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Parametric cost method for enabling technologies of hybrid propulsion aircraft

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Introduction

Today climate changes and pollution is a real problem for the World and rapid changes are needed. Passengers who use the aircraft for the mobility have doubled in the last 10 years from about 2 to 4.6 billion in 2019 with a forecast of 8.2 billion in 2037 (Source IATA).
In Italy, air traffic is growing due to the airport system which closes 2019 with 193.1 million passengers, 4% more than in 2018, and 1.6 million air movements, equal to + 2.7%, always on the previous year.
But for the planet this increasingly accelerated mobility (also due to the increase of low-cost companies) will be detrimental, if companies do not collaborate to the reduction of the levels of emissions (NO_x and CO_2) per passenger per unit of space travelled.
According to data released by the Air Transport Action Group, a consortium of experts in the aviation sector that deals with issues related to sustainable development, the sector would today produce about 2% of the CO_2 emissions produced by human activity globally (3% than the European ones). According to the data of the European Environment Agency, in 2016 13% of the CO_2 emissions due to the transport sector. To make a comparison, cars from all over the world would account for 72% of the sector's total emissions. Airplanes are the most polluting means of transport. To fly produces 285 grams of CO_2 for each passenger for every kilometer traveled. A car produces 42 gr per passenger per kilometer. About 8 out of 10 tons of this CO_2 emitted concerns long sections, over 1500 km.
According to estimates by Supporting European Aviation, air traffic (over 1 million flights) in Europe would have generated 20.7 million tons of CO_2 in July 2019.
The European Commission accounts for the 10 most polluting big companies in Europe, nine coal-fired power plants, and in tenth place an airline, with 9.9 mega tons of equivalent pollutants produced in 2018.
In order to reduce this source of pollution, the possibility to use planes with electric or hybrid engines has been being studied for several years in order to significantly reduce emissions.
The 'decarbonisation' of the airline industry will be a crucial part of the global effort to contain climate change. So far, it has seemed like a titanic challenge. The fuel currently used for airplanes - kerosene - has an energy density 60 times higher than that of the latest generation electric batteries. The significant progress achieved in the field of electric vehicles in recent years suggests that 'electric flights' are an achievable goal; however, in this phase, a 'hybridization' appears more feasible than a complete electrification, with a reduced initial impact.
The aviation industry is currently not subject to regulations on CO_2 emissions, but the sector has already voluntarily committed to achieve reduction targets for several years. For example, the

International Air Transport Authority (IATA) aims to cut emissions by 50% by 2050 compared to 2005 levels.

There have been constant improvements in battery technology in recent years, with electric vehicles managing to generate more power from smaller cells.

Instead, we believe that the airline industry is on the verge of hybridization, as was the automotive industry 10 years ago. Industry engineers have already started to imagine hybrid aircraft for the regional 30-40 seat aircraft market. UBS recently hypothesized a new scheme for the use of fuel and electric thrusters during a typical flight, illustrated hypothetical power mix of a hybrid flight Source: UBS estimates

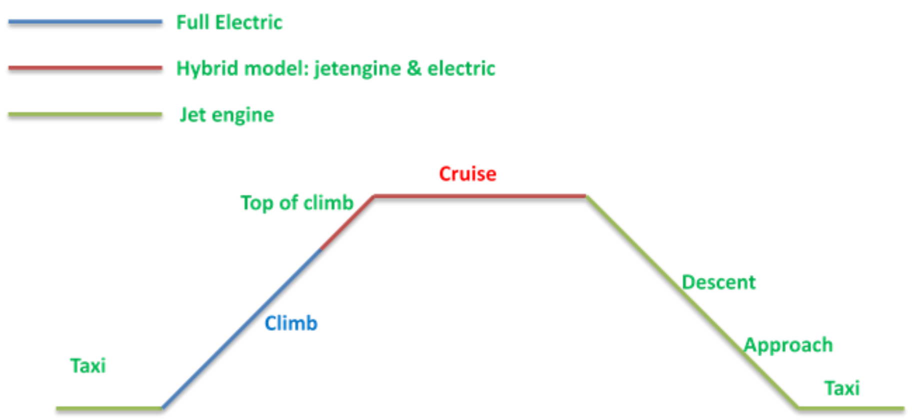


Figure 1 - UBS typical mission scheme for hybrid propulsion

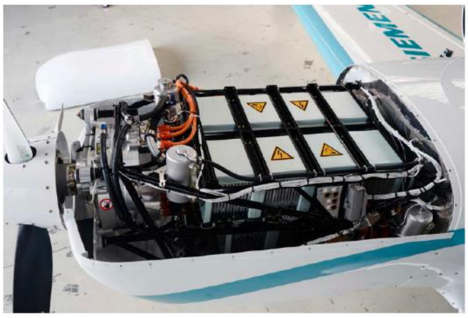
For aviation, it is a radical change, which aims to reduce NO_x by 50% in 2050 [1].

Flightpath 2050 [1] is an ambitious project promoted by the European Commission by the major airlines and manufacturers, as well as by research institutes. The main objectives are to satisfy the growing demand in recent years, guaranteeing ever more reliable mobility. Other fundamental aspects are linked to the development of new technologies capable of reducing greenhouse gas emissions; in particular as found in the text of Flightpath 2050:

technologies and procedures available allow to 75% reduction in CO2 emissions per passenger kilometer and to 90% reduction in NOx emissions. The perceived noise emission of flying aircraft is reduced by 65%. These are relative to the

- capabilities of typical new aircraft in 2000;
- aircraft movements are emission-free when taxiing;
- air vehicles are designed and manufactured to be recyclable;

In the world of ultralight aircraft, this huge step has already taken, as demonstrated by the fully electric Siemens $Extra$ 330 LE [2] (Figure 2) ultralight aircraft.



Aircraft data	
Wingspan	8.0 m
Length	7.5 m
Height	2.6 m
Wing area	10.7 m²
Technical data electrical propulsion system*	
$P_{cont.}$ (MTOP = MCP)	230 kW
N_{max}	2,250 rpm
$M_{cont.}$	1,000 Nm
U_{ZK}	580 V
η_{Motor}	max. 95%
$T_{cooling\text{-}inlet}$	90° C
m_{motor} incl. prop bearing	50 kg

Figure 2 - Extra 330 LE ultralight aircraft

Other studies, such as the Airbus with the E-fan 1.0 [3], also a fully electric two-seater light aircraft with ducted propeller and high wing configuration (Figure 3, Figure 4), have been carried out. The latter made his first flight over the English Channel demonstrating high autonomy about 1 hour [3].

Figure 3 - E-Fan 1.0 during his first flight

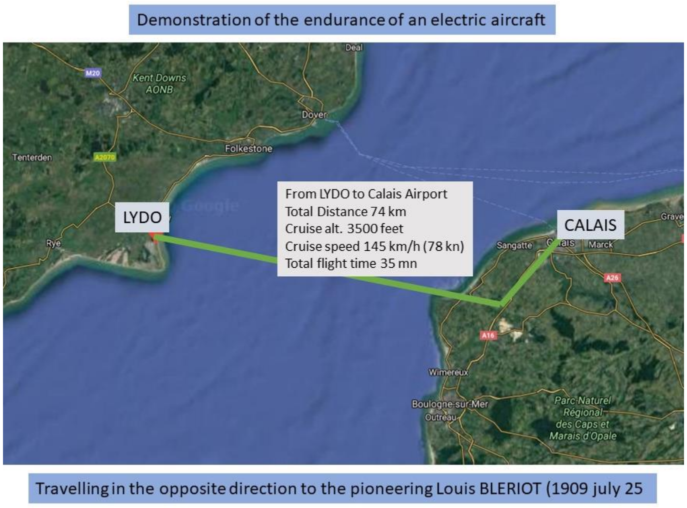


Figure 4 - E-Fan1.0 first flight itinerary

These examples make it clear how research is moving towards eco-sustainable mobility and that the future focused on the electricity propulsion.

Considering the state-of-the-art of the technologies, regional transport aircraft hybridization is impossible to obtain in that electric motor power density and battery energy density know-how is limited.
For this, the great designers and worldwide manufacturers of aircraft such as Boeing, Airbus and Leonardo, together with all the main European companies, thanks to the Clean Sky JU project [4] , are developing new technologies to allow the passage of commercial aircraft, from electric, to hybrid propulsion.
Many hybrid aeronautical propulsion studies have been carried out by research institutes such as NASA developing a new aircraft concept that pairs better with the new power plant. Two examples are the X-57 [5],[6],[7]and PEGASUS [13]. The last project, developed by NASA, has examined an ATR-42, a 50 seats regional aircraft.
Another example of hybrid propulsion is the E-Fan X [8] , the latest in a fleet of already two electric aircraft E-Fan 1.0 and E-Fan 1.2.The E-Fan X derive from the collaboration between Airbus Rolls Royce and Siemens which aimed to design and build a 100 passenger hybrid aircraft. The base aircraft was a BAE 146, to which containing modified engine. The new engine was a series hybrid with a 3000 kW ICE and a 2 MW electric motor. The date of the first flight is planned for 2035.

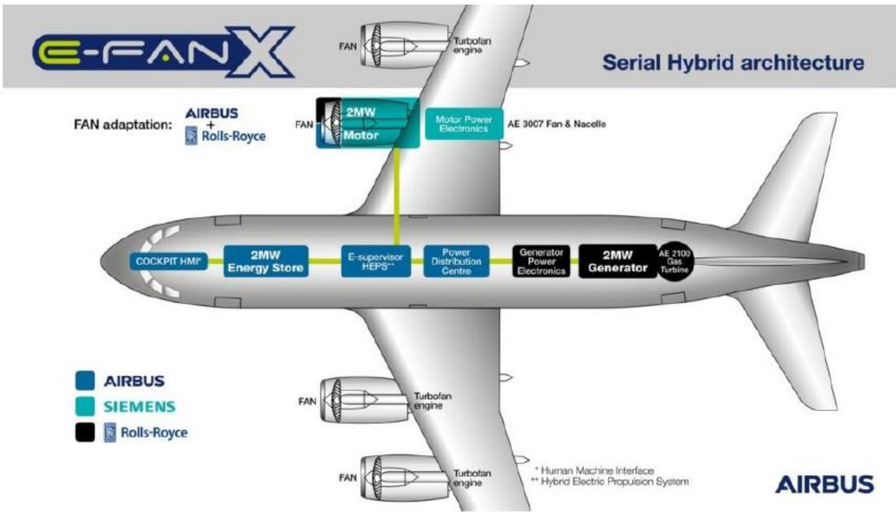


Figure 5 - E-Fan X

World of the hybrid, already known in the automotive field, represent an unexplored field for commercial civil aviation due to the great investment required and the limited knowledge and technologies available.
The aim of the study addressed in the thesis was to develop a cost analysis model capable of estimating the costs for the development of enabling technologies for the hybridization of regional aircraft, given the low technology readiness level (TRL) for such technologies.
Despite the great step forward made by automakers and ultralight aircraft companies in the hybrid and electric fields, it is difficult to hypothesize to scale these technologies for powers that are

three orders greater; just think that the power needed to carry out a typical mission for an ATR-42 is 4MW, while for an ultralight like the Extra330 LE it is just 230 KW while for a car is 50 kW.

It is therefore necessary to develop new technologies as well as new most performing and innovative materials capable of generating high powers with low weights in order to make sustainable air mobility possible.

Chapter 1

1. Hybrid propulsion: state of the art

As seen in the introduction, today, internal combustion engines (ICE) have a significant advantage over batteries thanks to the energy density of the fuel. The disadvantage lies in the high cost of fuel and abuse both in terms of emissions and noise. The battery electric aircraft (BEA) has a significant advantage in terms of energy efficiency, and also in terms of pollution, being zero emissions. Hybrid electric aircraft (HEA) are therefore able to exploit both the advantages of the ICE and those of the BEA, using two sources of energy. At state-of-the-art considering the most electric aircraft (B787), it is capable to generating energy for 1.5 MW, for a regional electric hybrid aircraft 5 MW is needed as shown by a study carried out by Safran Figure 6 [14] .

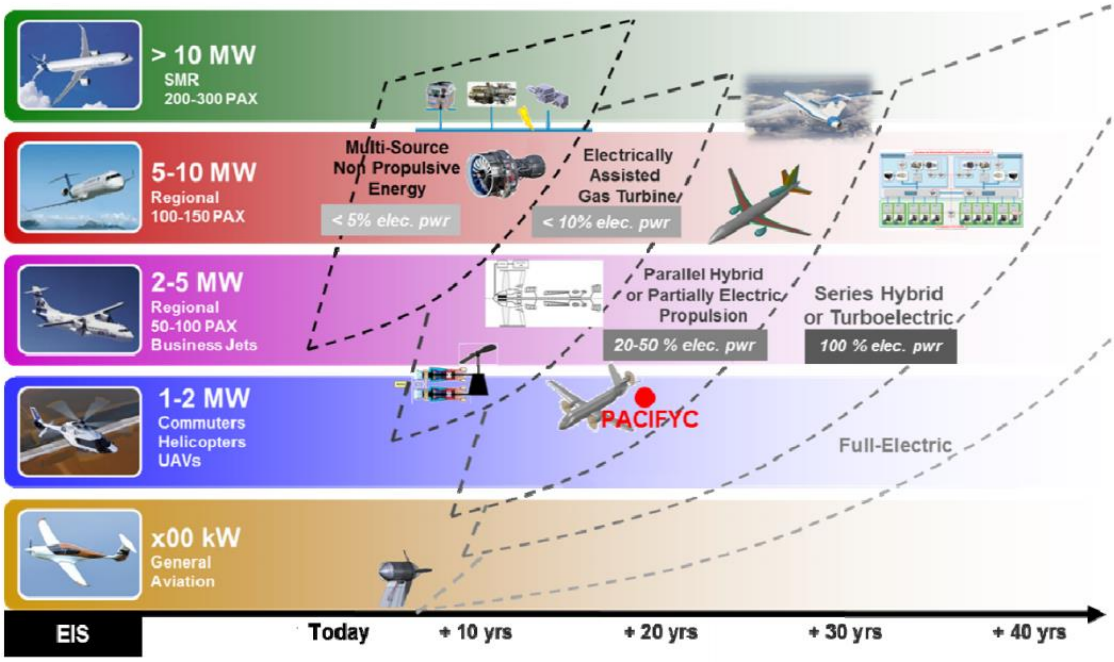


Figure 6 - Hybrid electric aircraft future trands.

As seen in the introduction, in the aeronautical field, there are examples of aircraft and hybrid concepts for future sustainable mobility. To date there are about 20 electric or hybrid aircraft with fixed wing and with equipment that have made the first flight, even if only 3 of them are on the market. A study conducted by the National Accademy [9] indicates a table in which the technological objectives for engine and generator batteries in which the hybrid and electric aircraft that have already integrated the first flight and those deriving from studies recorded by the Associates (e.g. Clean Sky 2), from industries and start-ups born after the boom of electrified mobilization.

Name	1st flight yr	Arch. [1]	Seats	TOGW (kg)	Max power (kW)	e_b (W hr/kg)	Range (nmi)/ Endur	Remarks
Lange Antares 20E	2003	E	1	660	42	136	NA	1st elec. aircraft w/ airworthiness cert.; commercially avail. motorglider
Fishman Electraflyer C	2008	E	1	283	13.5		90min	Converted motorglider; Li-Po battery
Boeing HK-36 FCD	2008	FC	1	860	75	NA	45min	30kW fuel cell; experimental
Yuneec E430	2009	E	2	470	40	154		Clean-sheet composite airframe; commercialization abandoned
Siemens/Diamond E-Star	2011	SHE	2	800	70			30kW Wankel engine, experimental
Pipistrel Taurus Electro G2	2011	E	2	450	40			Commercially avail.
Pipistrel Taurus Electro G4	2011	E	4	1500	150	180	244	Won NASA Green Flight Challenge; experimental; 400+ pmpg
IFB Stuttgart eGenius	2011	E	2	950	60	204	244	Competed in NASA GFC; experimental
Embry-Riddle Eco-Eagle	2011	PHE	2	1075	105	125	170	Unofficial participant in GFC; 75kW rotax, 30kW elec; exp.
Fishman Electraflyer ULS	2012	E	1	238	15		120min	Commercially-available under US ultralight rules
Chip Yates Long ESA	2012	E	1	680	192			Experimental
Siemens/Diamond E-Star 2	2013	SHE	2	800	80			5kW/kg motor; experimental
Airbus E-Fan	2014	E	2	600	60	207	60min	2x30kW fan; experimental
Cambridge SOUL	2014	PHE	1	235	20	144		12kW elec, 8kW petrol; recharges in flight; exp.
Pipistrel Alpha Electro	2015	E	2	550	60	171	70	Commercially avail.
Airbus E-Fan 1.2	2016	SHE	2	600	60			2x30kW fan, 50kW range extender; experimental
Siemens Extra 300 (330LE)	2017	E	1	1000	260			95% eff. motor, >5kW/kg incl. inverter, 580VDC; exp.

Name	Target EIS yr	Arch. [2]	Seats	TOGW (kg)	Max power (MW)	e_b (W hr/kg)	Design Range (nmi)	Remarks
NASA X-57 "Maxwell"	2018	E	2	1360	0.144	130		2x72kw tip motors; manned demonstrator; leading-edge DP
NASA STARC-ABL	2035	TE	154	60000	2.6 [3]		3500	-9.4% fuel burn; tube/wing config. w/ tailcone BLI prop.
NASA N3-X	2045	TE	300	227000	50		7500	-10% FB due to EP; supercond.; HWB w/ BLI dist. prop.
Boeing SUGAR Volt	2035	PHE	154	68040	1.0 [4]	750	3500	-10.9% FB due to EP; Strut-braced wing w/ battery pods
Bauhaus Luftfahrt Ce-Liner	2035	E	189	109300	33.5	2000	900	C-wing, supercond. motors, aggressive tech assumptions
Airbus VoltAir	2035	E	~33	~33000		750+	~900	Superconducting electronics; BLI; laminar-flow wing
Airbus/R-R E-Thrust	2050	SHE	90		9.0	1000	Rgnl	Superconducting; BLI and high bypass ratio; embedded fans
ESAero/Wright ECO-150R	2035	TE	150	60-75k	12.7		1650	FB ≈ 737-700; 16 motors embedded in wing; no supercond.
Eviation Alice	2019	E	11	6350	0.780	260	560	3 pusher props; Kokam Li-Ion batteries
XTI Tri-Fan 600	2024	SHE	6	2404	1.5		1200	VTOL; tilt-fan configuration
Ampaire Tailwind	2020s	E/SHE					350	Tail-mounted boundary layer ingestion thruster
Zunum	2020s	SHE	12	5216	1		700	Conventional regional jet layout; straight NLF wing

Table 1 - List of hybrid or electric aircraft concept [10]

In the table are listed:

- Aircraft names
- Year of the first flight
- Hybrid configuration used: E = Electric FC = fuel cell; SHE/PHE=Series/parallel hybrid; TE=Turboelectric;
- Number of seats
- Take off gross weight (TOGW) including the weight of all the propulsion system with the respective fluids
- Maximum power
- Energy density of batteries
- Range or endurance
- Specific characteristics for each aircraft.

Results obtained from the studies carried out by National Academies of science engineering medicine [9] indicate that electricity can bring significant improvements in terms of emissions and noise as well as a reduction in costs (DOC) per flight.

When evaluating the feasibility of electric hybrid propulsion, the two fundamental technological keys are: specific power and specific energy.

The specific power is the power per unit of mass of a specific component and is measured as kW / kg; this value is used in reference to electric motors, obviously an attempt is made to obtain the highest possible value.

Specific energy is the amount of energy per unit of mass and is measured as Whr / Kg; this parameter is used to characterize the batteries.

Making a first comparison with the conventional propulsion, it is known that the value of the energy density of a lithium-ion battery is 60 times lower than that of the jet-A aircraft fuel; 200 Whr / kg of batteries compared to 12000 Whr / kg of Jet-A.

The impact of these values in practice is found in the equation of the Breguet range.

In the case of kerosene:

$$R_f = \frac{L}{D}\eta_p\eta_{int}\eta_{eng}\frac{e_f}{g}\ln\left(\frac{1}{1-\frac{m_f}{m_{TO}}}\right)$$

- L/D = Lift to Drag ratio
- η_p = propulsive efficiency
- η_{int} = efficiency due to propulsion integration losses
- η_{eng} = thermal combustion engine efficiency
- e_f = fuel specific energy
- m_f/m_{TO} = fuel weight to take off gross weight ratio

For battery:

$$R_b = \frac{L}{D}\eta_p\eta_{int}\eta_e\frac{e_b}{g}\frac{m_b}{m_{TO}}$$

- η_e = total efficiency of the electric propulsion system
- e_b = battery specific energy
- m_b = battery mass

So the operating range being proportional to the specific energy, makes that the electricity is 60 times lower and considering a plausible range you would have to take on tons of batteries by reducing the paying load.

The state of the art of energy storage technologies according to a report by the NAE [9] commission will reach values of 400-600 Whr / Kg in 2035.

Another key parameter in the search for electric propulsion is in the choice between direct (DC) or alternating current (AC) in the distribution buses, as well as the operating voltage to be used. Studies carried out by Vratny et al. [11] indicated a better behavior of the variable voltage in hybrid architecture; moreover, an high voltage system is overall more efficient but results in reduced weight and reliability. For reliability, in fact, Paschen's law states that the air gap insulation is safe up to 327 V and for this reason in civil aviation it is limited to voltages of 270 V. All this translates into the need, for the development of hybrid propulsion, to develop new durable and light highly insulating materials and technologies capable of managing operating voltages of the order of kV.

For the distribution of energy, at the state of the art, the continuous (DC) one is considered so as to eliminate the need to synchronize the phases of multiple electrical components but involves penalties in terms of weight and efficiency due to the necessary AC / DC converter. In this case, therefore, the power electronics, also due to the necessary redundancies, would have a greater weight than the motors themselves.

The following paragraphs will analyze all the technologies in detail, also analyzing the different configurations for hybrid propulsion.

1.1 Design arrangement

Recent studies on the feasibility of hybrid propulsion for civil aviation show a low TRL (Technologies readiness level) related to many of enabling technologies for hybrid propulsion; for other hand, the design is already well defined. The possible hybrid propulsion configurations (Figure 7) differ according to the type of power generation and the arrangement of the propulsion system itself.

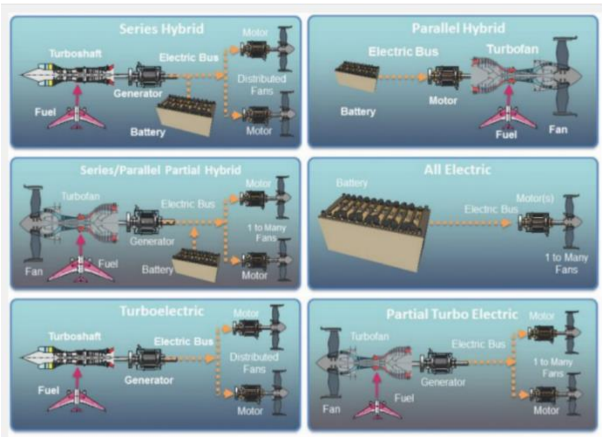


Figure 7 - Hybrid configuration [9].

For the power generation, in addition to the full electric power that, at the state of the art, is in fact impossible to achieve due the lower power in term of MWatts as Stéphane Cueille, Safran reveals - *"Batteries have an energy density 60 times less than kerosene. Even if you multiply the current density by five you would need 180 tonnes of batteries to fly an A320 single aisle aircraft more than 3,000 nautical miles. The aircraft's take-off weight is only 80 tonnes, so that gives you an idea of the challenge. "*-, there are all the possible configurations that include the coupling of an internal combustion engine and a battery.For the type of power consumption, it can be concentrated or distributed according to the number of fans present. The concentrated configuration provides a single fan for the generation of thrust, so there is a single electric motor that moves a fan using both, the batteries energy and the conventional motor; the other one, distributed, provides for the use of multiple electric motors connected to multiple fans that allow new aerodynamic solutions, like blown wing, which allows to reduce the size of the wings like to NASA X-57 [5][6][7] (Figure 8). This project, still in the experimental phase, involves the modification of a *Tecnam P2006T* by replacing the engines with twelve electric motors using the energy supplied by 850lb of batteries with a total capacity of 47 kWh.

Figure 8 - NASA X-57 configuration [5][6][7].

1.2 Series hybrid system

The series hybrid system (Figure 9) consists of a conventional internal combustion engine connected to a generator which sustain a battery and an electric motor connected to a fan. Battery provides power in the take-off and climb phase to reduce the ICE (Internal Combustion Engine) necessary power. This system allows the engine to be designed to work always in optimal conditions, therefore at maximal efficiency, as well as for the generator that will always operate at maximum efficiency. Thanks to the batteries that provide for the power peaks (take-off and climb), the ICE has a power 50% lower than a conventional aircraft [4]. Another advantage is the ability to place the thermal engine anywhere.

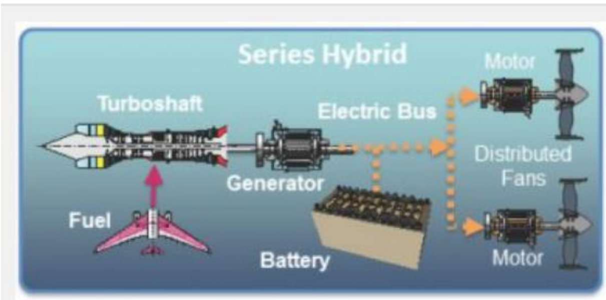


Figure 9- Serial hybrid configuration [9].

The disadvantages of this philosophy is due to the excessive weight of aircraft due to the batteries that must guarantee 50% of the total power and to the generator that could develop powers in order of MW. Another penalizing factor is given by the triple energy conversion from chemical to mechanical (ICE), electrical mechanical (generator) and from electrical to mechanical (electric fan motor), which provides a serious loss of propulsion system efficiency. The example showed in the figure below (Figure 10) represent the Siemens *«DA36 E-Star 2»* [15] project in which a motor glider is powered by a 94 HP electric motor with a power density of 5kW / Kg and with 40 HP Wenkel motor that powers the motor. electric and recharge the batteries. During the take off and climb phases the batteries provide an auxiliary power of 80 kW.

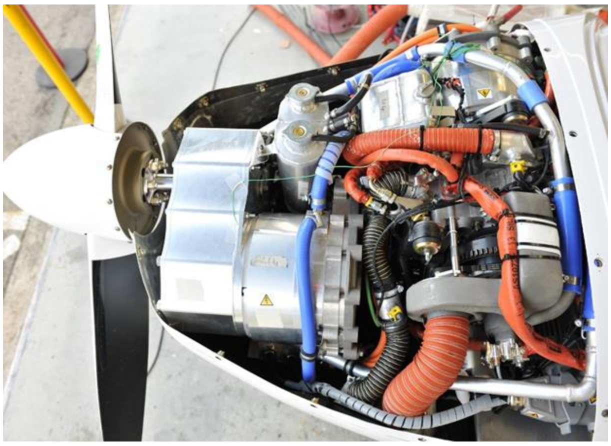


Figure 10- DA36 E-Star 2. Pannon Air Service/Diamond Aircraft Hungary [15].

