**ELectric Innovative Commuter Aircraft**

# D4.1 State of the art of hybrid aircraft design projects

| | Name | Function | Date |
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# 1 Executive Summary

In this report, some of the most relevant hybrid-electric design projects are presented. The main objective is to explore the current panorama in which the ELICA project fits, considering projects aligned with the European Commission's "Flightpath 2050" goals. These call for significant reductions in aircraft CO2 emissions and noise to ensure the aviation industry's sustainable development. The document deals with active projects aiming to enter the market in the short or medium term as well as ruinous or cancelled projects. All the projects described here envisage the integration of disruptive technologies aimed at delivering a more environmentally friendly aviation as soon as possible. A distinction is made between projects still in the definition phase and projects in an advanced development state, i.e. with a technology readiness level (TRL) higher than 6.

# 2 References

## 2.1 Definitions and Abbreviations

### 2.1.1 Terms & Definitions

| Term | Definition |
|---|---|
| Sea Level Static | Operating point at sea level (0m) and zero velocity |

Table 1: Terms & Definitions.

### 2.1.2 Abbreviations & Symbols

| Abbreviations | Description |
|---|---|
| AR | Aspect Ratio |
| BLI | Boundary Layer Ingestion |
| CAS | Calibrated Air Speed |
| DEP | Distributed Electric Propulsion |
| EIS | Entry Into Service |
| IFR | Instrumental Flight Rules |
| MIL | Minimum Induced Losses |
| PAV | Personal Air Vehicle |
| SAT | Small Air Transport |
| S/L | Sea Level |
| STOL | Short Take-Off and Landing |
| TAS | True Air Speed |
| TLAR | Top Level Aircraft Requirements |
| TRL | Technology Readiness Level |
| VTOL | Vertical Take-Off and Landing |

Table 2: Abbreviations.

## 2.2 Tables & Figures

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# 3 Introduction

Nowadays, the growing sensitivity towards the problem of environmental pollution raises new demands for environmental sustainability that technological progress should support in the closest future. In particular, the society imposes two main objectives that research has the obligation to pursue: the efficient use of pre-existing technologies and the introduction of new technologies specifically developed to increase sustainability. Aviation currently contributes between 2% and 3% to global emissions [1]. Nonetheless, a significant reduction of aviation emissions is the current objective of developed countries for a number of important reasons, including the prospect of future further restrictions by legislation policy and the market growth requiring new technologies to be consolidated and certified. The main pollutants emitted by aircraft engines are carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NOX), sulfur oxides (SOX), unburned hydrocarbons (HC), particulate matter (PM) and soot. The contribution of aircraft emissions to climate change is a long-standing issue in literature [2, 3]. However, noise emissions cannot be considered a negligible part of the polluting emissions from aviation: in particular, when coming to quantification of the environmental cost, Schipper concluded that noise is responsible for about 75 of the total cost [4]. The only possible way to reduce global emissions is through disruptive technologies and concepts integrated by innovative design methods. When looking at the expected results of the research activities, it can be observed that the margins of reduction change with the aircraft category. The most important goals can be obtained by working on rotor aircraft and short-medium range aircraft, while this margin is significantly lowered moving to large commercial aircraft. Considering that 90% of global emissions from commercial operations are produced by large commercial aircraft carrying more than 100 passengers per journey, the impact of the emissions from general aviation turns even less significant with respect to the global anthropic emissions. Nevertheless, the Small Air Transport (SAT) segment is seen as the bridge to overcome the gap from experimental aircraft to commercial aviation, thanks to the possibility to rapidly apply the new hybridization technologies [5]. It is believed that the success of many technologies can be better proved and demonstrated at the level of SAT rather than on large passenger transport segment. This is the case of alternative propulsion system, which has been already introduced on light aircraft and has received a great deal of attention over the past years[1]. Thus, the SAT segment can be a viable platform to develop a systematic approach to fully design such aircraft system, to define a best practice, and to trace a technological roadmap for larger platform and aircraft demonstrators. On the other hand, the interest in general aviation market is pushed by the growth of domestic flight, also thanks to the new market opportunities created by the introduction of hybrid-electric propulsive systems (Figure 1). In fact, although airlines have shifted their focus from regional aircraft with fewer than 50 seats to aircraft with 70-90 seats, which tend to have a superior operating economy, this new paradigm of air operations has contributed to the significant loss of connectivity for many regional airports. Interest in finding more cost-effective solutions for regional aircraft with fewer than 50 seats could potentially encourage airlines to open new markets, re-establish service at smaller airports and increase mobility for all European passengers. In conclusion, the Small Air Traffic can still significantly contribute to the reduction of global emissions by partially sustaining the public transport in densely populated areas. Electrical propulsion can reduce carbon and nitrogen oxide emissions if new technologies enable higher specific powers and reliability. Batteries and fuel cells provide electrical power with no emissions, but only if the energy sources are sustainable. Fuel cells convert the chemical energy of a fuel into electrical power without any combustion and their exhaust cells is totally carbon-free if hydrogen is used as the fuel. If a hydrocarbon fuel is used, the fuel cell exhaust still contains $CO_2$ in direct proportion to the amount of fuel consumed, but there are no $NO_X$ or particulate emissions. However, safety in storage and utilisation is of paramount concern if hydrogen is used as fuel. Cryogenic system and superconducting materials (operating at temperatures from 20 to 77 K) seem not feasible for commuter aircraft because of their size, weight, and safety constraints (due to the required robustness and redundancy), even with LNG stored at 112 K. Sustainable aviation fuels (SAF) should produce approximately the same amount of $CO_2$ of a conventional jet fuel, but recycling the carbon already present in the

