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# MARKET ANALYSIS, TLARS SELECTION AND PRELIMINARY DESIGN INVESTIGATIONS FOR A REGIONAL HYBRID-ELECTRIC AIRCRAFT

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## Abstract

This paper is framed in the context of the GENESIS Project (Gauging the ENvironmEntal Sustainability of electrIc and hybrid aircraft Systems), which complies with the European Union topic JTI-CS2-2020-CFP11-THT-13 (Sustainability of Hybrid-Electric Aircraft System Architectures) as part of the Clean Sky 2 programme for Horizon 2020. The research work is focused on gauging the environmental sustainability of electric aircraft in a life-cycle-based, foresight perspective to support the development of a technology roadmap for transitioning towards sustainable and competitive electric aircraft systems. The analyzed aircraft segment is regional aircraft, to identify, design and assess prospectively the best energy storage and transmission topology. Different alternatives including batteries, fuel cells, hybrid and conventional powertrain technologies are evaluated and compared over different time horizons. In particular, the paper is focused on the description of the workflow implemented to define the Top-Level Aircraft Requirements for a non-conventional regional class hybrid-electric aircraft with 50 passengers, and on the identification of key specifications in terms of on-board energy storage, shaft power level and weight.

**Keywords:** Market analysis, Hybrid-electric propulsion system, Aircraft design chain, Distributed electric propulsion.

## 1. Introduction

### 1.1 Global Context

Nowadays, global society is moving towards increasing environmental sustainability. The reduction of the transport industry environmental footprint has begun through a technological transformation and the gradual replacement of fossil-based fuels with alternative energy sources (biofuels, hydrogen, or electricity via batteries). In this context, the aviation sector has a fundamental role to play, in light of the growing market demand and the difficulties inherent in the technological transition, even bigger than in other transport sectors. The GENESIS project[1] (Gauging the ENvironmEntal Sustainability of electrIc and hybrid aircraft Systems), which complies with the European Union topic JTI-CS2-2020-CFP11-THT-13 (Sustainability of Hybrid-Electric Aircraft System Architectures) as part of the Clean Sky 2 programme for Horizon 2020, focuses on gauging the environmental sustainability of electric aircraft (A/C) in a life-cycle-based, foresight perspective to support the development of a technology roadmap for transitioning toward sustainable and competitive electric A/C systems. Technical University of Denmark (DTU) is the coordinator of the project, and several core-partners are involved. The purpose of the present work is to offer an overview of the current market scenario and the derivation of the design requirements for a 50 passengers regional class hybrid-electric aircraft, carried out for the intent of the GENESIS Project. The future analysis scenario is the result of a deep analysis of the international transport network and data from air segment market and passenger demand (Figure 1).

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[1] https://www.genesis-cleansky.eu/

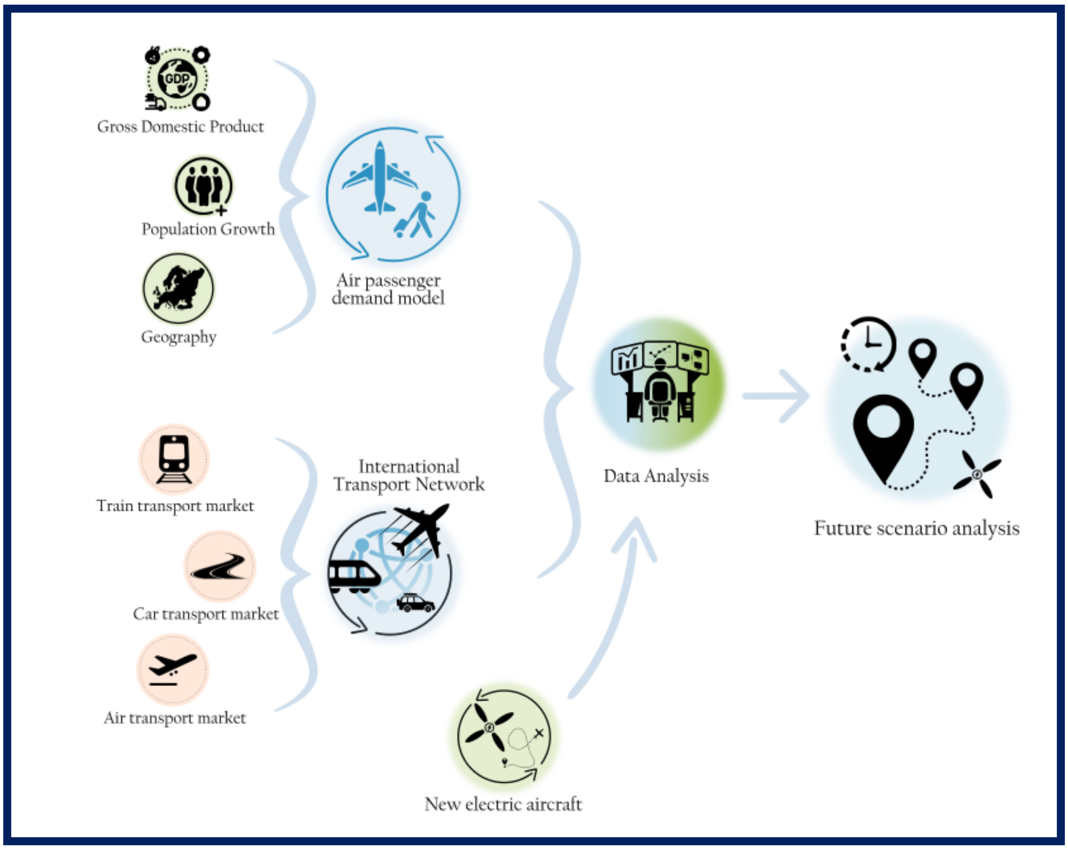

Figure 1 - Future scenario analysis and derivation of TLARs process.

## 1.2 Paper Outline

In the present section, the structure of the article is briefly presented. Section 2 describes the drivers for the definition of a new regional aircraft, focusing on the environmental impact of conventional airplanes. In section 3, a deep market analysis is done to define benchmark aircraft used for the derivation of Top-Level Aircraft Requirements (TLAR). After presenting the general requirements, in section 4 several enabling technologies are reviewed, seeing electrification as a key strategy for reducing environmental impact. Among these, distributed electric propulsion has been identified as the most promising innovative technology.  Moreover, a general scheme of hybrid-electric powerplant is described and how to derive a multitude of specific architectures from it, depending on the degree of hybridization or the number and type of energy sources and electrical units, is explained in great detail. Section 5 describes the complete approach for the design and the integration of hybrid-electric propulsion architectures within the aircraft design chain developed for the purposes of the project. In particular, a configuration with 2 thermal engines, 8 distributed electric motors and a battery group is chosen for the initial assessment of the mission energy requirement. The reference powers of the individual propulsive elements, as well as the estimated hydrogen masses for hybridization based on hydrogen fuel cells, are derived. The preliminary results serve as a basis for the interaction with the industrial partners of the GENESIS project. This, as illustrated in section 6, is facilitating the generation of surrogate models that will feed the design chain for a re-assessment of the analysed configurations. Finally, section 7 draws the conclusions of the work.

## 2. Market Scenario

### 2.1 Environmental impact of aviation

The increasing awareness of the environmental impact of technological progress has led the aviation industry to focus on new driving factors when designing new aircraft, different from the ones of the past century. The climate change, in fact, has moved the aviation industry to explore more-electric and hybrid-electric propulsions as a potential path for reduced emissions. However, 74.5% of transport emissions comes from road vehicles and the global aviation industry produces around 2%

of all human-induced carbon dioxide ($CO_2$) emissions, and it is responsible for 12% of $CO_2$ emissions from all transports sources [1]. The carbon dioxide emissions released by global fossil fuel combustion and industrial processes have seen a dramatic rise since the birth of the industrial revolution (Figure 2) [2]. Since 1950, aviation emissions increased almost seven-fold, and since 1960 they have tripled. More recently, in 2019, the world saw roughly 36.44 billion metric tons of carbon dioxide emitted. Despite the fact that 2020 showed a noticeable reduction in emissions due to the impacts of COVID-19, they will increase again.

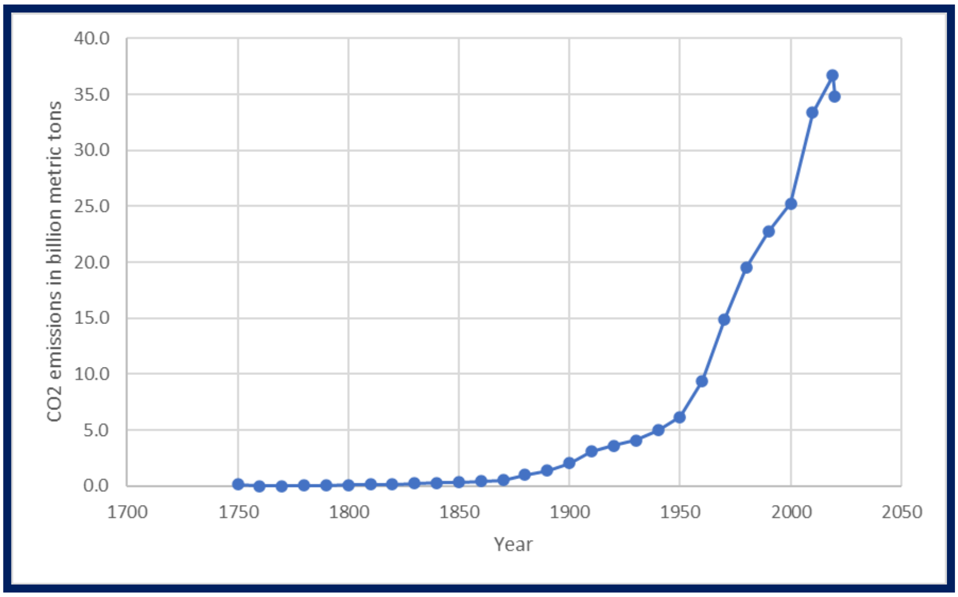

Figure 2 - Global historical $CO_2$ emissions, from 1758 to 2020 [2].