1.3 Parallel hybrid system

In this arrangement, there are two propulsion lines, one with internal combustion (conventional) and one electric, connected through a mechanical clutch that in turn is combined with a fan. (Figure 11)

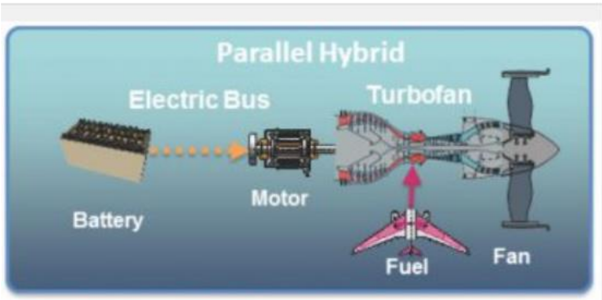


Figure 11 - Parallel hybrid configuration [17].

Thanks to the clutch both, the electric and the thermal motors can provide propulsion in pairs by on their own, it is also possible to avoid the generator, since the electric motor during the cruise phase can act as a generator by recharging the batteries and there is no continuous energy conversion with consequent increase in the efficiency of the propulsion system.

The disadvantages are due not only to the size and weight of the engine, but also to the low efficiency of the conventional engine that could work dynamically.

The (Figure 12) shows the first example of hybrid propulsion made in a German company Flight Design in 2009, they created a test bench for a propulsion system for a light sport aircraft. The engine consists of a 40HP electric motor and 115HP Rotax motor managing in order to generate 160HP in total. By comparison with the Rotax 160HP model have been highlighted a reduction in fuel consumption and a greater planing in the case of planting the engine.

Figure 12 –First hybrid parallel avionic engine [18] .

Another aircraft model analysed [13] was the one developed by Antcliff et other. This model highlighted how the parallel hybrid engine for a regional aircraft (ATR 42) have the potential to reduce operating costs by decreasing the total propulsive energy used (Figure 13).

Figure 13 - Conceptual Design of the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) Concept [13].

In addition to an innovative propulsion system, this proposed configuration also introduces new concepts; BLI and wingtip propulsion (Figure 13).

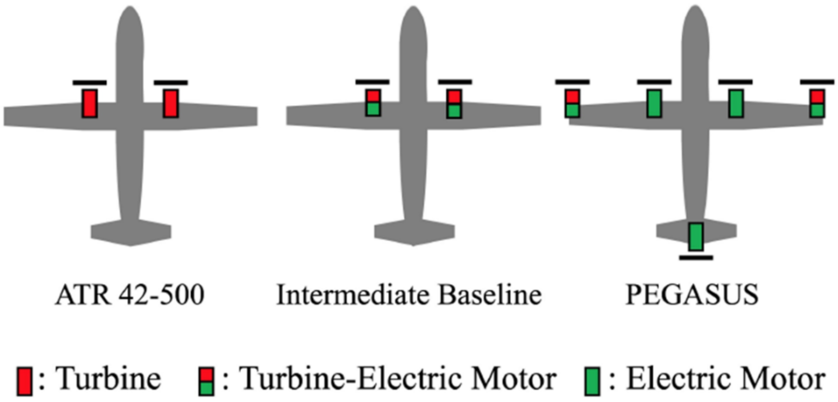


Figure 14 - Pegasus innovative configuration [111].

The two hybrid thrusters located at the ends of the wings (wingtip) sized for cruise, take the rotational component of propeller flow by attenuating induced drag. This system leads to a decrease in power required for the cruise flight with the same wing area.

These engines exploit the parallel hybrid configuration in the power assistant model that consists in exploiting the power of the electric motor during the take-off, landing and take-off phases. This method allows to having a reduced ICE of size and power compared to the conventional one.

The fully electric "internal" thrusters are powered by batteries with a specific energy of 500 Wh / Kg and contribute to the thrust during the flight phases described above and then could be closed again during the cruise due to the poor aerodynamic behaviour (Figure 15) .

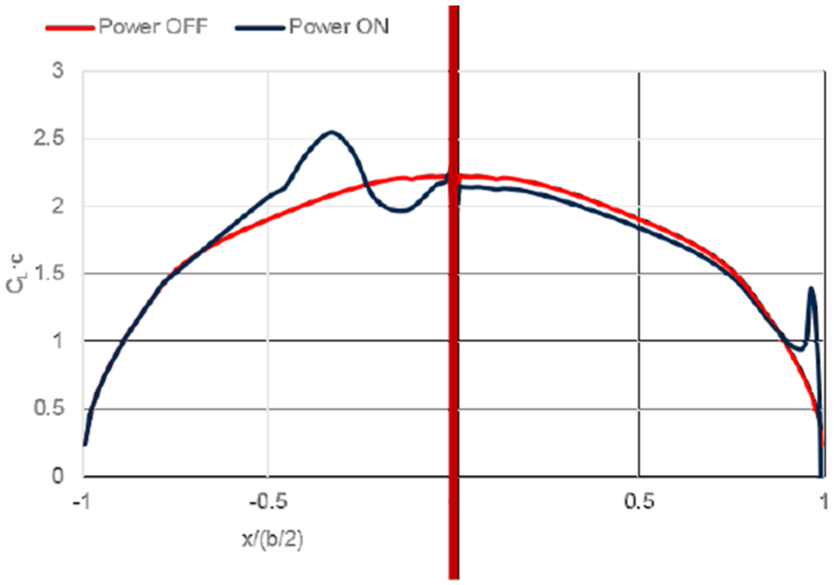


Figure 15 - Lift wing distribution comparison [13].

BLI (Boundary Layer Ingestion) technology (Figure 14) provides a tail propeller capable of ingesting the boundary layer of the fuselage. According to studies [19], by ingesting 50% of the boundary layer there is a 70% reduction in the momentum deficit generated by a typical fuselage and an 10% increase in propulsion efficiency.

The last problem to analyse is the operating range and the problems related to the autonomy reserve considering that the operating range for this Pegasus aircraft is 400 nm.
The project plans to use only the electric propulsion generated by the two in-board engines and the BLI engine for ranges less than $200\ nm$ while for missions between 200 and $400\ nm$ all five engines will be used, taking advantage by the four engines on the wings for take-off and for cruising only the wing tip propellers and the BLI.
For the reserve mission imposed by the regulations, either 20% of the remaining battery charge is used, which however involves replacing them, or resizing the gas turbine of the hybrid engine to meet the reserve mission. Despite a larger engine size, this solution is the more efficient of the two in terms of weight.

Chapter 2

2. Enabling technologies

For the feasibility of electric flight there are three fundamental principles:

- Energy concept: it is the energy that can be totally converted into useful work. The exergy of a system is given by the sequence of energy conversion efficiencies of each component. This implies that since there is no Carnot limit as for thermal engines, the gap between thermal and electric motor at the current state of the art is 20-30 in terms of efficiency.
- Specific power and Ragone metrics: it is the combination of the energy source with the power converter. More than the energy and the power density of the source, for the purposes of feasibility, it is important to determine the parameters referring to the combination of source and power converter.
- Degrees of freedom of hybridization: it is necessary to consider the possibility of combining multiple energy sources and converters in order to generate the powers necessary for flight.

Considering these three concepts, all the components present in hybrid systems are analysed in order to identify the state of the art and the future trend of the technologies necessary for the implementation of a new flight concept.

So the enabling technologies for the hybrid as well as including batteries, electric motors, power management systems, are also linked to the new aerodynamic concepts such as the wingtip propellers and the BLI. The latter will be analysed individually in order to determine the state of the art and future trends.

2.1 High density energy battery

In the state of the art, battery technology uses graphite, lithium or metal oxides (Co, Mn, Fe, Po) as the material for electrodes. This limits the specific energy to a value <300 Wh / Kg, allowing the flight of 3 hours for small demonstration aircraft and UA*Vs*.

Another technology in development are lithium-sulphur batteries, which offer theoretical energy densities about five times higher than lithium-ion ones with energy density of 450 Wh / kg (Figure 16) [21].

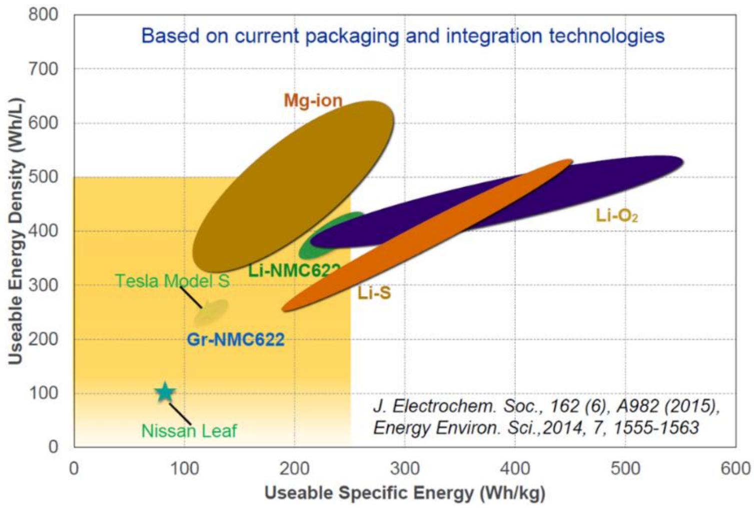


Figure 16 - Different battery technologies. Specific Energy vs Energy density.

In the yellow box there are batteries on the market, the colored areas represent the power field of each technology.

The development of new battery technologies as well as their increase in energy density is very rapid in fact in the past the specific energies of the batteries increased by 7% per year (Figure 17 - Energy density at cell level future trend.) [22]. Obviously it is necessary to consider the theoretical limits (Figure 17), referred to the potential chemical characteristics of the materials, from the real ones in which the drop due to the assembly of more cells is also considered (Figure 16).

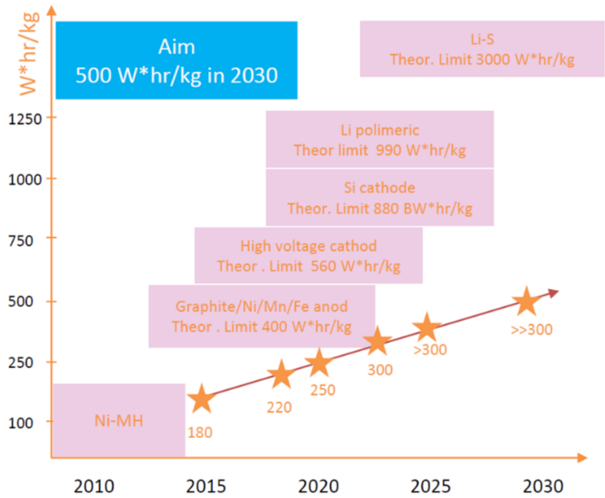


Figure 17 - Energy density at cell level future trend.

In this scenario, batteries with 1000-1500 Whr / Kg seem to be possible in the medium-long term (5-7 times the present value). The theoretical limit does not consider the masses of the packaging and electrolytic cells, that drastically lower the specific energy level.

In addition to the weight due to the packaging, it is necessary to consider the loss of energy due to the connection of multiple cells necessary to form a battery pack. Initially the total loss from cell to battery pack was 30%, in the state of the art there is a loss of 15% due to the innovative materials and integration between cells and pack (Figure 18) [21].

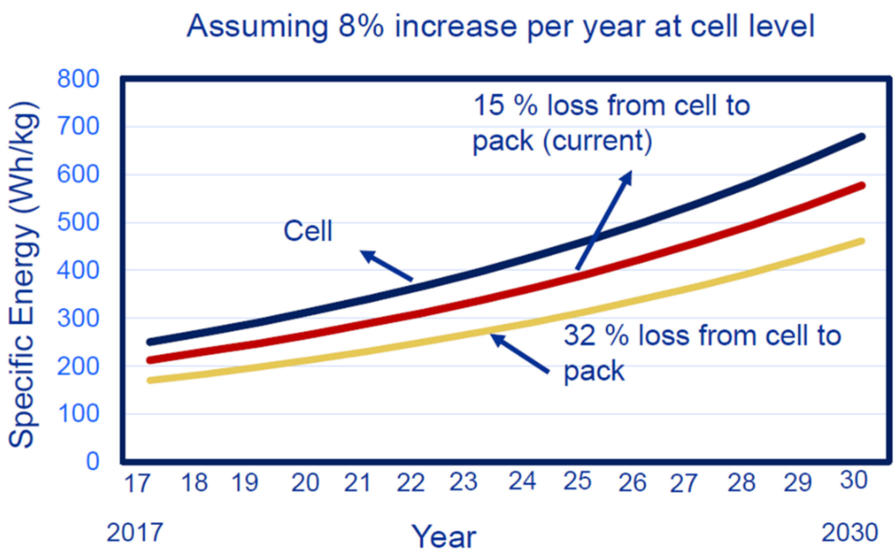


Figure 18 - Power loss from cell to pack future trend.

For a regional aircraft, considering a power between 2-5 MW, a battery energy density of 500 Wh / Kg is required [23].

2.2 High power density motors and power electronics

A fundamental component for hybridization is the electric motor which, based on the type of configuration, is connected directly to the fans (series) or to a clutch (parallel). In the first case, this component must supply the torque necessary to operate the fans, in the second case it must compensate for the power peaks during take-off and climb and then act as a generator during the cruise phase to recharge the battery pack.

The constrains for this technology is the weight, in particular the minimum power density required to develop hybridization. Considering the *PEGASUS* [13] case, a power density equal to 10 hp / lb (16.5 kW / Kg) had been considered. From the study presented by NASA in 2014 (Figure 19 - Electric motor future trend.) [21], the target for this technology is expected to be reached in 2025. The electric motor will be developed with superconducting technology and with a cryogenic cooling system due to the high powers that make it overheat.

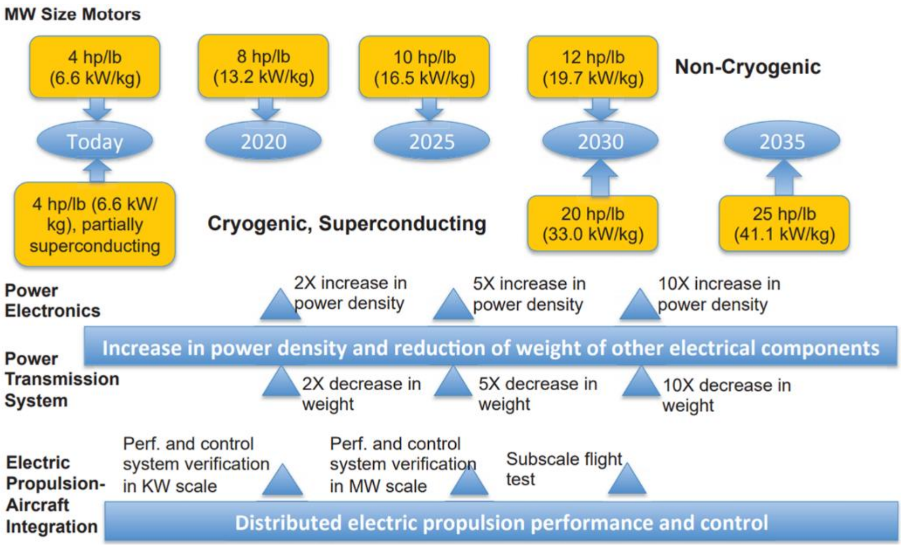


Figure 19 - Electric motor future trend.

At the state of the art the motors necessary for hybrization are those with permanent magnets. Let's first analyze the advantage of applying this technology:

- no electricity is absorbed by the field excitation system and therefore there are no excitation losses which result in a substantial increase in efficiency,
- higher power density and / or torque density than when using electromagnetic excitation,
- better dynamic performance than motors with electromagnetic excitation (higher density of magnetic flux in the air gap),
- simplification of construction and maintenance

For these reasons, the electric motor candidate for hybridization is that with permanent magnets; in particular this technology can bring improvements not only in performance but also for power density (output power and weight ratio). For the type of motor, on the other hand, we opt for brushless motors given the improvements in the field of drives, a semiconductor that guarantees better control of the motor that controls to work with high efficiency in a wide range of speeds.

Permanent magnet synchronous or sinusoidal brushless motors are used more and more widely in the industrial sector. They are essentially intended for drives high performance, in which the specific details justify their cost which is usually high due to the presence of valuable permanent magnets in the mobile element (rotor).

The electromechanical conversion they implement follows the principle of operation of the electrodynamic systems in which, however, the conductors on which the forces act are located in the fixed part (stator) and the rotor is set in motion by the physical reaction principle.

The power losses in this case will all be in the stator, not in the rotor, requiring easy removal of heat through the frame or a liquid cooling system.

There are also constructive examples [20] of brushless PM motors (Permanent Magnets) that have replaced the ferrite and Alnico magnets, demonstrating a huge improvement in terms of power density and dynamic performance.

In addition to the motor, there are also all the components necessary to manage the large electrical power, such as inverters or the PMU (Power Management Unit). Then, there are all the connections between the various electrical components that must be able to transfer energy with minimal dispersion (power bus).All these auxiliary technologies are currently under experimental phase except for the inverter (Figure 20) [21] already sufficiently that was sufficient developed as technology.

	Continuous Power Rating, MW	Specific Power Goal kW/kg	Efficiency Goal %	Switch Material	Cooling
General Electric	1	19	99	SiC/Si	Liquid
Univ. of Illinois	0.2	19	99	GaN	Liquid
Boeing	1	26	99.3	Si	Cryogenic

Figure 20 - Inverter SoA.

Chapter 3

3. Cost analysis model

The aim of the present thesis is to create a parametric model of the cost analysis for the hybridization of a regional aircraft. The development of such a model is strongly limited by the sacre knowledge on the argument and may be developed considering only the few studies and normalization available so far; this also limit the level of detail and the approaches that can be obtained. Therefore, we moved in accordance to the document drawn-up by the ISPA (International Society of Parametric Analysts) [36], the estimates of future costs must be consistent with the collection of historical data and cannot have a level of detail lower than that found. The parametric technique therefore requires a very accurate collection of historical data including the costs for development, including working hours, and that for other factors that most influence the development of the costs. The development of a parametric model in accordance with the ISPA document (Figure 21) is divided into several activities, grouped in six steps:

1. To define the dependent variable of what the CERs will estimate (Cost Estimate Report). As better is the definition of the dependent variable, as the simpler it will be to collect comparable data for the development of the ERC.
2. To select the independent variables on which the estimate of the dependent variable will be based. The technical data for the determination of the fundamental cost predictors can be taken from different various sources, including Enterprise Resource Planning (ERP), technical drawings, specifications, production processes used, tools and skills of the development team. In the case of the development of a CER for a new advanced model, is mandatory to refer to experts in the specific sector of interest. The variables determined here must all be easy to quantify; Performance-related variables have been preferred since the values are known already before the design and therefore easy to find.
3. To determine the links between dependent and independent variables. This step is the heart of the ERC development and is the most expensive step in terms of worked hours. In this activity it is also necessary to carefully check all the extrapolated data to avoid having incorrect cost forecast in the model.
4. To analise relationships between dependent and independent variables in order to obtain a mathematical model that correlates both. There are different approaches for the analysis, from graphical to mathematical including moving averages and linear regression.
5. After testing different models, select the one that provides for the best dependent variable starting from the independent one. If there are several correlations giving a comparable predictive value, it means that the independent variable considered is a good predictive tool

6. The last step presupposes the presentation of the results obtained, evidencing a method to test the model, may be to use the method to predict an already known value and thus verify its reliability.

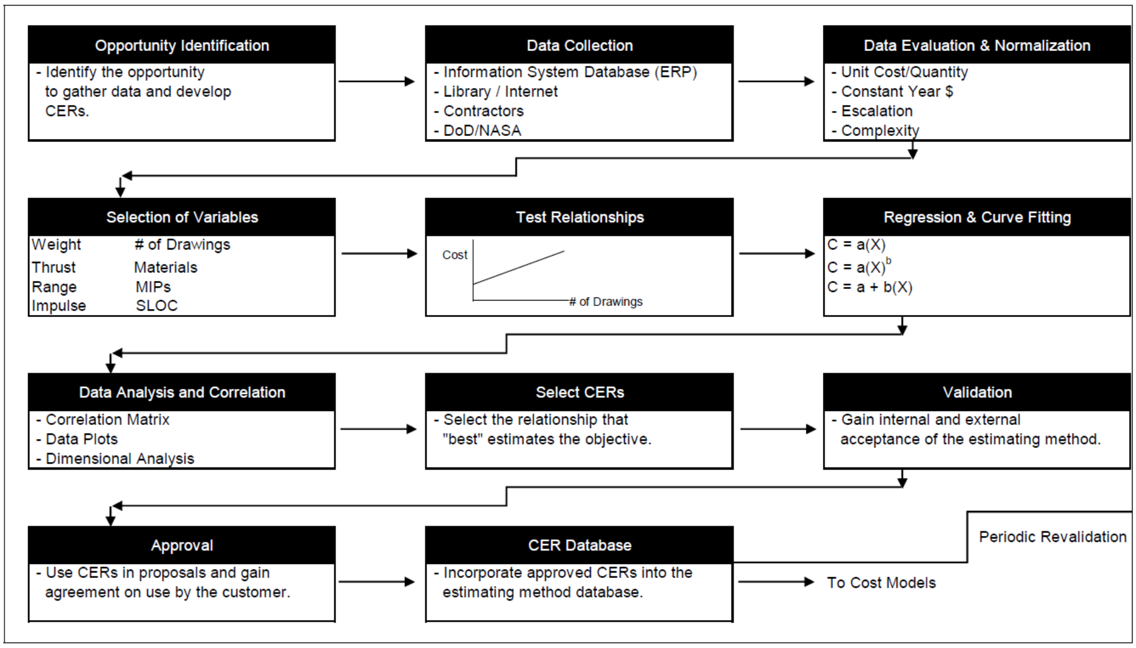


Figure 21 - CER development process [36].

So, to provide a cost model for enabling hybrid technologies is to generate a database.
Given the complexity of hybrid technology and the low technological readiness level, it was difficult to find results on enabling components for hybridization such as electric motor batteries and power electronics. Also it was even more difficult to find a correlation between funding and Technology Readiness Level (TRL) step, due to the fact that the projects in this field are still in development.
Therefore, in order to generate a data collection, we analysed the projects contained in the Call for Proposal (CfP) [25][27][28][29][31][32]0[34] of the Clean Sky 2 JU [4] project including, the European research for hybrid propulsion ones.

3.1 Database creation

3.1.1 Description of technologies employed

The transparency in terms of financing, timing and technological development of the analysed documents allowed to extrapolate the data enough to generate the database.
The data include:
- TRL step, technological level up-grade required for a research project according to EASA Technology Readiness Level definition [24];
- Fund, global funding for each project;

- Months, months spent for carrying-out each research activity
- Component level of the study.


Clean Sky 2

Annex III:
4th Call for Proposals (CFP04):
List and Full Description of Topics

Call Text

- 21 June 2016 -

Figure 22 - Clean Sky Call Text [27]

Area	No. of topics	Indicative Funding (in M€)
IADP Large Passenger Aircraft	13	10.60
IADP Regional Aircraft	5	3.18
IADP Fast Rotorcraft	5	3.50
ITD Airframe	15	9.80
ITD Engines	9	8.56
ITD Systems	10	12.28
TA Small Air Transport (SAT)	(2)	(2.00)
TA ECO Design 2	-	-
TA Technology Evaluator 2	-	-
TOTAL	57	47.92

Note: Figures in brackets indicate that these activities are identified as having benefits for the Transverse Areas i.e. SAT and ECO Design but which launch and budget reside inside the concerned SPDs and not in the Transverse Areas as such.

Figure 23 - Clean Sky 2 Number of topic, different technologies areas and indicative funding[27]

Type of action (RIA or IA)	RIA		
Programme Area	ENG		
Joint Technical Programme (JTP) Ref.	WP3		
Indicative Funding Topic Value (in k€)	900 k€		
Duration of the action (in Months)	36 months	Indicative Start Date[44]	Q1 2017

Identification	Title
JTI-CS2-2016-CFP03-ENG-01-07	Advanced mechatronics devices for electrical management system of Turboprop
Short description	
An advanced electrical machine together with the electrical power management will be studied, designed & manufactured. Following partial tests at partner facility, demonstrator hardware will be delivered for engine ground tests.	

Figure 24 - Clean Sky 2 Topic short description[27]

Tasks		
Ref. No.	***Title - Description***	***Due Date***
	T0	**Q4 2016**
Task 0	Project management and reporting	T0+36
Task 1	Concept studies (with TM)	T0+2
Task 2	Contribution to specifications (with TM)	T0+3
Task 3	Preliminary design	T0+10
Task 4	Detailed design	T0+12
Task 5	Production & functional tests	T0+20
Task 6	Support during engine tests	T0+30
Task 7	Environmental tests	T0+30
Task 8	Components dynamic models	T0+12

Figure 25 - Clean Sky 2 Topic tasks and date [27]

Deliverables & Milestones			
Ref. No.	***Title - Description***	***Type (*)***	***Due Date***
D1	Specifications (contribution of partner and TM)	R	T0+3
D2.1	Preliminary dynamic models	D	T0+6
D2.2	Final dynamic models	D	T0+12
D3	Preliminary Design Review	RM	T0+10
R4	Critical Design Review	RM	T0+12
D5	Equipments delivery	D	T0+24
R6	TM engine tests preparation	RM	T0+24
D7	Component tests reports (including environmental tests)	R	T0+34

** Type: R: Report - RM: Review Meeting - D: Delivery of hardware/software*

Figure 26 - Clean Sky 2 Topic deliverables and milestones description [27]

Below is a brief description of the extracted technologies analysed, paying attention to the values extrapolated and used in the database.

- Advanced mechatronics devices for electrical management system of Turboprop:

Indicative Funding Topic Value (in k€)	900 k€		
Duration of the action (in Months)	36 months	**Indicative Start Date**[44]	Q1 2017

Figure 27 – Cost and time data about: - Advanced mechatronics devices for electrical management system of Turboprop- tecnology

Scope of work:

The partner will be responsible for the design, production and testing of an integrated and advanced mechatronic system, consisting essentially of:

- A power supply device
- Associated control electronics
- The system will be integrated into the (PAGB) and will be tested during the engine tests.
- The system is mechanically driven by 2 concentric shafts:
- Shaft 1 (internal), nominal speed around 1700 rpm
- Shaft 2 (external), nominal speed around 18000 RPM

The system will perform the following functions:

- Generator: the system must be able to function as a generator, in order to supply at least 16 kW continuously, with an output voltage of 28 V DC or 270 V DC. A compromise will be made to choose the best level voltage.
- Motor: the system must be able to function as a motor, in order to supply a mechanical power of 16 kW to the external shaft with an estimated torque of 20-28 Nm with an input voltage of 28 V DC or 270 V DC .The generator and engine functions will not work simultaneously.
- Power transmission: the system must also be able to generate up to 1 kW of electricity to a device that rotates with the internal shaft (shaft 1). It must be possible to select the power level, at least ON / OFF, from the power electronics.
- The power transmission function must be able to operate in generator mode and in engine mode.
- Diagnosis: the system must carry out a diagnosis to detect internal faults and inability to operate in both modes
- Interface: the system must interface with another device, receive orders and send health conditions. The means of communication will be defined later.

The estimated mass of the mechatronic system must be less than 10 kg. The package of these features will be shared with the PAGB wrappers.

