aircraft, do not offer sufficient energy-to-mass and energy-to-volume densities (Ref 7) without a relevant negative impact on

aircraft maximum take-off weight and in turn on the payload or aircraft size. As a result of nowadays research efforts toward the improvement of such performance indices, it is possible to design and fly an electrically propelled aircraft, as demonstrated by some existing examples, both prototypical and production models, in the categories of ultralight and general aviation (Ref 8).

Whatever the selected aircraft configuration is, hybrid electric solutions based on conventional battery technology to store the required electrical power will be affected by the addition of an extra weight, represented by the batteries themselves. The battery mass will trigger the detrimental "snowball" effect on the aircraft weight, as shown in Fig. 1. The more the demand for electric power the higher the battery mass is and in turn the aircraft maximum take-off weight.

To break the detrimental loop of the snowball effect on the aircraft weight convergence process, or to mitigate its negative impact, an alternative approach to store electrical energy in a conventional battery system installed in the aircraft is to combine energy storage and load-bearing capabilities in multifunctional structures, or structural batteries (SB), which have come to the forefront of research since the late 1990s.

Structural batteries are hybrid and multifunctional composite materials that can provide electrical energy storage (like conventional lithium-ion batteries) being at the same time a structural element carrying loads. In a very overall classification criteria (Ref 9), structural batteries can be embedded batteries (Fig. 2 left) being multifunctional structures where lithium-ion battery cells are efficiently embedded into a composite structure or more often sandwich structure; and laminated structural electrodes where the electrode material possesses an intrinsic load-bearing and energy storage function (Fig. 2 right). A more detailed classification of SB can be found in (Ref 10).

Apart from the considered SB type, the key performance indicators (KPIs) of such a technology are those schematically shown in the chart in Fig. 3.

The two sets of properties shown in Fig. 3 are usually in contrast; in fact, the more the demand on the electrochemical side, the lower the structural properties are, and vice versa.

Traditional battery packs are mainly used to provide electrical energy, but the structural battery packs take this role much further crating a solid structure that strengthens the structural body; some works can be found in the literature about the assessment of the impact the structural batteries may have in the aviation field. An estimate of the potential of integrating
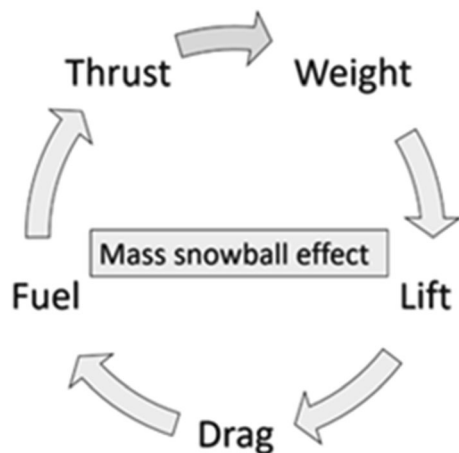
energy storage within aircraft structures is shown by Adam et al. (Ref 11). A range extension of about 11 and 66% could be achieved by exploiting 10–40% of the aircraft maximum take-off weight (MTOW) to store electric power in the aircraft structure, assuming ideal and full substitution.

It is equally important to show the differences in mechanical and/or storage performance; more researchers focused on the last year their attention on these applications. Schutzeichel and al. in the work (Ref 12) highlight the electrotermochemical characterization of the carbon fibers as structural anodes, while Leijonmarck et al. (Ref 13) embedded in a cathode-doped matrix material to be used as a negative electrode in a lithium-ion battery, and Shirshova et al. (Ref 14) performed a systematic analysis of bicontinuous liquid–epoxy systems to realize stiff structural solid electrolytes.

Potentially this concept is then used to estimate the multifunctional capabilities of relevant structures; for optimizing the volume of a structure, Scholz et al. (Ref 15) found that the entire propulsive battery ($\sim$ 20 kWh) for two small all-electric aircraft (2 seaters with 600 and 750 kg MTOW) could be replaced by structural batteries with a minimum energy density of around one-third to one-half of the conventional battery pack.

The possibility to embed structural batteries in the cabin floor panel of an A220-like aircraft has been investigated by Nguyen et al. (Ref 16); they demonstrated that this application of SB can be used to feed the in-flight entertainment systems by considering minimum specific energy of 144 Wh/kg, a specific power of 290 W/kg, an in-plane elastic modulus of 28 GPa and compressive strength of 219 MPa.

An investigation of the required energy and power densities of structural batteries as well as the achievable reduction of the fuel burn and GHG for an A320-like aircraft has been conducted by Karadotcheva et al. (Ref 17). They found that for a 1500 km mission of an MEA a minimum of 90 Wh/kg and 55 W/kg of the structural batteries embedded into the 50% of aircraft structure could lead to a 5.6% fuel efficiency improvement. For a HEA, the required SB energy and power density should be about 200 Wh/kg and 120 W/kg considering the 100% of SB integration within the structure with a main conventional battery pack having 400 to 600 Wh/kg). For AEA, these values rise to 400 Wh/kg for the SB and 700 to 800 Wh/kg for the conventional battery pack.