[1] https://en.wikipedia.org/wiki/List_of_electric_aircraft

biosphere and with reduced $NO_X$ emissions. They may be an option in the immediate future since they do not require a radical change in the engine architecture. Apart from the energy sources, airframe-propulsor integration shall increase the impact of advanced propulsion systems, as in the case of distributed propulsion, which use multiple propulsors to achieve beneficial aerodynamic-propulsion interaction [6, 7, 8, 9, 10]. Also, boundary layer ingestion and laminar flow technology may contribute to improve the aerodynamic efficiency by reducing the aircraft parasite drag. The high efficiency associated with electric propulsion also reduces the penalty for cruising at higher speeds which is connected to the use of fuel. Finally, airframe offers various key technologies to further improve performance versus weight ratio and even favour safety. That is the case of smart intelligent systems to monitor the whole airframe in IoT (Internet of Things) and Industry 4.0 perspectives. In addition, some challenging but promising advancements are forecast by introducing novel and multifunctional materials.

Figure 1: The growing segment of SAT and PAV requires always more disruptive technologies and heavier payloads.

Electric propulsion may be the next revolution in air transportation, but its development is limited by current battery technology and electric charging infrastructure. Today's batteries and maintenance systems are not sophisticated enough to sustain commercial all-electric aircraft. Many electric aircraft concepts currently being studied rely on future innovations to solve these problems and could be waiting decades for a suitable power system. The state of the art is presented in this document, through a summary of some of the most significant existing projects. In Section 4 several classical technologies and approaches are briefly reviewed. These enabling technologies define the design space of most of the active or past projects. Section 5 deals with some of the main innovative electric and hybrid-electric design projects, currently under development or which, in some cases, have passed the early stages of research and experimentation and have already started to produce and distribute units.

# 4 Main innovative technologies employed in hybrid-electric design projects.

This section contains insights into some of the most promising innovative technologies applicable in the design of electric or hybrid-electric aircraft. They have already been the central subject of D5.1 - Enabling Technologies, to which reference should be made for further details regarding the state of the most promising technologies currently under study. The information reported in the following paragraphs has been extracted from the aforementioned document in order to reintroduce the key strategies that most of the projects currently active or already successful rely on. Section 4.1 offers an overview of the available propulsive technologies in a general perspective, and Section 4.2 will deal specifically with the aerodynamic benefits of wingtip-mounted propellers, Distributed Electric Propulsion (DEP) and Boundary Layer Ingestion (BLI).

## 4.1 Propulsion

High powers and large energies are needed to fly at high speeds over long distances. The maximum power required for an aircraft is the power at take-off and it scales with aircraft weight. Fuel efficiency has always been a primary design criterion for commercial aircraft since it is an important determinant of aircraft range, size, and economics. Overall, the fuel burn per seat mile of gas turbine–powered commercial aircraft has been reduced by 70 percent since service started in the 1950s, at an average rate of about 2% per year since 1970 (see Figure 2). About half the gain has been the result of improvements to the airplane, the rest to the engine.