The dimensions of the mechatronic system must be reduced to a minimum and such as to adapt with an external diameter of 170 mm and a maximum length of 135 mm. The internal diameter must not be less than 85 mm.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables & Milestones			
Ref. No.	***Title - Description***	***Type (*)***	***Due Date***
D1	Specifications (contribution of partner and TM)	R	T0+3
D2.1	Preliminary dynamic models	D	T0+6
D2.2	Final dynamic models	D	T0+12
D3	Preliminary Design Review	RM	T0+10
R4	Critical Design Review	RM	T0+12
D5	Equipments delivery	D	T0+24
R6	TM engine tests preparation	RM	T0+24
D7	Component tests reports (including environmental tests)	R	T0+34

Type: R: Report - RM: Review Meeting - D: Delivery of hardware/software

Figure 28 - Deliverables and milestones for: -Advanced mechatronics devices for electrical management system of Turboprop- project

- High Speed HVDC Generator/Motor

Indicative Funding Topic Value (in k€)	1000 k€		
Duration of the action (in months)	66 months	**Indicative Start Date[19]**	Q1 2017

Figure 29 - Cost and time about: -High Speed HVDC Generator/Motor- tecnology

Scope of work:

The main objective of this CfP is to design, develop and manufacture a new compact high speed, high efficiency and low weight generator which acts as the primary power source for the CTR Tiltrotor NextGen. The generators will be mounted in the fixed gearboxes of the motors and will be driven at a speed proportional to that of the propeller rotor. The nominal speed is considered to be 24000 rpm. The generator HVDC power supply (± 270 VDC) will be supplied to the electricity distribution system for distribution to the respective loads, including critical flight safety loads. Generator control will ideally be provided by a generator control unit (GCU) however a separate unit can be considered if adequate justification can be provided. As a secondary function, while on the ground, the generator must also be able to act as an engine to drive various systems through the aircraft's gearbox. In this configuration, HVDC power will be supplied to the controller from the APU generator.

It is extremely important that the operational status of the generator system is understood during all flight phases and aircraft operating conditions. Therefore, the equipment must incorporate comprehensive health monitoring, including PBIT, CBIT and IBIT, which can be used to optimize maintenance actions and fault detection.

Implementation:

The requirements of the HVDC generator can be considered in two parts:

1. Requirements for the HVDC generator

The HVDC generator must provide a nominal output of ± 270 VDC, incorporating any necessary rectification and control / HUMS sensors. The unit must have the guide bearing and guide groove necessary for interfacing with the gearbox and must incorporate a cutting section of the transmission shaft to avoid damage to the gearbox in case of generator seizure. The unit must be cooled by an integrated cooling system without direct use of the transmission cooling system.

2. Control and protection requirements

The generator control unit must provide the control, protection and adjustment necessary for the generator output to ensure continuous and safe operation of the system. It provides interfaces to aircraft systems through a combination of discrete signals, analog signals and data bus connections to allow the crew to safely control and monitor the system. The unit must incorporate PBIT, IBIT and CBIT which monitors the status of the unit and generator and provides maintenance data through the data bus system.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title - Description***	***Type***	***Due Date*** [T0+mm]
D.1	Initial System Definition	R	T0+3
D.2	Configuration development and Preliminary Design Review deliverables	R / D	T0+6
D.3	Detailed HW and SW design, Critical Design Review deliverables	R / D	T0+26
D.4	Fully representative rig units provided	D	T0+37
D.5	Technical documentation supporting TRR, Qualification Test Plan and Procedures	R	T0+44
D.6	Qualification Test Reports, EFA DDP	R	T0+48
D.7	EFA shipset and spare units	D	T0+48
D.8	Amended design documents according to flight trials results	R	T0+66

*Type: R: Report - RM: Review Meeting - D: Delivery of hardware/software

Figure 30 - Deliverables and milestones for: - High Speed HVDC Generator/Motor- tecnology

- Electrical Components

Indicative Funding Topic Value (in k€)	500 k€		
Duration of the action (in Months)	30 months	**Indicative Start Date**[25]	Q1 2017

Figure 31 - Cost and time about:- Electrical components- tecnology

Scope of work:

The goal is to design, develop, manufacture, test and qualify up to TRL6 a high voltage direct current (HVDC) technology for cables, connectors, contacts and wiring insulation, protection and installation elements intended to be used on a demonstrator LifeRCraft Fast Rotorcraft.

The goal is to develop and qualify the electrical components dedicated to the 270 V DC network by defining and validating the wiring installation rules through laboratory tests.

All the components and materials that will be developed within this project:

- They must comply with the REACH regulation.
- They must be optimized in terms of weight and cost.

39 ok dove uhm The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones (when appropriate)			
Ref. No.	***Title Description***	***Type***	***Due Date***
M0	Kick off Meeting	Review	T0 + 1 month
M1.T1	Product Description Review	Review	T0 + 3 months
M1.T2	HVDC Ageing Test Method	Delivery	T0 + 9 months
M1.T3	Installation Rules Review	Review & Delivery	T0 + 9 months
M1.T4	Design Review 1 (DR1)	Review	T0 + 15 months
M1.T5	P1 Samples manufacturing	Delivery	T0 + 18 months
M1.T6	Qualification Test Report	Delivery	T0 + 21 months
M1.T7	Design Review 2 (DR2)	Review	T0 + 24 months
Ref. No.	***Title Description***	***Type***	***Due Date***
M1.T8	P2 Samples manufacturing	Delivery	T0 + 27 months
M1.T9	Qualification Test Report FSQ (File Synthesis of Qualification). (Extrapolation to serial product)	Delivery	T0 + 30 months
M1.T10	Qualification Test Report for Harnesses (QTR1)	Delivery	T0 + 30 months
M2.T10	Electrical components available for program delivery	Delivery	T0 + 30 months

Figure 32 - Milestones for Electrical components technologies

- Innovative cooling system for embedded power electronics

Indicative Funding Topic Value (in k€)	800 k€	**Type of agreement**	Implementation Agreement
Duration of the action (in Months)	28 months	**Indicative Start Date**[58]	Q2 2017

Figure 33 - Cost and time about Innovative cooling system for embedded power electronics

Scope of work:

Today it is estimated that the state-of-the-art thermal management system has a specific mass of about 5 kg / kW for passive solutions (hydraulic cold plate). The main technical objective for this topic is the development of advanced heat sinks using an innovative technology that guarantees high thermal conductivity and uniform heat diffusion on the heat sink surface in order to achieve a mass / power ratio towards 2 or 3 kg / kW. This technology will be assessed as regards the feasibility of meeting the requirements and constraints of aeronautical applications.

The aim is to develop advanced heat sinks using the innovative annealed pyrolytic graphite (APG) technology which guarantees very high thermal conductivity and uniform heat diffusion on the surface of the heat sink. This solution can be completed at a later stage by an extremely advanced Metal Matrix Composite (MMC) technology used for the primary heat transfer surfaces of a heat sink. This MMC technology is highly innovative and offers significant potential for next generation heat dissipation devices. Therefore, the development of highly advanced heat sinks for an application in "more electric" aircraft will be proposed in two phases:

1. The heat sink with APG technology and optimized aluminum bent fin as a first step;

2. The heat sink that uses APG and MMC technologies as a second step to evaluate this promising research.

For this topic, the evaluation of the heat sink prototypes is foreseen as an autonomous effort, but will also be conducted within a mechanical structure to represent an energy management system that integrates four (4) power electronic modules equipped of innovative heat sink technology and cooled by air flow.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type***	***Due Date***
Trade Review	state of the art and thermal analysis	Document	T0+2M
Design review 1 RUN 1	Preliminary design review of the heat sink RUN 1 (stage a)	Document	T0+5M
Design review 2 RUN 1	Conception design review of the heat sink RUN 1	Document	T0+8M
Article review RUN1	deliver prototypes RUN 1 according to the definition	Hardware	T0+12M
Test review RUN1	Evaluate electrical, mechanical and robustness performances according to evaluation procedures specification jointly by the applicant and Topic Managers company	Document	T0+16M
Design review RUN 2	Conception design review of the heat sink RUN 2 (stage b)	Document	T0+18M
Article review RUN 2	deliver prototypes RUN 2 according to the definition	Hardware	T0+24M
Test review RUN 2	Evaluate electrical, mechanical and robustness performances according to evaluation procedures specification jointly by the applicant and Topic Managers company	Document	T0+28M
Design review Test bench	Conception design review of the test bench	Document	T0+10M
Design review mechanical structure	Conception design review of the mechanical structure	Document	T0+12M
Integration review	Integration of the mechanical structure	Hardware	T0+18M
Test review mechanical structure	Evaluate electrical, mechanical and robustness performances of the mechanical structure equipped with the updated heat sinks according to evaluation procedures specification jointly by the applicant and Topic Managers company	Document	T0+24M

Figure 34 - Milestones for Innovative cooling system for embedded power electronics development

- High Density Electrical Connectors

Indicative Funding Topic Value (in k€)	500		
Topic Leader	Zodiac Aerospace	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	24	**Indicative Start Date21**	Q1 2018

Figure 35 - Cost and time for High Density Electrical Connectors development

Scope of work:

The objective of this topic is to support the development of computer systems with high physical I / O density, through a standard, low cost approach and a modular interface, which can be widely used in the A / C systems industry. The proposed approach will require the development of a new connector standard. The applicant will propose a fully compatible set of physical interface solutions (connectors), based on the installation constraints, which will be detailed at the beginning of the project.

With extensive experience on the interface of A / C systems, the applicant will propose a harness approach that addresses the key blocks of the installation of high density connection systems: operator access ergonomics (installation and maintenance of both the system and the A / C wiring), the insertion and extraction of the electronic boards and the variable exposure to electromagnetic effects.

In addition, interfaces must meet the following general requirements:

- Modular: to be able to host different types of interfaces (in terms of power and frequency). Being able to build connection interfaces based on reusable and adaptable predefined blocks.
- Standard: based on industry standard building blocks. In addition, the applicant must define a roadmap for the standardization of the building blocks developed under this topic.
- Design to cost: the target production cost of the general connection solution must be 60% lower than the solution based on the current EN4165.
- Ergonomics: efficient operation of the installation of the connectors during the production of electronic boards. Efficient installation of connectors from the point of view of A / C wiring, as well as the structure of the system on the aircraft.
- Density of the connection points: it must be possible to host at least 210 connection points on an electronic card in 6UE format.

Based on the requirements provided by the subject responsible resulting from the analysis of the aircraft constraints, the project will be carried out in three phases: analysis of the state of the art, definition of the product and development of the parts.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones			
Ref. No.	**Title - Description**	**Type**	**Due Date**
M.1	State of the Art review	Review Meeting	03-2018
M.2	Cockpit Utility Management System physical interfaces plan review	Review Meeting	05-2018
M.3	Environmental Test readiness review	Review Meeting	12-2018
M.4	Results Assessment Review	Review Meeting	12-2019

Figure 36 - Milestones for High Density Electrical Connectors development

- E2-EM Supervisor and Control Algorithms

Indicative Funding Topic Value (in k€)	800		
Topic Leader	Leonardo Aircraft	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	36	**Indicative Start Date**[23]	Q1 2018

Figure 37 - Cost and time for E2-EM Supervisor and control algorithms development

Scope of work:

he objective of this topic is to design, develop, produce, test and integrate (at the "Iron Bird" ground structures) a higher level "Centralized Smart Supervisory" (CSS) hardware controller capable of managing lower level controllers of the "Smart-Grid System" and of the "Advanced Energy Storage and Regeneration System" in order to implement an optimal sharing of the electricity available on board during breakdowns and / or overload conditions, so as not to rely on the capacity of overload of the main generators.

The Smart Supervisory centralized control system must be fully interfaced with the "Iron Bird" test bench, activating or deactivating the energy management modes of the SGN and ESRS controllers in case of need depending on the specific configuration of the test (reproducing specifications flight phases of the aircraft and / or operating conditions).

The Smart Supervisory centralized control system must be able to communicate with other subsystem controllers, as well as with the Iron Bird central control system, through appropriate protocols (i.e. CAN). Its main purpose will be to coordinate the activities of the local controllers, in order to perform a complete energy management of the system.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title - Description***	***Type****	***Due Date***
D1	Analysis phase: Requirements matrix and support documentation	R	T0 + 3M
D2	E2-EM definition: Definition of energy management control strategy. Analysis of the results of the simulation models	R/D	T0 + 9M
D3	PDR: Preliminary Design Review and associated deliverables	R	T0 + 12M
D4	Firmware specification: Implementation of a preliminary firmware for energy management purposes	R	T0 + 21M
D5	CDR: Critical Design Review and associated deliverables	R	T0 + 24M
D6	Installation and commissioning: Delivery of the complete system with its associated documentation (preliminary DDP), installation and commissioning on site	R/HW	T0 + 30M
D7	Validation final tests and DDP: Validation test report and final results (final DDP)	R/D	T0 + 34M
D8	Optimization and support: The CfP Supplier shall support the rig operations to correct potential faults during this probation period	R	T0 + 36M

*Types: R=Report, D=Data, HW=Hardware

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1	Preliminary Design Review	R	T0 + 12M
M2	Critical Design Review	R	T0 + 24M
M3	Final results	R	T0 + 36M

*Types: R=Report, D=Data, HW=Hardware

Figure 38 - Milestone for E2-EM Supervisor and Control Algorithms development

- High density energy storage module for an electric taxi

Estimated Topic Value (funding in k€)	800		
Topic Leader	Safran	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	45	**Indicative Start Date**[76]	Q1 2018

Figure 39 - Cost and time for High density energy storage module for an electric taxi development

Scope of work:

This project will develop an energy recovery module. This equipment must provide a high density energy recovery capacity (30Wh / kg), with relative power converter, in order to perform regenerative decelerations of the aircraft.

A significant increase in power density (reduced size and weight) must be obtained compared to the current state of the art. The power module must have bidirectional power conversion capability to manage and store the energy regenerated by electric motors during aircraft deceleration. It must be modular and easily scalable to support a wide range of platform requirements with maximized reuse. The power module must be designed for optimal integration with the electric drive motor of the taxi system and the wheel actuator control unit, as well as with the electric taxi system module. The purpose of the activity includes the integration of communication interfaces and mechanical integration into an airplane or landing gear.

Specific requirements for the power module include:

- Bidirectional operation for energy storage and recycling
- Energy storage capacity the energy storage module must be able to store up to 700 Wh (2500 kJ)

- Power: the power module must be able to manage up to 50kW of power regenerated by the wheel actuator

- Bus voltage the power module must operate from the bus +/- 270 V DC

- Environmental conditions the power supply module must meet the DO-160 standard

- Electrical standards: the power supply module must meet the DO-160 standard

Quantified objectives:

- Weight:

- The target mass for storage technology is at least 30 Wh / kg
- The target mass for power electronics is at least 2 kW / kg
- The target mass for the whole unit is 40 kg.
- Volume: the power density of the target volume is 2kW / l

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

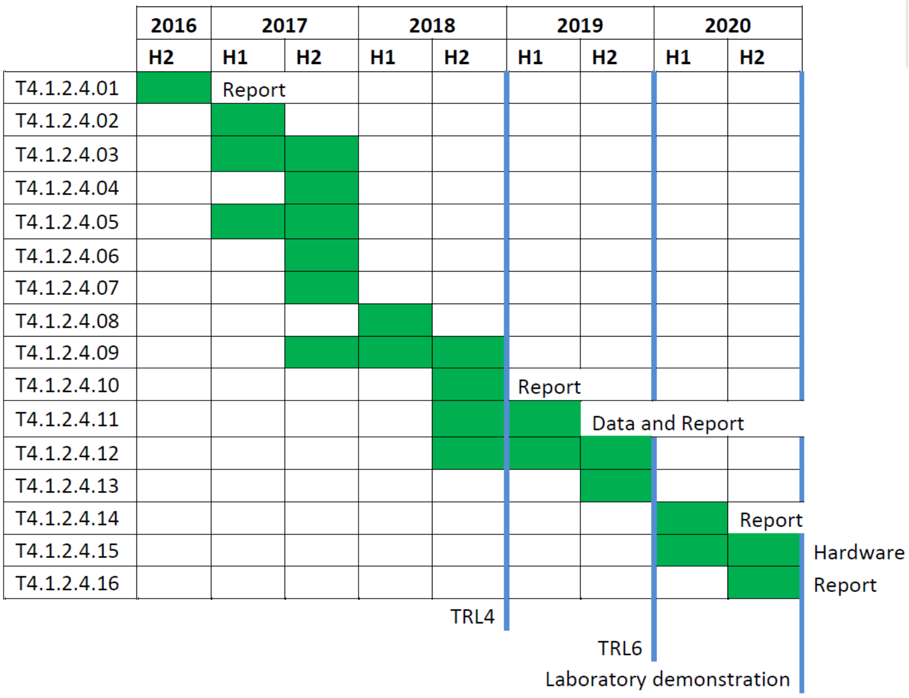


Figure 40 - Time to TRL map for High density energy storage module for an electric taxi development

- Power Module

Indicative Funding Topic Value (in k€)	500		
Topic Leader	Thales Avionics	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	18	**Indicative Start Date**[78]	Q1 2018

Figure 41 - Cost and time for Power module development

Scope of work:

The proposed activity aims to develop three types of power semiconductor devices with an expected maturity level up to TRL6. The enclosure of the power semiconductor device must be adaptable to allow the easy deployment of three different applications with the same base plate and packaging.

The three targeted applications are:

- HVDC (High Voltage Direct Current) fullbridge module consisting of power semiconductors with free rotation diode on each power semiconductor. The power module must be validated with an active HVDC converter that provides output power up to 5kW.
- LVDC (Low Voltage Direct Current) halfbridge module composed of upper and lower power semiconductors with free-rotating diode on each power semiconductor. The power module must be validated with an active HVDC converter that provides output power up to 5kW.
- Bidirectional controlled power module HVDC. The intended application is a contact matrix where no power reduction is required.

A number of power modules must be provided to allow the implementation of a contact matrix with four sources (three-phase HVDC, each source provides up to 50kVA) and 5 loads (three-phase HVDC with a consumption of up to 50kVA). The switching of each power module must be controlled via a CAN bus.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type***	***Due Date***
KOM	Kick Off meeting		T0
PDR	Predesign review		T0+3 months
CDR	Design review : power module definition and Test bench design reproducing environmental conditions (mechanical constraints and temperature variation, dedicated or combined conditions)		T0+7 months
TRR	Test readiness review: power module final test plan.		T0+13 months
QR	Qualification review : Tests results and reports for power module and demonstrators		T0+18 months

Figure 42 - Milestones for Power module development

- Screening and development of optimized materials for high temperature coils

Indicative Funding Topic Value (in k€)	500		
Topic Leader	Liebherr	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	36	**Indicative Start Date**[84]	Q1 2018

Figure 43 - Cost and time for Screening and development of optimized materials for high temperature coils development

Scope of work:

The main objectives of this topic are:

- Develop specific threads, impregnating paints and ingredients (resins) to obtain complete solutions for high temperature windings and to qualify these ingredients.
- Manufacture high temperature coils with these ingredients, integrate them into the application defined by the Topic Manager and demonstrate that the proposed solutions can be industrialized.

The solutions must respect aeronautical constraints (electrical, vibrations, duration, manufacturing process, etc.) and withstand a minimum temperature of 300 ° C.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title - Description***	***Type***	***Due Date***
D1	Definition of requirements	R	M3
D2	Materials, manufacturing processes and qualification test method trade-off synthesis report	R	M12
D3.1	Manufacturing of ingredients and magnet wire	S	M22
D3.2	Characterization and qualification tests of ingredients and magnet wire: synthesis report	R	M24
D4.1	Manufacturing of coil sub-assemblies	S	M28
D4.2	Qualification of sub-assemblies and definition of success criteria for process validation	R	M30
D5.1	Manufacturing of final product demonstrators	D	M34
D5.2	Characterization and testing of final demonstrators: synthesis report including process manufacturing validation with success criteria	R	M36
D5.3	Business case	R	M36
D5.4	Roadmap and associated risk analysis to reach full industrialisation	R	M36

Milestones (when appropriate)			
Ref. No.			
M1	Selection of materials, manufacturing processes and qualification test method following trade-off results	Milestone	M12
M2	Ingredients and sub-assemblies design qualified	Milestone	M24
M3	Final prototypes design validated	Milestone	M34

Figure 44 - Milestones for Screening and development of optimized materials for high temperature coils development

- Integrated electronics for actuator data and power management for Morphing Leading Edge activities

Indicative Funding Topic Value (in k€)	450		
Topic Leader	Fraunhofer	Type of Agreement	Implementation Agreement
Duration of the action (in Months)	36	Indicative Start Date[46]	Q1 2018

Figure 45 - Cost and time to Integrated electronics for actuator data and power management for Morphing Leading Edge activities development

Scope of work:

This topic provides for a unitary device consisting of two complementary subunits: one for controlling EMA actuators for driving the Morphing Leading Edge; the other able to manage the power needed to activate the system. Both sub-units are closely connected and must be able to work in an integrated way. The first goal of this topic is the development of a drive and control system for Morphing Leading Edge EMA actuators. The main challenge is to develop an intelligent control architecture to reduce the amount of data transferred through the control system. A large amount of data must be managed within the control strategy. Appropriate solutions for data acquisition and management must be considered and implemented.

The applicant must design and manufacture both a hardware platform and the software-based implementation of an appropriate control concept in order to test and evaluate the control and data processing approach. The system must also be capable of being used for the control and testing of actuators, e.g. in a small or large scale ground demonstrator (GBD). Therefore, advanced monitoring features and all parameters accessible through common data acquisition systems must be implemented. An open sensor interface must also provide the ability to extend the system for aerodynamic control algorithms.

The result of the wp is the development, production and testing of the integrated control device for actuators and subunits in a morphing structure. The tests will demonstrate compliance of this device with the requirements to allow use in the final GBD (WT / T) tests. All interfaces (for example, sensors or electronic units) will be specified in discussion with the Topic Manager at the beginning of the project.

The required activities include the following tasks:

1. Development of a hardware platform for an actuator drive and a control concept for morphing structures
2. Definition of specifications and interfaces for sensors and drive units of the actuator system
3. Development of control algorithms that are adaptable and verifiable through common simulation tools
4. Development of software capable of monitoring system parameters
5. Implementation of an advanced monitoring interface
6. Implementation of modular software with different control algorithms

7. Production, integration and testing of the entire platform.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones		
Ref. No.	***Title - Description***	***Due Date***
M1	**Preliminary Specification**	T0+6
M2	**Preliminary Hardware/Software design review**	T0+18
M3	**Critical Hardware/Software design review**	T0+24
M4	**Final Hardware delivery**	T0+30
M5	**Final Hardware test finished and reported**	T0+36

Figure 46 - Milestones for Integrated electronics for actuator data and power management for Morphing Leading Edge activities development

- Development of AC cabling technologies for >1kV aerospace applications

Indicative Funding Topic Value (in k€)	750		
Topic Leader	Rolls-Royce	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	24	**Indicative Start Date (at the earliest)**[26]	Q1 2019

Figure 47 - Cost and time for Development of AC cabling technologies for >1kV aerospace applications development

Scope of work:

The focus of this call is on the AC cables for interconnection between power electronics and motors / generators in general; they are likely to encounter some of the most hostile environments on the aircraft with high temperatures, high levels of contaminants and vibrations and high altitude all with harmful effects on the cable, its insulation system and its terminations.

There are three activities foreseen in this call:

• Acquisition and understanding of the implications of the use of HVAC in aerospace, including failure, lifing, arcing modes.

• Development of a cable modelling tool that can be used to assess the suitability of cables for use in aerospace HVAC systems, including the results of the previous point. The validation of the model will be done through physical tests on existing aerospace cables.

• Development and demonstration of an optimized HVAC cable in a representative aerospace environment at full power.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title - Description***	***Type****	***Due Date***
D1.1	Report on identified potential failure cases within HVAC cables in aerospace and state of the art assessment.	D, R	T0 + 4
D1.2	FMEA analysis of aerospace HVAC cables	D, R	T0 + 5
D2.1	Model validation report	R	T0 + 13
D3.1	Report capturing optimised aerospace HVAC cable design and test results.	D, R	T0+ 23
D3.2	Optimised validated cable samples available to RR	HW	T0+ 23

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1.1	Review of identified potential failure modes	D	T0 + 4
M2.1	Demonstration of model	D	T0 + 9
M2.2	Review of rig design and test plans	D	T0 + 9
M2.3	Review of validated model	D	T0+13
M2.4	Commissioning of test rig	D	T0 +11
M3.1	Cable design complete	D	T0 +16
M3.2	Cable manufacture complete	D	T0 +19
M3.3	Cable testing complete	D	T0 +23

Figure 48 - Milestones for Development of AC cabling technologies for >1kV aerospace applications development

- Innovative Primary and Secondary Electrical Distribution Network for Regional A/C

Indicative Funding Topic Value (in k€)	1400		
Topic Leader	Leonardo Aircraft	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	26	**Indicative Start Date**[19]	Q4 2018

Figure 49 - Cost and time for Innovative Primary and Secondary Electrical Distribution Network for Regional A/C development

Scope of work:

The purpose of this topic is to design, develop, produce, validate and integrate an innovative solid-state electricity distribution network for the future regional A / C, including the following subsystems:

• Two "centralized" primary power supply centers (PPC) (including primary and low voltage bus bars, primary contactors and I / O interfaces);

• At least four secondary (decentralized) distribution units (SDU) (including secondary bus bars HV and LV, secondary contactors and I / O interfaces), one of which integrates innovative "energy management" capabilities;

• Two AC / DC converters (rectifiers) to convert ACWF from 115 V to 270 V DC (from two real 40 kVA electric generators to a primary distribution network), according to the following scheme (for reference only). The parts highlighted in red are the components required by this topic.

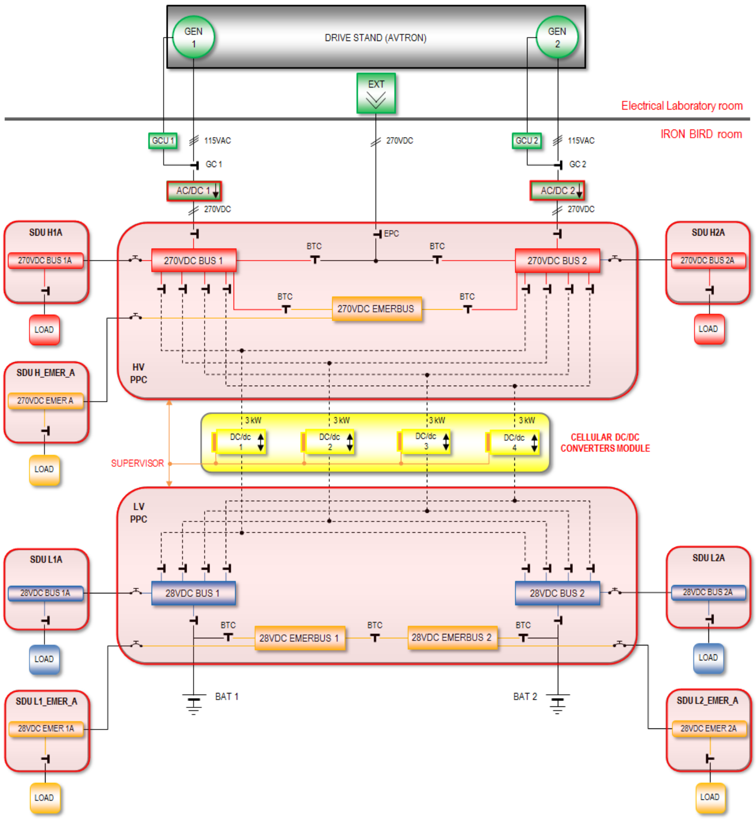


Figure 50 - Iron Bird Architecture for Innovative Primary and Secondary Electrical Distribution Network

The 270 V and 28 V DC PPCs may also be part of the same equipment. In any case, the PPCs must interface with the bidirectional cellular DC / DC conversion equipment (yellow box).

