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TECHNOLOGY ROADMAP AND CONCEPTUAL DESIGN OF HYBRID AND ELECTRIC CONFIGURATIONS IN THE COMMUTER CLASS

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Abstract

The growing sensitivity to the problem of sustainability requires a rethinking of how aviation is typically conceived by modern society. The aim of the research today must be to analyze the feasibility of disruptive solutions, which drastically reduce consumption and make it possible to meet the growing demand in the commercial aviation sector. The current level of technological maturity does not allow direct implementation on large commercial aircraft, which are responsible for most of the emissions from aviation. In this context, the Clean Sky 2 ELICA project aims to trace a technological roadmap towards green aviation, using the Small Air Transport as a test bed. Two different 19-seat commuter aircraft are presented in this work. The first one, with entry into service in 2025, presents a hybrid-electric architecture with batteries. The second configuration, with entry into service in 2035, is entirely propelled with hydrogen fuel cells, allowing the direct emissions of carbon and nitrogen oxides to be totally eliminated. Both configurations benefit from distributed electric propulsion.

Keywords: Hybrid-electric aircraft, Hydrogen-based propulsion, Preliminary aircraft design, Technology roadmap, Commuter aircraft.

1. Introduction

1.1 Global context

Despite aviation's contribution to global emissions is only about 2%, the aircraft is the most unsustainable means of transport currently available [1], also due to the rapid expansion of the sector [2]. On the other hand, the increasing perception of the environmental problem drives new demands of a more efficient use and management of existing technologies and the introduction of disruptive solutions specifically aimed at sustainability. Nowadays, 90% of aviation emissions are due to commercial aircraft carrying more than 100 passengers [3, 4]. However, reduction of carbon and noise emissions from general aviation and commuter airline can potentially impact global emissions generated by other means of transport with the same operative range. From this perspective, green door-to-door flights are a strategic objective for the market segment covered by Small Air Transports (SAT). From another perspective, SAT aircraft represent the necessary intermediate step to test the most promising technologies. The present-day technological levels of electronic components are not compatible with their implementation on more polluting, larger aircraft categories. Therefore, emerging technologies need to be applied first to smaller platforms, which will serve as a test bed to become familiar with their aeronautical application.

1.2 Hybrid-electric propulsion

Hybrid-electric propulsion is one of the most promising technological innovations, promising reduced direct emissions and increased propulsive efficiency [5]. It represents the potential solution to the energy transition problem. The radical replacement of aviation fuel, for instance, with hydrogen-based systems would involve a sudden and unrealistic adaptation of on-ground infrastructures. From the aircraft designer's point of view, when imagining a concept with an upcoming entry into service, the commercial attractiveness of the product must play a leading role, including aspects such as operational capabilities and constraints (i.e., airport needed infrastructures). This represents a driving factor in the aircraft design process, which must be environmentally friendly as well as economically competitive. As a matter of fact, electric propulsion actually opens to new market opportunities thanks to lower gaseous and acoustic emissions that make it ideal for use in an urban context. In this sense, SAT aircraft have the opportunity to exploit their maximum potential in synergy with the use of electric propulsion. Aiming for an ideal use in an urban context, lower gaseous and acoustic emissions and a reduced door-to-door time are essential objectives, all achievable through the use of hybrid-electric architectures such as Distributed Electric Propulsion (DEP) [6]. The related aero-propulsion benefits have the potential to improve ground performance, in particular to reduce take-off distance, thus allowing the aircraft to operate in most European airports and to unlock new routes. However, this is not sufficient to guarantee market attractiveness. High number of passengers and long range remain the most sought-after characteristics, therefore the transition to large commercial aircraft is inevitable.

1.3 Hydrogen-based propulsion

In this context, hydrogen is also a promising alternative to jet fuel because of its impressive specific energy (about 33 kWh/kg in terms of lower heating value). Hydrogen eliminates CO_2 emissions in flight, and it can be produced carbon-free. According to research conducted by the European Commission, H_2 combustion could reduce climate impact in flight by up to 75%, and fuel-cell propulsion by 75 to 90% with no direct NO_x emissions [7]. The only emissions produced by the chemical reaction with oxygen are water and heat. Moreover, hydrogen is stable, uniformly available on Earth, and it can be produced by electrolysis of water. As a drawback, it is a flammable and explosive gas so that it must be carefully stored and transported in special containers. In the context of hydrogen storage on aircraft, several problems need to be addressed. First, low density of pure hydrogen at ambient conditions involves the need for it to be compressed or liquefied (LH2) in order to safely store a significant amount [8]. The extraction of electricity from hydrogen can be efficiently achieved by means of continuously supplied fuel cells, power conversion units which are sized based on the power requirement. In particular, Proton Exchange Membrane Fuel Cells (PEMs or PEMFCs) are more promising for a non-stationary installation, presenting water vapor as the only waste product, limited start-up times and lower operating temperatures, which however makes cooling particularly challenging. Fuel cells will be ideally able to completely replace thermal engines, eliminating the main forms of pollutant emission. Before this becomes possible, the specific power levels need to increase to be compatible with the aeronautical needs. Moreover, airworthiness codes must be ready to allow the certification of these systems, guaranteeing operational safety.

1.4 The ELICA project

The project named ELectric Innovative Commuter Aircraft (ELICA)[1] is funded in the framework of Clean Sky 2, under the thematic topic titled Conceptual Design of a 19-passenger Commuter Aircraft with near-zero emissions. The ambition of this project is to design Small Air Transports with near-zero emissions, aligning with the environmental expectations of the European Commission manifested in Flightpath 2050 [9]. A complete aircraft design chain, named HEAD (Hybrid-Electric Aircraft Designer) has been employed for the purposes of the project. The tool has been completely developed in MATLAB by the researchers University of Naples “Federico II”. The implemented design process collects and adapts methodologies for the design of electric or hybrid-electric aircraft [5, 6, 10, 11, 12] and integrates them into a complete and multidisciplinary design chain, also including the modelling of the powertrain architecture at aircraft level and some fault-tolerance considerations. The collaboration with industrial partners has allowed the identification of enabling technologies, scenario analyses and trade-off studies, which have resulted in a technology roadmap towards the aviation of the future. In particular, two time horizons have been considered in the project: a short-term scenario, having 2025 as reference year, and a long-term scenario with 2035 year of entry into service. First, pre-design and sizing activity have been performed starting from a reference commuter aircraft in the same category, with respect to certification constraints and top-level design requirements. The optimization of the hybrid concepts has been performed based on the mission analysis, consisting in the simulation of the flight mission. The goal is the design of platforms with carbon emissions, nitrogen oxides and noise reduced by at least 50% compared to the reference platform.