A methodology to take into account the synergies between power system, aircraft architecture, mission profile and the multifunctionalization in designing and optimizing hybrid electric unmanned vehicle is proposed by Donateo et al. in Ref 18, 19. This approach has been used to assess the required level of multifunctionalization needed to maximize the endurance of the investigated configuration under the constraints imposed by the state of the art (SoTA) of the multifunctional material as found in the literature.

A detailed work about the preliminary design of a hybrid electric aircraft with SB is proposed by Riboldi et al. (Ref 20). This work presents an initial methodology for the preliminary design of an aircraft equipped with SBs. The use of SB panels is envisaged for 75% of the fuselage structure and some parts of the wing structure like the ventral skin panels, leading and trailing edges, where compressive loads are not excessive. The case study is a hybrid electric aircraft for general aviation (CS-23). They assumed an energy density of the structural battery equal to 125 Wh/kg, and they equipped about 46% of the structure with it to store about 54% of the total electric energy in the structure; the weight of the aircraft structure plus the
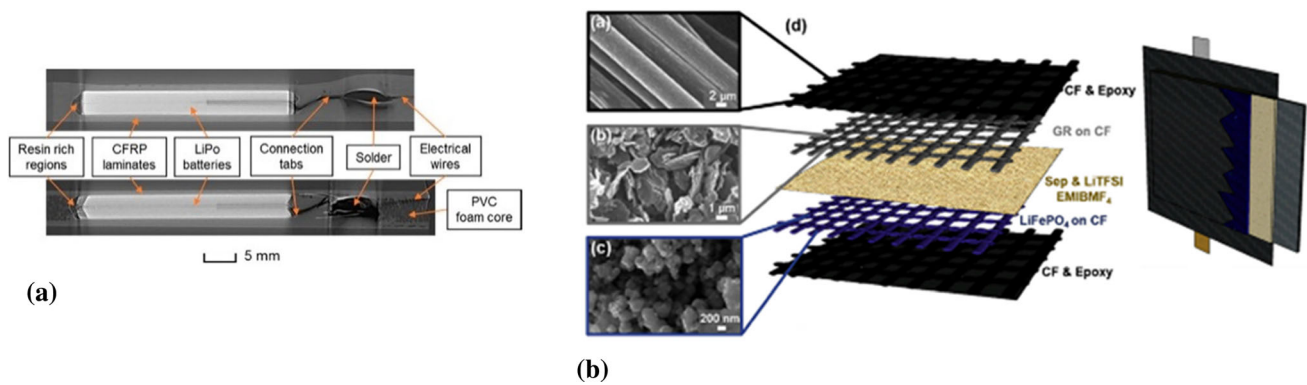

Fig. 1 A schematic of the snowball effect on aircraft weight

Fig. 2 Schematic of an embedded (a) and laminated (b) structural battery Panel (a) reprinted from *Composites Part A: Applied Science and Manufacturing*, Vol 136, K. Pattarakunnan, J. Galos, R. Das, A.P. Mouritz, "Tensile properties of multifunctional composites embedded with lithium-ion polymer batteries," Article 105966, Copyright 2020, with permission from Elsevier. Panel (b) reprinted from *Energy Storage Materials*, Vol 24, Kathleen Moyer, Chuanzhe Meng, Breeanne Marshall, Osama Assal, Janna Eaves, Daniel Perez, Ryan Karkkainen, Luke Roberson, Cary L. Pint, "Carbon fiber reinforced structural lithium-ion battery composite: Multifunctional power integration for CubeSats," Pages 676–681, Copyright 2020, with permission from Elsevier
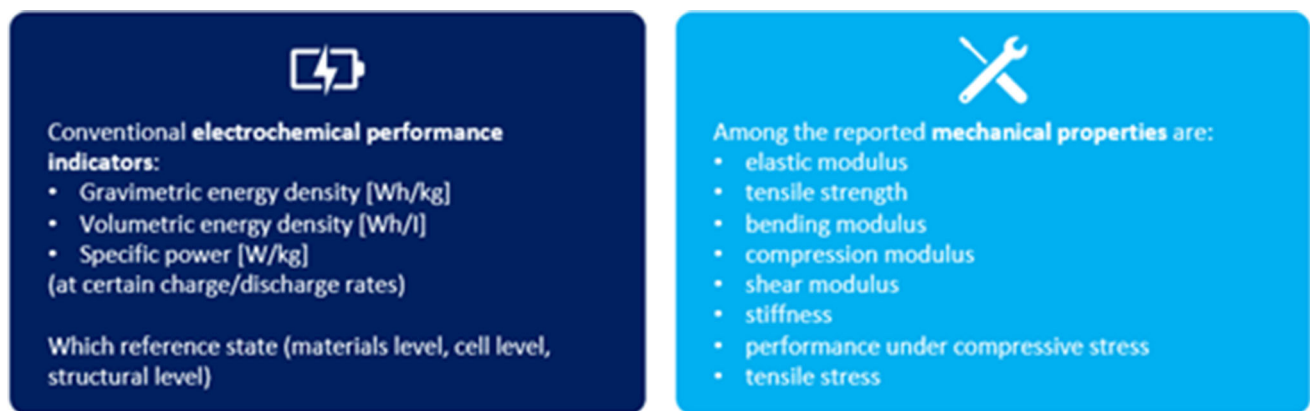

Fig. 3 Electrochemical and mechanical properties for a structural battery. Reproduced from *Aerospace* (Ref 10) under the CC BY 4.0 license

battery is projected to be reduced by about 20% compared to a conventional carbon fiber-reinforced polymer (CFRP) structure and about 29% compared to an Al alloy structure (and using a conventional battery pack).