The general system (primary and secondary electrical distribution network) must also interface with the Smart Supervisory centralized control for the Enhanced Electrical Energy Management strategy and must be integrated into the REG Iron Bird ground demonstrator; therefore it must interface with the overall demonstration infrastructure, mainly composed of the following subsystems:

- Electricity generation system (guide base + 115 V ACWF electric alternators);
- Engineering test station;
- Central control unit and interface unit;
- Data acquisition system

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title - Description***	***Type****	***Due Date***
D1	Analysis phase: Requirements matrix and support documentation.	R	T0 + 3M
D2	PDR: Preliminary Design Review and associated deliverables.	R	T0 + 9M
D3	CDR: Critical Design Review and associated deliverables.	R	T0 + 12M
D4	Installation and Commissioning: Delivery of the complete system with its associated documentation (preliminary DDP), installation and commissioning on site.	HW	T0 + 20M
D5	Final Validation Tests and DDP: Validation tests report and final results (final DDP).	R/D	T0 +22M
D6	Optimization and Support: Support the rig operations to correct potential faults during this probation period.	R	T0 + 26M

*Type: R=Report, D=Data, HW=Hardware

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1	Preliminary Design Review	R	T0 + 9M
M2	Critical Design Review	R	T0 + 12M
M3	System Delivery	HW	T0 + 20M

*Type: R=Report, D=Data, HW=Hardware

Figure 51 - Milestones for Innovative Primary and Secondary Electrical Distribution Network for Regional A/C development

- Design and Development of a high temperature HVDC busbar

Indicative Funding Topic Value (in k€)	500		
Topic Leader	Zodiac Aero Electric	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	24	**Indicative Start Date**[67]	Q2 2018

Figure 52 - Cost and time for Design and Development of a high temperature HVDC busbar development

Scope of work:

The aim is to design and develop prototype HVDC busbars suitable for resisting high temperatures. The busbar will be designed, its simulated performance and the prototypes tested up to the TRL6 demonstration. The result of the planned project is the integration of the components in the HVDC power management center of large aircraft.

Aeronautical energy distribution systems use a distribution panel typically composed of electromechanical components, distribution busbars and wiring. For the busbar component, temperature restrictions limit the potential for further integration and more compact designs for the distribution panel in terms of volume, weight and packaging. The evolution towards more electric aircraft requires more and more electronic commutations and, consequently, an optimization of the design of the distribution panel. In this sense, the key enabling technology is temperature control or the ability to operate at high temperatures. The objective of this topic is to develop an HVDC busbar capable of operating at high temperatures (at least above 180 ° C) that can withstand the aerospace environmental constraints (vibration, altitude, partial discharge, aging, etc.).

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones (when appropriate)			
Ref. No.	***Title – Description***	***Type****	***Due Date***
M1	Project kick-off meeting	Review	T0
M2	High Temperature HVDC Busbar prototypes Preliminary Design Review	Review	T0+3 Months
M3	High Temperature HVDC Busbar prototypes Detailed Design Review	Review	T0+6 Months
M4	High Temperature HVDC Busbar prototypes Validation Review (after stand-alone tests)	Review	T0+12 Months
M5	High Temperature HVDC Busbar final version Detailed Design Review	Review	T0+14 Months
M6	High Temperature HVDC Busbar final version Validation Review (after stand-alone tests)	Review	T0+24 Months

*Type: R=Report, D=Data, HW=Hardware

Figure 53 - Milestones for Design and Development of a high temperature HVDC busbar development

- Development of low rating and high power HVDC optimized fuses

Indicative Funding Topic Value (in k€)	500		
Topic Leader	Zodiac Aero Electric	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	24	**Indicative Start Date**[67]	Q2 2018

Figure 54 - Cost and time for Development of low rating and high power HVDC optimized fuses development

Scope of work:

The aim is to design and develop two types of HVDC optimized fuse prototypes: a low rating fuse for printed circuit board applications (up to 30 A) and a high power fuse (up to 300 A). HVDC fuses will be designed, their simulated performance and prototypes will be tested up to TRL6 within the demonstrators. The targeted application is a further integration into the HVDC power management center of large aircraft.

The HVDC (540 VDC) mains fuses currently available on the market have been developed for the energy industry and are not optimized in terms of volume, weight and packaging for aircraft electrical distribution applications. The goal of this topic is to develop two new optimized fuse solutions for integration into aircraft distribution / protection components.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1	Project kick-off meeting	Review	T0
M2	Fuse prototypes Preliminary Design Review	Review	T0+4
M3	Fuses prototypes Detailed Design Review	Review	T0+6
M4	Fuses prototypes Validation Review (after stand-alone tests)	Review	T0+13
M5	Fuses final version Detailed Design Review	Review	T0+16
M6	Fuses final version Validation Review (after stand-alone tests)	Review	T0+24

*Type: R=Report, D=Data, HW=Hardware

Figure 55 - Milestones for Development of low rating and high power HVDC optimized fuses development

- Novel mechanical drive disconnect for embedded Permanent Magnet machines

Indicative Funding Topic Value (in k€)	1100		
Topic Leader	Rolls Royce	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	18	**Indicative Start Date**[5]	Q2 2018

Figure 56 - Cost and time for Novel mechanical drive disconnect for embedded Permanent Magnet machines development

Scope of work:

The requirement for power density and high efficiency in electrical machines for aerospace applications can be difficult with safety and certification constraints. Permanent Magnet (PM) machines can meet both requirements, however, a mechanical disconnection is required to handle faults. The project will focus on the design and development of a new disconnection solution for a built-in generator, collaborating closely with the Topic Manager in exploring the feasibility of a "mechanical disconnection" Rolls-Royce patent and building it in hardware at TRL3 / 4 Mechanical disconnection is a fail-safe solution specifically aimed at electrical machines built into the core of gas turbines. Mechanical disconnection is an integral part of an electric machine and is different from conventional stand-alone disconnection solutions, such as a clutch. Upon activation, the mechanical disconnection actually "disassembles" part of an electric machine and disconnects the mechanical input (generation mode) or mechanical output (operating mode) from an electric machine.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1.1	Design of rotor with concept disconnect completed	D	T0 + 6
M1.2	Manufactured rotor with disconnect	HW	T0 + 10
M2.1	Design of stator complete with incorporated faults	D	T0 + 5
M2.2	Testing of stator completed	R	T0 + 12
M3.1	Full prototype assembled and ready to test	HW	T0 + 15

*Type: R=Report, D=Data, HW=Hardware

Figure 57 - Milestones for Novel mechanical drive disconnect for embedded Permanent Magnet machines development

- Advanced manufacturing for MW range power dense electrical machines for aerospace applications.

Indicative Funding Topic Value (in k€)	600		
Topic Leader	Rolls Royce	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	24	**Indicative Start Date**[6]	Q2 2018

Figure 58 - Cost and time for Advanced manufacturing for MW range power dense electrical machines for aerospace applications development

Scope of work:

The requirement for high power density and efficiency in electrical machines for aerospace application can be difficult with safety and certification constraints. Typically, the non-active part of electrical machines contributes 30 - 40% of the total weight. Reducing the weight of this part can significantly improve power density.

The Topic will focus on the design and development of non-active ultralight components of an electric machine, working closely with the Topic Manager up to TRL3 / 4. The focus will initially be on the carcasses and shafts.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1.1	Data on existing manufacturing methods	D	T0 +3
M1.2	Design of non-active component(s) finalised	D	T0 + 9
M2.1	Mechanical Integrity Test Data	D	T0 + 16
M2.2	Prototype fully assembled into an electrical machine - ready to test	HW	T0 + 22

*Type: R=Report, D=Data, HW=Hardware

Figure 59 - Milestones for Advanced manufacturing for MW range power dense electrical machines for aerospace applications development

- Development of power electronic technologies for >1kV aerospace applications

Indicative Funding Topic Value (in k€)	1300		
Topic Leader	Rolls Royce	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	24	**Indicative Start Date**[7]	Q2 2018

Figure 60 - Cost and time for Development of power electronic technologies for >1kV aerospace applications development

Scope of work:

Aerospace power electronics require high power density and more efficient performance. The technologies that contribute to this would be needed to operate at medium voltage (> 2 KV) and higher switching frequencies (> 10 KHz), while operating at high altitudes (> 30,000 feet). The project is divided into three Work Packages (WP) as below;

- WP1: active / passive technologies, including high speed machine units defined by the Topic Manager.
Identify and develop advanced passive and active components for medium voltage Aersopace (MV) drive applications. These will include concept study, modeling, prototyping and experimental testing of key components of a power converter that are suitable for operating with higher voltage / current, higher switching frequency, higher temperature and reduced weight in a laboratory environment.
- WP2: interconnection technology for medium voltage and high current applications.
Identify and develop appropriate interconnection technologies for Aerospace MV power systems and demonstrate the technology in a laboratory environment. These will include concept development, prototype construction and experimental validation of interconnection technologies that meet the requirements for power distribution in harsh environments at high altitudes.
- WP3: Packaging for high voltage medium voltage converters for aerospace applications. Identify light packaging methods and materials for high power medium voltage converters for aerospace applications. These will also include technologies such as 3D packaging, etc. This WP also includes the development of a complete converter to demonstrate the technologies developed within the project.
The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title - Description***	***Type****	***Due Date***
D1.1	Report on modelling and testing of the components considered	D, R	T0 + 16
D2.1	Interconnect technologies, hardware & prototype testing report	HW, R	T0 + 14
D3.1	Report on lightweight packaging technologies.	R	T0 + 5
D3.2	Converter hardware and testing report	R, HW	T0 + 24

*Type: R=Report, D=Data, HW=Hardware

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1.1	Review of identified technologies	D	T0 + 8
M2.1	Requirements capture document	R	T0 + 2
M2.2	Review of prototype design	D	T0 + 6
M3.1	Mid-point review of converter design	D	T0 + 10

*Type: R=Report, D=Data, HW=Hardware

Figure 61 - Milestones for power electronic technologies for >1kV aerospace applications development

- Development of a High Voltage Lithium Battery

Indicative Funding Topic Value (in k€)	500		
Topic Leader	Dassault Aviation	Type of Agreement	Implementation Agreement
Duration of the action (in Months)	18	Indicative Start Date[63]	Q2 2018

Figure 62 - Cost and time for Development of a High Voltage Lithium Battery development

Scope of work:

The goal of this topic is to deliver a battery system that reaches TRL 4 to the Core Partner. The battery system is designed to allow iterative updates in order to achieve the Core Partner's goals. The battery system will meet the following functional and system requirements:

- a single battery pack with a maximum weight of 55 kg including interconnections, housing, battery cells, connectors, protection devices and integrated electronics, with a peak power exceeding 500 W / kg for 2 minutes and over 200 Wh / kg at 1C. The packet must be divided into an even number of battery units, forming two groups of approximately equal mass;
- possibility to connect the package directly to a 115 V three-phase variable frequency network, using an optimized mass and volume approach, to charge the battery or provide AC power, either alone or in parallel with a typical 115 V AC aerospace alternator ;
- possibility to connect the package directly and simultaneously to two suitable three-phase electric motors or AC networks and to exchange a minimum total of 20 kW of power in both directions with the motors or AC networks;
- a high power recharge that allows a minimum speed of 60 W / kg from both the ground supply trolleys for an airport of 115 V AC / 400 Hz and from the three-phase network 240 V-380 V AC / 50 Hz.

A battery module must also contain information or software functions specific to the chemistry of the module.

The thermal control of each module must be as independent as possible from the thermal control of other modules, in order to minimize the risk of thermal leakage induced by neighboring modules. The minimum level of independence required is the level that ensures that even if a module enters thermal, the neighboring modules remain stable. The key temperature requirement is to prevent a chain reaction in which the modules escape one after another.

Finally, a battery unit also contains:

- Battery management module (BMS), sufficiently miniaturized and designed with a control architecture that respects the critical aspects of the BMS functions;
- External connectivity module (usually one) that provides connectors accessible from the outside for power and data;
- Power conditioning module, which adapts the voltage of the modules to each other or to the battery output voltage;
- Thermal control module, which removes heat from the battery compartment.

All modules are grouped in a housing that provides structural strength and thermal insulation.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title - Description***	***Type****	***Due Date***
D1	High Voltage Battery Innovation Roadmap	R	M1
D2	Preliminary FMEA / FMES	R	M2
D3	Report on Key Components and Technologies	R	M2
D4	Validation Test Reports	R	M4
D5	Cost model, including cost reduction plan if needed	R	M5
D6	Validated 3D and physical digital models of off-the-shelf components	SW	M3
D7	Validated physical and CAD models of TRL 4 battery pack	SW	M4
D8	Embedded software including programmable devices	SW	M4
D9	Hardware (one battery pack, cables and supporting user documentation)	HW	M5

*Types: R=Report, D-, HW=Hardware

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1	Project kick-off meeting	Review	T0+1 month
M2	Preliminary Design Review	Review	Applicant choice
M3	Critical Design Review	Review	Applicant choice
M4	Validation Review (after internal tests)	Review	Applicant choice
M5	Hardware delivery	HW	T0+15 months

*Types: R=Report, D-Data, HW=Hardware

Figure 63 - Milestones for Development of a High Voltage Lithium Battery development

- Assessment of arc tracking hazards in high voltage aerospace systems

Indicative Funding Topic Value (in k€):		750	
Topic Leader:	Rolls-Royce	**Type of Agreement:**	Implementation Agreement
Duration of the action (in Months):	30	**Indicative Start Date (at the earliest)[30]:**	Q3 2019

Figure 64 - Cost and time for Assessment of arc tracking hazards in high voltage aerospace systems development

Scope of work:

Arc tracking is a progressive failure mechanism that forms a charred route through an electrical insulation system, and is already a significant problem in existing aerospace electrical systems operating at 115 VAC and 230 V AC and can cause significant damage to the wiring. Furthermore, the impact of arc tracking on future systems operating at higher voltages, such as series electric hybrid systems, has not been evaluated. This project should quantify the arc tracking risk in megawatt aircraft electrical systems operating at high voltages (> 1.5kV DC). The project should develop fundamental understanding and consider what measures should be taken to safeguard the aircraft's electrical system from the resulting damage. The project should consider cable configurations that could be used in high voltage applications and different types of voltage (DC, AC, powered converter).

One of the major challenges faced in the field of hybrid propulsion is the need to increase the voltage of the system substantially above that previously used for aeronautical applications in order to reduce the weight of the entire electrical system, from the generator to the engine, to acceptable levels mainly through the reduction of the weight of the cable. For example, the current E-Fan X demonstrator project uses a DC bus voltage of 3kV. This is well above the 540 V DC used for the Boeing 787 aircraft, which in itself is twice the standard system voltage of 270 V DC in common use for many aircraft. For the purposes of this project, systems with bus voltages between 1.5 kV and 4.5 kV DC should be considered together with the other voltages that will be seen on the cabling system that are in the vicinity of AC sinusoidal waveforms and / or powered by converter. This project should quantify the risk of arc tracking in 1MW electrical systems for aircraft operating at high voltages (> 1.5kV DC and corresponding AC / converter voltage levels) through experimental techniques, using an environmental chamber or similar at temperatures, pressures and representative pressures of humidity. This should also include an investigation into safe separation (space requirements to ensure that there is no risk to other systems during an arc failure). Arc tracking modeling should be conducted to estimate the amount of current that will flow during a fault. It is likely that this model should represent the physics of the arc itself as well as taking a system-level view of the impedance of the system and the nature of the protection. The project should develop fundamental understanding (at TRL3) and consider what measures should be taken to safeguard the aircraft's electrical system from the resulting damage.
The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	**Title - Description**	**Type***	**Due Date**
D1.1	Literature Survey report on arc tracking hazards	R	T0 + 3
D1.2	Documented model of arc tracking across an insulator with user guide for model	R, D	T0 + 6
D2.1	Report on arc tracking test results and conclusions	R	T0 + 21
D3.1	Design guidance document for high voltage aircraft electrical systems	R	T0 + 24

Milestones (when appropriate)			
Ref. No.	**Title - Description**	**Type***	**Due Date**
M1.1	Modelling of the arc tracking process complete	D	T0 + 6
M2.1	Procedures defined for arc tracking tests	R	T0 + 9
M2.2	Experimental testing complete	HW	T0 + 17
M2.3	Validation of models complete	D	T0 + 19
M3.1	Measures to mitigate arc tracking risks captured	R	T0 + 23

Figure 65 - Milestones for Assessment of arc tracking hazards in high voltage aerospace systems development

- **I**nnovative pump architecture for cooling electrical machine**.**

Indicative Funding Topic Value (in k€)	800		
Topic Leader	Thales Avionics	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	30	**Indicative Start Date**[77]	Q1 2018

Figure 66 - Cost and time for Innovative pump architecture for cooling electrical machine. development

Scope of work:

Due to the continuous increase in electricity needs on board aircraft, electrical generation systems and more specifically VFSG (variable frequency starter generator) capable of emitting more and more power are required. This, however, also increases the loss of power due to various heating phenomena (copper losses, eddy current losses, mechanical frictions ...). For this reason, aircraft power generation applications require new oil cooling systems that serve high-power machines and that allow you to optimize mass, durability and availability as required by aircraft manufacturers.

As for the new high power VFSG developments, innovative pump projects are planned to allow:

- Improved integration of the pump and reduction of the scale to facilitate installation inside the machine, reduce the impact on the overall development of the machine and on the complexity of the project.
- Reduction of the maximum number of moving parts for greater durability and availability
- Optimization of pump efficiency

For example, these goals can be achieved by using a pump with no housing that can be installed directly inside the oil tank or a pump that runs at a higher speed and that does not use reduction systems to adapt to the speed of the machine.

The domain of the possible design is very wide and the TM foresees that the applicant perform an exhaustive study concerning:

- state of the art analysis
- Design and innovative architectures for the pump (innovation expected in terms of compactness and operating speed)
- selection of the preferred project, specification and definition
- production and testing of prototypes of the selected solution.

Performance required

- Minimum flow 23l / min
- outlet pressure higher than 10 bar
- operating speed range (ratio between maximum operating speed and minimum operating speed): x2.1, typically for a VFSG the minimum operating speed: 8000 rpm for 6-pole machines or 12000 rpm for 4-pole machines. Direct coupling of the shaft is preferable. If a gearbox is used between the VFSG shaft and the pump, the gearbox ratio must be minimized.

- overspeed capacity: minimum 5 minutes above + 20% of the maximum operating speed.

Interfaces

-The pump is located inside an electric generator

-Mechanical power is provided by the generator shaft.

-It is expected at the end of the TRL5 project.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type***	***Due Date***
KOM	Kick Off meeting		T0
PDR	Predesign review : pump architecture and technology selection		T0+8 months
CDR	Design review : pump definition and Test bench design freeze reproducing environmental conditions (mechanical constraints and temperature variation, dedicated or combined conditions)		T0+20 months
TRR	Test readiness review: test specification freeze.		T0+24 months
QR	Qualification review : Tests results and reports		T0+30 months

Figure 67 - Milestones for Innovative pump architecture for cooling electrical machine. development

- Aerospace standard Lightweight SSPC for High voltage >1kA application

Indicative Funding Topic Value (in k€)	900		
Topic Leader	Rolls-Royce	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	24	**Indicative Start Date (at the earliest)**[28]	Q1 2019

Figure 68 - Cost and time for Aerospace standard Lightweight SSPC for High voltage >1kA application development

Scope of work:

Operating voltages above 1 kV are mentioned very frequently and are in the public domain, however, due to the more rigid operating environment at high altitude, high power systems inevitably require higher operating currents which will probably exceed 1 kA in some applications.

As with any electricity distribution grid, hybrid and distributed propulsion architectures require protection solutions to cover all phases of the energy distribution, from the generation of higher primary voltage to lower voltage secondary distribution networks.

In combination with the increasing power requirements for protective devices, direct current (DC) is being adopted more frequently and this introduces further challenges; in particular the interruption of a high power circuit in fault conditions. Solid state technology offers the opportunity to minimize the size and weight of the system by electrically disconnecting two conductors using semiconductor materials; this eliminates the challenge associated with electrical

arcing and increases the possible switching speeds (compared to conventional contactor-based technologies).
The Topic Leader is looking for collaborative research partners that can support the development, at TRL 3/4, of a light and efficient solid state protection device, including the integrated isolation capability, to operate at a rated voltage including between at least 540 V DC (e.g. ± 270 V) and up to or greater than 1 kV DC with a rated current capacity between 500 A and up to or greater than 1 kA.
This call will be split into two work packages:
- WP1: component development
- WP2: analysis of thermal and electromagnetic interference (EMI)

WP1: development of a high power solid state protection device on TRL 3/4. This will include conceptual business studies, modeling, prototyping, functional demonstration and scalability studies. The goal is to identify the applicability of solid-state technologies as a means of providing electrical protection in the high-power sections of future aerospace power grids.
- T 1.1

Perform a commercial study to examine methods for maximizing efficiency in the state of solid state devices, with respect to cost and weight.
- T 1.2

Conduct a scalability study of solid state technology for electrical protection applications.
- T 1.3

Carry out conceptual design, development and functional tests of a solid state protection device prototype.
WP2:
Identify the integration requirements of the WP1 solid state devices, in particular considering the needs of thermal / cooling management and the EMI shielding necessary to make the device comply with the electromagnetic compatibility (EMC) standards.
- T 2.1

Develop a thermal model of the solid state device from WP1 and validate the simulation results using the data measured by the tests as part of activity 1.3.
- T 2.2

Develop an EMI model of the solid state device from WP1 and validate the simulation results using data measured by tests as part of activity 1.3.
The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Type: R=Report, D=Data, HW=Hardware

Deliverables			
Ref. No.	***Title - Description***	***Type****	***Due Date***
D1.1	Initial solid-state electrical protection device design	R	T0 + 7
D1.2	Report on trade study of maximising solid-state device efficiency, and the scalability of solid-state technology for electrical protection applications.	R	T0 + 9
D1.3	Design definition for high-power, lightweight and high efficiency solid-state electrical protection device.	R	T0 + 11
D1.4	Prototype hardware and report of testing results and analysis	HW, D	T0 + 22
D2.1	Report on development of thermal and EMI models, including simulation analysis and delivery of validated models.	R, D	T0 + 24

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1.1	Requirements capture document	R	T0 + 2
M1.2	Mid-point review of protection device design	D	T0 + 7
M1.3	Review of prototype protection device design	D	T0 + 11
M2.1	Review of thermal and EMI models	D	T0 + 18

Figure 69 - Milestones for Aerospace standard Lightweight SSPC for High voltage >1kA application development

- Model-Based identification and assessment of aircraft electrical and thermal loads architecture management functions

Indicative Funding Topic Value (in k€)	900 k€		
Duration of the action (in Months)	48 months	**Indicative Start Date**[61]	Q1 2017

Figure 70 - Cost and time for Model-Based identification and assessment of aircraft electrical and thermal loads architecture management functions development

Scope of work:

A model-based approach should be applied for the assessment of aircraft architectures for large passenger aircraft and its management functions.

CleanSky1 models must be reused and adapted appropriately. In CleanSky 1 a thermal management system (TMF) was modeled and developed for various functions of the electrical systems architecture system up to TRL3 in order to minimize peak thermal loads and optimize architecture, functionality and performance of the cooling system. The use case associated with the TMF must be implemented in the existing energy systems design process model. Missing elements need to be developed to assess the system's performance at the aircraft level. Methods to evaluate and optimize aircraft-level management functions must be applied and, where not available, they must be developed. For optimized architectures and their management functions, the advantages in terms of fuel consumption reduction and weight saving must be demonstrated by simulation for the electricity generation and distribution system, for the main consumption systems and the combination of both. .

Based on the optimal solutions identified by the simulation, support must be provided by a rapid prototyping approach, up to the demonstration activities that will be conducted on large-scale test benches including combined management functions.

The demonstration will be carried out within WP 6.4, starting from this call.

The goal is to reach a TRL5 for the energy management function at the end of the project.

In addition, support will be provided for the integration of the final management functions to allow demonstration up to a potential flight test that is not part of the project.

The electrical and thermal loads architectures of large aircraft and their global management functions must be identified and evaluated within WP6.0. The architectures and management functions must be demonstrated on large-scale test benches within the WP6.4. In particular architectures and management functions for:

a) Thermal management

b) Electrical management

c) Combined thermal and electrical management.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title - Description***	***Type***	***Due Date***
D_6.0.1_1	Specification of Requirement for Electrical and Thermal Management (T1,T2,T3)	R	T0+4 months
D_6.0.1_2	Demonstration of energy management functions in simulation environment (T1,T2)	R	T0+18 months
D_6.0.1_3	EMF implemented on Rapid Prototype Hardware (T1,T2, T3)	D	T0+28 months
D_6.0.1_4	Demonstration of energy management functions on rapid prototyping hardware (real-time capability) (T1,T2,T3)	R	T0+36 months
D_6.0.1_5	Planning document for support activities on ground test rigs. Specification of Software and HiL tests.	R	T0+40 months
D_6.0.1_6	Support for demonstration on ground test rigs. (T1,T2,T3)	R	T0+48 months

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type***	***Due Date***
M_6.0.1_1	TRL3 for EMF	RM	T0+18 months
M_6.0.1_2	TRL4 for EMF	RM	To+36 months
M_6.0.1_3	TRL5 for EMF (supporting action for Leading Partner)	RM	T0+48 months

*Type:

R: Report

RM: Review Meeting

D: Delivery of hardware/software

M: Milestone

Figure 71 - Milestones for Model-Based identification and assessment of aircraft electrical and thermal loads architecture management functions development

- High Performance Generation Channel Integration

Indicative Funding Topic Value (in k€)	800		
Topic Leader	SAFRAN ELECTRICAL & POWER	Type of Agreement	Implementation Agreement
Duration of the action (in Months)	48	Indicative Start Date[10]	Q2 2018

Figure 72 - Cost and time for High Performance Generation Channel Integration development

Scope of work:

This topic aims at the integration and demonstration, in the context of a developed control and supervision architecture, of a high performance high voltage direct current electricity generation system with a reliable mechanical insulation system for protection against highly dissipative failure modes. These technologies are essential for optimizing high density and efficiency power systems, for example using permanent magnet generators and allowing sharing between electrical sources to meet the needs of future more electric aircraft systems. The demonstration will use a high performance test bench that allows for the application of combinations of external effects, as well as the emulation of faults and the degradation of the hardware.

The aim of the work is the development and integration of a supervisory control architecture that will be used to control a high performance high voltage direct current electricity generation system. This will be used to demonstrate the system-level performance of intelligent power modules and a rapid disconnection developed on the basis of 2 other specific topics, but mainly it will aim to demonstrate the reachability of certain objectives for the dynamic controllability of electricity in order to use this controllability to optimize future systems.

Preliminary application studies indicate the following approximate specification points:

- Mechanical drive requirements: 60kW
- Overload of short-term mechanical transmission: 120kW
- Generator rotation speed: 5000-35000 rpm
- Continuous electrical load requirement: 45kW
- Short term electrical overload: 90kW
- Maximum heat dissipation by conditioned liquid cooling during continuous operation: 10kW

The goal will be to validate the performance of the tailor-made components individually as required and as a system, against the strict operational requirements of the application

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title – Description***	***Type****	***Due Date***
D3.1	Preliminary Requirements Specification	R	T0+3
D3.3	High-level test plan	R	T0+12
D3.5	Quick Disconnect test procedure	R	T0+27
D3.7	Generator Channel test procedure	R	T0+33
D3.9	Generator Channel Test report	R	T0+44
D3.10	Final report	R	T0+48

*Type: R=Report, D=Data, HW=Hardware

Milestones (when appropriate)			
Ref. No.	***Title – Description***	***Type****	***Due Date***
D3.2	Test Rig Preliminary Design Review	D	T0+7
D3.4	Test Rig Design Review	D	T0+12
D3.6	Quick Disconnect Test Readiness Review	D	T0+27
D3.8	Generator Channel Test Readiness Review	D	T0+33

*Type: R=Report, D=Data, HW=Hardware

Figure 73 - Milestones for High Performance Generation Channel Integration development

- Quick Disconnect System

Indicative Funding Topic Value (in k€)	600		
Topic Leader	SAFRAN ELECTRICAL & POWER	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	36	**Indicative Start Date**[9]	Q2 2018

Figure 74 - Cost and time for Quick Disconnected System development

Scope of work:

This topic will develop and demonstrate a new highly robust and reliable fault detection and mechanical isolation system to mitigate the risks of potentially highly dissipative failure modes associated with the high-performance electricity generator technologies required for future energy-optimized aircraft. Future optimized electricity systems with an active distribution of power between electrical sources will use high speed and high efficiency electric generators. The wide range of operating speeds of these generators and the technologies used to maximize their power density, as well as the greater criticality of the power supply system, increase the severity of potential failure modes.