Besides the problem of pollution and emission, the amount of oil is limited. Considering the growing demand and the depletion of oil reserves, the price of crude oil has been steadily climbing for many years, following a clearly visible trend. However, transport accounts for around one-fifth of global carbon dioxide emissions (Figure 3). Road travel accounts for three-quarters of transport emissions. Most of this comes from passenger vehicles – cars and buses – which contribute 45.1%. The other 29.4% comes from trucks carrying freight. Since the entire transport sector accounts for 21% of total emissions, road transport accounts for 15% of total $CO_2$ emissions. Aircraft contribution represented 2.5% of total $CO_2$ emissions in 2018 and 11.6 % of transport [1, 3].

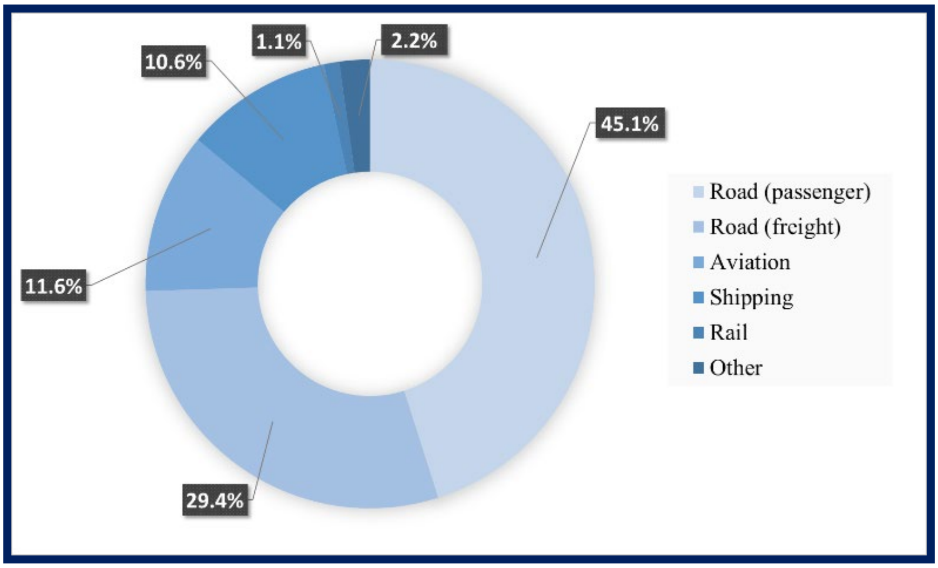

Figure 3 - Global $CO_2$ emissions from transports [3].

## 2.2 Emissions from aircraft classes

Besides these data, the airline passenger efficiency is satisfying with an average occupancy of aircraft of 82%, greater than other forms of transport [4]. Aviation, in fact, turns out to be one of the most efficient, safest and most reliable modes of transportation in the world today but, despite this, aviation emissions need to be reduced to comply with the key objectives mentioned in EUROPE2020 and in Flightpath2050. Innovation in technology and approaches today will help facing the environmental expectations and the growth of demands. In fact, the aviation sector is growing fast and will continue to grow. The most recent estimates suggest that demand for air transport will increase by an average of 4.3% per annum over the next 20 years [5]. The environmental impact of aviation depends on the different segments and aircraft classes. It can be measured by the Revenue Passenger Kilometers (RPKs), that is the sum of the products obtained by multiplying the number of revenue passengers, $P$, carried on each flight stage by the corresponding stage distance, $D$:

$$RPKs = \sum P \bullet D \; [km] \tag{1}$$

Passenger flights are responsible for approximately 85% of commercial aviation $CO_2$ emissions. In 2019, this amounted to 785 million tons (Mt) of $CO_2$ and this value increased by 33% in the previous 6 years (Figure 4). Over the same period, the number of flight departures increased by 22% and revenue passenger kilometers increased by 50%. This means that passenger air traffic increased nearly four times faster than fuel efficiency improved. More than 60% of all passenger flights were operated on narrowbody aircraft in 2019, and these accounted for more than half of all RPKs and passenger $CO_2$ emissions. On average, global passenger aircraft emitted 90 g $CO_2$ per kilometer in 2019. That is 2% lower than in 2018, and 12% lower than in 2013. However, smaller regional aircraft that are used on shorter flights emitted nearly 80% more $CO_2$ per kilometer than the global average for all aircraft [6].

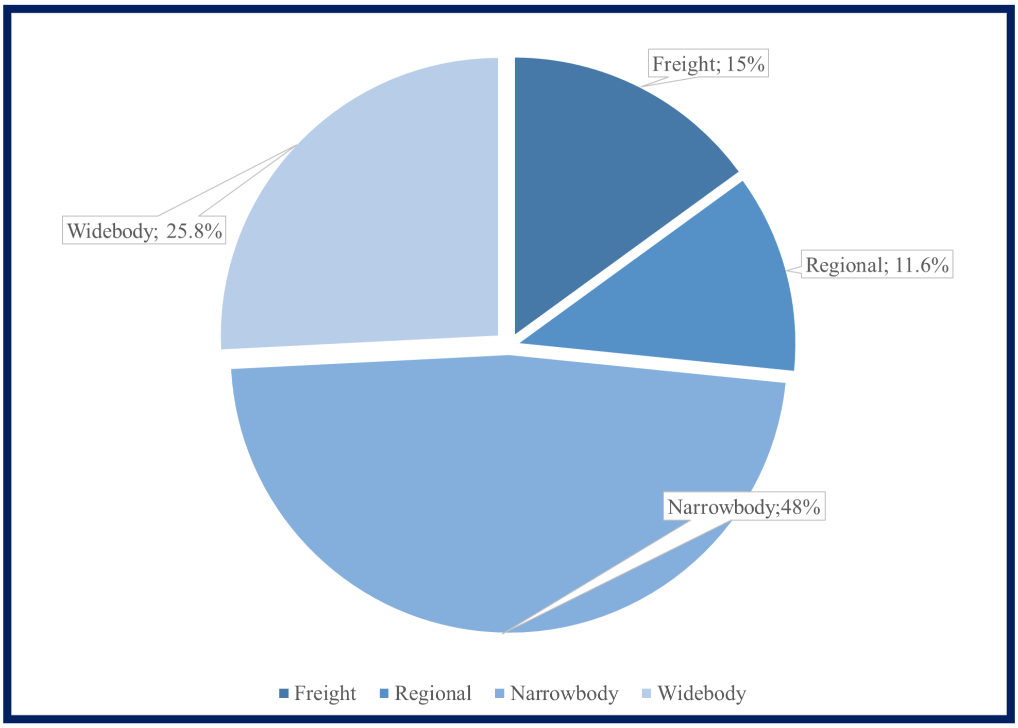

Figure 4 - Global $CO_2$ emissions from different aircraft classes in 2019 [6].

On average, narrowbodies and widebodies had similar carbon intensity, but regional aircraft $CO_2$ emissions intensity is definitely higher than other classes (Table 1) [6]. It is here remarked that this paper wants to focus on the environmental sustainability of hybrid-electric aircraft in the regional class, to identify, design and assess prospectively the best energy storage and transmission topology. In light of this, it is convenient to consider the emissions from the top six regional aircraft in the last decade. The most fuel efficient of the top 10 regional aircraft are turboprop aircraft: the De Havilland

Dash 8-400 and the ATR 72-600 [6], as shown in Table 2. These two accounted for most of the global departures by regional aircraft, with more than 1 million flights each. However, they rank in the middle of the 10 aircraft analyzed because larger regional jets have a higher number of seats and longer flight distances [7].