[1] ELICA project website: https://www.elica-cleansky-project.eu/

1.5 Paper outline

The aim of the present work is to introduce two different aircraft concepts in the 19-seat commuter category, with entry into service (EIS) years 2025 and 2035. The concepts were conceived in the context of the ELICA (ELectric Innovative Commuter Aircraft) project and include a careful evaluation of the masses of electrical and mechanical components, aiming for high technology readiness level (TRL). However, the results reported in this work should be considered as preliminary, as they represent the progress of the project at the end of its second year. Section 2 provides an overview of the preliminary technological assumptions. In particular, subsection 2.1 shows the design requirements of the new platform, derived from a detailed market analysis conducted within the project. In subsection 2.2, a technology roadmap is outlined, identifying two different philosophies of electrification that land on two different commuter aircraft concepts. In subsection 2.3, the methodology employed for aircraft design is briefly presented to the reader. Concepts are designed based on the simulated analysis of the flight mission, in order to correctly assess the energy requirements, consumption, and emissions. Section 3 illustrates the main characteristics of a hybrid-electric aircraft concept with lithium-ion batteries, with assumed EIS year 2025. The restriction about the maximum take-off weight imposed by the CS-23 [13] represents an essential limitation to the level of hybridization actually achievable for this category of aircraft. If the certification authorities do not modify this limitation, the only way to substantially reduce the environmental impact will be the use of a propulsion entirely based on hydrogen. Therefore, section 4 presents a concept entirely based on the use of PEM fuel cells, with EIS year 2035. Both concepts make use of distributed electric propulsion in order to improve take-off performance and ensure a competitive take-off performance thanks to the increase in lift capabilities. Finally, section 5 draw the conclusions of the work.

2. Methodologies and Assumptions

2.1 Top-level aircraft requirements

A market analysis carried out in the framework of the ELICA project has identified some top-level aircraft requirements (TLARs) to drive the design toward a competitive aircraft. The requirements formed the basis of the design process through the definition of a reference mission, addressed as design mission. The simulation of the design mission and the verification of its feasibility in compliance with the certification constraints leads to convergence on the desired solution. However, a typical mission of 200 nm has been considered as the most important for usual aircraft operation and for the evaluation of environmental impact of the proposed solution. Indeed, the goal for the present study is the reduction of fuel consumption and relative emissions for the typical mission. All most relevant mission requirements are shown in Table 1.

Table 1 - Top-level aircraft requirements of the ELICA project.

Parameter	Value	Unit
Maximum Take-Off Mass	19000	lbf
Number of passengers	19	-
Design range	≥ 500	nm
Typical range	200	nm
Take-off field length	≤ 1000	m
Ceiling - One Enine Inoperative (OEI)	≥10000	ft
Ceiling – All Engine Operative (AEO)	≥20000	ft
Cruise altitude	10000	ft
Cruise Mach number	0.32	-
Alternate altitude	5000	ft
Alternate range	100	nm
Alternate Mach number	0.28	-
Holding time	30	min
Holding altitude	1500	ft
Holding Mach number	0.22	-
Climb speed	170	kts
Descent speed	120	kts

The maximum payload has been fixed through statistics at 2000 kg and a design payload of 1767 kg (93 kg per passenger) has been considered. The major limitation on the hybridization of an aircraft of this category is represented by the maximum take-off weight (MTOW), as detailed in the next subsection.

2.2 Technology Roadmap

In the last decade, several research projects have been aimed at the hybridization of aircraft by means of electric storage devices as an alternative energy source, to replace fossil fuels partially or totally. Although the efficiency of electric components is generally above 90%, while the efficiencies of modern gas turbines is around 30%, this is still not sufficient to obtain the desired reduction in emissions [10]. In fact, when compared to jet fuel in terms of energy stored, the current battery technology loses its attraction. By the year 2035, the specific energy of batteries is expected to settle between 250 and 350 Wh/kg at cell level, even lower at the pack level, values that are far from the specific energy of jet fuel, around 12 kWh/kg. In this context, hydrogen is a more promising alternative to jet fuel because of its enormous amount of specific energy and the significant reduction in polluting emissions.

The most promising estimates about today's specific power levels of a PEMFC are around 1.6 kW/kg, related to applications in the automotive sector [14]. Kadyk et al. [15] estimate that this value could rise to 8 kW/kg in the future. Considering that the specific power of the gasturbines is generally around 4 kW/kg, it would be sufficient to reach at least this value at system level in order to facilitate a complete replacement of conventional propulsion systems. Since 2035 is a relatively close target year, the less optimistic value of 2.5 kW/kg has been assumed for the purposes of the ELICA project. This hypothesis on the technological level supports the needs of the project, which must reconcile the desired drastic reduction in emissions in compliance with regulatory restrictions. Furthermore, considering the higher specific energy value of hydrogen compared to that of jet fuel, it is possible to compensate for the remaining weight penalty by reducing the maximum weight to be carried on board. The chosen parameter does not include the weights of thermal management system, fuel system components and cryogenic hydrogen tank, estimated separately at this stage of the project. In summary, the main technology parameters assumed are reported in Table 2.

Table 2 – Technology levels of batteries and fuel cells assumed for years 2025 and 2035.

Parameter	2025	2035
Battery Specific Energy (Wh/kg)	270.0	333.0
Battery Specific Power (W/kg)	500.0	500.0
Fuel Cell Specific Power (W/kg)	1600.0	2500.0

The transition to a clean aviation by 2035 should pass through hybrid-electric concepts powered by both jet-fuel and batteries in 2025 to land on a concept fully powered with hydrogen (see Figure 1). This will be an inevitable conclusion if the technological levels are confirmed to align with the expectations, and if the goal will remain that of a near-zero emissions aviation.