This paper wants to investigate the potential benefits in terms of fuel burn reduction achievable through integrating an underdevelopment concept for a structural battery into the hybridization process of a 9-seater commuter aircraft. Starting from a conventional reference aircraft with an all-aluminum alloy structure, this work will address the potential structural mass that can serve as SB and will estimate the potential energy and power demand to fulfill the design mission of the reference aircraft. The best hybridization strategy to fulfill the top-level aircraft requirements (TLARs) and the design mission with the minimum MTOW will be identified, and the benefits in terms of fuel burn reduction will be shown.

2. The Proposed Concept for Structural Battery

In this section, the proposed concept for a structural battery is shown as reported in a schematic concept as illustrated in Fig. 4.

Considering the current state of the art, to maximize the mechanical properties of the final product, carbon fiber with

twill architecture is used to get both the SB anode and the cathode (functionalizing it with $LiFePo_4$). The separator between the electrodes is made of glass fiber, while a solid battery electrolyte should be used to achieve better mechanical performance, and finally, as it regards the binder's material, copper and aluminum foils (respectively, for anode and cathode) are used to avoid galvanic corrosion. The mechanical performance of the proposed material is shown in Table 1, and compared with a conventional carbon fiber-reinforced polymer, the same table also shows the comparison of the electrochemical properties of the considered SB with a SoTA of a conventional battery.

What it can appreciate is that the mass density is higher, indeed while almost all other properties are close to a conventional CFRP material apart from the compression strength and the in-plane shear strength. Those two parameters will drive some assumptions that will be made to select the aircraft structural parts that can serve as structural batteries.

The gravimetric energy density we may achieve is about 28% of the corresponding value of a conventional SoTA battery. By reporting the gravimetric energy density and the elastic modulus of the proposed SB concept on the current 2025 SoTA chart, it can be appreciated that the proposed concept lies in the middle of the nowadays state-of-the-art product in terms of SB, see Fig. 5.
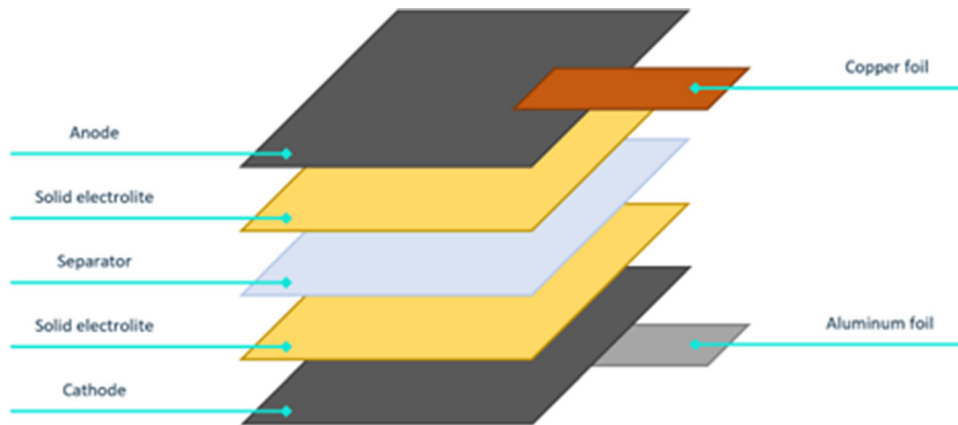
Fig. 4 Schematic of the proposed SB concept

Table 1 Comparison between mechanical and electrochemical properties of the proposed SB

| Property	CFRP	Proposed SB
Mass density	1600 (kg/m^3)	1800 (kg/m^3)
Tensile modulus	70 (GPa)	70 (GPa)
Shear modulus	5.2 (GPa)	5.0 (GPa)
Ultimate tensile strength 0°	600 (MPa)	560 (MPa)
Ultimate compression strength 0°	570 (MPa)	280 (MPa)
Ultimate tensile strength 90°	600 (MPa)	560 (MPa)
Ultimate compression strength 90°	570 (MPa)	280 (MPa)
Ultimate in-plane shear strength	90 (MPa)	52 (MPa)
Ply thickness	0.20 (mm)	0.275 (mm)
Battery type	Conventional	SB
Gravimetric energy density, e_b	265 (Wh/kg)	75 (Wh/kg)
Power density p_b	900 (W/kg)	150 (W/kg)
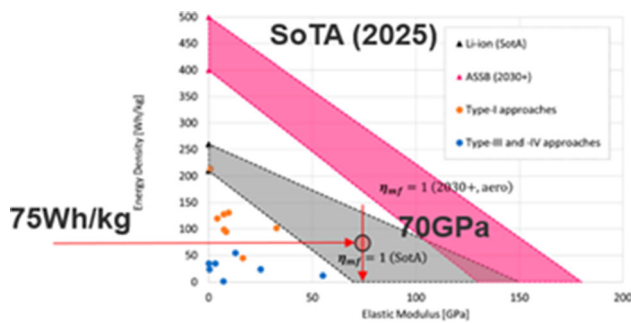
Fig. 5 Gravimetric energy density vs elastic modulus, SoTA and aviation application needs. Adapted from *Aerospace* (Ref 10) under the CC BY 4.0 license

Although these numbers are continuously increasing year by year, in this work, the aim is to show what it can be done in terms of hybridization of a commuter aircraft exploiting the nowadays capabilities of the current available SB technology.