Table 1 - Passenger $CO_2$ emissions and intensity by aircraft class in 2019 [6].

| | Departures (% of total) | RPKs (billions) | RPKs (%) | Average distance (km) | $CO_2$ emissions (Mt) | $CO_2$ intensity (g $CO_2$/RPK) |
|---|---|---|---|---|---|---|
| **Regional** | 29 | 345 | 4 | 551 | 56 | 162 |
| **Narrowbody** | 63 | 4588 | 53 | 1322 | 393 | 86 |
| **Widebody** | 8 | 3777 | 43 | 4675 | 336 | 89 |
| **Total** | 100 | 8710 | 100 | 1378 | 785 | 90 |

Table 2 - Passenger $CO_2$ emissions from the top 10 regional aircraft types in 2013 and 2019 [6].

| Aircraft | Average seats | $CO_2$ emissions (Mt) | | Difference (%) |
|---|---|---|---|---|
| | | 2013 | 2019 | |
| **Embraer E190** | 100 | 8.76 | 9.54 | 9% |
| **Embraer E175** | 77 | 2.53 | 6.94 | 174% |
| **CRJ900** | 80 | 3.37 | 6.40 | 90% |
| **De Havilland Dash8-400** | 73 | 2.84 | 3.96 | 39% |
| **Embraer E195 11** | 116 | 2.50 | 3.51 | 41% |
| **ATR 72-600** | 69 | 2.00 | 3.28 | 64% |
| **Embraer ERJ145** | 50 | 6.07 | 3.04 | -50% |
| **CRJ200** | 50 | 5.75 | 2.95 | -49% |
| **CRJ700** | 68 | 4.07 | 2.90 | -29% |
| **Embraer E170** | 74 | 2.68 | 2.44 | -9% |

The regional turboprop market has been growing fast in the last few years. In fact, 58% of the current regional network has been created in the last 15 years [8]. The bulk of growth comes from the Asia-Pacific region. Europe is once again creating routes while growth in China is simultaneously gaining momentum. However, although some are very well populated, many countries still have poor regional connectivity, contrasting with mature European and North American markets as shown in Figure 5.

Many communities rely on regional aircraft to connect to other countries and regions in the world. Through an adapted technology and capacity, turboprops efficiently answer this essential market need. Almost 50% of global airport rely exclusively on regional aircraft [8]. The choice of the GENESIS project to focus on the regional turboprop platform is motivated by the growth of the sector, which makes it even more urgent to take the path of decarbonization for this class. Regional aircraft, in fact, provide a valuable travel solution that qualitatively complements any alternative mode of ground transportation, and regional air transport is a quick enabler of economic development as it requires shorter lead-time to implement connectivity. Either through tourism development or by establishing business, interlinking secondary and tertiary cities allow every community to be connected and benefit from world economic growth – a key component of sustainable development.

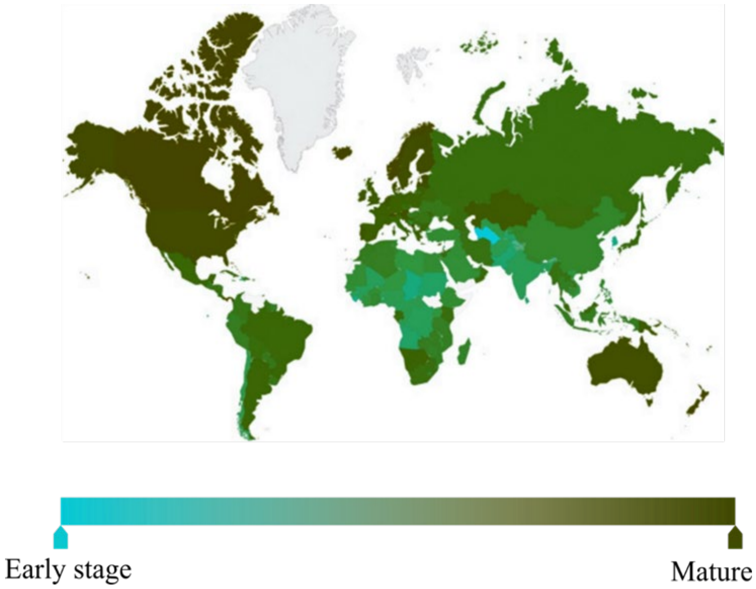

Figure 5 - Regional networks maturity stage [8].

# 3. Selection of TLARs

## 3.1 The roots of the GENESIS TLARs

The reasons that promote the future electrification of aircraft have been presented in the previous section. From this point of view, the design of new concepts integrating hybrid power sources and highly efficient propulsive systems is a crucial aspect of future aviation. The most important link between the market scenario analysis and the TLARs is the definition of the *reference mission*. The mission defines the average operation of an aircraft and can be used to execute performance calculations. For this reason, it must reflect the characteristics desired by the end customer. To obtain a reliable forecast of future scenarios and to make the best design choices, it is indispensable to deeply search for data coming from the air segment market and the whole international transport network, with particular attention to passenger demand. In order to define the aircraft TLARs, data of regional aircraft up to 100 passengers on short-haul flights, usually feeding larger carriers airline hubs from small markets, have been considered. The data have been obtained from official sources, composed of Type Certificate Data Sheets, Aircraft Flight Manuals or Pilot Operating Handbook, and official statements by manufacturers. Table 3 reports the benchmark aircraft selected for this application.

Table 3 – Regional aircraft data collected for the selection of the TLARs of the GENESIS project.

| Aircraft | Manufacturer | Year | Country | Average seats | Number of units | Powertrain |
|---|---|---|---|---|---|---|
| ATR 42 | ATR | 1984 | Italy - France | 42-50 | 436 | Turboprop |
| ATR 72 | ATR | 1989 | Italy - France | 66-74 | 1500 | Turboprop |
| CRJ100 | Bombardier Aerospace | 1991 | Canada | 50 | 560 | Jet |
| CRJ700 | Bombardier Aerospace | 1997 | Canada | 66-78 | 750 | Jet |
| Dash8-300 | Bombardier Aerospace | 1989 | Canada | 45-56 | 959 | Turboprop |
| Embraer E145 | Embraer | 1995 | Brazil | 49-55 | 888 | Jet |
| Fokker 50 | Fokker | 1985 | Netherlands | 50-58 | 63 | Turboprop |
| SAAB 2000 | SAAB | 1992 | Sweden | 50-55 | 63 | Turboprop |

## 3.2 Technical benchmark study

The first and most important step of a technical benchmark study is to define the parameters that are indicative for the product performance. Therefore, it must be understood how the product works and how customer benefit is generated. The analyses conducted for the purposes of the GENESIS project are reported from Figure 6 to Figure 12. First of all, the maximum number of seats are compared in order to localize the GENESIS project in the reference market (Figure 6). Then, the most interesting parameters are analyzed. A first relevant example is the take-off distance (Figure 7), which is directly related to the Maximum Take Off Weight (MTOW) (Figure 8). Take off distance of regional airliners is often disregarded, because they are often operated from large airports with runways designed for bigger aircraft. However, economic feasibility studies show that point to point connections which are not covered by narrowbody airplanes can be more profitable and a competitive niche for regional aircraft. The shorter the required runway, the more airports can be part of the route network. Another relevant parameter is the range because it influences which routes the aircraft will cover (Figure 9). Finally, the cruise speed is also considered, since it affects the number of flights that can be carried out in a single day, and therefore the Direct Operating Costs (DOC) (Figure 10).

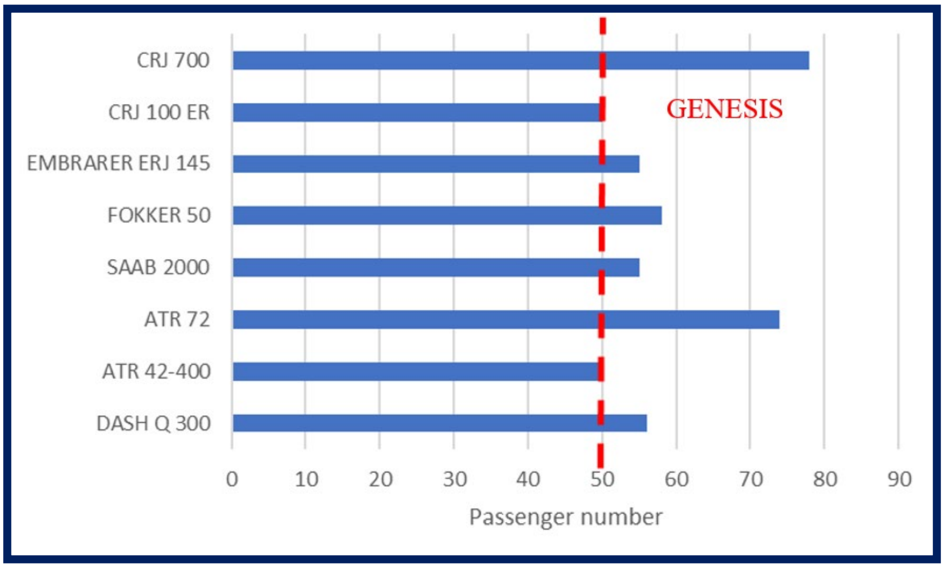

Figure 6 - Aircraft regional segment data comparison – Maximum number of seats.