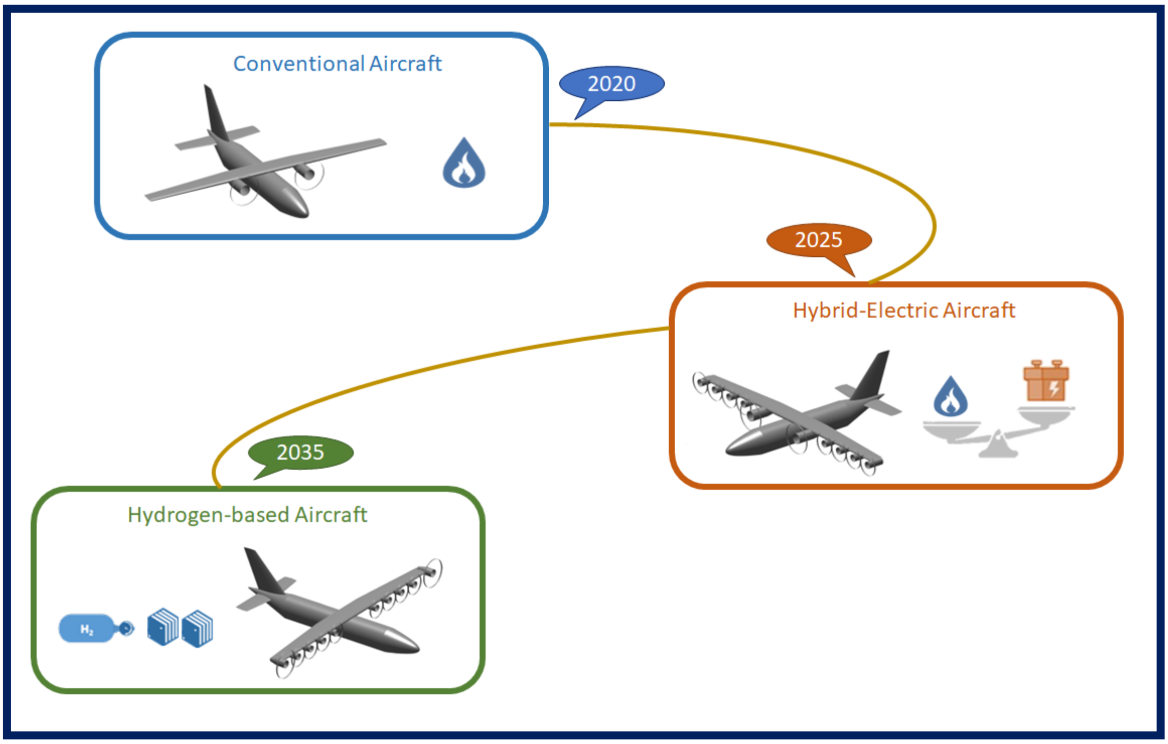

Figure 1 - Roadmap towards a green aviation (2020-2035).

2.3 Aircraft design chain

The design chain employed has already been discussed in previous works by the same authors [5, 11, 16, 17]. The conceptual design process aims to choose a single aircraft configuration, which suits the TLARs and complies with all aviation regulations and requirements. Such investigation may be included in an optimization loop targeting, for instance, minimum weight penalties, emissions, and direct operating cost. The design workflow is usually composed of three main phases: pre-design, sizing, and analysis. The pre-design process moves from the statistical definition of the main geometrical characteristics depending on TLARs. This is useful for initializing the solution when tackling the design of an entirely new aircraft, forming the basis for the exploration of the design space. The sizing activity starts after fixing the characteristics of the propulsive architecture in terms of geometry, hybridization parameters, and operating modes [5, 11, 16]. The introduction of the aero-propulsive effects (e.g., distributed electric propulsion and tip-mounted propellers) can enlarge the design space leading to new opportunities [10, 18, 19]. However, the environmental impact of all-electric or hybrid-electric propulsion is often directly related to energy saving percentages along the operative life. In this sense, an accurate evaluation of the mission requirements in terms of power and energy needed would be preferrable for the scope, but it is generally not possible during the sizing phase, which is subject to excessive uncertainty. In the following, the reader will be shown two different innovative configurations designed and refined through a mission analysis process (Figure 2) [17]. During the flight mission simulation, energetic requirements and flight performance are assessed, which is necessary to verify the compliance with TLARs and regulation constraints, to refine aerodynamic and mass characteristics, and to optimize the aircraft in an iterative process. The contributions of the industrial partners within the project have allowed to move research towards a higher technology readiness level (TRL). Response surfaces providing information on the weight and efficiency of the powertrain components made it possible to consider the realistic effects of flight conditions (Mach number, altitude and throttle setting) on the performance of the aircraft. At the design level, this is affecting the sizing of the components and the resulting aircraft mass breakdown. More important, information on the fuel flow emitted by the propulsion system is essential to correctly assess the consumption and environmental advantage of the solution. Since the simulation of the effect of altitude and flight Mach number on the PEMFC behavior has not been sufficiently investigated, a semiempirical model has been used to reconstruct the efficiency and fuel flow of the system, based on a preliminary design of the centrifugal compressor and air intake.