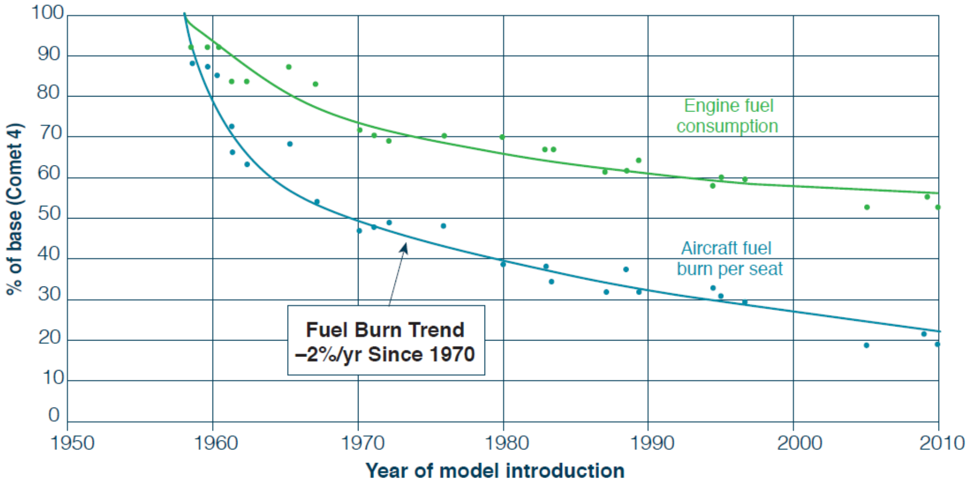



Figure 2: History of commercial aircraft fuel burn per seat-mile [6].

Recent studies have estimated possible improvement of 30-35% in simple cycle gas turbines' overall efficiency with respect to nowadays engines in service. It may be possible to achieve thermodynamic efficiencies of 65-70% and propulsive efficiencies of 90-95%. Improvements in turbomachinery performance and reduction in cooling losses could improve thermodynamic efficiency by 19% and 6%, respectively. This gain will also require the optimization of the thermodynamic cycle from specific levels of component performance characteristics, temperature capability, and cooling. The practical limits to propulsive efficiency cannot be addressed at the engine level alone, but require integration within the airframe and airplane configuration [6]. Improvement of thermodynamic efficiency requires larger pressure at compressor exit and higher turbine inlet temperatures, while reducing structural weight and aerodynamic losses. Advanced materials, such as ceramic matrix composites, can reduce fuel burn by decreasing the engine structural weight and further improvements are expected with long lasting turbine blade resisting at 1,700°C. If the overall engine efficiency increase is directly linked to fuel burn, then it may be argued that carbon and presumably also $NO_X$ emissions will reduce by the same amount in the 2035-2050 timeframe. Historical data, presented in Figure 3, show a 25% reduction in jet engines' cruise thrust specific fuel consumption over 40 years, with turboprop gaining from 10% to 30% more efficiency over regional jets and large turbofans. However, fuel consumption and emissions from cruise data are not sufficient to describe the impact of the advancing technology. As concern turbofan engines, it has been shown [11] that during the last 40 years, thrust specific emissions during a landing-take-off cycle have been almost constant. Also, despite significant investments in aero engine technology, emissions savings are decreasing over time. This explain why even if all the above mentioned technological improvements are successfully integrated in a turboprop engine, they will not be sufficient for the target emissions reduction.