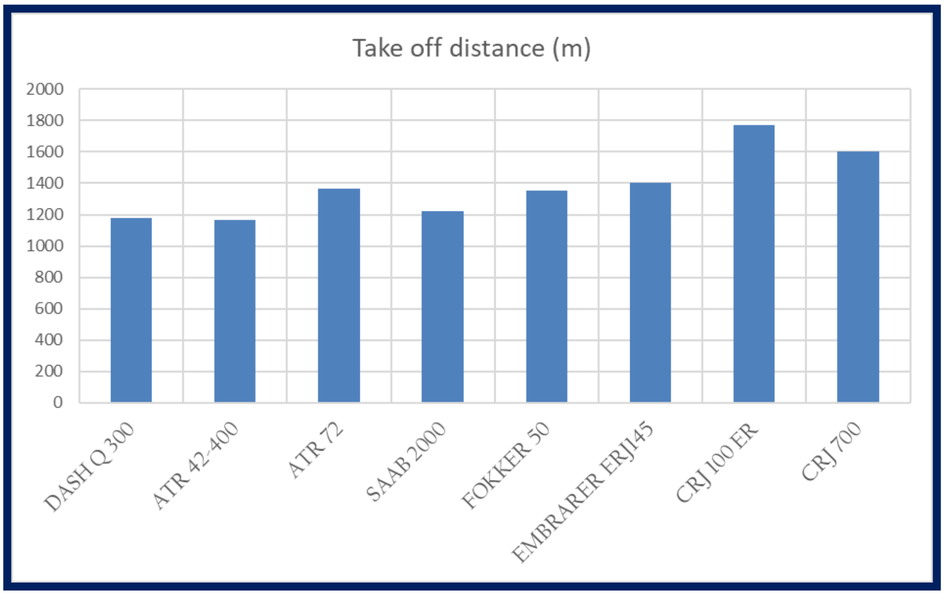

Figure 7 - Aircraft regional segment data comparison – Take off distance.

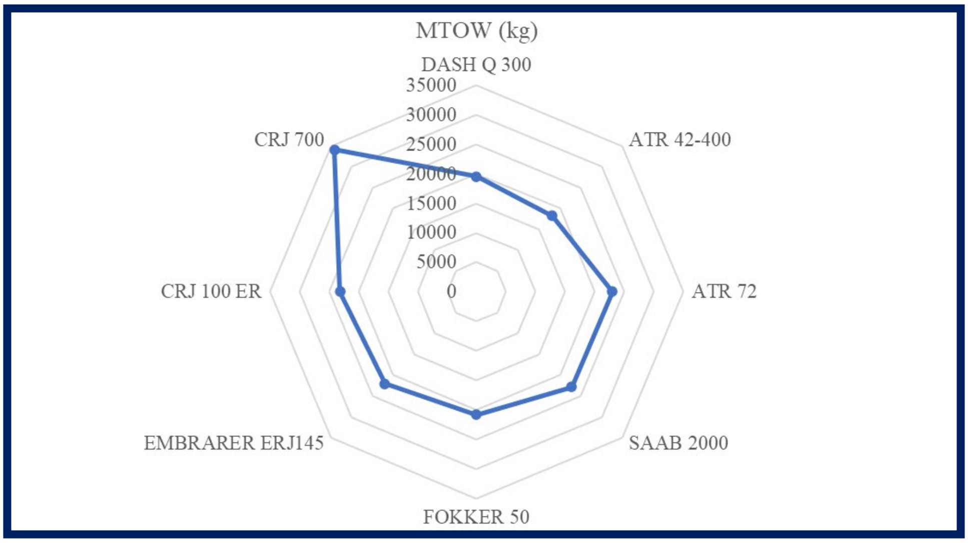

Figure 8 - Aircraft regional segment data comparison – Maximum Take Off Mass.

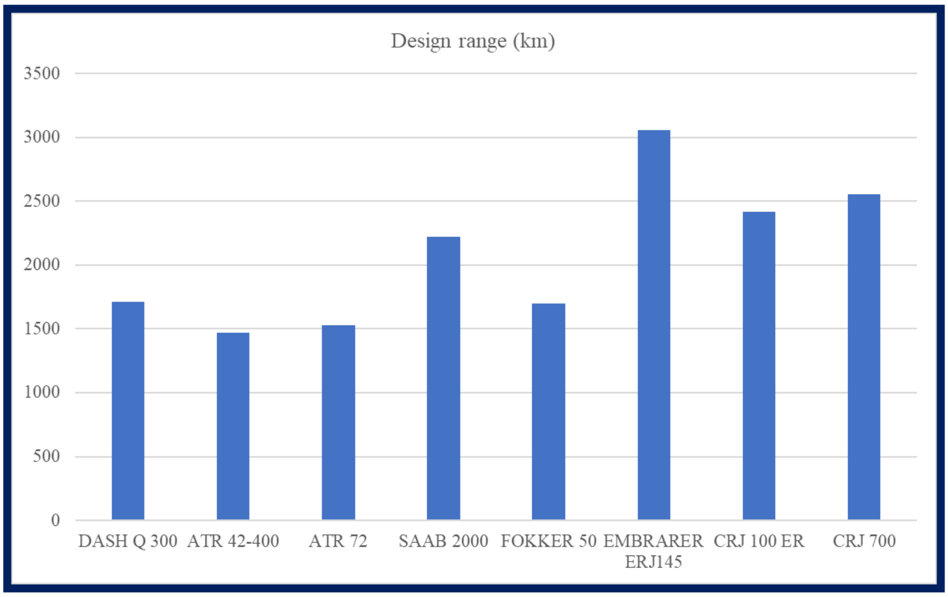

Figure 9 - Aircraft regional segment data comparison – Design range.

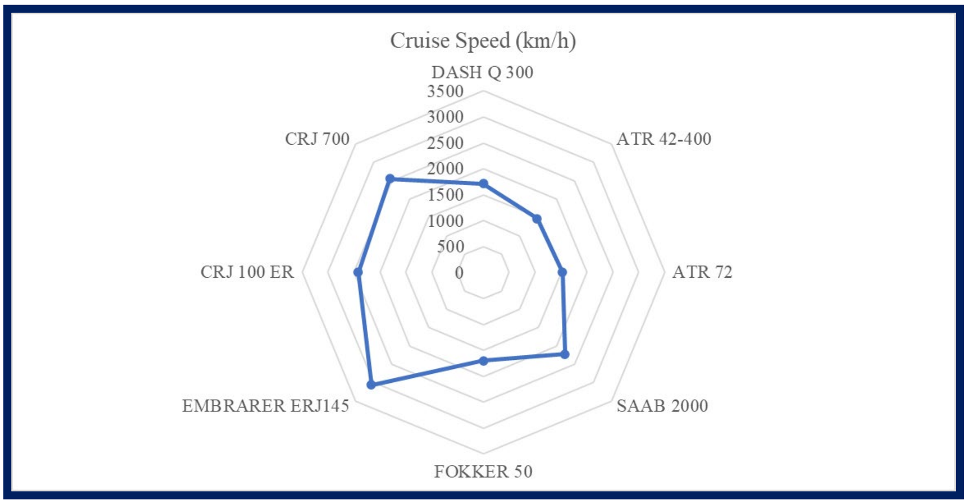

Figure 10 - Aircraft regional segment data comparison – Cruise speed.

As for the selection of the design range, it is useful to consider also competitivity with other means of transportation. Over many regional transport systems, high speed rail is competing with air transportation, often considering time and distance factors. Airports are usually located far from city centers, while conventional and high-speed train stations are much closer. For short distances of less than 150 km, conventional rail services are usually more competitive (air transport is almost never flown over these distances) than high speed. This is mainly due to higher frequencies of services for conventional rail. The main service window for high-speed rail is between 150 and 775 km, a segment over which it generally has a time advantage over air transportation. For distances over 800 km, air transportation is usually more advantageous. However, if there were no high-speed rail services, air transportation would be more advantageous over distances of 350 km (Figure 11) [9]. These considerations led to a design mission of 600 nm for the GENESIS project.

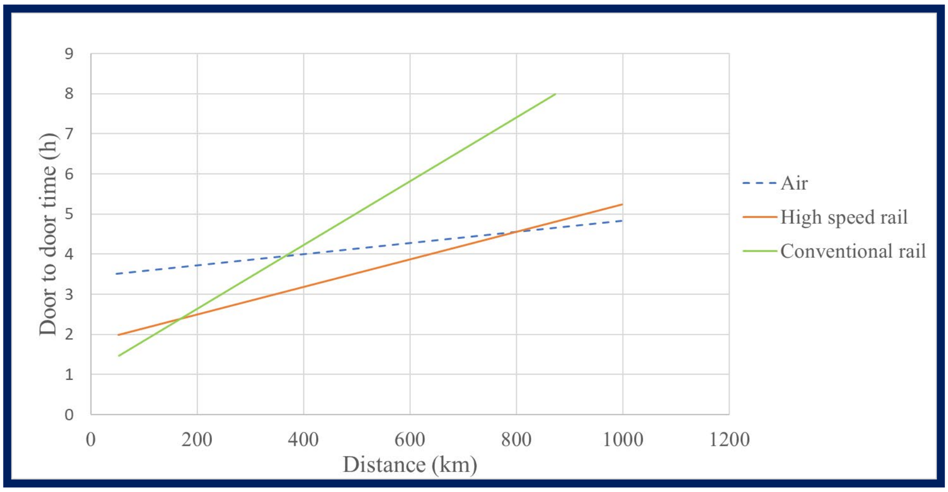

Figure 11 - Breakeven distance between conventional rail, high-speed rail and air transportation.

Beyond competing aircraft, a crucial aspect concerns the airports from which the aircraft will be operated. In this sense, a decisive factor is represented by the Take-Off Field Length (TOFL), in relation to the world airport runways. In order to serve more than 90% of world airports, the TOFL should be no higher than 1200 m. In fact, less than 10% of world airports have a runway shorter than 1200 m (Figure 12). In this way, TOFL is chosen lower than the mean of the benchmark aircraft (1362 m) in order to serve more regional airports.