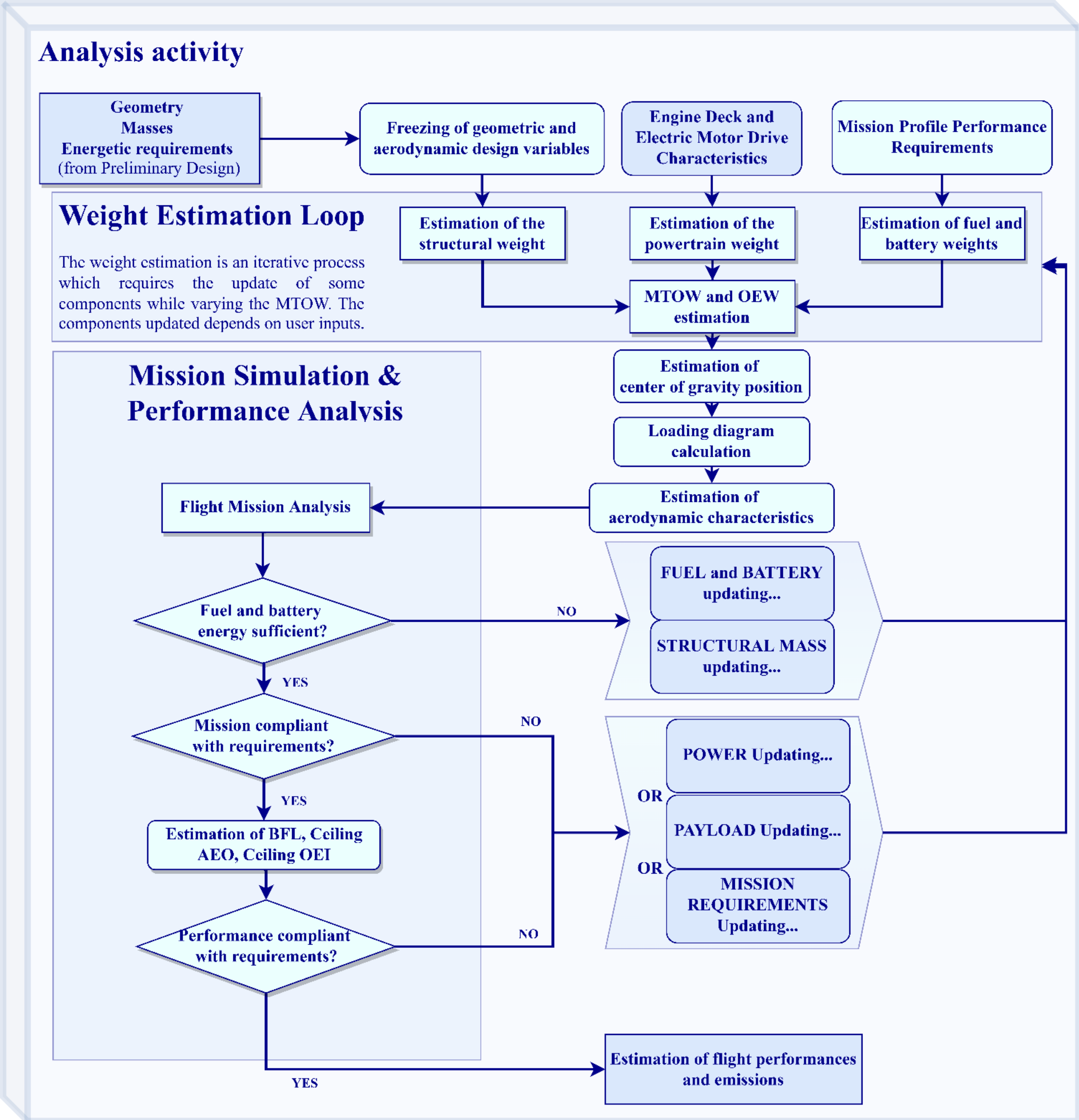

Figure 2 - Workflow of the analysis module of in-house software HEAD.

3. Hybrid-Electric Concept (EIS 2025)

3.1 Concept Description

Figure 3 shows the configuration analyzed with entry into service year 2025. The configuration has 8 distributed electric propellers, which allows a reduction of the wing surface equal to 20% compared to the reference baseline. A positive trend in terms of aerodynamic benefit was found when increasing the number of distributed propellers [11]. However, the number of distributed propellers was limited in order to contain the expected costs of production and maintenance. When it comes to electric aircraft, it is important to properly define the propulsive architecture. At the conceptual design level this need must be combined with an adequate level of abstraction in order to generalize the design chain and make it flexible to handle different configurations, by varying the interconnections between the individual components and the number of connected elements. In case of two distinct power sources (namely, carbon-based fuel and electric storage device), the scheme represented in Figure

4 can be used as a general model [5].

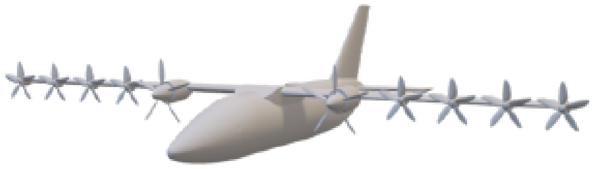

Figure 3 – Hybrid-electric concept with distributed electric propulsion (EIS 2025).

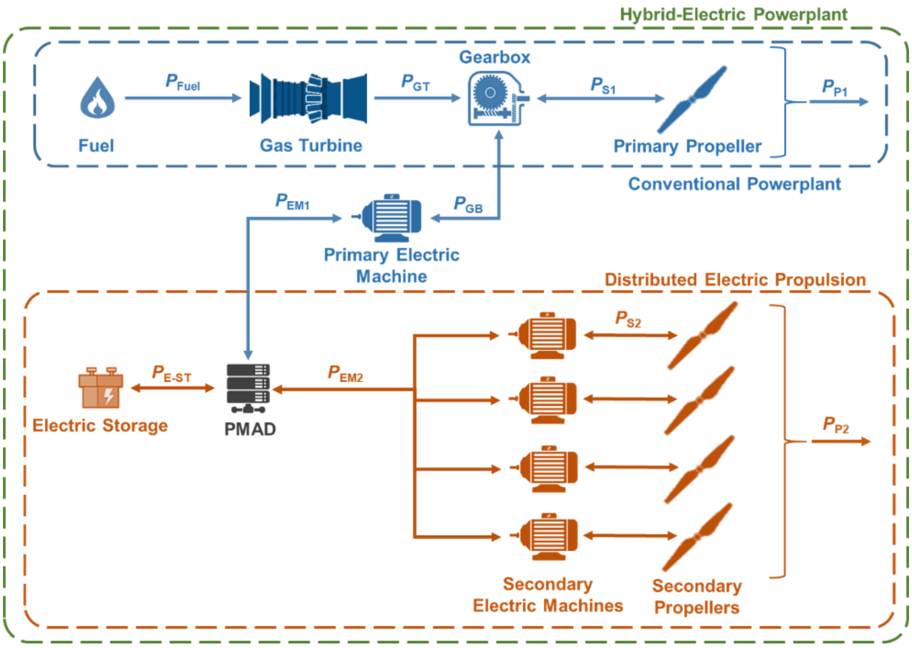

Figure 4 – Hybrid-electric powerplant architecture model.

The total shaft power is distributed on two different propulsive lines: the primary propulsive line, colored blue in the figure, and the secondary propulsive line, colored red. In this way it is possible to describe separately the main propulsive system, responsible for producing thrust during cruise, and the secondary system useful to improve take-off and climb performance. In fact, the secondary line is generally representative of a set of high-speed propellers distributed along the span (as in the case of DEP) and is potentially responsible for an increase in wing's lifting capability. The effects of propulsive interaction, in terms of increase in lift and drag coefficients of the wing, are included based on the method reported by Ref. [19]. In Figure 4, P_{EM1} represents the power exchanged by the primary electric machine (working as a motor), P_{GB} is the power entering the gearbox, and P_{EM2} is the power exchanged by the electric motor of the secondary propulsive line. P_{S1} and P_{S2} represent the total shaft powers, respectively provided by the primary and secondary line. The power distribution is managed by a Power Management And Distribution (PMAD) system, which constitutes the node where the energy is split between the two lines. In this regard, an important design parameter is the shaft power ratio, defined in Eq. (1), which represents the ratio between the power delivered to the shafts of the secondary propulsive line and the total shaft power (see also Ref. [5, 6, 10, 11]).

$$\varphi = \frac{P_{S2}}{P_{S1} + P_{S2}} \tag{1}$$

The hybridization level is also measured with the so-called supplied power ratio, defined in Eq. (2), which is the ratio of power provided by the electric storage, P_{E-ST}, with respect to the total power supplied to the system, where P_{Fuel} is the power associated with the consumed fuel [5, 6, 10, 11].

$$\phi = \frac{P_{E-ST}}{P_{E-ST} + P_{Fuel}} \tag{2}$$

The sizing activity has been carried out considering three design variables: number of distributed propellers, shaft power ratio, and supplied power ratio. Furthermore, the shaft power ratio has been limited to a maximum of 0.7 (at take-off) to avoid oversizing the secondary line, not used during the cruise. Figure 5 and Figure 6 show more details about the power distribution strategy in the take-off and cruise configurations. A serial-parallel architecture was selected in order to be able to split the power on two separated propulsive lines. In this way it was possible to take advantage of the aero-propulsive interactions benefits coming from DEP at take-off, but to be able to have a higher efficiency in cruise, when the architecture is used as parallel.