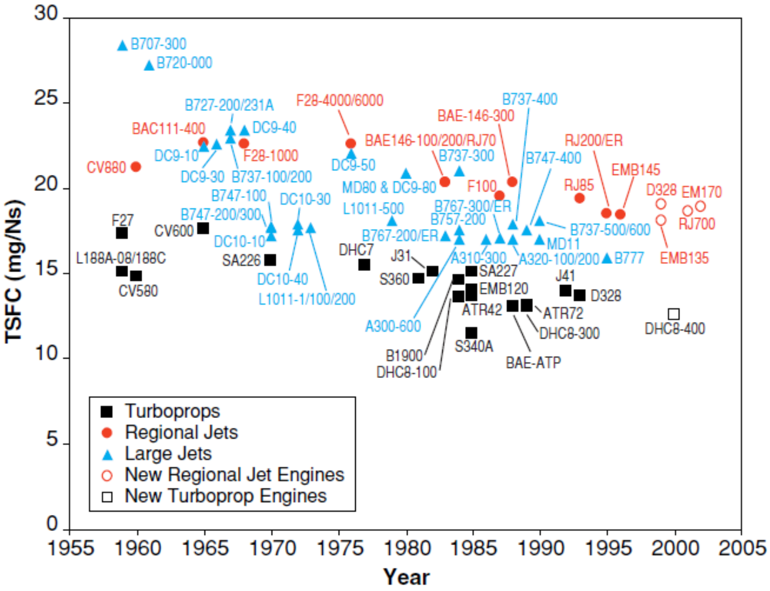



Figure 3: Thrust Specific Fuel Consumption over time for jet engines [12].

### 4.1.1 Sustainable Aviation Fuels

Jet fuel is a generic term that encompasses many specific variants. Jet A is the most common form of jet fuel used by commercial aviation in the United States, while Jet A-1 predominates in the rest of the world [6]. Sustainable Aviation Fuels (SAF) are alternative to petroleum-based jet fuels, fully compatible with the existing aircraft and fuel infrastructure, miscible with conventional jet fuels. The European Union define a SAF as bio-fuels which life cycle greenhouse emissions are reduced with respect to fossil fuels by at least 50% for production plants older than 5 October 2015, 60% for production plants built later, 65% for installations from year 2021. Burning SAF will produce nearly the same amount of $CO_2$ per unit of fuel as conventional jet fuel, but the use of SAFs reduce net life-cycle carbon emissions up to 90 % because they enable reusing or recycling carbon that is already in the biosphere to create the fuel. Currently, six production pathways have been certified by the American Society for Testing and Materials (ASTM) for blending with conventional aviation fuel [13]:

- Fischer-Tropsch Synthetic Paraffinic Kerosene (**FT-SPK**);
- Fischer-Tropsch Synthetic Paraffinic Kerosene and Aromatics (**FT-SPK/A**);
- Hydroprocessed fatty acid Esters and free Fatty Acid (**HEFA**);
- Hydroprocessing of Fermented Sugars – Synthetic Iso-Paraffinic kerosene (**HFS-SIP**);
- Alcohol-To-Jet Synthetic Paraffinic Kerosene (**ATJ-SPK**);
- Co-processing.

**Hydrogen** can be used as alternative power source for conventional propulsive systems. It is an attractive fuel because of its enormous amount of specific energy (about 40,000 Wh/kg against the 13,000 Wh/kg of kerosene), it is stable, uniformly available on Earth, the outputs of the chemical reaction with oxygen are pure water and heat, and it can be produced by electrolysis of water. As drawbacks it is a flammable and explosive gas, so that it must be carefully stored and transported in special containers, it is the lightest element in the universe, it has a very low density at ambient conditions (0.08 $Kg/m^3$ against the 1.225 $Kg/m^3$ of air). Moreover, pure hydrogen must be stored as a compressed gas in a pressurized tank or as a liquid in a cryogenic tank. It may be also safely stored as a metal hydride, a heavier compound that is stable at ambient conditions that can be safely heated to separate the hydrogen. Finally, the hydrogen can be extracted from a hydro-carbon like jet fuel, a process known as reformation. The pressurized hydrogen seems to be the most efficient solution, followed by the cryogenic tank [14]. Thrust is generated through the combustion of hydrogen in a modified jet engine, which eliminates most but not all green-house gases emissions. A recent Clean Sky 2 study states that hydrogen propulsion has the potential to reduce $CO_2$ equivalent emissions up to 90% [15]. Nevertheless, hydrogen technology is not currently ready for a mature application in aviation industry. Hydrogen may also be used to produce *synfuel* (synthetic fuel), a SAF like a biofuel, but with the potential of obtaining zero net carbon emissions if $CO_2$ is captured from air. The production of a synfuel from hydrogen requires electricity, which should be generated in a sustainable way. A synfuel has the potential to reduce the climate impact up to 60% with respect to conventional (kerosene) aviation.