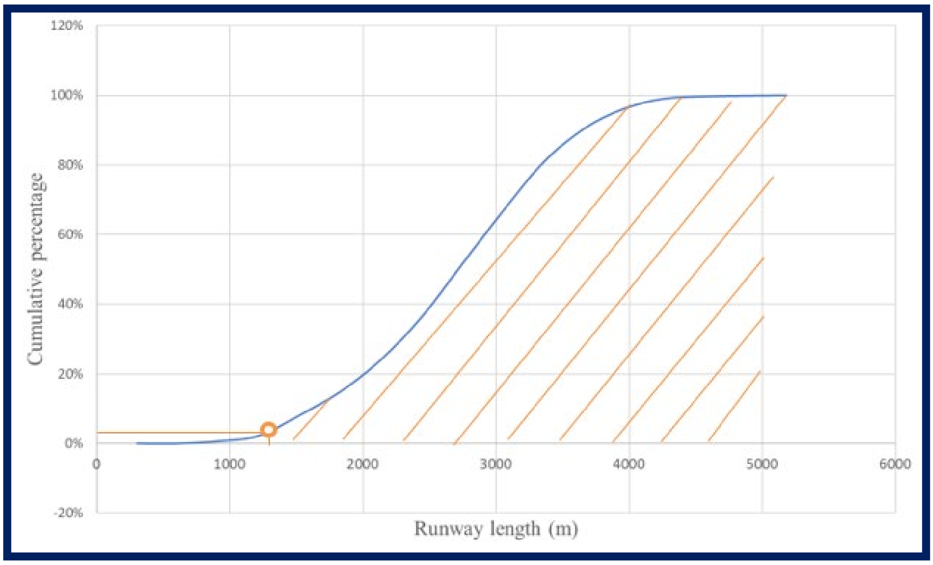

Figure 12 - World airports runway[2].

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[2] https://ourairports.com/data/

### 3.3 TLARs for (hybrid) electric 50 passengers regional class aircraft

In the light of the above-mentioned considerations, the TLARs required for the GENESIS project have been defined. The set of aircraft requirement is reported in Table 4. Three different time horizons are considered in the project: a *short-term* scenario, with reference Entry Into Service (EIS) year 2030, a *medium-term* scenario (EIS year 2040), and a *long-term* scenario (EIS year 2050+). In addition to the parameters already discussed in the previous paragraphs, also limitations on the MTOW are set, mainly based on statistics. The system weight reduction led to the possibility to increase the passenger number with a moderate increment of MTOW. This is the reason why in the medium and long-term it is possible to modify the MTOW requirement up to 27000 kg in order to also increase the passenger number [10]. However, in order to combine the demanding field length with a relatively high MTOW, innovative technologies are required in order to improve the low-speed performance of the aircraft. The solution chosen is Distributed Electric Propulsion (DEP). In this regard, the next sections will briefly describe the approach chosen for the design of an aircraft that integrates, at the same time, both innovative technologies such as DEP, and alternative energy sources.

Table 4 - Initial set of TLARs for the GENESIS project.

| Description | Value | Unit | Notes | Notes for medium and long term time horizon |
|---|---|---|---|---|
| Design mission | 600 | nmi | | |
| Typical range | 200 | nmi | | |
| Time to Climb (Design Mission) | 13 | min | 1500 m - 200FL @ MTOW | |
| Cruise Speed | 295-300 | KTAS | @200 FL | |
| Take-Off Field Length | <1200 | m | At SL, ISA and MTOW | |
| Landing Field Length | <1200 | m | At SL, ISA and MLW | |
| Design Payload | 4750 | kg | 50 passengers – 95 kg per passenger | |
| MTOW | <24000 | kg | | <27000 kg |

## 4. Hybrid-electric aircraft design

### 4.1 Propulsion system general characteristics

The growing sensitivity towards environmental sustainability drives the demand for a revolution in the aerospace propulsion sector, requiring a reduction in carbon emissions that cannot avoid the involvement of disruptive technologies and the use of alternative energy sources. The design of new concepts that employ hybrid-electric propulsion architectures represents the most promising solution to the problem, as long as the energy sources considered are renewable. There are several variants of the logic schemes of an electric propulsion system [10, 11, 12, 13]. The basic distinction is between turbo-electric, hybrid electric, and all-electric architectures. A simplistic representation of the hybrid series/parallel electric powertrain is given in Figure 13. The presented diagram refers to the case of two energy sources, where the thermal power source is marked as *primary*, and the electric energy storage as a *secondary* source.

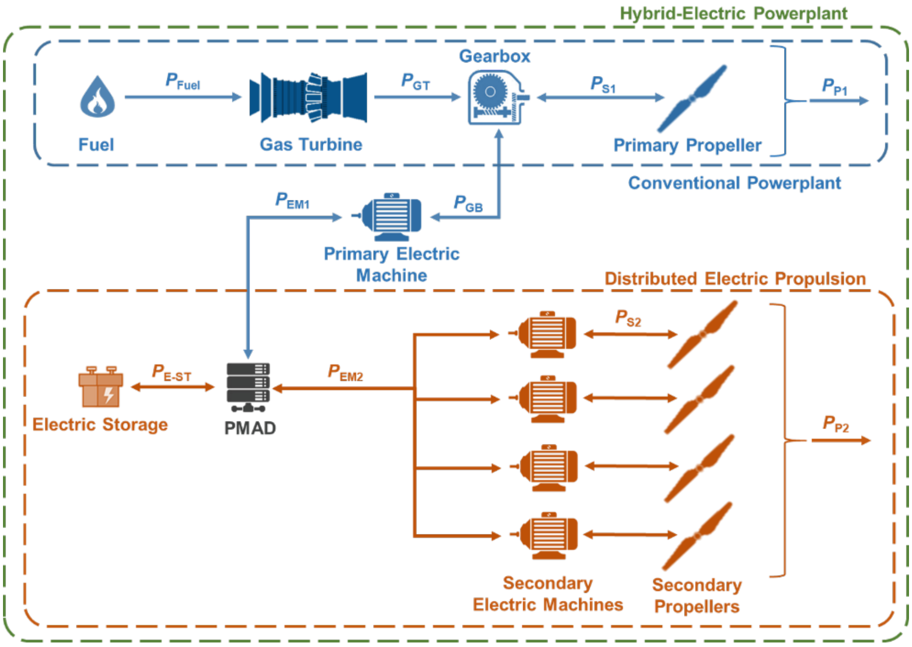


Figure 13 - Example of hybrid-electric propulsive scheme.

In order to quantify the hybridization level of a hybrid-electric propulsive scheme, two parameters are typically used. The first one is the so-called *supplied power ratio*, $\Phi$, which is defined as the ratio between the electric power, $P_{E\text{-}ST}$, and the total power supplied:

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

where $P_{Fuel}$ is the power associated with the combusted fuel. The second parameter is the ratio between secondary shaft power and total shaft power and is named the *shaft power ratio*, $\varphi$. It is very useful when dealing with high-lift propellers and distributed electric propulsion, since it quantifies the use of such systems:

$$\varphi = \frac{P_{S2}}{P_{S1} + P_{S2}} \tag{3}$$

where $P_{S1}$ is the primary shaft power, and $P_{S2}$ is the secondary shaft power. The scheme presented in Figure 13 generally corresponds to the serial/parallel hybrid-electric concept. The flexibility of this concept allows for a greater optimization of the mission strategy, even allowing to reverse the operating mode of the elements, with the primary electric machine capable of eventually reversing the direction of the energy flow as needed, working as a motor or generator depending on the flight segment. Moreover, during the phases in which there is no need for a significant amount of propulsive power (i.e., the descent phase) some or even all the propellers may no longer be required as thrust-generators, but rather as absorbers of the energy contained in the external flow. To better manage all possible combinations, it is possible to define up to 9 different combinations of the direction of the incoming and outgoing powers in the different elements of the propulsive scheme. These so-called *operating modes* describe all the possible combinations of usage of propellers, electric storage, and primary electric machines. Each operating mode can be treated separately by means of proper systems of linear equations, generally referred to as *powertrain equations*. These equations also include the effect of the efficiencies of the individual components of the powertrain as operating conditions vary. Dealing with hydrogen-based configurations, it is worth to highlight the main differences with respect to the scheme reported in Figure 13. In case three propulsive sources are used, namely kerosene, batteries and hydrogen, solid oxide (SO) or proton-exchange membrane (PEM) fuel cells should be imagined arranged in parallel with the electric-storage devices, as they both supply electricity in the form of direct current. In case of a deeper use of fuel cells, i.e., complete replacement of the thermal system with hydrogen fuel cells, the architecture reported in Figure 14 can be adopted.