In view of the greater criticality of the electrical system, the increasing amount of mechanical energy stored, the very significant amount of mechanical energy available from the turbine and the potential new modes of electrical failure of the generators, an effective and reliable means of mechanical isolation of the generator from the turbine it is necessary in order to ensure control of possible generator failure modes that could be more harmful to the surrounding systems and equipment.

The main target will be the mechanical failures that cause the loss of integrity of the bearings or the structure, and therefore a poorly limited axial or radial movement of the rotating components.

The activity will not aim to demonstrate the behavior of a complete generator with imposed failures, but the performance of the developed hardware will be tested with a standard generator in difficult conditions (vibrations, misalignment) as part of the related integration work package. Initial validation will occur through dynamic behavioral analyzes and physical tests of rapid disconnection under laboratory conditions, emulating the turbine and generator using the appropriate drive motor and load respectively. The tests will require specialized skills in order to allow the simultaneous evaluation of the effects of multiple disturbances, such as mechanical load combined with vibrations and temperature. Furthermore, in order to evaluate the robustness, the effects of manufacturing tolerances and wear conditions must be evaluated.

The test equipment will be able to emulate and characterize the effects of mechanical failures with consequent relaxation of the axial and / or radial constraints surrounding the disconnection device (not as a complete generator) in difficult environmental conditions.

The particular challenges relate to the robustness and reliability required in harsh environments, combined with the stringent size and weight requirements.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	***Title – Description***	***Type****	***Due Date***
D1.1	Preliminary Requirements Specification	R	T0+3
D1.2	Shaft Coupling Topology and Materials Trade Study Report	R	T0+12
D1.3	Disconnect System architecture definition	R	T0+12
D1.5	Initial Simulation & Analysis Report	R	T0+15
D1.6	Final Simulation & Analysis Report	R	T0+24
D1.8	Two Disconnect System ship sets for integration	HW	T0+28
D1.9	Test and Validation Report	D	T0+34
D1.10	Final Report	D	T0+36

*Type: R=Report, D=Data, HW=Hardware

Milestones (when appropriate)			
Ref. No.	***Title – Description***	***Type****	***Due Date***
D1.4	Quick Disconnect Concept Design Review	R	T0+15
D1.7	Quick Disconnect Detailed Design Review	R	T0+24

*Type: R=Report, D=Data, HW=Hardware

Figure 75 - Milestones for Quick Disconnected System development

- Design and development of a long stroke Piezo Electric Actuator

Indicative Funding Topic Value (in k€)	800		
Topic Leader	SAFRAN	Type of Agreement	Implementation Agreement
Duration of the action (in Months)	36	Indicative Start Date (at the earliest)121	Q1 2019

Figure 76 - Cost and time for Design and development of a long stroke Piezo Electric Actuator development

Scope of work:

The purpose of this topic is to design and develop a prototype of a long stroke piezoelectric actuator with higher stroke and load capacities. The functionality and performance of the actuator will be evaluated on a prototype laboratory in order to obtain a TRL4.

Recent research has shown that piezoelectric electric drive technology can be beneficial for Landing Gear (LG) locking actuators, both in terms of performance requirements and weight targets.

Piezoelectric actuators have traditionally been used in applications that require high positioning accuracy and reliability but relatively short strokes, e.g. optics, sensors, instrumentation drives etc. Piezoelectric actuators have no sliding parts and do not require lubrication which would have the advantage of reducing maintenance operations.

The purpose of the proposed research topic is to develop a long stroke actuator based on piezoelectric technology for future actuation applications with A / C locking.

The target is typically the next generation of single aisle aircraft developed in the next decade which will likely place a much greater emphasis on electrical actuation.

The project aims to improve piezoelectric electric drive technology in order to achieve the performance required for future A / C landing gear uplock and downlock systems.

The purpose of this research project will be to ensure the scalability of existing technologies to the application requirements.

The main research areas for potential innovation and performance increase are:

• Investigate alternative power configurations
• Use of different materials for the basic stack
• Highly dynamic energy storage devices
• Identify new methods of thermal management

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	Title - Description	Type*	Due Date
D1	Preliminary studies and concept validation report	R	M09
D2	Laboratory prototype specification	R	M22
D3	Laboratory Prototype	HW	M29
D4	Test report	R	M36

**Type: R=Report, D=Data, HW=Hardware*

Milestones (when appropriate)			
Ref. No.	Title - Description	Type*	Due Date
M1	Conceptual Review validated	R	M09
M2	Design Review passed	R	M22
M3	Technology Maturity Review (TRL4) achieved	R	M36

*Type: R=Report, D=Data, HW=Hardware

Figure 77 - Milestones for Design and development of a long stroke Piezo Electric Actuator development

- Development of an optimized DC-DC converter for a smart electrical system

Indicative Funding Topic Value (in k€)	700		
Topic Leader	Safran	Type of Agreement	Implementation Agreement
Duration of the action (in Months)	18	Indicative Start Date (at the earliest)133	Q1 2019

Figure 78 - Cost and time for Development of an optimized DC-DC converter for a smart electrical system development

Scope of work:

The goal of this study is to design a modular bidirectional DC / DC converter (LVDC to HVDC, 4-30kW) that is highly efficient (efficiency> 96% to mitigate thermal problems) and achieves power density of over 5kW / kg not considering the packaging.

This converter could also be used to improve the quality of the mains supply using hybridization with super-capacitors or batteries, to supply or absorb transient loads (flight control actuators for example). To be able to meet these demanding requirements, it is necessary to increase the voltage variation interval and the dynamics must be fast enough.

It is therefore necessary for this topology to use broadband semiconductors (GaN for LVDC and SiC for HVDC) and / or soft switching to increase the switching frequency and reduce the size and mass of all passive components (capacitors, inductors, transformers) .

The proposed innovative topology will contribute to:

- Reduce losses (soft switching and broadband semiconductors)
- Weight reduction (passive component and thermal management)
- Increase availability
- Improve the quality of the power supply and an easy reconfiguration of the network

The state of the art uses the MOSFET Si technology on the LVDC side with a switching frequency of 100 kHz. GaN technology will allow switching at higher frequencies, reducing passive components, increasing the control band and reducing response times on transients. This new technology, associated with gradual switching, will help increase efficiency and power density (actually 3.6 kW / kg at maximum power with the heat sink).

The final prototype must meet aeronautical constraints for qualification, be representative of the mass and volume of the final product and be able to provide its performance within its operating environment. Prototype development must consider the requirements for future industrialization.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	Title - Description	Type*	Due Date
D1	Compliance matrix and non-compliance justification	R	T1
D2	Architecture overview	R	T2
D3	3D Model	R/D	T3
D4	Performance simulation report	R/D	T3
D5	Detailed analyses report	R	T4
D6	Prototypes	HW	T5

**Type: R=Report, D=Data, HW=Hardware*

Milestones (when appropriate)			
Ref. No.	Title - Description	Type*	Due Date
M1	Technical Specification Review	R	T1 + 1 month
M2	Architecture presentation	R	T3 + 1 month
M3	Detailed design presentation	R	T4 + 1 month
M4	Prototype Inspection Review	HW	T5 + 1 month
M5	Project ending meeting	R	T5 + 2 month

**Type: R=Report, D=Data, HW=Hardware*

Figure 79 - Milestones for Optimized DC-DC converter for a smart electrical system development

- Development of a HVDC current limiter

Indicative Funding Topic Value (in k€)	650		
Topic Leader	Zodiac Aero Electric	Type of Agreement	Implementation Agreement
Duration of the action (in Months)	24	Indicative Start Date (at the earliest)137	Q1 2019

Figure 80 - Cost and time for HVDC current limiter development

Scope of work:

The objective of this topic is to develop an optimized current limiter to be integrated in an energy distribution center for HVDC aircraft, capable of operating at high temperatures 100 ° C for normal operating conditions and with a small amount of volume available for cooling, the current limiter must provide low losses (only a few tens of watts).

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables			
Ref. No.	Title - Description	Type*	Due Date
D1	Current limiter prototypes definition and specifications	R	T0+6
D2	Technical synthesis and prototypes validation test report	R	T0+13
D3	Prototypes delivery	HW	T0+13
D4	Detailed design refinement	R	T0+16
D5	Report on the current limiter validation test and TRL6 demonstration	R	T0+24
D6	Delivery of the current limiter	HW	T0+24

*Type: R=Report, D=Data, HW=Hardware

Milestones (when appropriate)			
Ref. No.	Title - Description	Type*	Due Date
M1	Current limiter prototypes Preliminary Design Review	Review	T0+3
M2	Current limiter prototypes Detailed Design Review	Review	T0+6
M3	Current limiter prototypes Validation Review (after stand-alone tests)	Review	T0+10
M4	Current limiter final version Detailed Design Review	Review	T0+16
M5	Current limiter final version Validation Review (after stand-alone tests)	Review	T0+24

*Type: R=Report, D=Data, HW=Hardware

Figure 81 - Milestones for HVDC current limiter development

- Multifunctional Aircraft Power Network with Electrical Switching

Indicative Funding Topic Value (in k€)	1100		
Topic Leader	Fokker	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	30	**Indicative Start Date (at the earliest)38**	Q1 2019

Figure 82 - Cost and time for Multifunctional Aircraft Power Network with Electrical Switching development

Scope of work:

The topic contributes to the development of advanced electrical distribution system architectures to be integrated into the multifunctional fuselage demonstrator. The design, development, production and validation of a "multifunctional aircraft power supply with electrical switching" must provide a hardware and software system with a technology readiness level of 4. The development includes:

- Controlling a data network and switching on the power buses controlled by the bus controller unit (BCU).

- Solid State Bus Tie Contactor (SSBTC)

- Loads with representative impedances and integrated bus-controlled switching

- Study of their performance when integrated with the MFFD (Multifunctional Fuselage Demonstrator) bus.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones		
Ref. No.	Title – Description	Due Date
MS1	Kick-off meeting	t0
MS2	System Model and Requirements Review	t0 + 8
MS3	TRL3 Assessment Review	t0 + 18
MS4	Communication design finalized	t0 + 24
MS5	TRL4 testing completed	t0 + 27
MS6	TRL4 Assessment Review	t0 + 28

Figure 83Milestones for Multifunctional Aircraft Power Network with Electrical Switching development

- Green and cost efficient Conceptual Aircraft Design including Innovative Turbo-Propeller Power-plant

Indicative Funding Topic Value (in M€)	4		
Duration of the action (in Months)	72	**Indicative Start Date**[4]	01/04/2016

Figure 84 - Cost and time for Green and cost efficient Conceptual Aircraft Design including Innovative Turbo-Propeller Power-plant development

Scope of work:
The aim is to improve the efficiency of a 90-seat regional turboprop aircraft. The aim is to research and develop two configurations, one conventional, a wing mounted turboprop configuration, and innovative one, which includes a new aerodynamic design mainly based on the laminar concept, drastic lowering of emissions and noise.
The development includes all the design phases and the following tests for the two configurations:

	Life cycle cost module	Aerodynamic Design	Power-plant design	Advanced low noise propeller studies	Low noise propeller anti-icing/de-icing system	Safety Assessment	Wind Tunnel Test model and specification
Conventional architecture	Yes	No	Yes	Yes	Yes	No	Yes
Innovative architecture	Yes	Yes	Yes	Yes	No	Yes	Yes

Table 2 - - Tests foreseen in the project: Green and cost efficient Conceptual Aircraft Design including Innovative Turbo-Propeller Power-plant

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Milestones		
Ref. No.	*Description*	*Due Date*
	SHORT TERM MILESTONES	
M1	Design Review (technology concept formulated)	T0 + M6
M2	Aircraft Simulation Model Tool (Life cycle cost Module)	T0 + M10
M3	Design Review (experimental proof of concept)	T0 + M15
	MEDIUM TERM MILESTONES	
M4	Innovative intermediate configuration, engines dataset -- Loop 2	T0 + M23
M5	First conceptual low noise propeller down-selection based on Aero-Acoustic results	T0 + M30
M6	Conventional final configuration, engines dataset -- Loop 3	T0 + M38
	LONG TERM MILESTONES	
M7	WT model CDR	T0 + M42
M8	Specification of activities of high and low-speed WTT oriented to test on laminar wing	T0 + M50
M9	Manufacturing (and release) of the models for the high and low speed tests (Innovative configuration)	T0 + M56
M10	Low Noise Propeller final assessment	T0 + M74

Figure 85 - Milestones for Green and cost efficient Conceptual Aircraft Design including Innovative Turbo-Propeller Power-plant

- Intermediate Compressor Frame for Ultra High Propulsive Efficiency

Indicative Funding Topic Value (in M€)	3,5		
Duration of the action (in Months)	96	**Indicative Start**	01/04/2016

Figure 86 - Cost and time for Intermediate Compressor Frame for Ultra High Propulsive Efficiency development

Scope of work:

This call aims at reaching TRL 5-6 maturation by mid-2021 for a set of specific technologies dedicated to the ultra-high power efficiency (UHPE) concept. The chosen architecture is an Ultra High Bypass Ratio turbofan (ducted architecture) with a by-pass ratio preliminary anticipated within the range of 15-20. The purpose of this WP is to select and test the Intermediate compressor frame concept, which will be part of and fit with the optimized concept of ultra-high power efficiency (UHPE). This optimization has to take into account the interface aspect of this component, between the LP compressor and the HP compressor and the (possible) function of engine suspension. On the module side, mature robust, efficient and lightweight Intermediate Compressor Frame technologies, up to TRL6 through Ground Testing of the UHPE.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

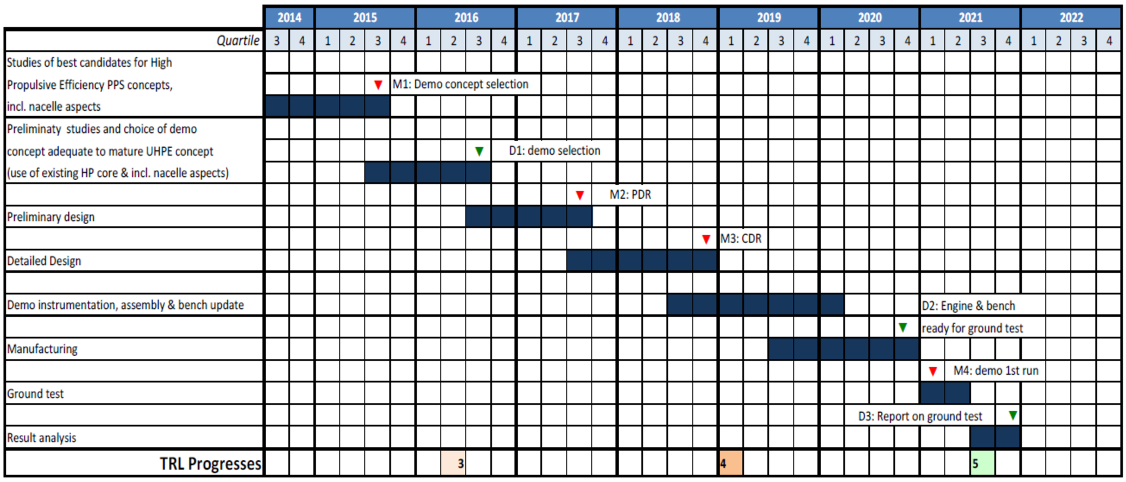


Figure 87 - Overall UHPE Snecma schedule

- Advanced mechatronics devices for electrical management system of Turboprop

Indicative Funding Topic Value (in k€)	900 k€		
Duration of the action (in Months)	36 months	**Indicative Start Date**[44]	Q1 2017

Figure 88 - Cost and time for Advanced mechatronics devices for electrical management system of Turboprop development

Scope of work:

The turboprops in the 1800-2000shp class currently have a traditional brushed 28Vdc generator, reliable technology that allows easy control of the output voltage level, but heavy and with a low Time Between Overall (TBO).

The aim is to design, produce and test a system with a lower weight and additional functions consisting of:

- A power supply device
- Associated control electronics

The system must perform both the function of generator, in order to provide at least 16kW continuous, with an output voltage of 28 V DC or 270 V DC and of motor, in order to provide a mechanical power of 16 kW to the external shaft with an estimated torque of 20-28 Nm with an input voltage of 28 V DC or 270 V DC.

The associated control electronics must instead be able to select the power level, at least ON / OFF, from the power electronics, perform the diagnosis in order to detect internal faults and inability to operate in both modes and must be able to interface with another device, receive orders and send health conditions.

The estimated mass of the mechatronic system must be less than 10 kg. The dimensions of the mechatronic system must be reduced to a minimum and such as to adapt to an external diameter of 170 mm.

The useful data for the determination of the times have been extrapolated from the list of milestones and deliverables shown below:

Deliverables & Milestones			
Ref. No.	***Title - Description***	***Type (*)***	***Due Date***
D1	Specifications (contribution of partner and TM)	R	T0+3
D2.1	Preliminary dynamic models	D	T0+6
D2.2	Final dynamic models	D	T0+12
D3	Preliminary Design Review	RM	T0+10
R4	Critical Design Review	RM	T0+12
D5	Equipments delivery	D	T0+24
R6	TM engine tests preparation	RM	T0+24
D7	Component tests reports (including environmental tests)	R	T0+34

** Type: R: Report - RM: Review Meeting - D: Delivery of hardware/software*

Figure 89 - Milestones for • Advanced mechatronics devices for electrical management system of Turboprop development

- High Performance Electrical Components for Bleed Control

Indicative Funding Topic Value (in k€)	900		
Topic Leader	Safran	**Type of Agreement**	Implementation Agreement
Duration of the action (in Months)	30	**Indicative Start Date (at the earliest)**[7]	Q1 2019

Figure 90 - Cost and time for High Performance Electrical Components for Bleed Control development

Scope of work:

The primary objective is the development of two components: electro mechanical actuator (EMA) for suction guide vanes and electric vent control valve, as regards demonstrating their reliability in harsh environments.

The particular challenges concern the robustness and reliability required in harsh environments, being integrated with the electrical components, combined with the strict requirements of size, weight, efficiency and compatibility with aeronautical performance standards.

Below the main data used to time estimation;

**Type: R=Report, D=Data, HW=Hardware*

Deliverables			
Ref. No.	***Title – Description***	***Type****	***Due Date***
D2.1	Preliminary Requirements Specification	R	T0+3
D2.2	Module Architecture Report	R	T0+6
D2.3	Industrialisation Assessment Report	R	T0+12
D2.6	Test report	R	T0+27
D2.7	Two components shipsets for integration	HW	T0+27
D2.8	Final report (incl. reliability prediction)	R	T0+30
Milestones (when appropriate)			
Ref. No.	***Title – Description***	***Type****	***Due Date***
D2.4	Preliminary Design Review	D	T0+12
D2.5	Detailed Design and Manufacturing Review	D	T0+18

Figure 91 - Milestones for High Performance Electrical Components for Bleed Control development

- BLI configurations of classical tube and wing aircraft architecture - Wind tunnel tests insight into propulsor inlet distortion and power saving

Indicative Funding Topic Value (in k€):		3500	
Topic Leader:	Safran Tech	**Type of Agreement:**	Implementation Agreement
Duration of the action (in Months):	36	**Indicative Start Date (at the earliest)[6]:**	Q3 2019

Figure 92 - Cost and time for BLI configurations of classical tube and wing aircraft architecture - Wind tunnel tests insight into propulsor inlet distortion and power saving development

Scope of work:

The main purpose of this project is to study the optimal configuration, in terms of dimensions and geometries of a BLI (bundary layer ingestion) tail thruster. This engine exploits the ingestion of the turbulent boundary layer of the fuselage by conveying it appropriately to a propulsion system located in the tail, allowing an improvement in propulsion efficiency.

The development of this project involves the definition of one or more BLI configurations with CFD analysis and finally using a scaled prototype in a wind tunnel in order to determine the improvements obtained in terms of efficiency compared to the traditional configuration.

Below the milestones:

Milestones (when appropriate)			
Ref. No.	**Title - Description**	**Type***	**Due Date**
MS_1	Specification Review	R	T0+4
MS_2	Scale Models, Test Bench and ADS COR	R	T0+5
MS_3	Scale Models, Test Bench and ADS PDR	R	T0+7
MS_4	Scale Models, Test Bench and ADS CDR	R	T0+12
MS_5	Manufacturing Review	R	T0+23
MS_6	Component Testing Review	R	T0+24
MS_7	Testing Preparation Review	R	T0+27
MS_8	Wind Tunnel Test Review	R	T0+30
MS_9	Final wind tunnel test data delivery Review	R	T0+34
MS_10	Synthesis Review	R	T0+36

*Type: R=Report

Figure 93 - Milestones for BLI configurations of classical tube and wing aircraft architecture - Wind tunnel tests insight into propulsor inlet distortion and power saving development

- Demonstration and test of low-loss, high reliability, high speed, bearing-relief generators

Indicative Funding Topic Value (in k€):		800	
Topic Leader:	University of Nottingham	**Type of Agreement:**	Implementation Agreement
Duration of the action (in Months):	24	**Indicative Start Date (at the earliest)[101]:**	Q3 2019

Figure 94 - Cost and time for Demonstration and test of low-loss, high reliability, high speed, bearing-relief generators development

Scope of work:

Conventional, contact bearing technology is mature but limits generator efficiency, maximum rotational speeds and reliability. This project will demonstrate a new class of bearing-relief generators where radial forces are controlled electromagnetically taking loads off the bearings and additionally suppressing any rotor vibrations. This programme of work will look at the development of a setup able to demonstrate the benefit of the proposed control technologies. The setup will include instrumentation to measure the electrical power from the generator. The generator developed by the topic manager will feed 3 separate 3-phase converters. The setup will also monitor the generator rotor spatial position, the net bearing loading during operation as well as the ability to apply the normal torque at pre-defined duty cycles and axial and radial load to the generator at the point of coupling. The programme of work will also look at accurately measuring the bearing losses under different loading conditions.

The milestones for this call are present below:

Milestones (when appropriate)			
Ref. No.	**Title - Description**	**Type***	**Due Date**
M1	Prelimenary design review.	R	T7
M2	Critical design review.	R	T10
M3	Demonstration-setup assembled	HW	T20
M4	Demonstration-setup commissioned	HW	T22

*Type: R=Report, D=Data, HW=Hardware

Figure 95 - Milestones for Demonstration and test of low-loss, high reliability, high speed, bearing-relief generators development

- Structural energy storage and power generation functionalities in composite structures

Indicative Funding Topic Value (in k€)	1130 k€		
Duration of the action (in Months)	36 months	**Indicative Start Date**[9]	Q1 2017

Figure 96 - Cost and time for Structural energy storage and power generation functionalities in composite structures development

Scope of work:

The project must be oriented towards the development of an innovative composite material and / or structural elements that will act as battery capacity and power generation with probably a combination of different technical solutions within the same battery frame of a classic aircraft, such as the 24-voltage delivery power generation with energy transfer capability. The expected result is a real 2m² prototype that represents a typical fuselage structure with both functions, obviously not forgetting the primary function of the structure, the load transfer, which must in no case be compromised. Furthermore, the conditions during the fabrication of the parts of the structure, the assembly of the main components and the assembly of the final structure are very different for the large structural parts and assemblies compared to the installation of the system.

The expected technological solution must be provided with some underlying data from the development of the simulation for verification with respect to the Topic Manager requirements. The time that must elapse before TRL2-technological concept and application definition is used to experimentally verify compliance with key showstopper requirements. And through a detailed simulation while the time necessary for the validation of the TRL4 prototype in a laboratory environment will be used for the completion of the fundamental test pyramid of developed solutions, storage and energy generation technologies, which will be implemented on the prototype.

Everything within the time frame is detailed below

Deliverables			
Ref. No.	***Title - Description***	***Type***	***Due Date***
D1.1	Concept description of battery composites incl. the basic demonstrator	Report	T0 + 6
D1.2	Evaluated battery composites development	Report	T0 + 22
D2.1	Concept description of power generation structural materials acting incl. the basic demonstrator	Report	T0 + 6
D2.2	Evaluated power generation development	Report	T0 + 22
D3.1	Concept description of structural super capacitor incl. the basic demonstrator	Report	T0 + 6
D3.2	Evaluated structural super capacitor development	Report	T0 + 22
D4.1	Coupons test results	Report	T0 + 12
D4.2	Structural behaviour of battery, piezo. comp, and of super capacitor	Report	T0 + 26
D5.1	Battery Composite physical demonstrator	Hardware	T0 + 15
D5.2	Battery Composite demonstrator summary incl. functional test report	Report	T0 + 34
D6.1	Power generation physical prototype	Hardware	T0 + 17
D6.2	Power generation prototype summary incl. functional test report	Report	T0 + 34
D7.1	Structural super capacitor physical demonstrator	Hardware	T0 + 17
D7.2	Structural super capacitor demonstrator summary incl. functional test report	Report	T0 + 34
D8.1	Power management for demonstrators	Hardware	T0 + 20
D8.2	Power management for demonstrators summary incl. functional test report	Report	T0 + 34
D9	Final report	Report	T0 + 36

Figure 97 - Milestones for Structural energy storage and power generation functionalities in composite structures development

- Development of methods for deriving optimized shapes of morphing structures

Indicative Funding Topic Value (in k€)	350 k€	**Type of agreement**	Implementation Agreement
Duration of the action (in Months)	25 months	**Indicative Start Date**[35]	Q2 2017

Figure 98 - Cost and time for Methods for deriving optimized shapes of morphing structures development

Scope of work:

Morphing structures are a promising solution for noise and drag reduction in future aircraft. They are intended to replace or supplement current aircraft high lift devices which today typically have the disadvantage of gaps in deployed position, sources of noise radiation and aerodynamic drag. Morphing structures replace these devices by a gapless solution based on skin deformation of the wing.

The tasks comprise method development for integration of drag, lift and material limitations concerning its morphing capability in one optimization process and application of the process to a morphing leading edge. Additionally, a kinematics development validate by 3D CFD analyses of resulting shapes is expected.

The proposed activities can be organised as following:

Deliverables			
Ref. No.	***Title - Description***	***Type***	***Due Date***
1	Method for aerodynamic optimization considering mechanical boundary conditions	Report	M8
2	Optimization results for morphing leading edge	Report/ Data	M14
3	Aerodynamic performance estimation of different morphing leading edge design solutions	Report	M25

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type***	***Due Date***
1	Optimization results for morphing leading edge	Report/ Data	M14
2	Aerodynamic performance of selected morphing leading edge design solutions is estimated	Report	M25

Figure 99 - Milestones for Methods for deriving optimized shapes of morphing structures development

- Natural Laminar Flow adaptive wing concept aerodynamic experimental validation

Indicative Funding Topic Value (in k€)	1200 k€	**Type of agreement**	Implementation Agreement
Duration of the action (in Months)	18 months	**Indicative Start Date**[15]	Q2 2017

Figure 100 - Cost and time for Natural Laminar Flow adaptive wing concept aerodynamic experimental validation development

Scope of work:

Within the present project, an existing 1:7 scaled complete powered wind tunnel model will be modified to include new morphing high lift device shapes (droop nose, fowler flaps) to achieve an improved turboprop green configuration. As second step of the activities low speed wind tunnel tests will be performed to validate performances in take-off, landing and approaching conditions.