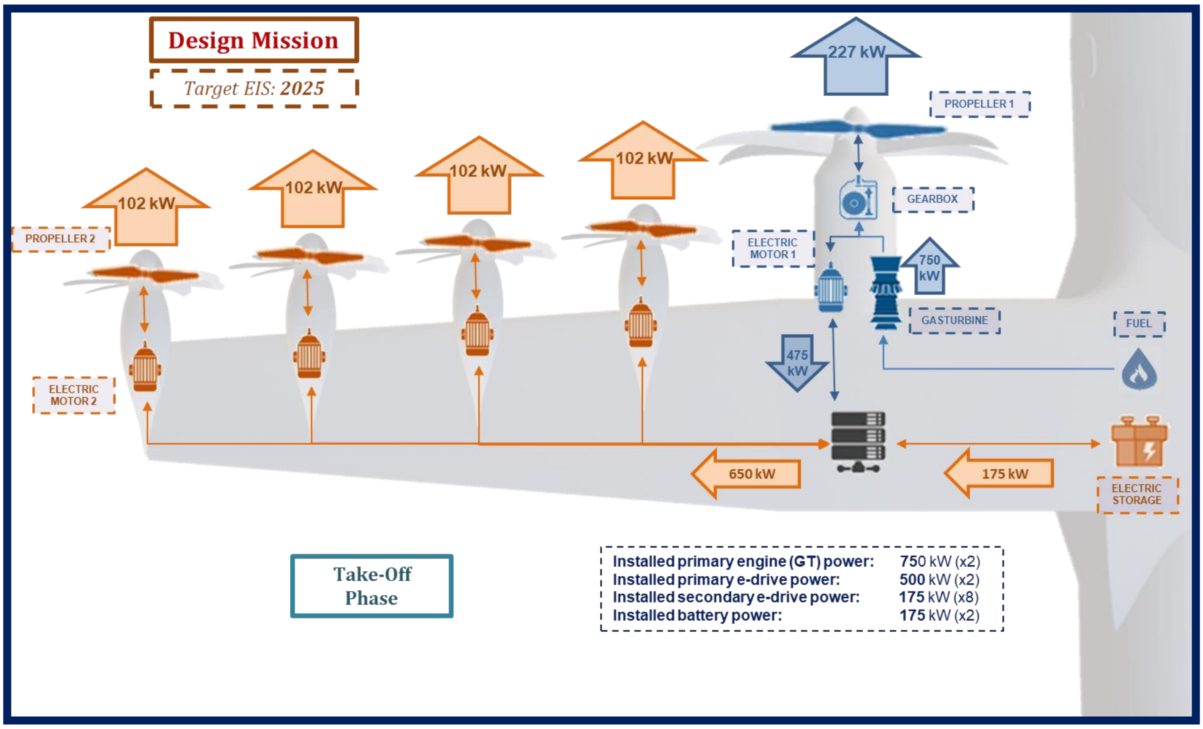

Figure 5 - Design distribution of powers at take-off (EIS 2025).

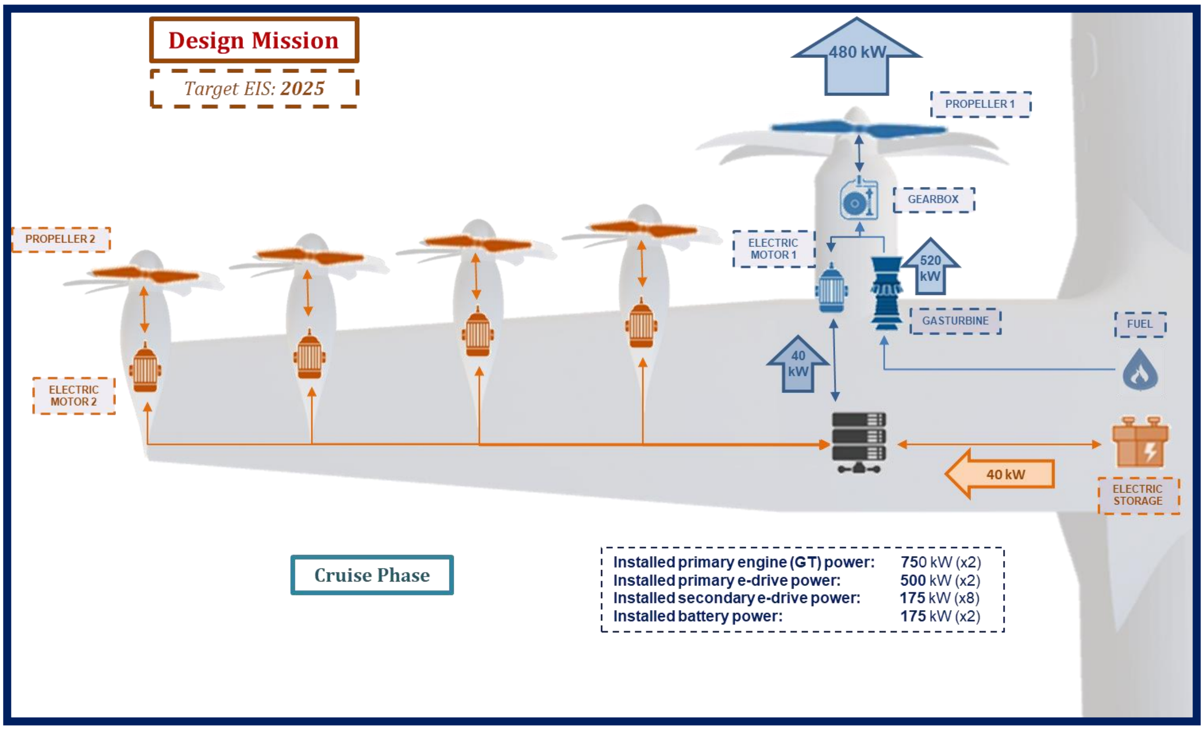

Figure 6 – Design distribution of powers at cruise (EIS 2025).

Table 3 and Table 4 reports the main mass characteristics of the aircraft. The data provided by industrial partners have supported a reliable assessment of the powertrain masses. It is worth noting here, that it has been necessary to limit the battery mass to 700 kg, due to reaching the certification limit of 19000 lb (8616 kg) [13]. This mass is too small to allow for a significant reduction in fuel consumption and emissions. Since the authors' goal was to provide a near-zero emissions solution, the reason for the radical change in configuration, explored later in section 4, lies in this result.

Table 3 - Mass breakdown (EIS 2025).

	Value (kg)
Airframe	2350.0
Powertrain (incl. Batteries)	2555.0
Systems	559.0
Payload	1767.0
Maximum Fuel	615.0
Operating Empty Mass	6231.0
Maximum Zero Fuel Mass	7998.0
Maximum Take Off Mass	8613.0

Table 4 – Detailed powerplant mass breakdown (EIS 2025).