3. The Reference Aircraft

Starting from the inspiring work performed by Riboldi et al. (Ref 15), this paper wants to move a step further into applying the SB enabling technology on a larger scale of aircraft. The selected reference aircraft is like the 11-seater Tecnam P2012 Traveller. This choice is made since the commuter aircraft (from 9 up to 19 seats) is the best platform to which apply enabling technologies dealing with the hybridization process, because of the compatibility between power required and gravimetry energy density of batteries (or structural batteries in this case). Moreover, this aircraft segment would have a larger impact on the aviation community.

Figure 6 shows the three views of the P2012 Traveller; it has a wingspan of 14 m with an overall length of 11.8 m.

The aircraft is an all-metal structure, high-wing, twin-engine, unpressurized, piston aircraft with a fixed tricycle landing gear. The 11-seater P2012 aircraft series has provided airlines, charter, air taxi, fractional and private-owned companies the perfect solution to support a varied yet affordable and complete business plan. The Traveller is feeding the market and replacing hundreds of vintage CS23/FAR23 twin-piston engine-aircraft and single-/twin-turboprop-engine aircraft. The P2012 aircraft series performances allow to operate from big hubs as well as small and remote unprepared airstrips. The maximum take-off weight short-field performance provides takeoff and landing run as low as 564 m (1849 ft) and 365 m (1198 ft), respectively. Cruise speed up to 194 kts and range up to 1760 km (950 NM) are accompanied by excellent fuel economy at any altitude thanks to the turbocharged piston engines which do not suffer the low-level high fuel consumption of turboprops.

4. Hybridization Process of the Reference Aircraft and Results

The hybridization process has been accomplished by means of an in-house developed tool named HEAD (Hybrid Electric Aircraft Design tool). This tool starts from the initial sizing of a conventional aircraft according to the assigned TLARs. The design mission considered is a 600 NM with 100 NM of alternate plus 30 min of loiter, takeoff and landing distances must be lower than 600 m and 400 m, respectively. The workflow adopted to fulfill the initial sizing for a conventional as well as for a hybrid electric aircraft is depicted in Fig. 7. After a preliminary sizing of a conventional platform accomplished by means of statistical data to fulfill the provided TLARs, the real sizing process is started. According to the
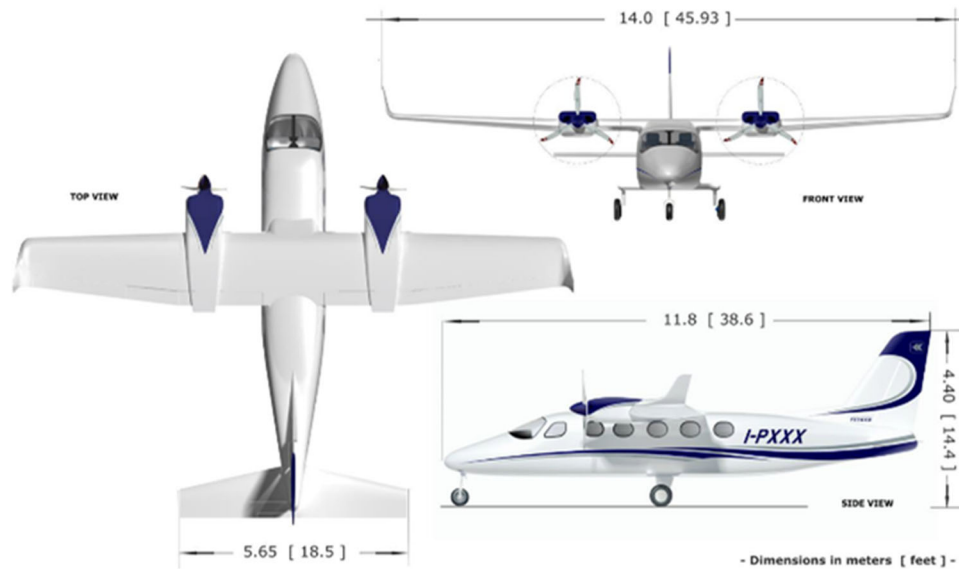
Fig. 6 Three views of the Tecnam P2012 Traveller

provided design mission and all the TLARs, a converged loop is performed about masses, aerodynamics, weight and balance, and mission analysis. The tool is conceived to fulfil the analyses for a conventional as well as full electric or hybrid electric aircraft also including the possibility to implement DEP solutions or different energy storage technologies (conventional batteries, fuel cells, hydrogen tanks, structural batteries, etc.) or even a combination of different energy storage solutions.

The initialization of a conventional aircraft is necessary to estimate the energy and/or the power needed to fulfill the design mission sizing the power plant and in turn the fuel required. Moreover, by deriving the energy profile along the mission, it is possible to understand the key flight phases that could benefit from a hybridization process.