Activities can be organized in the following Tasks:

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type***	***Due Date***
M1	Model Design: Modification to the existing TP green A/C model have been designed to integrate HLD technologies	R	M09
M2	Model ready: The design of the TP green complete scaled powered A/C integrating HLD morphing systems is performed.	R	M15
M3	Green Turboprop aerodynamic database: The experimental aerodynamic database concerning HLD and morphing shapes, is available._	R	M18

(*R=Report; D=Data, drawing)

Figure 101 - Milestones for Natural Laminar Flow adaptive wing concept aerodynamic experimental validation development

- Virtual-Hybrid-Real On Ground demonstration for HVDC & EMA Integration

Indicative Funding Topic Value (in k€)	400		
Topic Leader	Airbus Defence & Space	Type of Agreement	Implementation Agreement
Duration of the action (in Months)	24	Indicative Start Date (at the earliest)[73]	Q1 2019

Figure 102 - Cost and time for Virtual-Hybrid-Real On Ground demonstration for HVDC & EMA Integration development

Scope of work:

The aim of this topic is design, development and installation of a configurable virtual/hybrid/real ground test environment, aircraft and airframe representative, according to VISTAS EUROCAE standard for on-ground tested validation (up to TRL5 of technology integration of airframe) of flight control surfaces driven by electromechanical actuators powered by high voltage DC electrical generation (HVDC). The VISTAS standard was released on Nov-2017, by EUROCAE Working Group 97 titled "Interoperability of virtual avionic components" and was approved by the Council of EUROCAE on 10 November 2017. It provides the Virtual Component definition in terms of modelling and the Standardization of the interfaces. In the following picture, the virtual bench concept and the real test bench concept are represented through VISTAS approach. It can be noted that following this scheme the switching between real and virtual environments is immediate and in the cases of benches a huge cost avoidance can be obtained in terms of benches simplicity and wiring. Concepts like patch panels and fault insertion systems based on HW are virtualized.

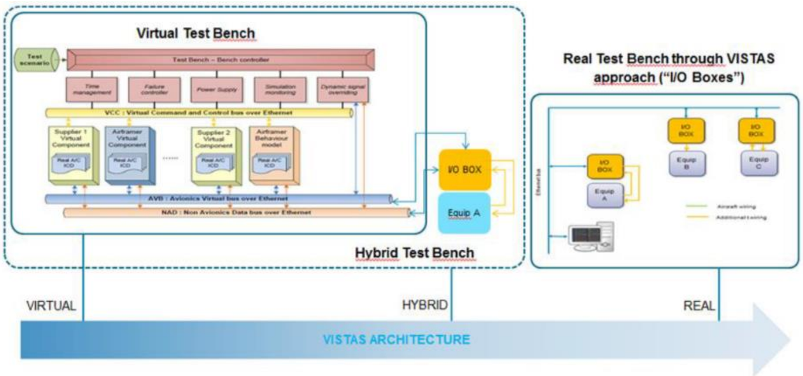


Figure 103 - VISTAS approach about bench architecture.

The deliverables and milestones are present below:

Milestones (when appropriate)			
Ref. No.	***Title - Description***	***Type****	***Due Date***
M1	VISTAS I/O Box & SW development PDR	R	T0+4
M2	VISTAS I/O Box & SW development CDR	R	T0+5
M3	VISTAS I/O Box HW delivery	HW	T0+9
M4	VISTAS I/O Box & SW development Closure	R	TO + 24
M5	HVDC Test Bench KOM	R	T0+1
M6	HVDC Test Bench PDR	R	T0+2
M7	HVDC Test Bench CDR	R	T0+3
M8	HVDC Test Bench POWER ON	HW	T0+10

Figure 104 - Milestones for Virtual-Hybrid-Real On Ground demonstration for HVDC & EMA Integration develo0pment

3.1.2 Database analysis

All technologies analysed, described above, are listed in Table 3

Advanced mechatronics devices for electrical management system of Turboprop
High Speed HVDC Generator/Motor
Electrical components
Innovative cooling system for embedded power electronics
High Density Electrical Connectors
E2-EM Supervisor and Control Algorithms
High density energy storage module for an electric taxi
Power Module
Screening and development of optimized materials for high temperature coils
Integrated electronics for actuator data and power management for Morphing Leading Edge activities
Development of AC cabling technologies for >1kV aerospace applications
Innovative Primary and Secondary Electrical Distribution Network for Regional A/C
Design and Development of a high temperature HVDC busbar
Development of low rating and high power HVDC optimized fuses
Novel mechanical drive disconnect for embedded Permanent Magnet machines
Advanced manufacturing for MW range power dense electrical machines for aerospace applications
Development of a High Voltage Lithium Battery
Development of power electronic technologies for >1kV aerospace applications
Assessment of arc tracking hazards in high voltage aerospace systems
Innovative pump architecture for cooling electrical machine
Aerospace standard Lightweight SSPC for High voltage >1kA application
Model-Based identification and assessment of aircraft electrical and thermal loads architecture management functions
High Performance Generation Channel Integration
Quick Disconnect System
Design and development of a long stroke Piezo Electric Actuator
Development of an optimized DC-DC converter for a smart electrical system
Development of a HVDC current limiter
Multifunctional Aircraft Power Network with Electrical Switching
Green and cost efficient Conceptual Aircraft Design including Innovative turbo-propeller power-plant Turbo-Propeller Power-plant
Intermediate Compressor Frame for Ultra High Propulsive Efficiency
Advanced mechatronics devices for electrical management system of Turboprop
High Performance Electrical Components for Bleed Control
BLI configurations of classical tube and wing aircraft architecture - Wind tunnel tests insight into propulsor inlet distortion and power saving
Demonstration and test of low-loss, high reliability, high speed, bearing-relief generators
Advanced investigation of ultra compact RQL reverse flow combustor
Structural energy storage and power generation functionalities in composite structures
Development of methods for deriving optimized shapes of morphing structures
Natural Laminar Flow adaptive wing concept aerodynamic experimental validation
Virtual-Hybrid-Real On Ground demonstration for HVDC & EMA Integration

Table 3 - Database

All the technologies analysed were divided according to the subsystem they belong to, looking for a possible trend in costs and similar times for technologies belonging to the same subsystem. The first analysis carried out exploits the data that correlate the TRL jumps to the necessary times, or the milestones, to determine the trends of the times based on the advance of the technology readiness levels (TRL).

The graphs obtained by interpolating the extrapolated values for each technology, in term of milestones and TRL jump, divided by subsystem, are shown below.

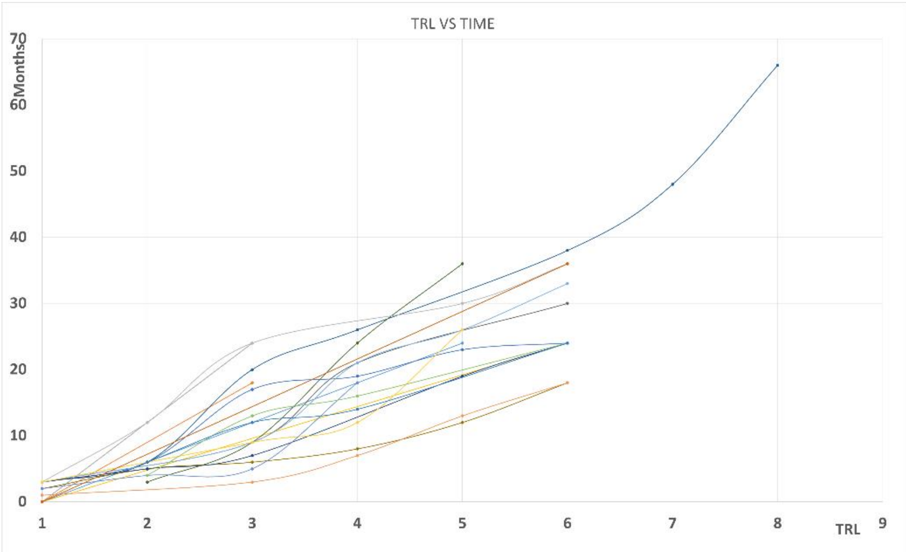


Figure 105 - Electric subsystem TRL vs Time

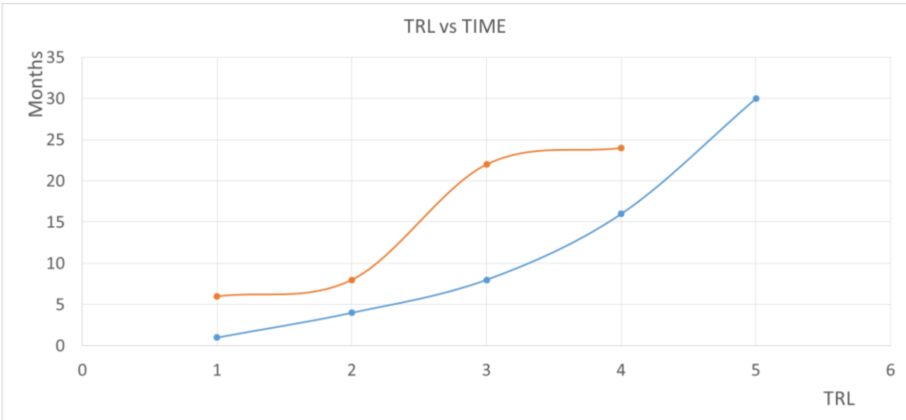


Figure 106 - Cooling system TRL vs Time

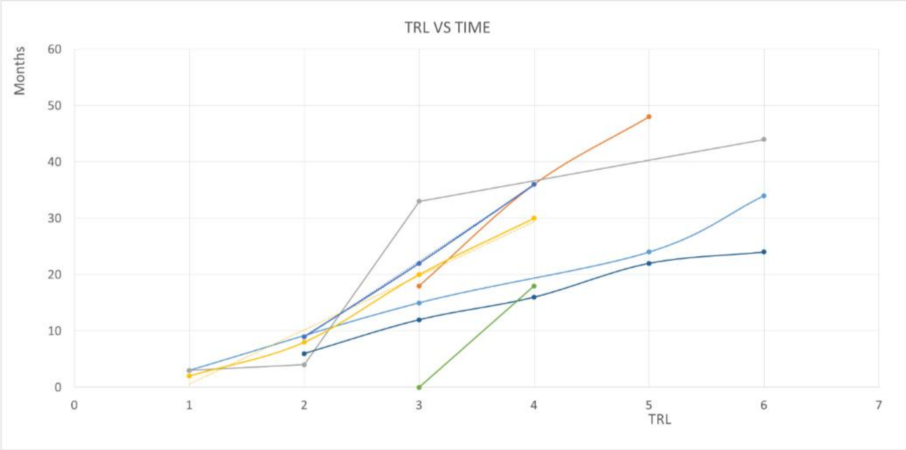


Figure 107 - On-board control subsystem TRL vs Time

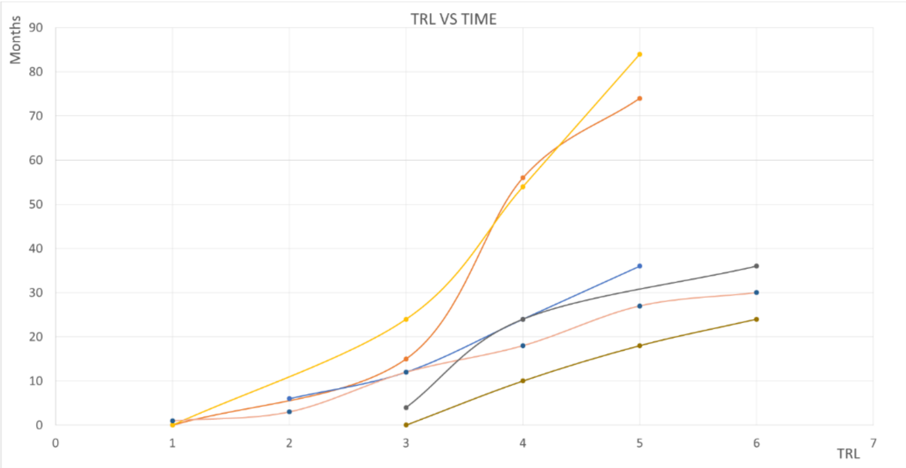


Figure 108 - Propulsion subsystem TRL vs Time

Figure 109 - Structural subsystem TRL vs Time

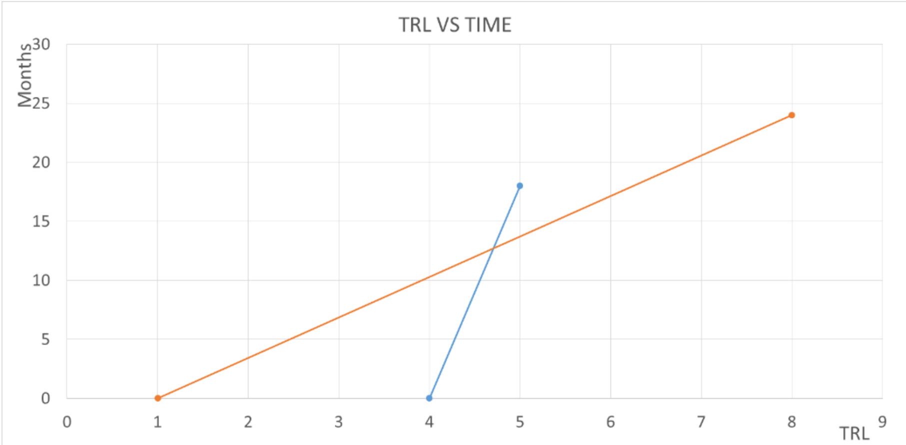


Figure 110 - Full aircraft TRL vs Time

The graphs reported have been obtained by interpolating the discrete points derived from the extrapolation with splines. We optimise the analysis by evaluating a future forecast. In other words, the values given in Figure 105 to Figure 110 refer to the overall development time of the technology and not to individual TRL jumps, then making a future forecast of the curves obtained from the interpolation if they are degressive a new law of interpolation will have to be determined. The various graphs refer to each subsystem and include all the technologies studied; given the lack of data that determines for some of the technologies a linear trend, a general time pattern shall be determined as a function of the TRL jump based on the underlying considerations.

From the graphs it is possible to identify the phases that involve a abrupt increase of the necessary times. The first steps of TRL can be easily reached as up to TRL 3 only software analysis and testing are required; from TRL 3 to TRL 5 there is a sharp time spike, this is justified because the achievement of the level of maturity requires the performance of tests on the components (TRL 4) and the component connected to its subsystem (TRL 5). The time needed to construct the prototypes to be tested and to carry out the tests therefore determine the surge of the times. In order to achieve the TRL 6, the curves tend to fall as at this stage a prototype representative of the system and the component to be tested in a relevant environment is to be tested, the difficulty is therefore to recreate the conditions of real use of the component and the subsystem. For the next steps of the TRL 6 we have only two data points that refer to the High Speed HVDC Generator/Motor (Figure 29)technology belonging to the electrical subsystem which provides for the development and realization of an electric generator engine and Virtual-Hybrid-Real On Ground demonstration for HVDC & EMA Integration (Figure 102) that it previews the development and the realization of a test bench for the present electric devices of the future hybrid aircrafts; from the course of these two technologies we can deduce an increase in the slope of the curves.

For costs, on the other hand, since there are no discrete data of costs over time, the graphs results linear.

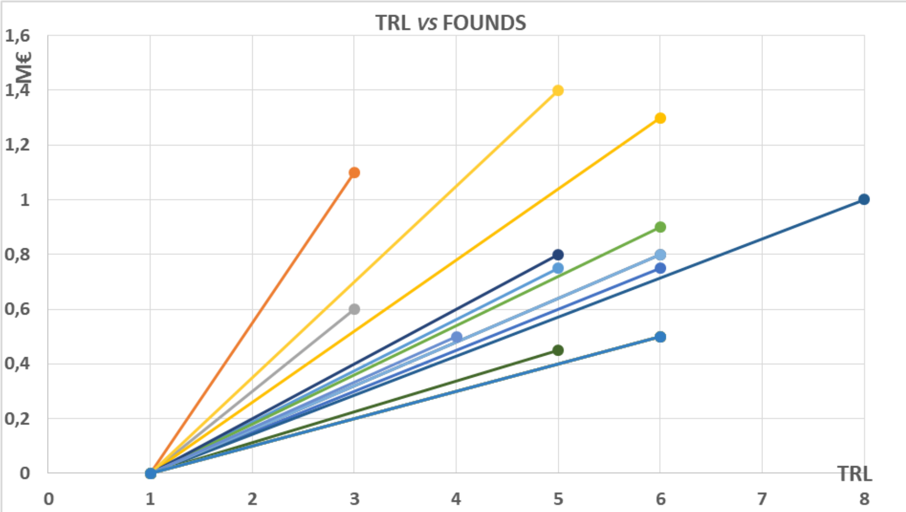


Figure 111 - Electrical sub system TRL vs Fund

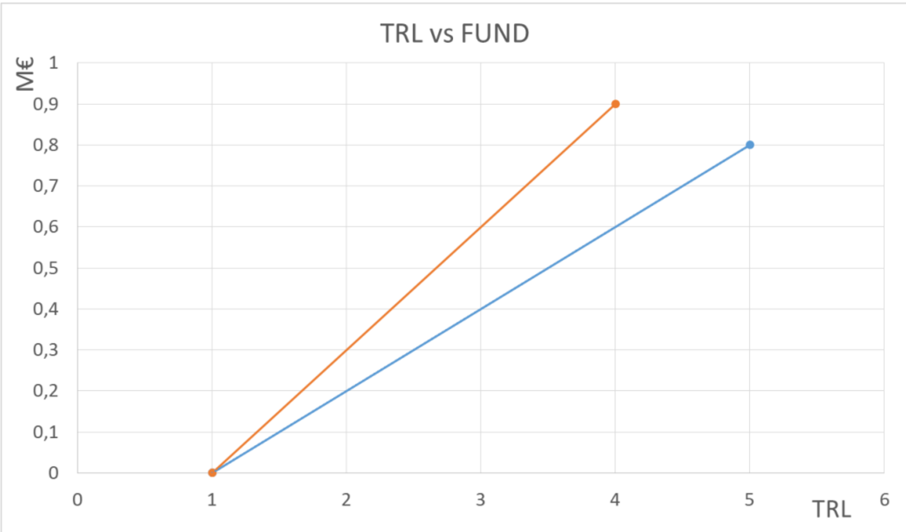


Figure 112 - Cooling sub system TRL vs Fund

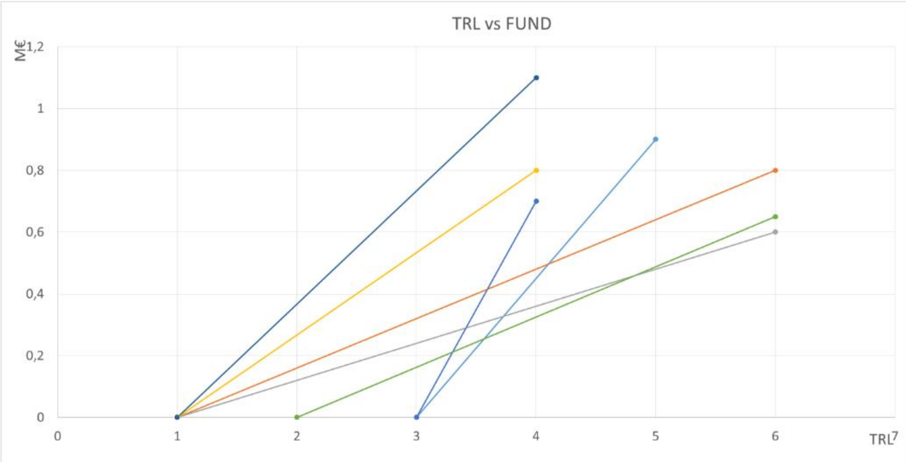


Figure 113 - On-board control sub system TRL vs Fund

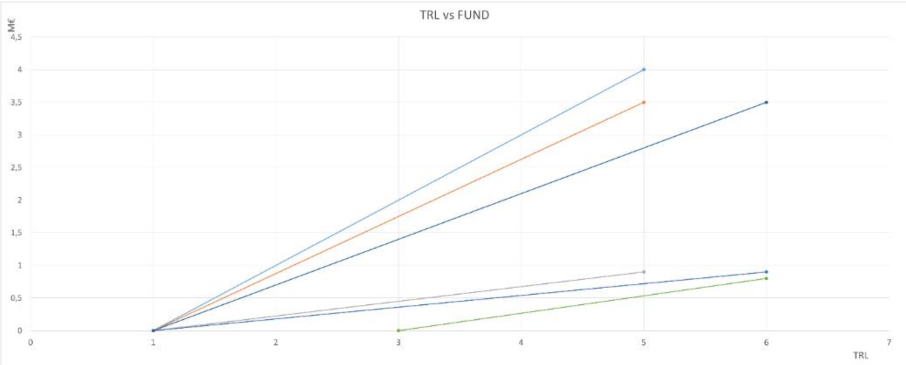


Figure 114 - Propulsion sub system TRL vs Fund

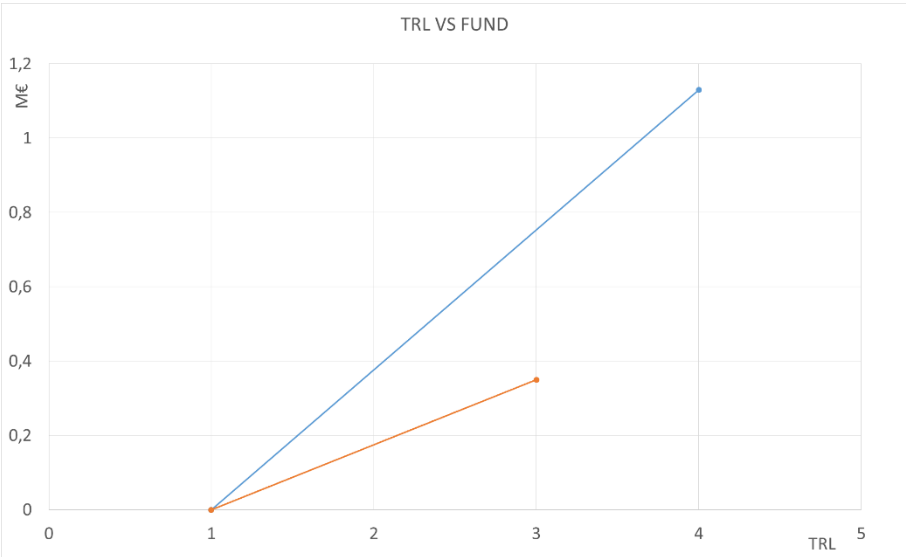


Figure 115 - Structural sub system TRL vs Fund

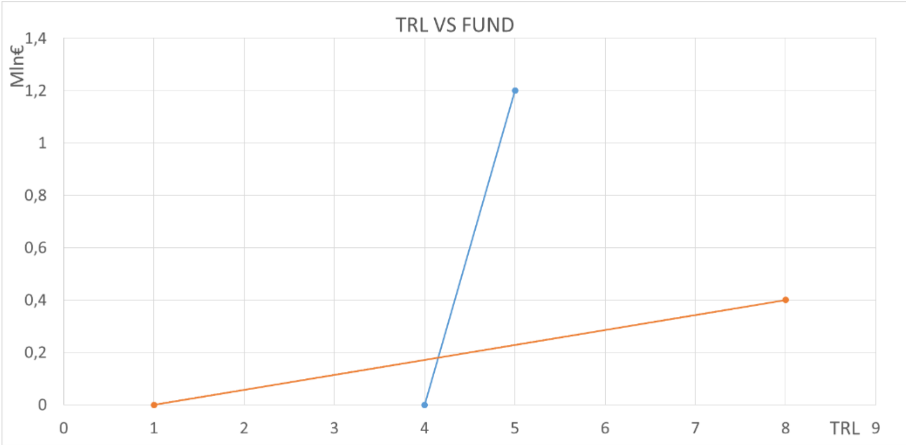


Figure 116 - Full aircraft TRL vs Fund

In the first graph, Figure 111 shows the trend of costs in relation to the TRL jump for the technologies of the electrical subsystem. Among all the technologies, it is possible to highlight those that, with the same increase of TRL, are more expensive, and those related to the development of solid state components that are still in the embryonic phase;the curves instead less dependent refer to the technologies that preview the development and the realization of sub-components or software of the electric system and therefore in terms of test and development costs involve a less use of economic resources. Figure 112 represents the technologies relevant to the cooling subsystem, only two technologies are available and the trend is comparable. Figure 113 refers to technologies related to electrical and avionics plant management systems. By analysing the development of the technologies that provide for the achievement of TRL 4 and 5 from TRL 3, it is assumed that most of the funds used for the development of on-board systems are necessary for these TRL steps, in particular for those technologies related to the control of the engine system. Figure 114 gives the scope of the propulsive subsystem; here it is possible to show the behaviour of the three technologies that presuppose a greater use of resources, whose behaviour is justified by the fact that they include innovative technologies such as BLI or that related to the development and testing of new propulsion plant configurations. The curves characterized by a minor slope, are referred to the innovation of single components; it becomes clear and plausible to use two factors for the estimation of the cost of technologies pertaining to the propulsive subsystem based on the level of component that is being studied. In Figure 115 we find the two technologies pertaining to the structural subsystem; as before also here the discrepancy in terms of funds necessary for the development is dictated by the jump of TRL expected. In the case of the red curve, the costs associated with the tests are not taken into account, so the total cost is lower. Figure 116 shows the technologies relevant to the entire aircraft. The discrepancy in the necessary funds is due to the different type of technology developed; while the red curve represents the cost for the development of a test bench for new hybrid electric technologies, The blue curve aims to achieve the TRL 5 for the development of an avionics system.

In all the reported graphs (Figure 112-Figure 114) we obtained have a linear trend due to the lack of discrete points, this behaviour, while being falsified by the lack of discrete data related to the cost trend as a function of the TRL step for space technologies, as reported in the ESA study [24] represent however the first acceptable approximation.