### 4.1.2 Electric Propulsion Systems

Electric propulsion systems convert the electric energy into mechanical energy, which is converted into thrust by a propeller or a fan. They are an effective way to reduce pollutant emissions as long as the energy sources are renewable. Electric propulsion can be **all-electric**, **hybrid-electric**, and **turbo-electric**. There are several variants of the logic schemes of an electric propulsion system [16, 17, 18, 19]. A possible representation of the hybrid series/parallel electric powertrain is given in Figure 4.

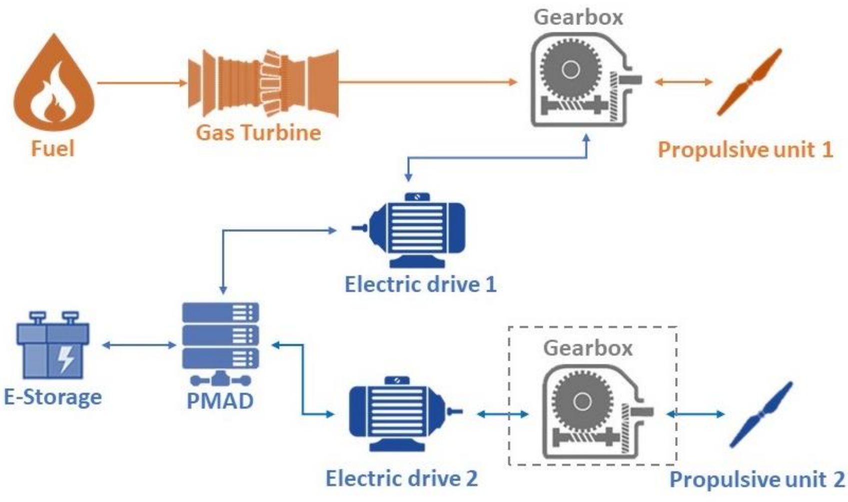
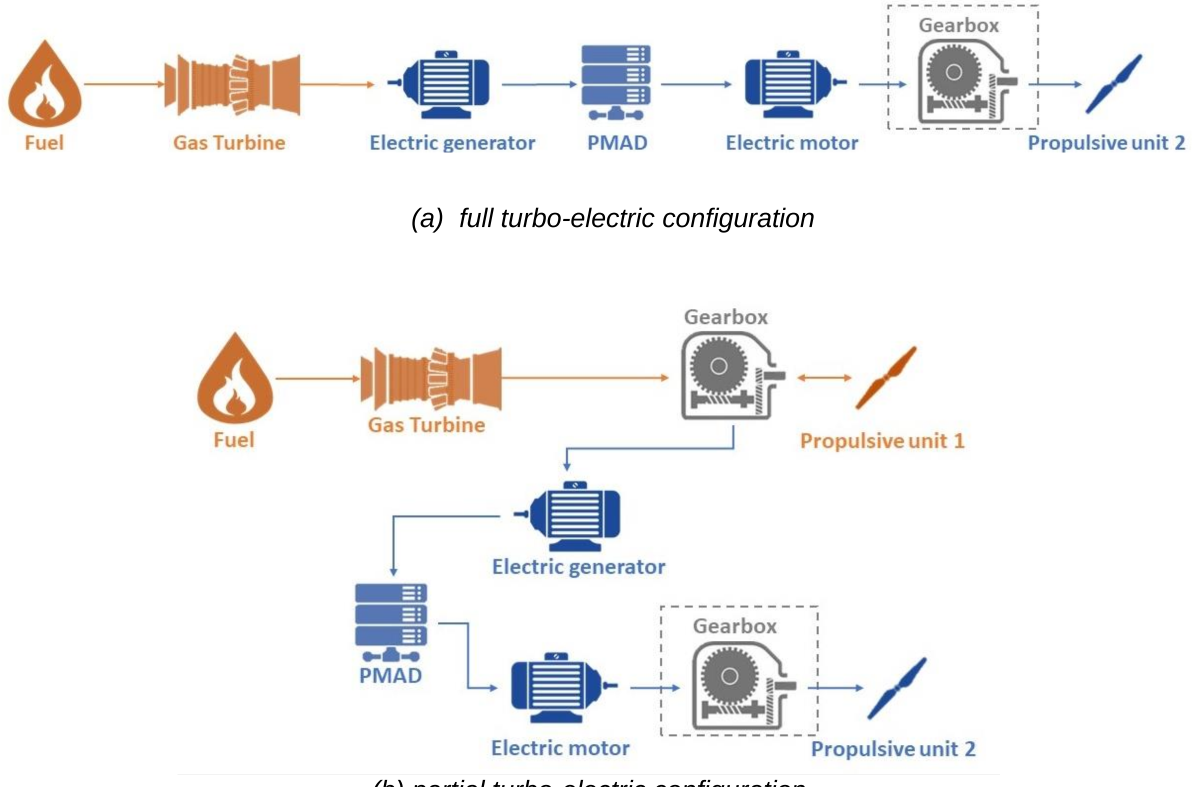



Figure 4: Hybrid-electric propulsion scheme.