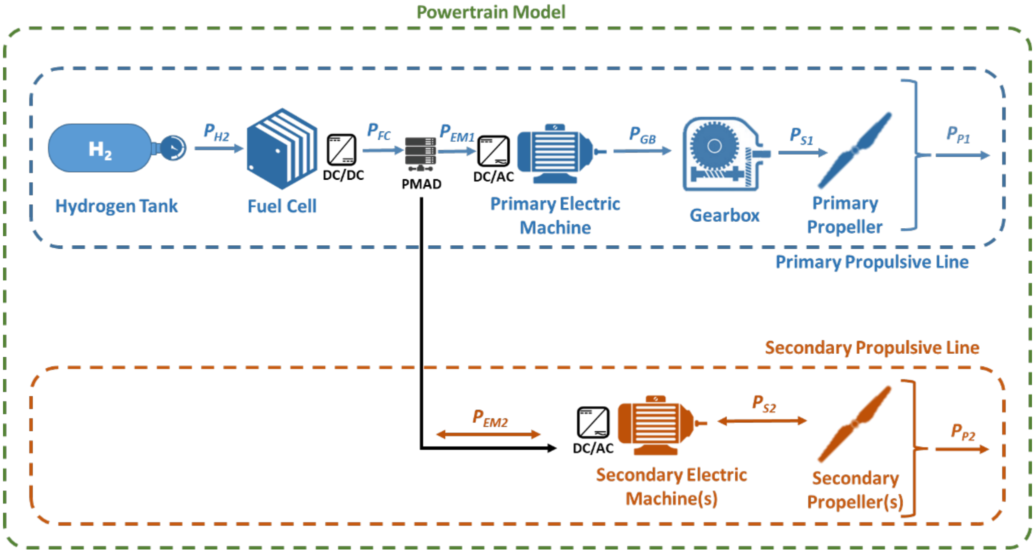


Figure 14 – Example of powerplant architecture based on fuel cells usage.

## 4.2 Enabling technologies

### *4.2.1* Batteries

Hybrid and all-electric vehicles are provided with high-voltage battery packs that consist of individual modules and cells organized in series and parallel. A cell is the smallest, packaged form a battery can take. A *module* consists of several cells generally connected in either series or parallel. A battery back is then assembled by connecting modules together, once again either in series or in parallel. Electrochemical cells store chemical compounds holding a voltage difference between the electrodes. The battery provides electric energy with a chemical reaction when the electric circuit at its poles is closed. Cells convert the energy stored in the chemical bonds directly into electricity, without producing heat or thermal energy as an intermediate stage of the energy conversion process. Thus, their efficiency in releasing energy can be very high. Current batteries can store below 250 Wh/kg. For regional hybrid-electric turboprop applications, it was estimated that specific energies higher than 500 Wh/kg would be needed for the accomplishment of the selected design mission. And for an all-electric system, the required specific energy would be around 2000 Wh/kg, keeping the same design range. While theoretical specific energy is much higher than this, in practice the attainable value is significantly lower, due to the necessity to account for the additional weight of components such as current collectors, electrolytes, separators, battery cases, and terminals. Furthermore, the need to simultaneously achieve a long life-cycle, low costs, and acceptable safety greatly increases the complexity of the overall challenge.

### *4.2.2* Fuel cells

In this context, hydrogen is a more promising alternative to jet fuel because of its enormous amount of specific energy: about 33 kWh/kg in terms of lower heating value [14, 15, 16]. Hydrogen fuel cells seem to be the most promising solution when the goal is to explore solutions that may drastically reduce the environmental impact of an aircraft system, by eliminating $CO_2$ and $NO_x$ emissions in flight. Considering also non-$CO_2$ emissions, $H_2$ combustion could reduce climate impact in flight by 50 to 75%, and fuel-cell propulsion by 75 to 90% [17]. Pure hydrogen may be stored as a compressed gas in a pressurized tank or as a liquid in a cryogenic tank [18]. It may be also safely stored as a metal hydride or extracted from a hydro-carbon like jet fuel, a process known as reformation. A fuel cell can be represented as a power conversion unit, continuously fueled to produce electric power, and sized based on the power requirement. PEM fuel cells are more promising for a non-stationary installation, presenting water vapor as the only waste product, with limited start-up times and lower operating temperatures, which however makes cooling particularly challenging. Basically, fuel cells are electrochemical cells converting the chemical energy of fuel into electrical power through redox reactions using an oxidizing agent. Regardless of the type of fuel cell, it consists of three components:

- An anode, the electrode at which the oxidation reaction occurs.

- A cathode, the electrode at which the reduction reaction occurs.
- An electrolyte, a substance that dissolves into ions, allowing the passage of electric current.

At the anode, a catalyst causes the fuel to undergo oxidation reactions that generate ions and electrons [14, 19, 20]. The ions move from the anode to the cathode through the electrolyte. At the same time, electrons flow from the anode to the cathode through an external circuit, producing direct current electricity. At the cathode, another catalyst causes ions, electrons, and oxygen to react forming water. The highest estimates about today's specific power levels of a PEM fuel cells bring to a value of 1.6 kW/kg, related to applications in the automotive sector [20]. This value, between 2 and 3 times lower than the specific power of an internal combustion engine, makes the transition of the propulsion system complex, affecting the distribution of the masses and consequently the flight performance. The analysis of possible future scenarios, with particular attention to the specific technological levels and the effect of integration on a flying platform, is of crucial importance in drawing up a technology roadmap that considers the real potential of hydrogen propulsion as well as problems related to its use. Among these, problems linked to safety, thermal management, and life-cycle considerations.

### 4.3 Aero-propulsive interactions

Improvements in aerodynamics have a direct impact on aircraft performance. Disruptive aerodynamic technologies may provide outstanding results in terms of fuel consumption and emissions reduction. However, the lack of established design methodologies allowing to reliably capture the advantages of new aerodynamic concepts usually represents a huge obstacle for the aircraft designer. For the propulsion system architectures previously examined, the correct positioning of primary and secondary propellers may provide several advantages in terms of wing loading and drag reduction. Distributing the secondary propellers spanwise and upstream of the wing can lead to an increase in the dynamic pressure, allowing for increased design wing loading. In this case we speak of distributed electric propellers [21]. In addition, installing propellers at the wing tips can significantly reduce the induced drag. In order to correctly account for these effects and to include their benefits at the aircraft design level, the implementation of dedicated strategies and methodologies is necessary.

## 5. Hybrid-electric aircraft design chain

### 5.1 Hybrid-Electric Aircraft Designer

The aero-propulsive effects introduced in Section 4.3, together with the assumptions about the scheme of the propulsion system described in Section 4.1 and the set of alternative power sources described in Section 4.2, have been included into a design chain, which combines the aircraft conceptual design activity and the analysis of mission energy requirements into a comprehensive multi-disciplinary approach, described in Figure 15. The conceptual design aims to choose a single aircraft configuration, which suits both TLARs and aviation regulations. In case of a hybrid-electric aircraft, it is important to explore different powertrain operating modes together with the selected mission profile, to maximize overall efficiency during the mission. Such investigations may be included in an optimization loop targeting minimum weight penalties, reduced emissions, and minimized DOC. Depending on the hybridization strategy selected, these targets can be met by means of different energy sources, such as batteries, hydrogen, biofuels, or conventional aviation fuel. The approach summarized in Figure 15 has been implemented in a MATLAB®-based software, named HEAD (Hybrid-Electric Aircraft Design), developed in-house at the University of Naples Federico II (UNINA), that constitutes a state-of-the-art conceptual design, analysis and optimization toolchain for conventional and hybrid-electric powerplant architectures. The conceptual design workflow is divided in three main modules. The *preliminary design* process moves from the statistical definition of the main geometrical characteristics of the aircraft, based on the given set of TLARs. This is a fundamental step when designing a completely new aircraft since it allows to quickly generate a baseline configuration. The next step is the *sizing process*, which starts after that the characteristics of the propulsive architecture in terms of geometry, hybridization parameters, and operating modes have been selected. The evaluation of aviation regulation constraints and mission requirements yields to the choice of the *sizing point*, which provides a specific combination of wing loading and weight-to-power ratio. The last step consists of the *analysis* of the energetic requirements and flight performance through the simulation of the mission, which is a crucial step to verify the compliance with aviation regulations and TLAR, as well as to perform optimizations.