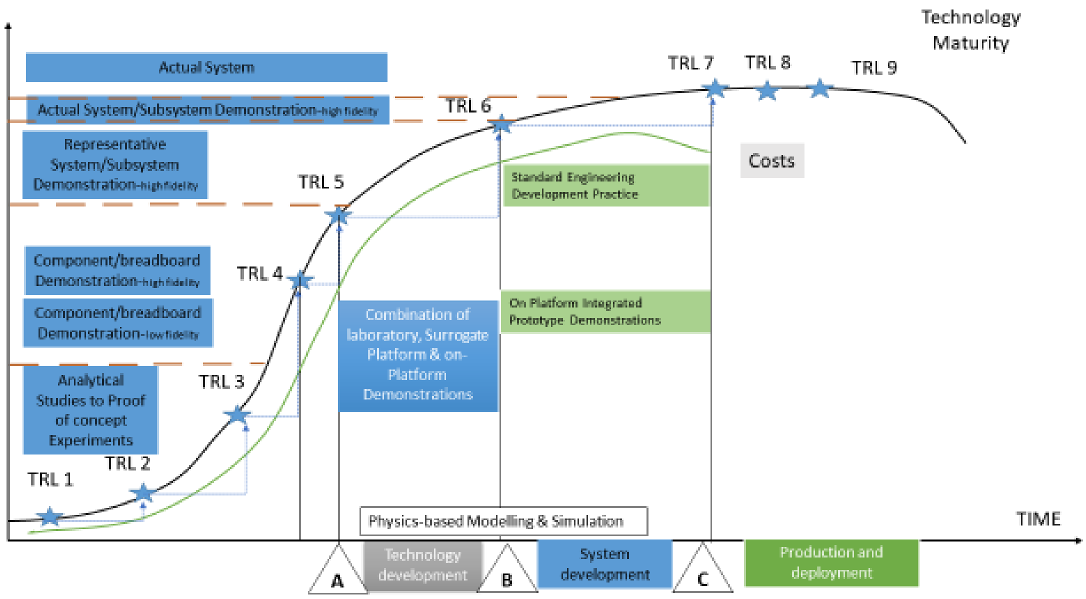


Figure 117 - ESA Time and cost vs TRL model

The definitions of each TRL compliance to ESA [24] specification are shown below:

- TRL 1 = observation of fundamental principles. The basic principle *is observed and described* - Potential applications are identified following basic observations.
- TRL 2 = formulation of a technological concept. The definition of the concept or application *is fully formulated*. - The potential applications and preliminary elements of the concept *are defined*, although not yet concretely demonstrated.
- TRL 3 = experimental proof of concept. Analytical and functional demonstration of the characteristics of the concept. - The concept *is well described* and the expected performances are demonstrated through analytical models supported by experimental data.
- TRL 4 = technological validation in a laboratory environment. Laboratory verification of the prototype and / or component. - The functional performance of the element *is demonstrated* with a prototype in a laboratory environment.
- TRL 5 = technological validation in the industrial sector. The critical functions of the component and / or prototype *are verified* in a controlled environment. - The critical

functionality of the element and its functional environment *are identified*. Small-scale prototypes *are built* to test performance in a controlled environment.

- TRL 6 = demonstration of technology in the industrial sector. Construction of a model for the demonstration of the critical functions of the component and / or prototype in a controlled environment. - The critical functionalities of the element *are verified* and the performances demonstrated, in a controlled environment, using models accurate in shape and functions.
- TRL 7 = demonstration of the prototype in a real operating environment. Construction of a model for the demonstration of the critical functions of the component and / or prototype in an environment similar to the operational one. - The performances are demonstrated in the operating environment, on the ground or if necessary in space. A fully representative model, in all aspects, of the flight model, *is built* with adequate margins to demonstrate performance in the operating environment.
- TRL 8 = definition and complete qualification of the system. The actual system *is built and accepted as ready for flight ("flight qualified*"). - The flight model *is built and eventually integrated into the final system, ready to fly*.
- TRL 9 = complete demonstration of the system in a real operating environment (functional test with enabling technologies and application to the specific industrial sector. The actual system *is successfully launched and operated*. - The technology is *mature*, the element is in service for the mission assigned and works in the real environment. The commissioning phase begins.

After these preliminary analyses, all next projects were analysed subdividing the system into different *affected subsystems*. Considering the aircraft as an entire system, the affected subsystems are all the systems that make it up as an electrical or avionic system. In this way it is possible to compare the costs and months spent, with the same jump of TRL, for projects belonging to different subsystems.

In the following table, all data relating to projects belonging to the electrical subsystem are given. From the values of costs and times for the development the curves and the respective equations are obtained, brought back in Figure 105 and Figure 111. This process is also carried out for the following subsystems:

- Cooling subsystem
- On-board control subsystem
- Propulsion subsystem
- Structural subsystem
- Full aircraft refer to those projects that include more than one aircraft subsystem

#	Project	TRL	Founds (Million€)	Estimated time (month)	Call date	Execution operation	Found/month [M€/month]
1	Advanced mechatronics devices for electrical management system of Turboprop	da 1 a 6	0,9	36	mar-15	RIA	0,025
2	High Speed HVDC Generator/Motor	da 1 a 8	1	66	mar-15	IA	0,015
3	Electrical components	da 1 a 6	0,5	30	mar-15	IA	0,017
4	Innovative cooling system for embedded power electronics	da 1 a 6	0,8	28	giu-16	IA	0,029
5	High Density Electrical Connectors	da 1 a 6	0,5	24	mar-17	IA	0,021
6	E2-EM Supervisor and Control Algorithms	da 1 a 5	0,8	36	mar-17	RIA	0,022
7	High density energy storage module for an electric taxi	da 1 a 6	0,8	45	mar-17	IA	0,018
8	Power Module	da 1 a 6	0,5	18	mar-17	IA	0,028
9	Screening and development of optimized materials for high temperature coils	da 1 a 6	0,5	36	mar-17	IA	0,014
10	Integrated electronics for actuator data and power management for Morphing Leading Edge activities	da 1 a 5	0,45	36	mar-17	IA	0,013
11	Development of AC cabling technologies for >1kV aerospace applications	da 1 a 5	0,75	24	apr-18	IA	0,031
12	Innovative Primary and Secondary Electrical Distribution Network for Regional A/C	da 1 a 5	1,4	26	nov-17	RIA	0,054
13	Design and Development of a high temperature HVDC busbar	da 1 a 6	0,5	24	nov-17	IA	0,021
14	Development of low rating and high power HVDC optimized fuses	da 1 a 6	0,5	24	nov-17	IA	0,021
15	Novel mechanical drive disconnect for embedded Permanent Magnet machines	da 1 a 3/4	1,1	18	nov-17	RIA	0,061
16	Advanced manufacturing for MW range power dense electrical machines for aerospace applications	da 1 a 3/4	0,6	24	nov-17	RIA	0,025
17	Development of a High Voltage Lithium Battery	da 1 a 4	0,5	18	nov-17	RIA	0,028
18	Development of power electronic technologies for >1kV aerospace applications	da 1 a 6	1,3	24	nov-17	IA	0,054
19	Assessment of arc tracking hazards in high voltage aerospace systems	da 1 a 6	0,75	30	ott-18	IA	0,025

Table 4 - Electrical sub system projects

From the equations of the curves obtained previously, a most reliable model was developed which, given the input of the initial and final TRL for each technology, provides the necessary time and cost values as an output.

YES = 1 NOT = 0	Start TRL	Final TRL	Founds (M€)	Time (months)
1	1	6	0,9	36,00
1	1	6	0,7145	35,98
1	1	6	0,5	28,27
1	1	6	0,8	16,00
1	1	6	0,5	21,75
1	1	6	1	57,00
1	1	6	0,8	31,41
1	1	6	0,5	17,66
1	1	6	0,5	33,22
1	1	6	0,5625	36,00
1	1	6	0,9375	30,00
1	1	6	1,75	36,00
1	1	6	1,75	32,50
1	1	6	0,5	39,99
1	1	6	2,75	45,00
1	1	6	1,5	60,00
1	1	6	0,8335	24,50
1	1	6	1,3	24,00
1	1	6	1,875	21,35
1	1	6	1	49,97
1	1	6	1,5	34,00
1	1	6	2,25	90,00
1	1	6	0,8	45,72
1	1	6	0,6	31,01
1	1	6	1,3335	70,00
1	1	6	3,5	90,00
1	1	6	0,8125	23,00
1	1	6	1,8335	58,00
1	1	6	5	92,50
1	1	6	4,375	103,71
1	1	6	1,125	51,00
1	1	6	0,9	31,86
1	1	6	3,5	50,00
1	1	6	1,3335	40,00
1	1	6	1,8835	53,00
1	1	6	0,875	62,50
1	1	6	6	90,00
1	1	6	0,2855	17,14

Table 5 – Most reliable linear model

The model initially developed was based on a linear trend hypothesis of the costs reported as function of the TRL step, this because, there are no data available to better identify the trend. Further analyses were subsequently developed in order to obtain / report the results according to each TRL phase.

The latter is the most specific model since the results refer to the individual technologies studied.

3.2 Cost drivers identification

The ESA model [24] was used to solve the scale problem. Exploiting the graph (Figure 117) and considering the entire area as a unit value, the percentages of expenditure were extrapolated for each TRL step. With the percentage values, the global financing, obtained from the linear model, was divided into the various TRL steps.

Percentage correlation between TRL and Fund							
1 to2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9
0,05	0,05	0,1	0,15	0,1	0,2	0,15	0,2

Table 6 - Percentage correlation between TRL and Fund.

To obtain a general model and derive an equation that can represent the trend of funds for different technologies, it is necessary to identify the cost drivers.

Cost drivers are parameters referring to specific aspects of enabling technologies, which influence the cost and time of technological development. A typical example would be the component level. The drivers show the level of the component on a scale scattered from the entire subsystem (e.g. an entire refrigeration system for electrical components) to the sub-component (e.g. cables capable of conducting kV). This parameter, indicating the level of technical complexity results universal and not specific. For these reasons cost drivers are fundamental to achieve the objective of this study.

Again, from the analyses of the Cfp (Call for Proposal) [25][27][28][29][31][32]0[34] contained in Clean Sky 2 JU [4] it was possible to extrapolate the different factors that influence the cost and development times:

- TRL step:
- Affected subsystem
- Component level
- # of component analysed
- # of link
- Technologic fields
- Power

We report below the cost drivers and comments the influence on the cost and development times. The most important driver is the TRL step. In fact this parameter is what plays a fundamental role in determining the cost and the time required for the development of the technology. Starting from a targeted TRL for a given technology, very different costs and time are obtained due to the requirements needed to increase the TRL level. For example if we consider the step from TRL 0 to 1 this provides very limited costs and times due to the lower state of the art. On the other hands, carrying out a step from TRL 4 to 5 er need to consider a relevant environment fields, this results in a significant higher expenditure of time and funds.

The second driver indicates the type of sub-system in which the technology is located. It is clear that results less expensive to test the technology of the electrical subsystem, for example an

electric motor is less expensive to test than a technology related to the avionic system, for example a wing morphing.
The third driver identified is the component level. This parameter is very functional even if two technologies of the same component level could have different costs based on the sub-system to which they belongs.
Two other important parameters are to the number of components analysed and the number of connections that the complete technology must have. The concept on which this drivers founds is linked to how many components need to be developed and their complexity.
Then there are the technological field. These drivers are the ones that indicates at the best the level of technological complexity in any technological fields meaning all the sectors involved for the development of the technology.
Since there are many electrical components, the power of the technology to be developed represent a solid parameter, if we plan to make a battery with an energy density of 1000 kW / Kg and obviously, this parameter was higher compared to the cost and development time needed for a 500 kW / Kg one . However, this driver remains impossible to determine today, due to the present technologies that do not provide for powers such as the development of a high efficiency thermal coating or for the development of a morphing wing. Therefore, it remains an additional parameter to be considered only for some of them.

3.3 Analysis method

Once the cost drivers have been determined, the analysis can be start. The values to be associated with the drivers must be defined starting from their separate analysis. The first driver analysed was the TRL step that makes a huge contribution to the overall funding for the development of a new technology. Concerning the technological fields, the same weight is assumed for all fields; these drivers thus becomes an input in our model. In order to compare the difference in development time among different projects, we only took into account the monthly cost, calculated as the ratio between the total funding allocated and the expected time for the development (Table 7 - Table 8).

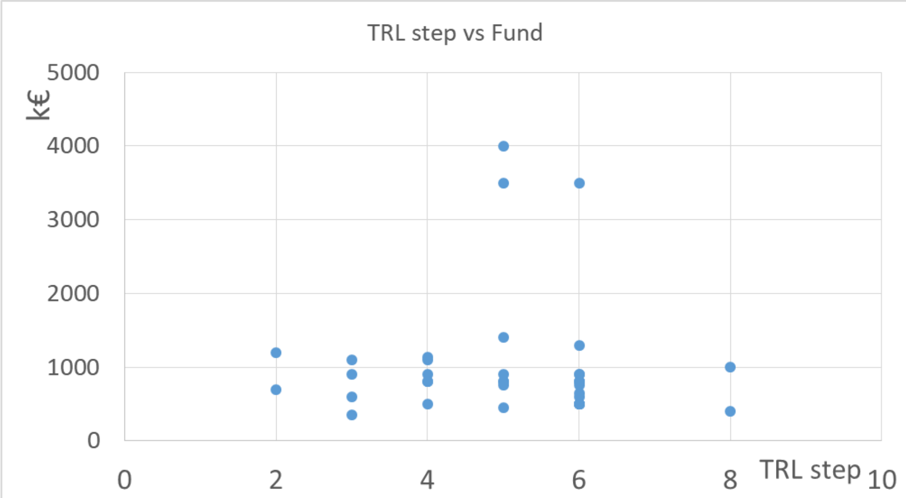


Table 7 - TRL step vs Fund considering all the projects

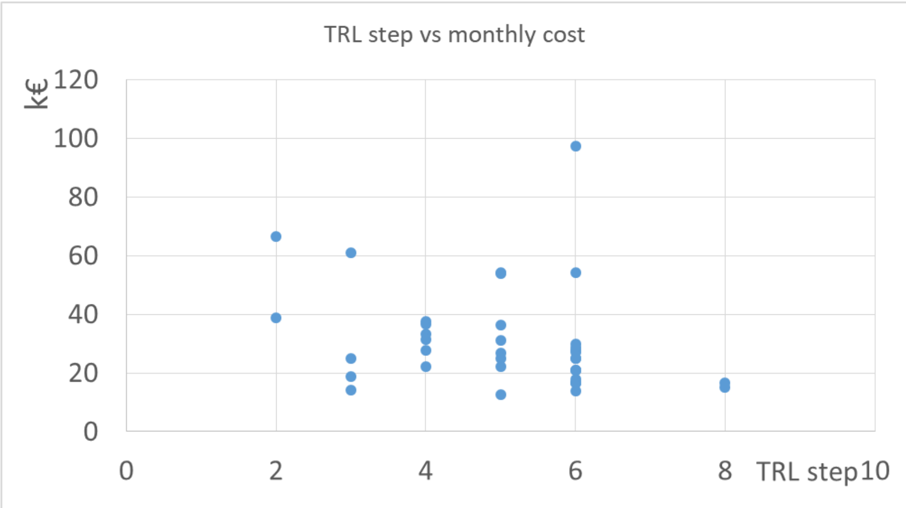


Table 8 - TRL step vs Monthly cost considering all projects

The developed analysis initially include all the technologies analyzed, however this method result not useful for the purpose of this work. The model was then refined considering all the projects that provide the same value for each driver in order to obtain comparable values.

For the analysis of the power driver, since there are different values for the technologies, all those comparable are grouped as shown below.

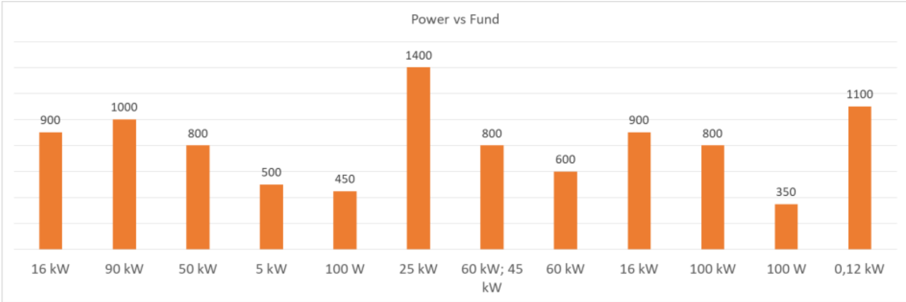


Table 9 - Power vs Fund analysis

We further proceeds with the determination of the weights. The first approach was to consider two input values in order to reduce the number of unknowns.

DRIVERS ANALYSIS	
component	100
All tecnology fields	100
sub-component	50

Table 10 - Drivers analysis start value

As previously shown, the technological fields are given equal weight, while for the component level driver the value 100 was obtained.

For the analysis of the power driver, the weights to be associated are searched for each power value which could be used as input value for the analysis of the following drivers.

	#	TRL	Affected subsystem	component level	Tecnologics fields	Power	Aera	Found
	36	1 a 5	avionic system	component	Aerodynamics; structural	100 W	ITD - Airframe	350
	10	1 a 3	avionic system	sub-system	Electric; control	100 W	ITD - Airframe	450
	Results							
	100 W	50						
sub-system		200						

Table 11 - Separate analysis results test

The weights obtained considering the global financing as the sum of as many rates as the drivers that compose it. For example, in the first case we have:

$$100\ W\ =\ 350(Found) - 100(component) - 100 * 2(Tecnologics\ field) =\ 50\ k€$$

$$Subsystem =\ 450(Found) - 50\ (100W) -\ 100 * 2(Tecnologics\ field) =\ 200\ k€$$

These reported analyses are not very refined to determine the weights of the different drivers analysed, so a most refined analysis was carried out.

In next step was we give equal weight to all drivers by dividing the global funding of each project by the number of drivers that competed for it, thus obtaining the values for each one of them.

Afterwards, to define a unique value for each drivers, we performed a geometric mean among all the values obtained.

At the end of this analysis, the initially input data, i.e. the monthly cost of each project, was used as a test to verify the effectiveness of the method.

Then considering each individual project, the monthly cost was determined considering the weights of the drivers and comparing with the actual cost indicated in the Cfp. This allowed us to obtain the percentage error to respect to the true data for each project analysed Table 12.

	monthly cost	Arithmetic average		Geometric average	
#		err	err%	err	err%
10	0,0125	-0,020723904	62,37648673	-0,0061	32,79569892
9	0,013888889	-0,019272236	58,11695534	-0,001411111	9,222948439
36	0,014	-0,010559528	42,99564829	-0,0016	10,25641026
3	0,016666667	-0,011125095	40,03018927	-0,001533333	8,424908425
23	0,016666667	-0,005952062	26,31475126	0,001666667	-11,11111111
24	0,016666667	-0,009951948	37,38717429	-0,005833333	25,92592593
38	0,016666667	-0,003047143	15,45689567	-0,000166667	0,99009901
7	0,017777778	-0,011513094	39,30608201	-0,004722222	20,98765432
22	0,01875	-0,011151136	37,29335302	-0,00325	14,77272727
5	0,020833333	-0,004989417	19,32178701	-0,001666667	7,407407407
13	0,020833333	-0,004691535	18,38025111	-0,003666667	14,96598639
14	0,020833333	-0,003040343	12,7351259	0,001333333	-6,837606838
6	0,022222222	-0,003647192	-16,41236317	-0,001777778	7,407407407
25	0,022222222	0,002144435	9,649955317	0,004922222	-28,45215157
16	0,025	-0,000195624	-0,782497529	0,0015	-6,382978723
1	0,025	-0,002750629	-11,00251709	0,0025	-11,11111111
19	0,025	-0,002227525	-8,910100865	0,004	-19,04761905
31	0,025	-0,016053181	-64,21272298	-0,0095	27,53623188
20	0,026666667	0,003049017	11,43381292	0,002166667	-8,843537415
27	0,027083333	0,000856813	3,163618648	0,001583333	-6,209150327
8	0,027777778	0,002434556	8,764401285	0,007277778	-35,50135501
17	0,027777778	-0,007195965	-25,90547221	0,000277778	-1,01010101
4	0,028571429	0,000585853	2,050486504	-0,000628571	2,152641879
32	0,03	-0,006040615	-20,13538202	0,0035	-13,20754717
11	0,03125	0,005775007	18,48002152	-0,00795	20,28061224
35	0,031388889	-0,018580999	-59,19610441	0,005288889	-20,2639421
34	0,033333333	0,007106813	21,32044015	0,007833333	-30,71895425
30	0,036458333	-0,004140411	-11,35655574	-0,002341667	6,035223368
28	0,036666667	0,011323445	30,88212219	0,007666667	-26,43678161
21	0,0375	0,006664684	17,77249001	0,007	-22,95081967
26	0,038888889	0,012662369	32,56037727	0,006888889	-21,52777778
12	0,053846154	0,07958147	52,20584105	0,009846154	-22,37762238
29	0,054054054	0,103088109	9,286998089	0,003254054	-6,405618217
18	0,054166667	0,088846734	35,97525952	-0,012133333	18,30065359
15	0,061111111	0,017110156	27,99843711	0,003611111	-6,280193237
37	0,066666667	-0,004644031	-6,966046104	0,005866667	-9,649122807
33	0,097222222	-0,014045799	-14,44710763	0,001722222	-1,803374055

Table 12 - Same value for all drivers analysis percentage error.

The values reported in Table 12 indicates the percentage errors (underestimate or overestimate) related to the monthly cost necessary to carry out the research projects. The values shown in the table are the same. The latter also reports the results obtained considering the arithmetic mean as well as the geometric one. The green boxes refer to errors below 20%.

The table shows a better trend using the geometric average with a percentage of 66% of tests below 20% of error.

This method still involves significant errors for the forecast of development costs; therefore, we proceed with a different analysis.

In the latter analysis we considering the drivers separately but compared to the previous model, we try to correlate different drivers, for example considering all the projects with the same affected subsystem and component level.

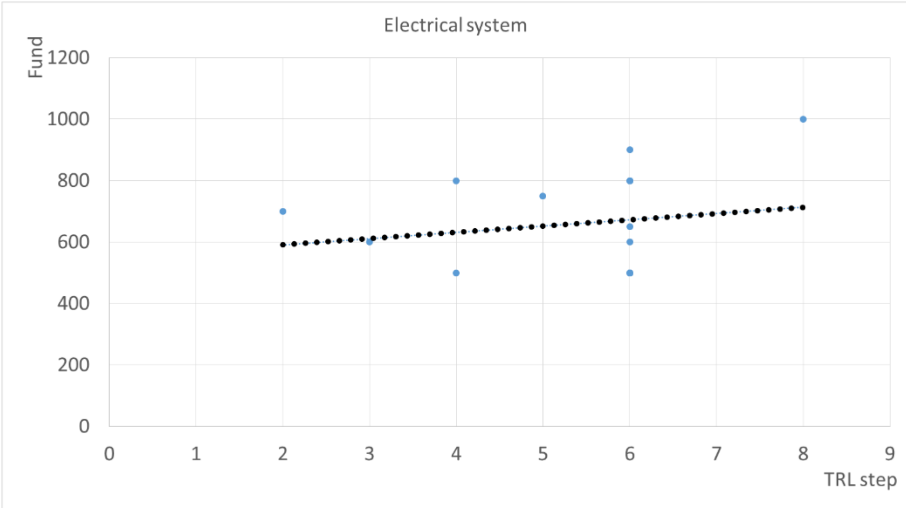


Table 13 - TRL step vs Fund for electrical system driver

Graphing the values of the global financing and monthly cost *vs* TRL step, the equations of the trend lines that represent the trend of costs as a function of the TRL jump imposed were obtained. The TRL step of each project is given by the jump in the technological readiness expected. The problem therefore arises by comparing technologies that have the same jump but with different initial and final TRL values. We consider from TRL 0 to 1 or from 4 to 5 both to have the same increase but obviously the fund used was notably different.

To solve this problem, we use the ESA chart. Taking as a reference the value for a unitary step between 4 and 5 for example, we compare this value with the value for TRL between 0 and 1 and we obtain a factor n that could be used to scale the value of the global and monthly financing of the technology will be scaled.

#	TRL	Affected subsystem	component level	Tecnologics fields	Power	Aera	Fund k€	Monthly cost (K€)	TRL step	n	TRL step / n	TRL step / n
1	1 a 6	electrical system	sub-system	Electrical; mechanic	16 kW	ITD- Engine	900	25	6			
2	1 a 8	electrical system	Component	Electrical; thermal; mechanic	90 kW	IADP - Fast rotorcraft	1000	15,15151515	8			
3	1 a 6	electrical system	sub-component	Electric; thermal	270 V DC network	IADP - Fast rotorcraft	500	16,66666667	6			
4	1 a 6	electrical system	sub-component	Electric; thermal	3 kW/Kg	ITD - System	800	28,57142857	6			
5	1 a 6	electrical system	Component	Electric	1300 V 50 Hz	IADP - Large passanger	500	20,83333333	6			
7	1 a 6	electrical system	sub-system	Electric; mechanic	50 kW	ITD - System	800	17,77777778	6			
8	1 a 6	electrical system	Component	Electric	5 kW	ITD - System	500	27,77777778	6			
9	1 a 6	electrical system	sub-component	Electric; materials; thermal; stuctrural;	300 °C	ITD - System	500	13,88888889	6			
11	1 a 5	electrical system	sub-component	Electric	>1kV ac	IADP - Large passanger	750	31,25	5			
12	1 a 5	electrical system	sub-system	Electric; control	25 kW	IADP - Regional	1400	53,84615385	5			
13	1 a 6	electrical system	Component	Electric; thermal	180 °C	ITD - System	500	20,83333333	6			
14	1 a 6	electrical system	Component	Electric	30 A; 300 A	ITD - System	500	20,83333333	6			
16	1 a 3	electrical system	Component	Manufacturing;	25kW/kg	IADP - Large passanger	600	25	3			
17	1 a 4	electrical system	Component	Electric; thermal ; chemical	500W/Kg	IADP - Large passanger	500	27,77777778	4			
21	1 a 4	electrical system	component	Electric; Thermal	700 V CC	IADP - Large passanger	900	37,5	4			
23	1 a 6	electrical system	software	Electric	60 kW; 45 kW	IADP - Large passanger	800	16,66666667	6			
24	1 a 6	electrical system	sub-system	Electric	60 kW	IADP - Large passanger	600	16,66666667	6			
26	3 a 4	electrical system	Component	Electric	>5kW/Kg	ITD - System	700	38,88888889	2	2,2	318,181818	17,67676768
27	1 a 6	electrical system	Component	Electric	300 A	ITD - System	650	27,08333333	6			
28	1 a 4	electrical system	Component	Electric		IADP - Large passanger	1100	36,66666667	4			
34	3 a 6	electrical system	Component	Electric	100 kW	ITD - System	800	33,33333333	4	1,3	615,384615	25,64102564

Table 14 - Electrical system "n" factor

As further analysis for the refinement of the model, in particular for better weight determination for drivers, separate analysis of the drivers is considered by comparing the technologies pertaining to the same subsystem and selecting among all those having the same component level in order to obtain a higher level of accuracy. Below are the most revealing graphs as they include a sufficient number of data including the analysis described:

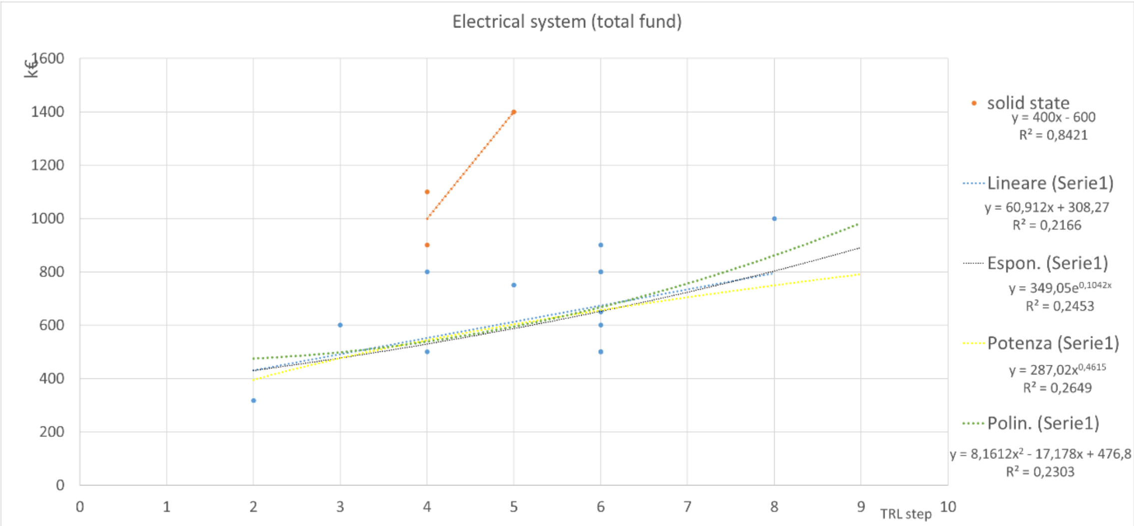


Figure 118 - separate analysis total fund vs TRL step

This graph shows all the technologies pertaining to the electrical subsystem. There is a different trend for the three orange points that have values out of scale compared to all the others. This behavior is due to the type of analyzed technology that is the solid state one. For this type of technology we consider a different trend characterized by the equation shown in the figure. The other points in the graph refer to all the technologies of the electrical subsystem regardless of their component level, we use different curves to approximate the trend of the values according to the TRL step and we evaluate the effectiveness of each curve with the R^2 parameter whose typical value for the cost analysis is 0.7. Precisely to improve this parameter we decide to consider only the technologies of the electrical subsystem afferent to the component level "component"; in this way the dispersion of the data is reduced and it is possible to increase the accuracy of the interpolating curves. Below is the graph containing the technologies considered:

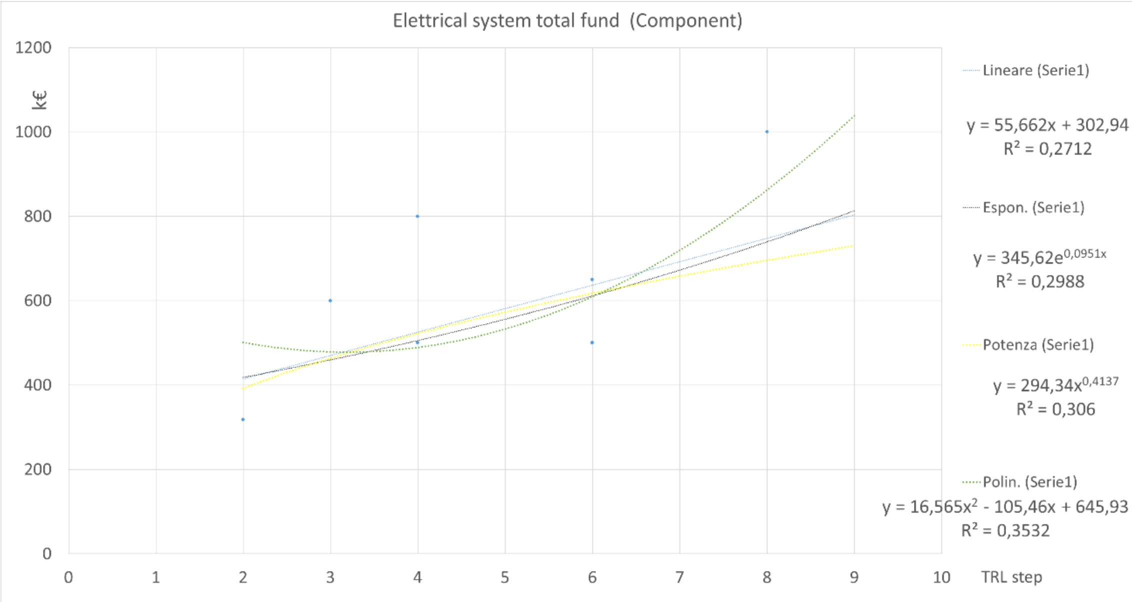


Figure 119 - Electrical subsystem total fund vs TRL step considering only component level "component"

In this graph, where we find all the technologies of the electrical subsystem of the component level, we notice a better behavior of the interpolating curves, in fact the factor R^2 is in the around of 0.3 regarding the previous one that was on 0.2/0.25. From this analysis we consider as representative curve of the technologies of the electrical subsystem the polynomial one that has a factor R^2 higher. The same analysis has been carried out for the other subsystems analyzed that we see in detail.