The weight breakdown for the conventional reference platform is summarized in Table 2. The overall MTOW is about 3710 kg (close to the one of the real P2012 Traveller), the estimated fuel needed to fulfil the design mission is about 588 kg, and the structural mass is about 1122.5 kg. The latter has been estimated assuming an all-aluminum alloy structure. Particular attention must be focused on the wing and fuselage structural masses that are equal to 339.3 and 430.5 kg, respectively. The structural elements of the wing and the fuselage will be the vessels of the structural batteries.

The energy history along the mission profile of both design and typical mission profiles is shown in Fig. 8. As it can be appreciated by the breakdown of Table 3, the total energy consumption is about 6700 and 3500 kWh for the design and typical mission, respectively.

To fulfil the hybridization process, there is the need to assess the potential battery mass storable in the structure in the form of a structural battery. The idea behind this work is not to design a new aircraft rather than convert in a retrofitting fashion the existing P2012 conventional aircraft. Thus, the aircraft sizing (in terms of external shape, i.e., wing reference area and fuselage sizes) would not be changed a part for the weight breakdown.

The use of SB in the fuselage does not raise issues bound to stress limits; due to their comparatively limited aerodynamic loading, the specific load resistance of SB is a primary matter of concern when it comes to placing them in the wings.

To estimate the amount of structural mass that can host SB, the same assumption made by Riboldi et al. (Ref 15) has been considered.

To avoid areas of heavy compression loads, wing upper skin panels and the whole empennage surface will be not considered as suitable for hosting SB. According to Riboldi et al. (Ref 20), the lower wing skins panels, the wing leading and trailing edges have been assumed as suitable components to host structural batteries, and the whole fuselage structure has been considered suitable for a 100% structural battery integration (Fig. 9).

Starting from the estimate of critical flight loads according to CS23/FAR23 (Ref 21) and considering the structural properties of the material selected to serve as multifunctional element (see Table 1), the effective structural masses have been estimated and compared with the conventional all-aluminum alloy reference aircraft, as shown in Table 4. By considering wing and fuselage structures made of CFRP plus SB (only for the specified part of the wing and fuselage), the overall structural weight is increased by 10% with respect to the conventional all-aluminum alloy structure.

Once the estimate of the structural masses is available, it is possible to calculate the amount of SB installed onboard the aircraft. The overall SB mass that can be hosted in the selected structural components is about 551 kg which is the sum of a 38% of wing structural mass equipped with SB and 75% of the fuselage structural mass hosting the SB technology. Thus, by assuming the gravimetric energy density of 75 Wh/kg the overall electric energy storable onboard is about 41 kWh. This value is only a very small fraction of the required energy to fulfill the design mission of the selected aircraft. The latter confirms that with the current state of the art of SB it is still not possible to fly such an aircraft in a full electric mode. However, a hybridization strategy can be defined to exploit the potential 41 kW/h of electric energy that can be stored in the aircraft structures. The selected power plant architecture is the one illustrated in Fig. 10.
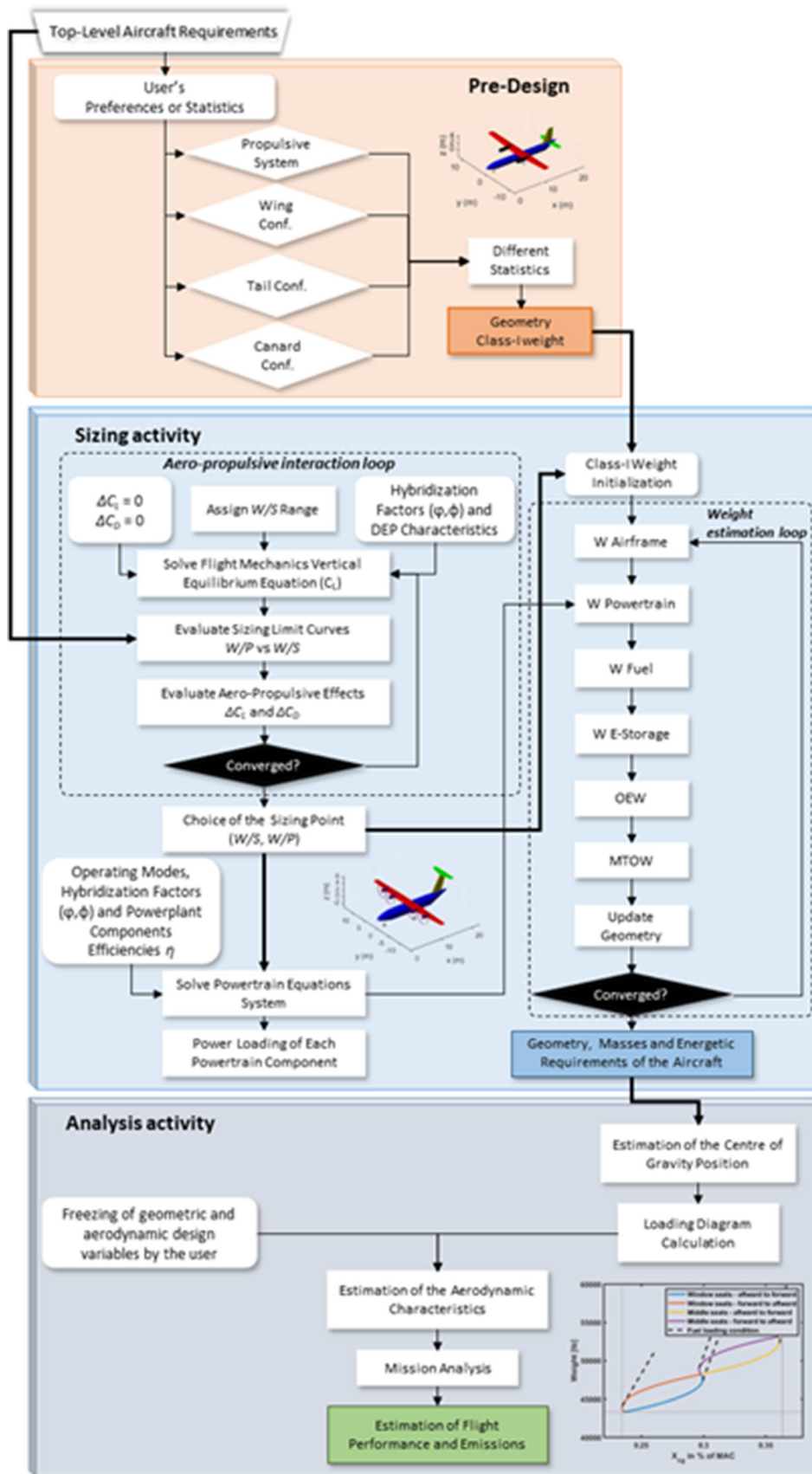
Fig. 7 HEAD workflow: from initialization to mission analysis through converged loop on aircraft weight