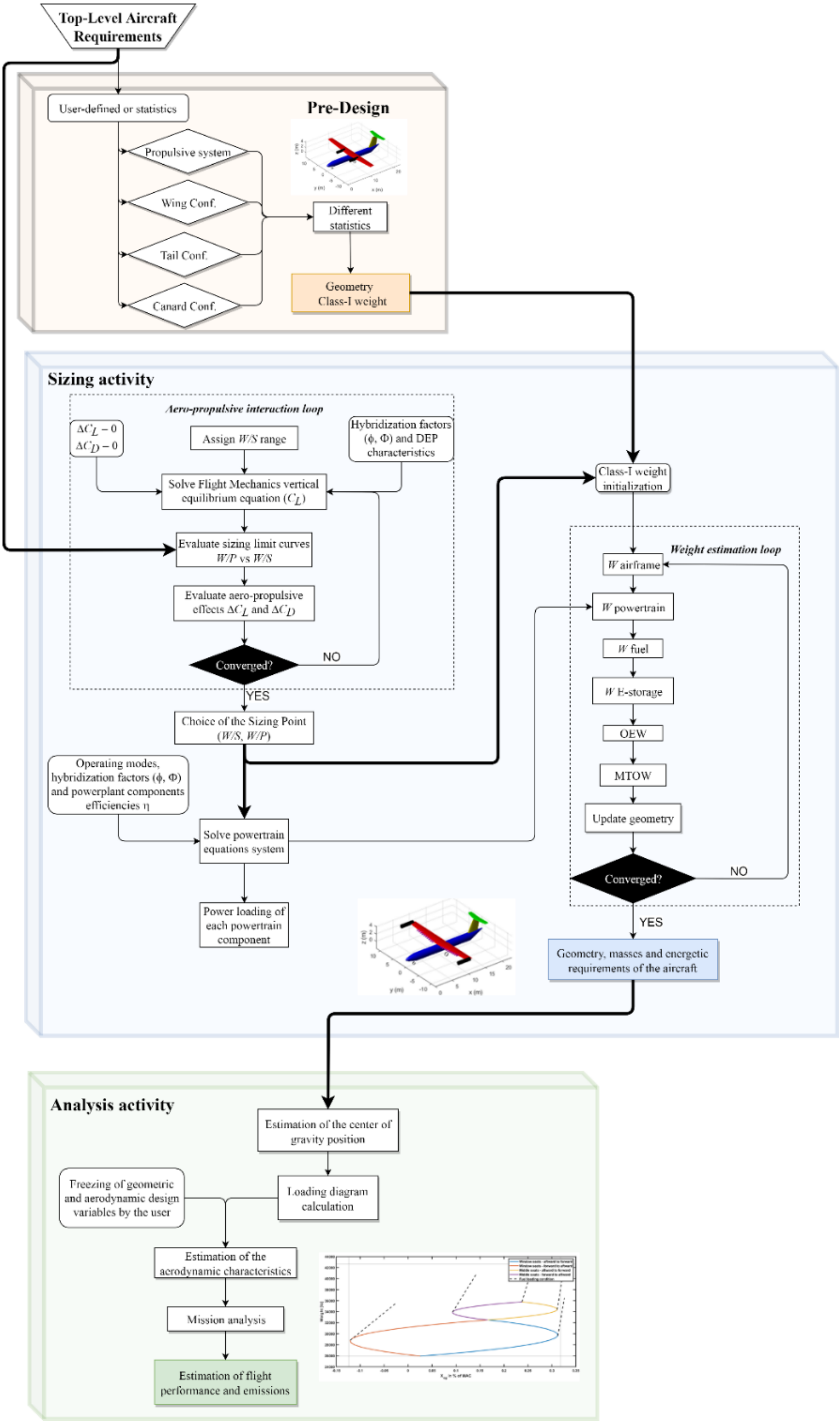
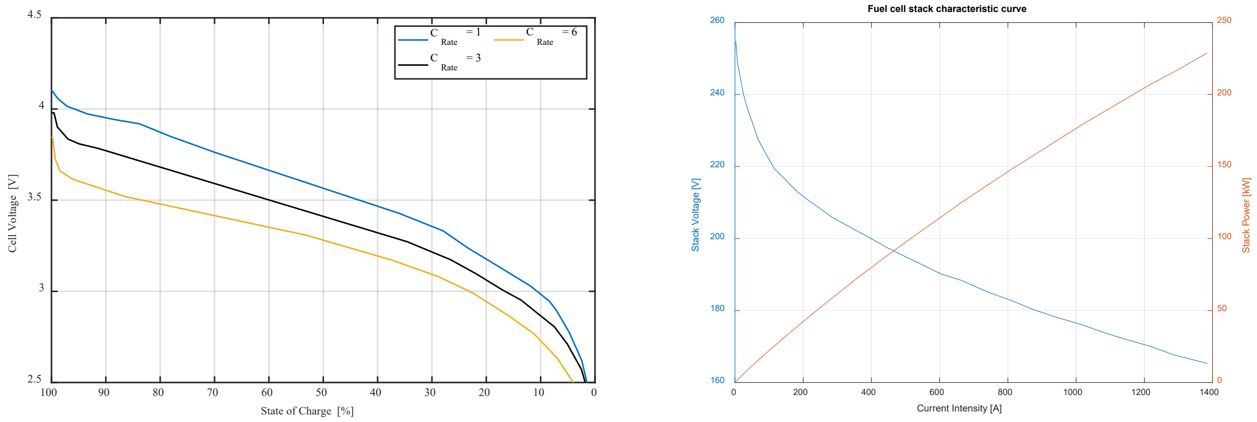


Figure 15 - Hybrid-electric aircraft design chain workflow.

For correctly modelling the fuel consumption, HEAD relies on an external *engine deck* file, which includes information characterizing the engine in terms of power, thrust, power-specific fuel consumption, and main pollutants emission indices (EI) at different engine ratings, operating conditions (i.e., flight altitude, flight speed, and ISA temperature deviation), and throttle settings. The information included in this deck, together with data on engine dry mass, size, and costs, may be eventually scaled using the results provided by a dedicated module for preliminary engine sizing, specifically built for a turboprop engine application. For the GENESIS project, this *rubber engine* module was generated using results produced by thousands of thermodynamic cycle simulations at design point performed with a gas turbine engine performance calculator (GasTurb[3]).

For the correct modelling of battery behavior, specific curves representing the discharge characteristics of the individual cells are interrogated. An example of battery discharge curve is provided in Figure 16a, where each curve relates to a different $C_{rate}$ value, i.e., current intensity. The voltage response of the cell can thus be interpolated or extrapolated linearly starting from the assigned curves, given values of the state of charge and of the current intensity. A $C_{rate}$ equal to 1 means that the discharge current will discharge the entire battery in 1 hour, and the total discharge capacity is equal to the $C_{rate}$ times the current intensity. Transient responses are not considered; however, they are believed to be reasonably negligible. A very similar approach applies to the fuel cells, for which HEAD needs operating curves of the single stack in order to model their operation. Figure 16b provides an example of these curves.



(a) (b)

Figure 16 - Examples of battery capacity versus battery voltage at different discharge rates (a) and PEM fuel cell stack characteristic curves (b).

## 5.2 Preliminary application of the aircraft design chain

This section provides some preliminary results produced for the GENESIS project in terms of application of the aircraft design chain. These results helped to outline reasonable demands for the different power sources involved in the project, depending on the selected time horizon. For these analyses, the set of TLARs of Table 4 was considered, as well as the design mission characteristics reported in Table 5.

Table 5 - Design mission ranges and durations.

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| Mission range | 600 | nmi |
| Alternate range | 100 | nmi |
| Holding duration | 30 | min |
| Fuel reserve | 5 | % |

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[3] https://www.gasturb.de/

Distributed electric propulsion was identified as the most promising powerplant configuration, especially for the short-term time horizon. In fact, it fits perfectly with the use of batteries as secondary energy sources. The serial/parallel partial hybrid-electric powertrain was selected as the powerplant scheme for these preliminary investigations since it is the most promising in terms of flexibility and global efficiency for the aircraft platform considered. Unlike synthetic fuels, the use of hydrogen as a primary/secondary energy source calls for new safety regulations. The serious safety and thermal management problems induced by the use of hydrogen require parallel work by the regulatory authorities, which must update the certification rules in order to guarantee the airworthiness of this new category of aircraft. This scenario is not likely to be realized within the next decade. In fact, specific powers above 2 kW/kg were identified as the minimum requirement to make the use of fuel cells competitive in aviation, and aircraft equipped with similar systems are expected to become commercial not earlier than 15 years [17]. For these reasons, fuel cells were identified as the main propulsive technology to bet on for the medium-term and long-term scenarios, given the potential of hydrogen propulsion to reduce climate impact by up to 90% [17]. However, a value of 4 kW/kg would be required from the fuel cell system to ease the transition from a traditional to a hydrogen-based configuration. Even for hydrogen-based platforms, the use of electric motors distributed along the wing can be useful to aim for high-efficiency wings, but it is important to quantify the real gain of such a complication in terms of weight, already highly penalized as a result of the liquid hydrogen ($LH_2$) tanks and fuel systems, as well as analyzing the acquisition and maintenance costs. An accurate weight estimate is necessary in order to properly take these aspects into account, starting from the structural masses of the aircraft and with particular reference to the wing, which, in the case of DEP, may be the subject of an optimization. However, for these preliminary analyses a semi-empirical method was used to estimate the weights [22]. A hybrid-electric architecture with two thermal engines, two battery packs and 8 DEP (4 on each semi-wing) was adopted for the analyses. The choice on the number of distributed propellers was driven by the results of previous investigations and the desire to limit the number of engines for reasons of weight, costs, and additional aerodynamic drag, while ensuring full coverage of the wing. Two propellers were installed at the wing tips to mitigate the drag increase. The aircraft was supposed to benefit from the aero-propulsive effects exclusively during the take-off, climb, and landing phases. A shaft power ratio equal to 0.8 in take-off, and equal to 0.5 in climb and landing, was assumed for the short and medium-term scenarios. For the long-term, a higher value, equal to 0.9, was assumed for the take-off segment. As for the characteristics of the batteries, the values reported in Table 6 were adopted according to the time horizon selected. Usage of Li-ion batteries was supposed for these preliminary calculations. For the medium and long-term scenarios, it was supposed that the thermal engines could be totally replaced by battery and fuel cells technologies. For the short-term, a specific energy of 12 kWh/kg was assumed for hydro-carbon fuel, coupled to a thermal engine efficiency of about 30% during all the design mission phases. For the fuel cell system of the medium and long-term perspectives, a 33 kW/kg specific energy was selected for hydrogen. Efficiency of the fuel cell system was assumed equal to 60% for both scenarios.