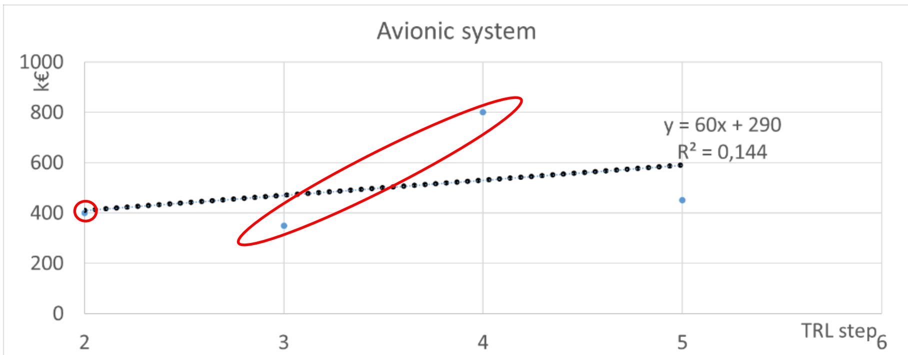


Figure 120 - Avionic subsystem fund vs TRL step

The data in the red box has the same "component level". We find a plausible trend since as the TRL jump increases the funding. as noted above, the "sub-sys" seems to require less input than the development of a component.

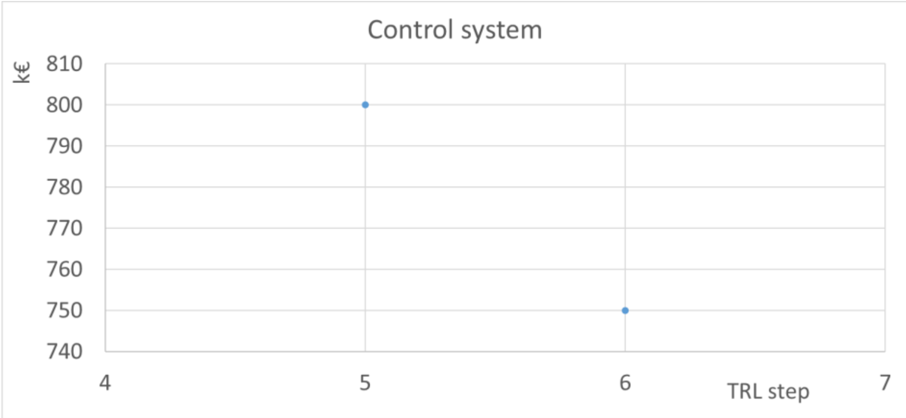


Figure 121 - Control subsystem fund vs TRL step

The behavior of this graph is due to the different "component level". In fact, for the development of a software compared to that of a component, there are much lower test costs.

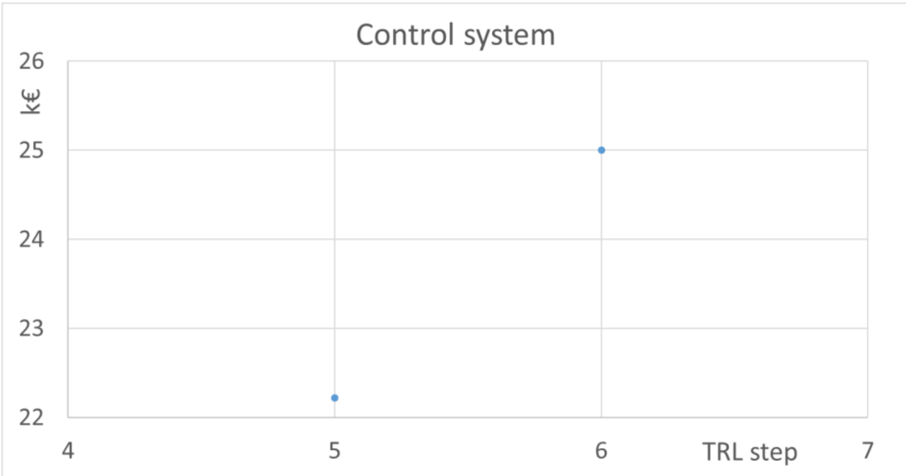


Figure 122 - Control subsystem monthly cost vs TRL step

The different behavior between found and monthly cost is given from the fact that for the development of a software it is necessary less time, is for the implementation and therefore the design that for the tests demanded; there is therefore a difference between the monthly and the total cost of developing the technology.

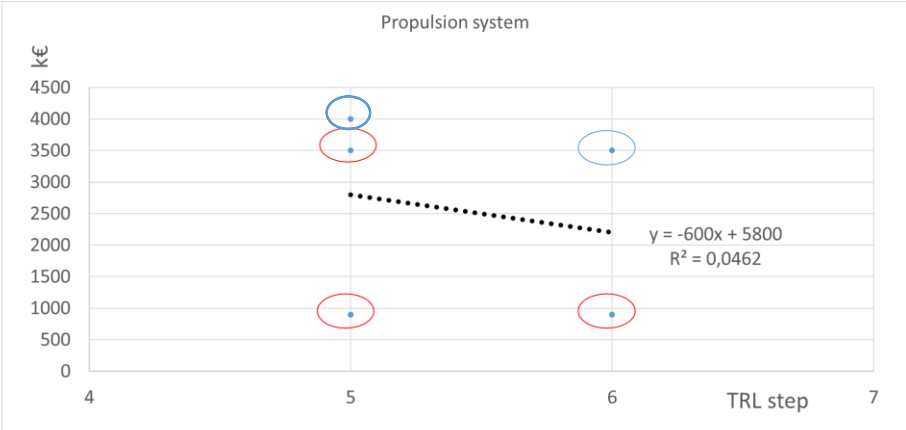


Figure 123 - Propulsion subsytem fund vs TRL step

Also in this case as before we analyze the trend of the monthly cost according to the TRL step:

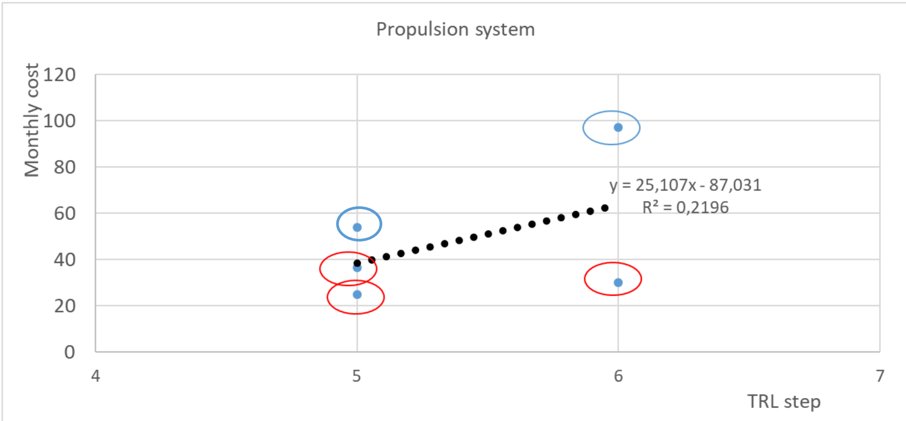


Figure 124 - Propulsion subsystem monthly cost vs TRL step

In this case we see an increase of the costs for the level subsystem (blue) regarding the level component (red), this course is visible in various analyses carried out symptom that the model works.

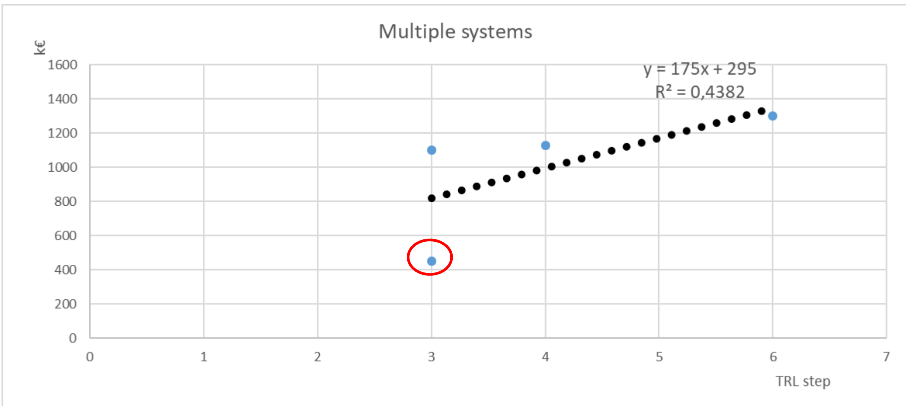


Figure 125 - Multiple subsystem fund vs TRL step

Here we find the technologies that relate to more "affected subsystems". In this case, the data could reflect the actual behaviour of the development financing development as a function of the

TRL jump. Moreover, with the exception of the present data circled in red, all the technologies afferisce to the same "component level. Let us therefore carry out a further analysis by looking only at technologies with a component level.

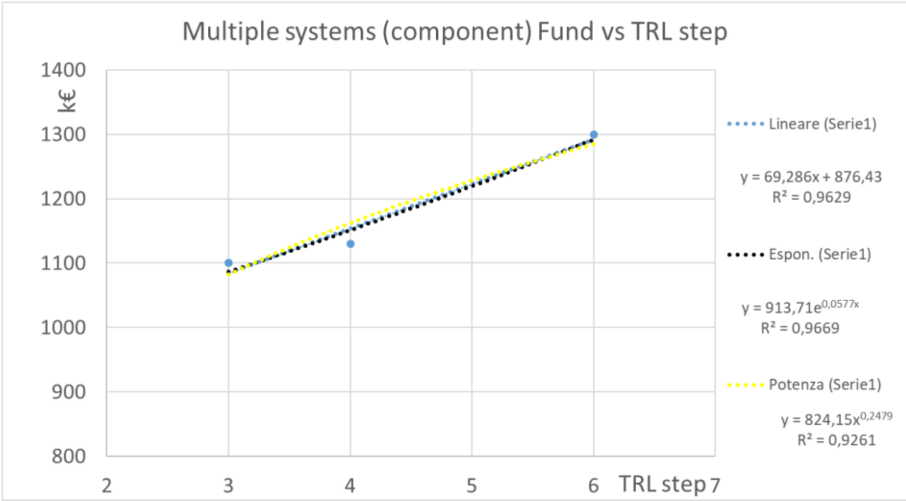


Figure 126 - Multiple subsystem fund vs TRL step only component level

Come per il caso del sottosistema elettrico considerando le tecnologie con due cost drivers uguali (affected subsystem e component level) si riduce la dispersione dei dati e si hanno quindi delle curve che meglio approssimano il trend delle tecnologie.

?

Chapter 4

4. Results and future development

In this chapter the results obtained using the last analysis are discussed.

The aim of the research was the development of a model for the analysis of costs related to the search for technologies for regional hybrid propulsion.

The analysis of the state of the art makes it clear that there is a need to the development of new technologies able to satisfy the energy required to develop MW of power. Design projects developed by NASA such as PEGASUS (Figure 13) provide for an energy density of batteries and electric motors with power densities that still require 10 years of development. All this progress involves the search for new technologies and new materials that will bring about significant changes in aviation. It is therefore difficult to obtain data necessary to create a database, given the importance and profound change of the technological process; for these reasons the cases analysed are European research, containing the projects of the major European manufacturing companies collaborate.

The following is proposed the cost analysis for the development of a regional hybrid aircraft developed by NASA [13].

We consider a conventional regional aircraft as ATR 42-500 with the following characteristics:

- Range 600nm with backup mission including 5% of total fuel and additional 85 nm.
- 48 passengers
- Cruise Mach 0.475

The propulsion is constituted by a parallel hybrid system, in how much it has a more direct connection between source of energy and motor that concurs to have greater global yields. In other words, the two propulsion lines, both electric and fuel, are separated so the energy is not transformed several times before being used; This involves a value of propulsive efficiency combined between electrical and conventional between the minimum value 40% given by the conventional line and 93% for the electric one.

For the electric propulsion line in this research [13] concluded that to have the benefits in terms of weight and specific consumption the power requirements listed in tab are necessary

Electric requirements		
Electric motor	8 [hp/lb]	13,152 kW/Kg
Power electronics	10 [hp/lb]	16,44 kW/Kg
Battery	500 Wh/Kg	500 Wh/Kg

Table 15 - Electrical requirements for hybrid ATR 42-500 [13]

The aim is therefore to determine the development costs for these technologies, so that the cost of the hybridisation of a conventional regional aircraft can be assessed. Let us consider a linear trend of the cost in function of the TRL jump and consider a factor of technological scale proportional.

Analyzing therefore the specifications reported in (Table 15), with the hypotheses made, we select the equation referred to the electrical subsystem, in particular that related to the electric motor, the electronic power and the batteries, available in the database (table with reported technologies). By comparing the technology analysed with the one required in terms of power, the scale factor to be applied to the overall cost of developing each technology is determined. Below the technologies extracted from the database with the respective project power requirements:

- High Speed HVDC Generator/Motor

Characteristic	Requirement
Nominal Power	90kW
Nominal Voltage	± 270VDC
Nominal Speed (100%)	24000 rpm
Speed Range	70% to 110%
Overspeed	120%
Efficiency	90 to 95%
Cooling	Liquid
Overload	150% for 2 mins 200% for 5 secs
Weight Objective	23Kg max
MTBO (Generator)	7500 Hrs

Figure 127 - High speed HVDC Generator/motor power output [25]

In this case the project provides for the development and construction of an HVDC generator/engine up to TRL 8 including cooling system. The power density required in this project is half (4 hp/lb) of that required (8 hp/lb) in NASA's study (Table 15). For this reason we consider a scale factor of 2.

- Innovative cooling system for embedded power electronics

In view of the power requirements for the hybridization of the regional aircraft, it is necessary to develop a thermal management system for the electrical power components (e.g. transformer). This project aims at the development of a non-cryogenic cooling system able to manage the thermal flow of components with wattages of the order of MW allowing the operation in the optimal thermal range.

- Development of AC cabling technologies for >1kV aerospace applications

For the transport of electricity from the generator to the user (electric motor), are necessary aerospace cables to withstand the demands of aerospace High Voltage (HV), high current, high frequency operation in an aerospace environment. For this reason it is necessary to consider the development of connecting components between fundamental parts of electric line.

Requirements for this project are:

- Power >1MW
- Frequency >10kHz
- Voltage rating > 1kW AC

Development up to TRL 5.

- Development of a High Voltage Lithium Battery

This project involves the development up to TRL 4 of a lithium-ion battery that has 200 Wh/kg of energy density at the battery level, so also considering the pack and the refrigeration system. All necessary connections with the other components of the propulsion system are also provided. Considering this design, in accordance with Table 15, a scale factor of 2.5 is necessary to achieve the necessary value for the hybridization of the regional aircraft.

- Development of power electronic technologies for >1kV aerospace applications

Development of power electronic technologies for >1kV rated aerospace hybrid electrical applications. Focusing on but not limited to high voltage insulation design for high power dense converter, matched thermal management for power electronics, packaging of passive components and High Voltage High Current Interconnects.
Since the maximum weight of the component is not specified, it is impossible to determine the specific power of the electronic power but considering the figure soa inverter it is noted that these components at the state of the art already have the required power density, so the value of the financing necessary for the development of the technology is not scaled.

- Assessment of arc tracking hazards in high voltage aerospace systems

One of the main challenges facing the development of a hybrid aircraft is the need to significantly increase the system voltage in order to reduce the weight of the entire electrical system. For example, the current demonstration project E-Fan X (Figure 128) uses a DC bus voltage of 3kV. This is well above the 540V DC used for the Boeing 787 more electric aircraft, which itself is twice the standard system voltage of 270V DC in common use for many aircraft.

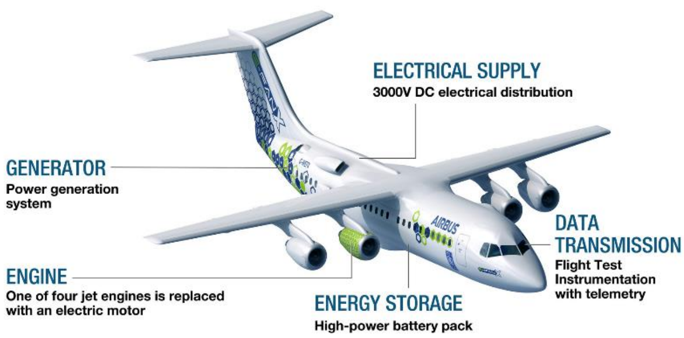


Figure 128 - E-Fan x main characteristics [37]

Arc tracking is a progressive failure mechanism that forms a charred path through an electrical insulation system that can cause significant damage to wiring. This represents today a great problem for the conventional aircrafts, therefore for the future hybrid aircrafts, where the tensions turn out an order of magnitude, so is indispensable a system able to found failures. This project, being calibrated on the powers of a hybrid aircraft, is in line with the demands of power of the NASA study.

Therefore, considering the classic configuration of the reference aircraft (ATR 42-500) in which there is a parallel hybrid propulsion system, we have identified the necessary technologies

Tecnologies
High Speed HVDC Generator/Motor
Innovative cooling system for embedded power electronics
Development of AC cabling technologies for >1kV aerospace applications
Development of a High Voltage Lithium Battery
Development of power electronic technologies for >1kV aerospace applications
Assessment of arc tracking hazards in high voltage aerospace systems

Table 16 - Enabling technologies compliance to NASA study

Identified the technologies necessary for the development of an electric propulsive line, we now report the trends in cost for the development of the technologies listed above.

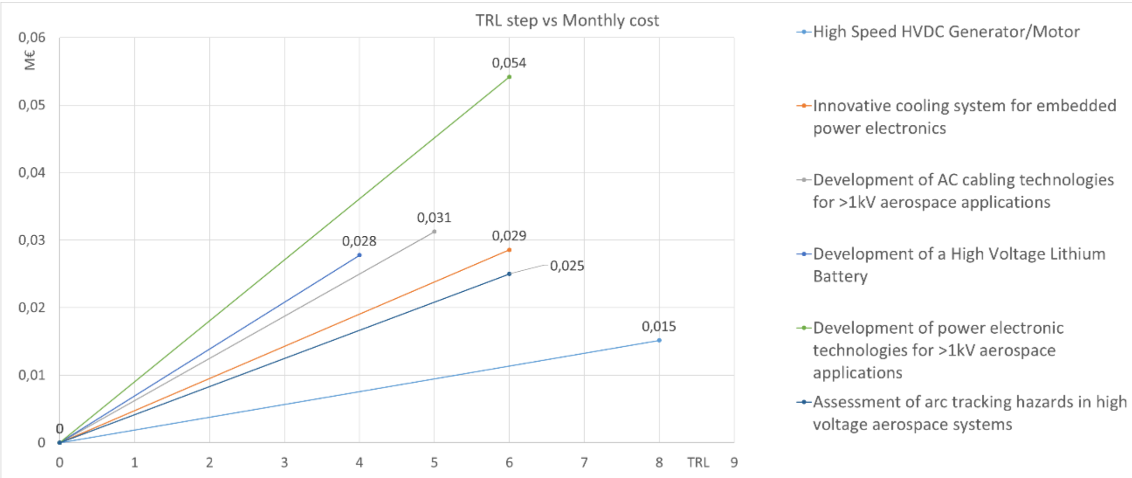


Figure 129 - TRL step vs Monthly cost for enabling technologies compliance to NASA study

Trends show that the costs for battery development, together with those for power electronics, are the most expensive. The technology of the electric motor reported in the cfp has as objective the attainment of a density of power equal to 4 hp/lb, therefore we consider a factor of scale equal to 2 for the application from us considered; for the battery it has instead a factor of scale equal to 2.5. All this makes to change the scene, we report therefore the trends considering the scale factors.

Figure 130 - - TRL step vs Monthly cost for enabling technologies compliance to NASA study considering scale factor

This represents the development cost trend for individual technologies complying with the requirements of Table 15. The technology that mainly affects the costs is the battery that as reported in several studies is the real constraint for the development of hybrid aircraft. According to the trends analyzed in the Chapter 2 the batteries will reach acceptable energy density values in 2025 which considering a performance improvement of 7% per year [22] means to have batteries 35% more powerful than those in the state of the art. The other enabling technologies such as the electric motor, the energy transmission system and the power electronics, do not need radical technological advances, therefore less funds are needed for the development of these technologies.

To determine the cost for the development of technologies, the objective of this work, we determine the monthly cost for the development up to TRL 9 of the technologies. Starting from the final value of the TRL of the projects analysed and taking into account a linear trend of costs in relation to the TRL jump, the value of the necessary financing is calculated. The results are shown in the Table 17.

Tecnologies	Monthly cost up to TRL 9
High Speed HVDC Generator/Motor	0,342
Innovative cooling system for embedded power electronics	0,432
Development of AC cabling technologies for >1kV aerospace applications	0,567
Development of a High Voltage Lithium Battery	1,575
Development of power electronic technologies for >1kV aerospace applications	0,81
Assessment of arc tracking hazards in high voltage aerospace systems	0,378

Table 17 - Monthly cost up to TRL 9

Having considered the monthly cost for the development of the technologies, in order to have the total financing it is necessary to consider the previewed times for the development. To avoid the problem, for the technologies that already meet the power requirements in Table 15, we consider the times reported in the cfp obviously climbed to reach TRL 9, for the batteries we take advantage of the trends analyzed in Chapter 2; values are given in Table 18

Tecnologies	Time in months to achive TRL 9
High Speed HVDC Generator/Motor	77
Innovative cooling system for embedded power electronics	42
Development of AC cabling technologies for >1kV aerospace applications	48
Development of a High Voltage Lithium Battery	60
Development of power electronic technologies for >1kV aerospace applications	48
Assessment of arc tracking hazards in high voltage aerospace systems	45
TOT	320

Table 18 - Time in months to achieve TRL 9

Given then the monthly cost for development and the time needed we calculate the total financing of each technology and consequently the value of the global financing.

Tecnologies	Time in months to achive TRL 9	Monthly cost up to TRL 9	Total Fund M€
High Speed HVDC Generator/Motor	77	0,342	26,334
Innovative cooling system for embedded power electronics	42	0,432	18,144
Development of AC cabling technologies for >1kV aerospace applications	48	0,567	27,216
Development of a High Voltage Lithium Battery	60	1,575	94,5
Development of power electronic technologies for >1kV aerospace applications	48	0,81	38,88
Assessment of arc tracking hazards in high voltage aerospace systems	45	0,378	17,01
TOT	320	4,104	222,084

Table 19 - Total funds to technologies development up to TRL 9 considering developing, testing, direct and indirect costs

The results represented in Table 19 take into account the following additional costs :

- Cost of equipment for the first prototype of the components necessary for the hybridization of the aeroplane in question
- Cost of testing equipment
- Cost of facilities
- Cost of direct and indirect materials and equipment
- Cost for integration and testing of the integrated component and the entire platform.
- Costs incurred directly.

The cost of resources is very high and it is therefore plausible that the problem of the hybridization of a regional aircraft is approached by more companies as for the projects E-Fan X or Zunum. The data reported refer to the development of technologies only, not therefore to the development of the complete aircraft, which is outside the scope of this work, it is also important to consider a technological growth factor, specific to each company. Another important aspect to consider are the available capabilities, this aspect can make to vary a lot the development cost; if we consider the technological jump from TRL 4 to 5 they are necessary benches whose cost is not considered in the values brought back in Table 19.

The model generated in this research provides a level of accuracy and detail related to the amount of data available in the database, is therefore necessary for the reliability and robustness, increase the projects analyzed, also considering new technologies and hybrid aircraft concepts. The set of possible configurations and therefore of the necessary technologies is very wide being the theme of the hybrid still at the dawn in the field of commercial aviation.

From the work done, therefore, it is necessary to deepen the study, expanding the database with more research projects and looking for better trends; it also remains a valid tool for a rough estimate in case studies as described in Chapter 4

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