In this parallel hybrid architecture, there are two parallel propulsion shafts, powered by combustion (ICE) and electric sources (motor/generator), which are mechanically coupled. Battery-powered EM and ICE shafts are both coupled to a shaft that drives the propeller, so either or both can provide propulsion. This hybrid architecture may also allow charging the batteries when the ICE drives the propeller and the EM through the coupling. In this case, the EM operates as an electric generator. Differently from series and series–parallel, there is no electric generator on the ICE's shaft, and machines may be sized smaller since the propelling power is provided by both, with corresponding weight reduction (Ref 22). The disadvantages of this configuration are the extra mass by the mechanical coupling and the need for a more sophisticated propulsion control system. Additionally, the ICE's operation may be less optimal in different flight stages than in a series configuration since it is involved in thrust generation (Ref 23).

The overall hybridization factor is fixed by the amount of the battery mass that is possible to install onboard; in this exercise, a 17% of "gross" hybridization factor is available. The electric power will be used only for the two key phases of take-off and climb, where the power demand on the ICE can be reduced by exploiting the available electric energy. The latter will help into scaling the maximum power of the ICE leading to a lighter ICE power plant and lower fuel consumption. The splitting strategy between thermal and electrical power is defined by means of the power supply ratios being the ration between the electrical power over the total power needed for a specific flight phase. These parameters can be customized phase by phase and can be different according to the assigned mission profile in order to exploit the maximum potential of the hybrid electric powertrain toward the minimization of the fuel burn and electric energy demand (i.e., battery mass minimization).

The best strategy in splitting the total amount of electric and thermal energy has been found being 8% for the take-off and 4% in climb when the design mission of 600 NM is considered and 8 and 5.8% for take-off and climb, respectively, in the case of the typical mission. This translates into 22.5% net power
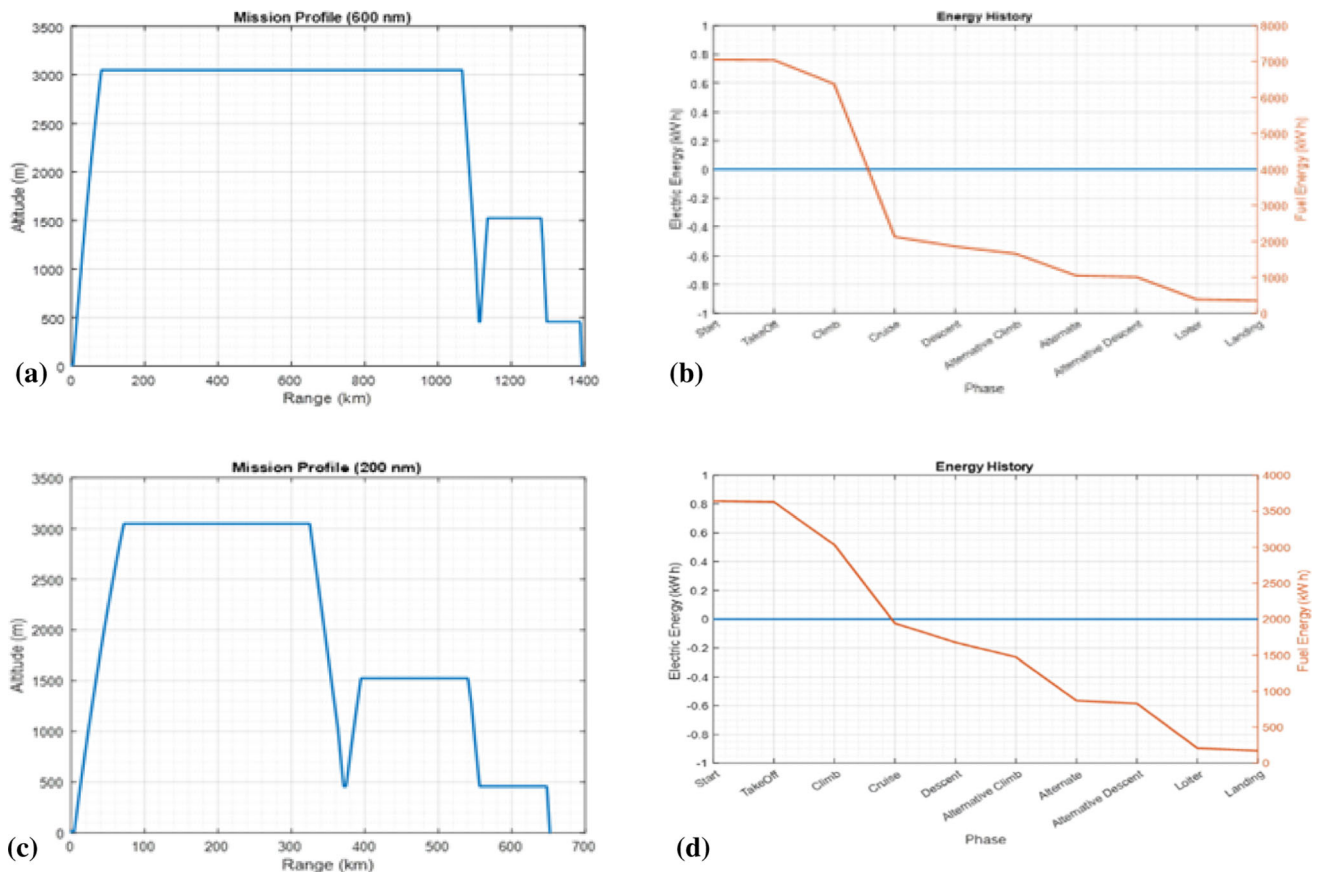
Table 2 P2012 conventional aircraft weight breakdown