	Value (kg)
Engine Group	459.0
Battery Mass	700.0
Primary Electric Machines	59.0
Secondary Electric Machines	244.0
Primary Propellers	214.0
Secondary Propellers	430.0
Thermal Management System	198.0
Power Electronics	103.0
Cables	148.0
Powertrain Mass	2555.0

3.2 Mission Analysis

The values of hybridization parameters are reported in Table 5 for each flight phase of the design mission and the typical mission.

Table 6 and Table 7 report the analysis of the energy requirements for the design and the typical mission, respectively.

Table 5 - Hybridization factors for each phase of both the design and the typical mission (EIS 2025).

Hybridization parameters	Design Mission	Typical Mission
	Shaft power ratios	
ϕ - Take-Off	0.70	0.70
ϕ – Climb	0.30	0.30
ϕ – Cruise	0.00	0.00
ϕ – Descent	0.00	0.00
ϕ – Climb To Alternate	0.00	0.00
ϕ – Alternate	0.00	0.00
ϕ – Descent from Alternate	0.00	0.00
ϕ – Loiter	0.00	0.00
ϕ – Descent To Landing	0.00	0.00
ϕ – Landing	0.70	0.70
	Supplied power ratios	
ϕ - Take-Off	0.07	0.07
ϕ – Climb	0.07	0.07
ϕ – Cruise	0.03	0.09
ϕ – Descent	0.00	0.00

ϕ – Climb To Alternate	0.00	0.00
ϕ – Alternate	0.00	0.00
ϕ – Descent from Alternate	0.00	0.00
ϕ – Loiter	0.00	0.00
ϕ – Descent To Landing	0.00	0.00
ϕ – Landing	0.00	0.00

Table 6 - Design mission analysis (EIS 2025).

	Time (min)	Range (km)	Altitude (m)	Fuel (kg)	Battery Energy (kWh)	Total Energy (kWh)
Take-Off	0.3	0.5	0 - 15	1.8	1.7	23.7
Climb	6.2	34.7	15 - 3048	31.5	28.3	405.6
Cruise	134.0	837.2	3048	372.0	115.2	4579.0
Descent	9.3	54.1	3048 - 457	14.2	0.0	170.8
Climb to Alternate	2.2	12.3	457 - 1524	11.9	0.0	142.5
Alternate	26.2	147.3	1524	70.8	0.0	850.1
Descent from Alternate	4.7	25.6	1524 - 457	7.8	0.0	93.4
Loiter	30.0	134.4	457	67.5	0.0	809.9
Descent to Landing	1.8	6.3	457 - 15	3.1	0.0	37.5
Landing	0.4	0.8	15 - 0	0.5	0.0	6.5
Total	215.1	1253.2	-	581.1	145.2	7118.9

Table 7 - Typical mission analysis (EIS 2025).

	Time (min)	Range (km)	Altitude (m)	Fuel (kg)	Battery Energy (kWh)	Total Energy (kWh)
Take-Off	0.3	0.5	0 - 15	1.8	1.6	23.0
Climb	5.9	33.1	15 - 3048	30.0	27.0	387.0
Cruise	45.4	283.2	3048	108.6	130.4	1433.9
Descent	9.3	54.1	3048 - 457	14.2	0.0	170.7
Climb to Alternate	2.2	12.3	457 - 1524	11.8	0.0	142.0
Alternate	26.2	147.3	1524	70.8	0.0	849.6
Descent from Alternate	4.7	25.6	1524 - 457	7.8	0.0	93.3
Loiter	30.0	134.4	457	67.4	0.0	808.9
Descent to Landing	1.8	6.3	457 - 15	3.1	0.0	37.5
Landing	0.4	0.8	15 - 0	0.5	0.0	6.5
Total	126.2	697.6	-	316.0	159.0	3952.4

In this way, the total fuel consumption was estimated through the simulation of the design and typical missions. Table 8 shows the values of block fuel and block energy, which include only the contributions of the nominal mission, excluding reserves. The results were compared with a 2014 aircraft reference [20]. The consumptions shown in Ref. [20] refer to design ranges and cruising speeds slightly different from those of the ELICA project (see Section 2.1). Therefore, a linear extrapolation of the consumption of the reference aircraft was carried out based on the information reported in Ref. [20], to make a fair comparison with the mission considered in this context. In Table 8, the block energy associated with the fuel consumed is obtained by multiplying the fuel mass by 12 kWh/kg, representing the energy density of kerosene. In the case of the hybrid-electric solution, the block energy also includes the electric energy spent by the batteries. The saving in typical mission block fuel, estimated to be -59.4%, is largely due to the innovative thermal engines specifically designed for the ELICA project.

Table 8 – Block fuel saving (EIS 2025).

	Design Mission		Typical Mission	
	Block Fuel (kg)	**Block Energy (kWh)**	**Block Fuel (kg)**	**Block Energy (kWh)**
Reference Aircraft	847.4	10168.8	390.3	4683.6
ELICA Hybrid-electric	**423.2 (-50.1%)**	**5223.1 (-48.6%)**	**158.3 (-59.4%)**	**2058.6 (-56.0%)**

4. Fuel Cell Powered Concept (EIS 2035)

4.1 Concept Description

The data reported in Section 3 showed how it is possible to obtain a fuel saving of more than 50% through the use of hybrid-electric architectures. This saving is also reflected in the total emissions. However, since the ultimate goal of the project is to investigate solutions that can pursue the goal of near-zero emissions by the year 2035, the transition to full-electric configurations is essential. This could not even be possible with the battery technology levels forecast for the year 2035, and the only viable solution seems to be that of a propulsion entirely based on hydrogen fuel cells.

This section describes the hydrogen-based configuration designed specifically for the ELICA project. Figure 7 shows the configuration analyzed with entry into service year 2035.

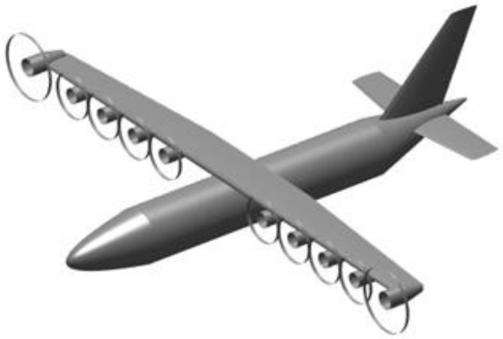

Figure 7 – Fuel cell based electric concept with distributed electric propulsion (EIS 2035).

The configuration has the same geometry as the 2025 configuration, except for a stretched fuselage that provides enough space to allocate the hydrogen tank (Figure 8). The cryogenic tank has been preliminary sized based on the approach proposed in Ref. [21].