Table 6 - Preliminary assumptions on technology level of Li-ion batteries for the three scenarios.

| | **Short-term** | **Medium-term** | **Long-term** |
|---|---|---|---|
| Specific Energy [Wh/kg] | 250 | 350 | 500 |
| Specific Power [W/kg] | 500 | 1000 | 1000 |
| Energy Density [Wh/l] | 600 | 800 | 800 |

Specification points in terms of required power from different energy sources for the three time horizons examined are reported in Table 7. These values of maximum power required are all related to the take-off phase. These analyses allowed also to perform preliminary hypotheses, for the medium and long-term scenarios, on the amount of $LH_2$ necessary to complete the design mission, supposing to use the fuel cell system as the primary power generator, coupled with a secondary battery system (as reported in Figure 14). For the medium-term, it was estimated that 304 kg of $LH_2$ would have been required by the design mission. This value went down to about 250 kg for the long-term, due to the overall technology improvement.

Table 7 - Power specification points for the three time horizons.

| Powertrain component | Number | Reference Power (kW) | | |
|---|---|---|---|---|
| | | Short-term | Medium-term | Long-Term |
| Gas turbine | 2 | 2400 | 0 | 0 |
| Fuel cell system | 2 | 0 | 1800 | 1400 |
| Battery pack | 2 | 550 | 1100 | 2000 |
| Primary electric machine | 2 | 1200 | 1200 | 100 |
| Secondary electric machine | 8 | 600 | 600 | 750 |

# 6. Future developments

## 6.1 The future of the GENESIS Project

The previous sections have provided an overview of the aircraft design work carried out within the GENESIS project. The ultimate goal of the project is to complete feasibility studies related to a range of different future scenarios, with respect to three different time horizons, and to develop life-cycle analyses that bring to light the real environmental impact of these solutions, also including the production and disposal phases. At the same time, considerations regarding the contextual renovation of the infrastructures and the acquisition and operating costs cannot be neglected, given the need to make predictions on scenarios that will realistically be established on the market. This has already been partially done through the identification of TLARs starting from the state-of-the-art and the emerging needs of the market. In parallel, the design chain that will allow the conceptual design of the aircraft has been prepared. As seen in Section 5.2, this served to provide specialized partners with guidance for the design of electric motors and generators, batteries, hydrogen tanks, fuel cells and power electronics. Preliminary results have been delivered to the partners to allow them to perform perspective analyses on the different powerplant technologies involved, and to ease the development of reasonable assumptions and surrogate models for the evaluation of weight penalties and costs linked to each element of the powerplant. The outcome of these design activities will be surrogate models, allowing to have more precise estimates of the mass of this system. Also, thanks to the contribution of Delft University of Technology (TUD), it will also be possible to integrate a surrogate model for the evaluation of the structural mass in presence of multiple concentrated masses, as in the case of distributed electric propulsion. By integrating partners' experience-based assumptions and the aforementioned simplified models into the design chain, also thanks to the support of SmartUp Engineering (SMARTUP), it will be possible to reiterate the design process, which refers to the activities of the Work Package 1 (WP1) of the project, for which UNINA is responsible (see Figure 17).

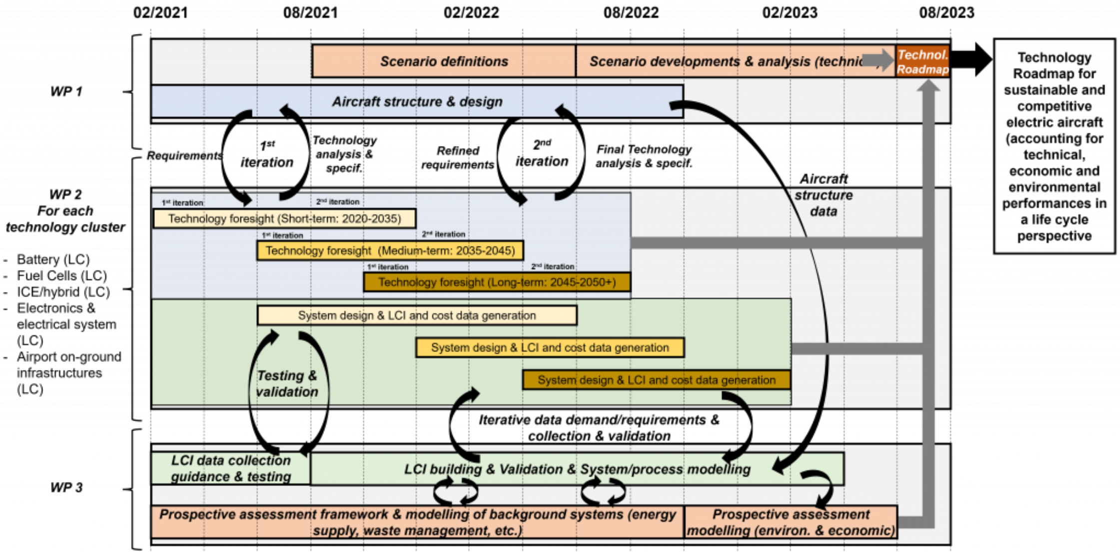

Figure 17 – Activity program of the GENESIS project.

The interactions with the specialized partners of WP2, whose main activities are coordinated by the Friedrich Alexander Universität Erlangen Nürnberg (FAU-LEE), are also qualitatively represented in Figure 18. This activity will allow to rely on much more realistic and reliable estimates of masses and efficiencies, which is a crucial step for the correct assessment of total energy saving and emissions reduction. The subsequent iterations of the design process will aim at identifying the maximum levels of hybridization allowed by the forecasted technological levels, for each of the scenarios analyzed, while matching TLARs and certification constraints.

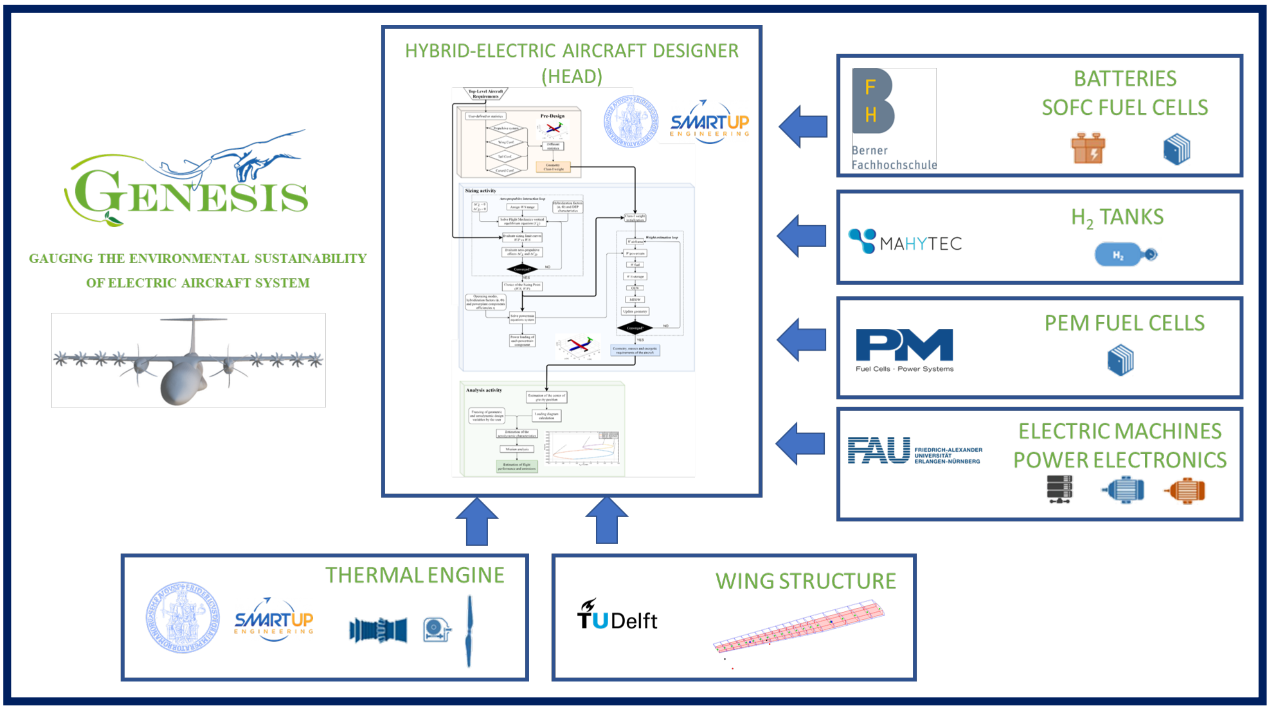

Figure 18 – Activity program of the GENESIS project.

## 7. Conclusions and outlook

The previous sections have highlighted the preparatory work performed for the GENESIS project in order to carry out design activities related to hybrid-electric regional aircraft platforms. A detailed market analysis has allowed to select the most suitable set of TLARs for such a configuration. A description of the design process of a hybrid-electric aircraft has been provided, including details on about the possible variants in terms of powerplant architecture and on the aero-propulsive effects that should be considered when designing an aircraft with these characteristics. The aircraft design chain that will be employed has been introduced. Preliminary applications of the design chain, based on initial assumptions by the authors, served as a starting point for the activities of the industrial partners in charge of the design of the structures and powertrain components, in order to create simple surrogate models suitable for conceptual design. Future developments of the GENESIS project will consist of preliminary aircraft design activities, integrating GENESIS partners' contributions in terms of general indications and models, enabling a much more reliable assessment of future aviation.

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## 9. Copyright Statement

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