Component	Weight, kg
Wing	339.3
Horizontal tail	60.5
Vertical tail	29.1
Fuselage	430.5
Control surfaces	60.1
Main undercarriage	90.2
Nose undercarriage	21.8
Nacelles	91.0
Dry engines	587.8
Propellers	87.7
Structure	1122.5
Power plant	769.6
Design fuel	588
Maximum takeoff mass	3709.3

(a)

(b)

(c)

(d)

Fig. 8 Tecnam P2012 Traveller energy history along the design mission of 600 NM (a) and typical mission of 200 NM (b)

Table 3 Tecnam P2012 Traveller-like aircraft mission profile energy histories

Phase	Time, min	Range, km	Altitude, m	Fuel burned, kg	Fuel energy consumed, kWh
Design mission					
Takeoff	0.51	0.659	15	1.20	14.41
Climb	14.57	81.219	3048	56.21	674.57
Cruise	184.25	983.942	3048	350.89	4210.67
Descent	12.14	45.955	457	22.05	264.65
Alternative climb	4.48	23.773	1524	17.17	206.06
Alternate	26.88	145.609	1524	50.15	601.82
Alternative descent	5.00	15.793	457	3.29	39.44
Loiter	30.00	…	457	51.79	621.47
Descent to landing	1.58	4.186	15	2.94	35.29
Landing	0.34	0.562	0	0.01	0.16
Typical mission					
Phase	Time (min)	Range (km)	Altitude (m)	Fuel Burned (kg)	Fuel Energy Consumed (kWh)
Takeoff	0.47	0.615	15	1.11	13.33
Climb	12.77	71.173	3048	49.29	591.43
Cruise	47.38	253.126	3048	91.07	1092.81
Descent	12.14	46.023	457	22.06	264.70
Alternative climb	4.45	23.622	1524	17.06	204.74
Alternate	26.89	145.700	1524	50.21	602.50
Alternative descent	5.00	15.854	457	3.29	39.46
Loiter	30.00	…	457	51.84	622.13
Descent to landing	1.58	4.187	15	2.94	35.30
Landing	0.34	0.563	0	0.01	0.16

Table 4 P2012 masses breakdown: conventional vs. hybrid electric with SB

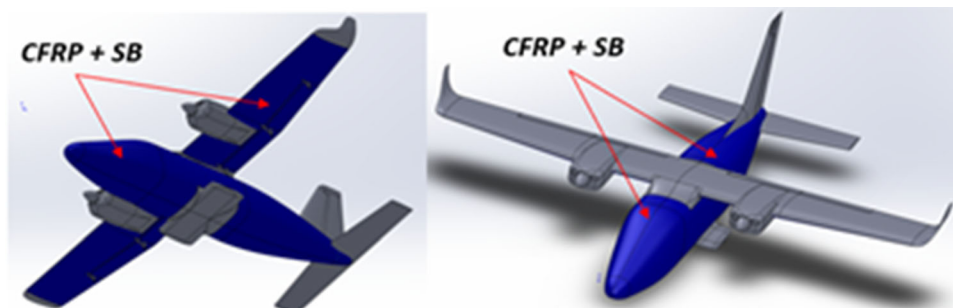| Component	Conventional all-aluminum alloy, kg	CFRP + SB, kg
Wing	339.3	346.1
Horizontal tail*	60.5	60.5
Vertical tail*	29.1	29.1
Fuselage	430.5	559.6
Structure	1122.5	1240.7
Power plant	769.6	630.7
Batteries	…	551.0

*Still all-aluminum alloy structure.