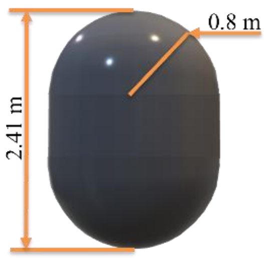

Figure 8 – Main dimensions of the liquid hydrogen tank (EIS 2035).

When it is intended to entirely replace the thermal component with hydrogen-based fuel cells, a tailored mathematical model needs to be adopted to describe the system. The scheme used for the purposes of this work is shown in Figure 9. It can be noticed that the only source of energy, in this case, is hydrogen, and the electrical power developed by fuel cells is named P_{FC}. The reason for this lies in the technological level chosen for the batteries. Since the battery specific power estimated for 2035 is about 500 kW/kg, the presence of fuel cells for which a specific power of 2.5 kW/kg (excluding cooling systems) is assumed makes the presence of the battery on board superfluous, especially in light of the constraint on the maximum weight. In Figure 9, P_{EM1} represents the power exchanged by the primary electric machine (working as a motor), P_{GB} is the power entering the gearbox, and P_{EM2} is the power exchanged by the electric motor of the secondary line. P_{S1} and P_{S2} represent the total shaft powers, respectively of the primary and secondary line. Again, the power distribution is managed by the PMAD system, which constitutes the node where the energy is splitted between the two lines. The shaft power ratio maintains the same definition given in Eq. (1). Since only the primary energy source is present, the supplied power ratio is always equal to 0 in analogy with the definition given by Eq. (2). Figure 10 shows more details about the power distribution strategy in the take-off phase. The partial turbo-electric architecture with fuel cells was selected in order to be able to place larger propellers at the wing tips for reducing the induced drag.

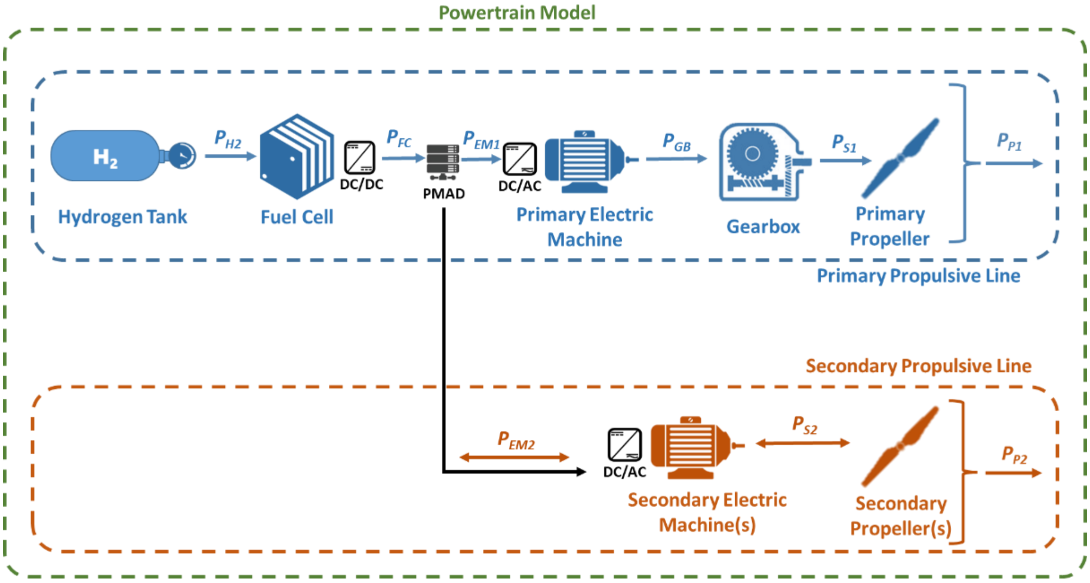

Figure 9 – Fuel cell based powerplant architecture model.

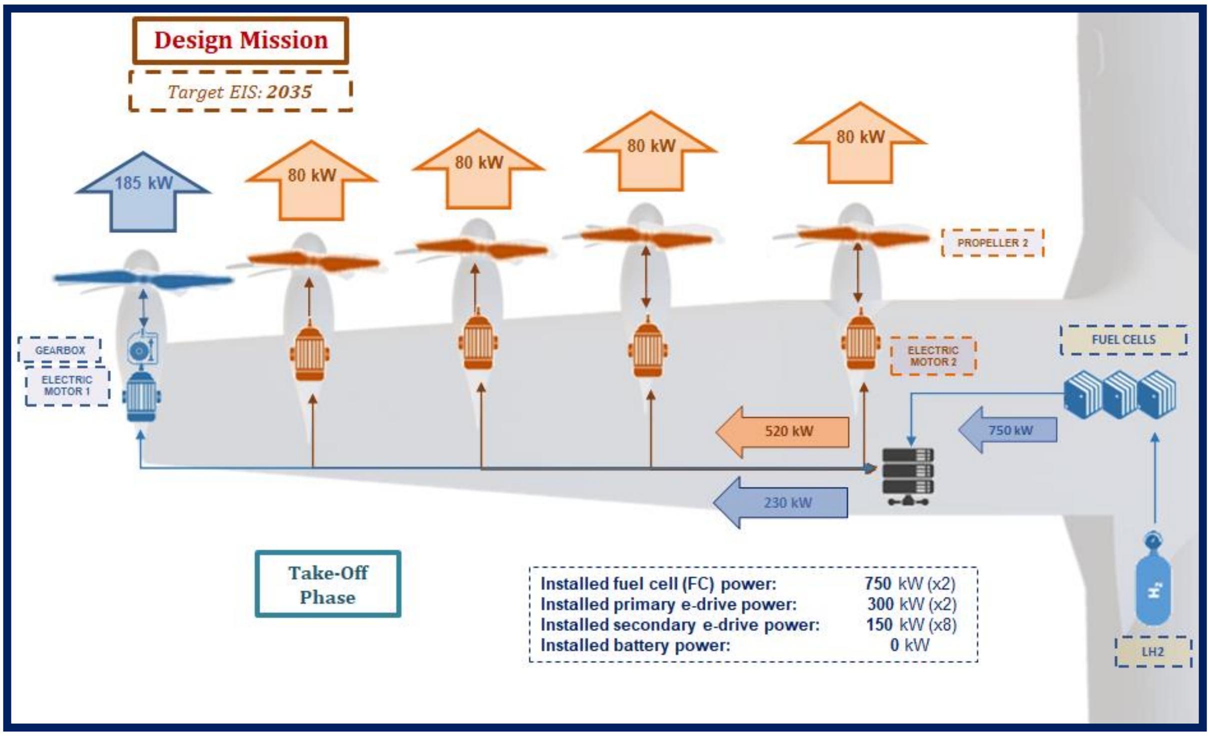

Figure 10 - Design distribution of powers at take-off (EIS 2035).