Fig. 9 Tecnam P2012 Traveller selected structural parts to host SB

delivered by the batteries at take-off and 12.2% in climb, for the design mission, and 22.5 and 17.0% for the typical mission, for take-off and climb, respectively.

Since the hybrid electric configuration is heavier than the reference one, 22.5% of the electric power is the minimum electric power needed to reach the same take-off performance. Being the battery mass fixed, all the residual electric energy that can be spent (assuming a residual state of charge of the batteries of 20%) is homogeneously consumed for the climb phase.

The energy histories of the hybrid electric solution are shown in Fig. 11 for both the considered mission profiles.

The selected hybrid electric configuration leads to a fuel saving of about 18% on the design mission and 20% for the typical mission with respect to the conventional P2012-like aircraft (353 kg HEA vs. 433 kg of the conventional and 132 kg HEA vs. 166 kg of the conventional aircraft).

In the HEA configuration, the required thermal power has been reduced thanks to the electric power from the batteries. This leads to a lower demand in terms of fuel mass, although the overall structural mass of the HEA solution has been increased by 10%.

Fig. 10 Schematic of hybrid parallel power train for the hybridization of a P2012-like 11-seater aircraft

5. Conclusions

This paper assessed a preliminary evaluation of the potential benefits of installing a SB concept underdevelopment into an EU research project on a 11-seater aircraft like the P2012 Traveller. A potential of 38 and 75% of wing and fuselage structural mass hosting the SB technology has been estimated. According to the current state-of-the-art gravimetric energy density of SB of 75 Wh/kg and the estimated amount of available structural battery mass, it has been demonstrated that a full electric solution is not viable. However, SB is still an intriguing enabling technology for the hybridization of such an aircraft. By adopting a hybrid parallel power train in which the electric energy is used to augment the ICE during the take-off and climb phase, a potential of 18-20% of the fuel burn has been achieved. Deeper investigations about the structural sizing of wing and in particular for the fuselage are needed for the most reliable estimate of the SB mass available on the aircraft. Structural battery is a promising enabling technology toward near-zero-emission aircraft. But by the materials point of view, the SB cell net energy density needs to be increased to fit aeronautical needs. SB integration concepts for aeronautic applications need to be developed to optimize the position, shape and distribution of SB cells within the structure to minimizing the onset of damage. Moreover, a reliable electrical wiring and connections will need to be integrated into the structure. Finally, a comprehensive understanding of the influence of SB integration on mechanical properties needs to be assessed at both a material and aeronautic structure levels by developing characterization and testing methods to assess the multifunctional performance of aeronautic structural battery composite elements in complex load cases.
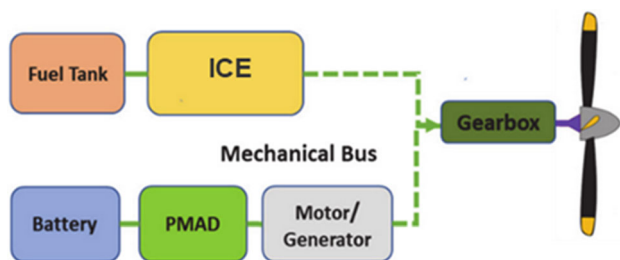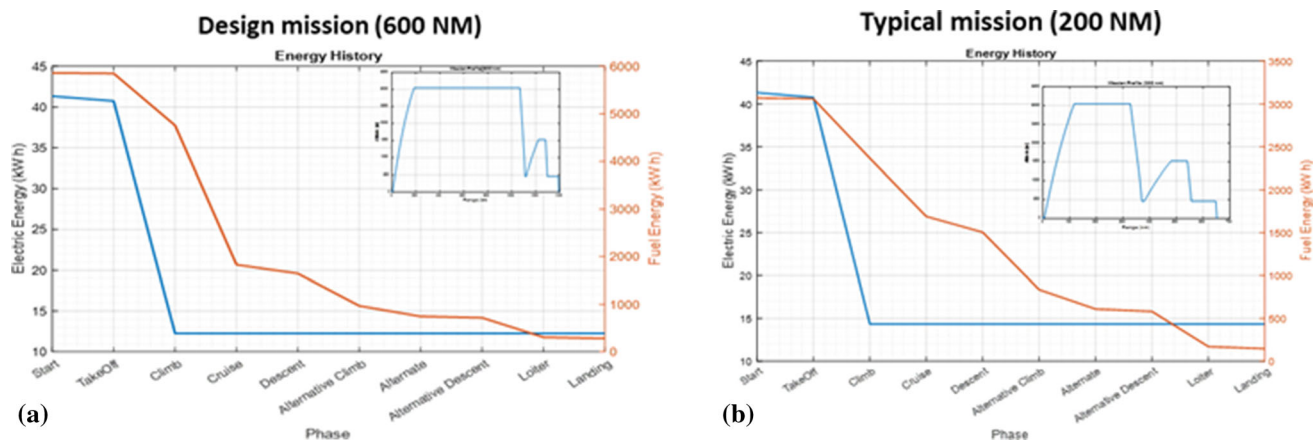
Fig. 11 Hybrid electric P2012-like aircraft: energy profile for design (a) and typical (b) missions

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