Table 9 and

Table 10 report the main mass characteristics of this configuration. Again, the data provided by industrial partners have supported a reliable assessment of the powertrain masses. The slight residual margin with respect to the certification limit is motivated by the uncertainty about the effective mass of the thermal management system, not refined at this stage of the project. If necessary, the next development will be to reconsider the hypothesis on the specific power of fuel cells. However, even assuming a value of 1.6 kW/kg at system level, the mass of the aircraft would still fall within the certification limits.

Table 9 - Mass breakdown (EIS 2035).

	Value (kg)
Airframe	2561.0
Powertrain (incl. fuel cells and hydrogen tank)	2048.0
Systems	578.0
Payload	1767.0
Maximum Fuel (Hydrogen)	270.0
Operating Empty Mass	5956.0
Maximum Zero Fuel Mass	7723.0
Maximum Take Off Mass	7993.0

Table 10 – Detailed powerplant mass breakdown (EIS 2035).

	Value (kg)
Fuel Cells	600.0
Hydrogen Tank	52.0
Primary Electric Machines	52.0
Secondary Electric Machines	162.0
Primary Propellers	214.0
Secondary Propellers	430.0
Gearboxes	67.0
Thermal Management System	302.0
Power Electronics	83.0
Cables	86.0
Powertrain Mass	2048.0

4.2 Mission Analysis

The value of shaft power ratio for each flight phase is reported in Table 11.

Table 12 and Table 13 report the analysis of the energy requirements, with reference to the design and the typical mission. The supplied power ratio is always equal to 0 since the only energy source present on board is the electric energy produced by the fuel cells (primary source only).

Table 11 - Hybridization factors for each phase of design and typical missions (EIS 2035).

Hybridization parameters	Design Mission	Typical Mission
	Shaft power ratios	
ϕ - Take-Off	0.70	0.70
ϕ – Climb	0.70	0.70
ϕ – Cruise	0.70	0.70
ϕ – Descent	0.60	0.60
ϕ – Climb To Alternate	0.70	0.70
ϕ – Alternate	0.70	0.70
ϕ – Descent from Alternate	0.60	0.60
ϕ – Loiter	0.70	0.70
ϕ – Descent To Landing	0.60	0.60
ϕ – Landing	0.70	0.70

Table 12 - Design mission analysis (EIS 2035).

	Time (min)	Range (km)	Altitude (m)	LH2 (kg)	Battery Energy (kWh)	Total Energy (kWh)
Take-Off	0.3	0.5	0 - 15	0.6	0.0	19.1
Climb	5.7	31.5	15 - 3048	11.3	0.0	368.6
Cruise	136.4	851.6	3048	146.7	0.0	4801.7
Descent	7.4	42.9	3048 - 457	3.2	0.0	104.2
Climb to Alternate	1.8	9.9	457 - 1524	3.4	0.0	113.1
Alternate	27.9	156.6	1524	26.4	0.0	863.6
Descent from Alternate	3.4	18.7	1524 - 457	1.5	0.0	48.4
Loiter	30.0	134.3	457	23.1	0.0	754.7
Descent to Landing	1.5	5.2	457 - 15	0.7	0.0	21.1
Landing	0.4	0.9	15 - 0	0.1	0.0	4.0

Total	214.8	1252.1	-	217.0	0.0	7098.4

Table 13 - Typical mission analysis (EIS 2035).

	Time (min)	Range (km)	Altitude (m)	LH2 (kg)	Battery Energy (kWh)	Total Energy (kWh)
Take-Off	0.3	0.5	0 - 15	0.6	0.0	18.6
Climb	5.6	30.7	15 - 3048	11.0	0.0	359.8
Cruise	47.5	296.9	3048	51.0	0.0	1667.6
Descent	7.3	42.8	3048 - 457	3.2	0.0	103.9
Climb to Alternate	1.8	9.8	457 - 1524	3.4	0.0	112.2
Alternate	27.9	156.8	1524	26.3	0.0	862.3
Descent from Alternate	3.4	18.7	1524 - 457	1.5	0.0	48.3
Loiter	30.0	134.3	457	23.0	0.0	752.3
Descent to Landing	1.5	5.2	457 - 15	0.7	0.0	21.1
Landing	0.4	0.9	15 - 0	0.1	0.0	4.0
Total	125.7	696.6	-	120.8	0.0	3950.2

Also in this case, the total hydrogen consumption was estimated through the simulation of the design and typical missions. To facilitate comparison with the conventional aircraft, which uses a different energy source, only the block energy is reported in Table 14 for both missions, which does not include reserves. The same considerations already made in Section 3.2, about the comparison with the data reported in Ref. [20], are also valid in this case. In Table 14, the block energy associated with the fuel consumed is obtained by multiplying the hydrogen mass by 32.7 kWh/kg, representing the energy density of hydrogen.

Table 14 – Block energy saving (EIS 2035).

	Design Mission	Typical Mission
	Block Energy (kWh)	**Block Energy (kWh)**
Reference Aircraft	10168.8	4683.6
ELICA Hybrid-electric	**5318.7 (-47.7%)**	**2175.0 (-53.6%)**

Since the emissions related to hydrogen fuel cells are essentially only water vapor, in the first instance it is possible to state that the reduction of pollutants settles at -100%. On the other hand, a complete analysis of the life cycle of the aircraft, and above all of the fuel itself, should be carried out in order to evaluate the real environmental impact of a full-electric hydrogen-based solution, also including the environmental cost of production, storage and transport of hydrogen. Only if the hydrogen refueling is carried out exclusively by means of renewable energy sources, then the complete cancellation of emissions can be confirmed.

5. Conclusions and outlook

This paper has presented the main results of the EU-funded ELICA project at the end of the second year. First, a brief overview of the main scenarios analyzed has been given, considering a full-electric commuter aircraft with 19 seats based on liquid hydrogen for 2035, and a transition solution for the year 2025 based on a hybrid-electric architecture with batteries. After a brief introduction to the methods used for aircraft design and analysis, contained within the HEAD in-house software, the main results have been presented for both configurations. The two configurations have been designed on the basis of the same top level requirements and in compliance with the CS-23 regulation code. All powertrain masses have been assessed based on industrial data provided by the project partners. The hybrid-electric configuration has shown a reduction of -59.4% on the block fuel of the typical mission compared to a 2014 reference aircraft, corresponding to a reduction of -56.0% on the total energy spent. The full-electric hydrogen-based configuration promises a reduction in block spent energy of -53.6%. This value, although slightly lower than that of the hybrid-electric configuration, would correspond to a -100% reduction in CO_2 and NO_x emissions during the mission. Future developments will concern the refinement of the masses of the thermal management system, and of aerodynamics by means of high fidelity analyses. Work will also be spent to allow an assessment of emissions during the entire life cycle of the aircraft, for each of the configurations analyzed.

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7. Copyright Statement

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