All of the possible main elements of a hybrid-electric powertrain are present and connected. The arrows indicate direction of the power flow. The power can flow through electric drives and propellers in both directions. Fuel and gas turbine can only provide power to other devices but cannot absorb or store power. An electric storage like a battery can be recharged in flight. The primary propulsive unit is powered by the gas turbine and may be boosted by an electric drive. The secondary propulsive unit is powered by an electric drive, whatever the source of the electric power, may be a battery, a fuel cell, a gas turbine generator. Gearbox on the secondary propulsive unit can be avoided if the secondary electric drives' RPM match those of the propellers. More details on the architecture can be found in D3.1. The following architectures of electric propulsion can be derived from the scheme of Figure 4:

- all electric
- hybrid-electric
    - parallel hybrid
    - series hybrid
    - series/parallel partial hybrid
- turbo-electric
    - full turbo-electric
    - partial turbo-electric

Turbo-electric propulsion is a special case characterized by the fact that the electric energy is completely generated by the gas turbine. The scheme of a turbo-electric powertrain can be derived from that of Figure 4 and is shown in Figure 5. The propulsion power in a pure turbo-electric powertrain is entirely achieved with electric power, while in a partial turbo-electric powertrain only a fraction of the electric power is converted in propulsive power. The power electronics – Power Management and Distribution (PMAD) system – between the gas turbine and the electric generator allows the former and the electric motors to rotate at different speeds. In this way, the gas turbine may operate at max efficiency most of the time, while propulsive units could be directly installed on the electric motor shaft, if the rotations speeds are compatible (otherwise a gearbox is necessary). In both the full and partial turbo-electric configurations, the power can only flow from the fuel to the propulsive units. In principle, it may be possible to extract power from one propulsive unit and move it to the other, but even with the absence of mechanical losses, there would be an aerodynamic drag increase, hence the system must be sized such that the propulsive units always consume power.




*(a) full turbo-electric configuration*



*(b) partial turbo-electric configuration*

Figure 5: Turbo-electric propulsion scheme.

A turbo-electric concept does not rely on electric energy storage, by definition. The overall efficiency of such powertrain is lower than the conventional gas turbine configuration, because of additional energy conversion and transmission losses. The effectiveness of turbo-electric architecture relies on its integration in the airframe, leading to beneficial aero-propulsive interactions that are unfeasible to obtain with a conventional powertrain. In fact, electric propulsion enables the possibility to distribute the propulsors on the wing (distributed electric propulsion, DEP) and to cancel most of the fuselage wake with boundary layer ingestion (BLI), which are discussed in the next paragraphs. A key benefit of DEP is the reduction of motor size and power required as there are many more motors. Also, electric motors can be easily scaled down, in contrast with gas turbines. The potential applications and timeframe for turboelectric concepts will be based largely on projected advances in the specific power of components. Current electric generators installed on in-service aircraft have a specific power around 2.2 kW/kg. Future trends are shown in Figure 6, where most of data is derived from research studies on possible future large passenger airplanes [6]. An average annual growth of 0.33 kW/kg is forecasted, so that a specific power of 10 kW/kg is expected in the next 25 years. For commuter and general aviation aircraft it is claimed that the electric motor power including power electronics will be below 1 MW, and the required specific power should be around 7 kW/kg [6]. In April 2015, Siemens announced the development of a direct-drive (2,500 RPM), 260 kW aircraft electric motor weighing a little over 50 Kg [20]. The motor specific power is on the order of 5 kW/kg, and it is capable of powering aircraft with a maximum take-off gross mass of 2,000 Kg. The potential availability of such an engine suggests that twin-engine commuter aircraft could be powered by electric motors using current technology. It will be the energy source to determine the potential range of such aircraft and hence their economic viability.

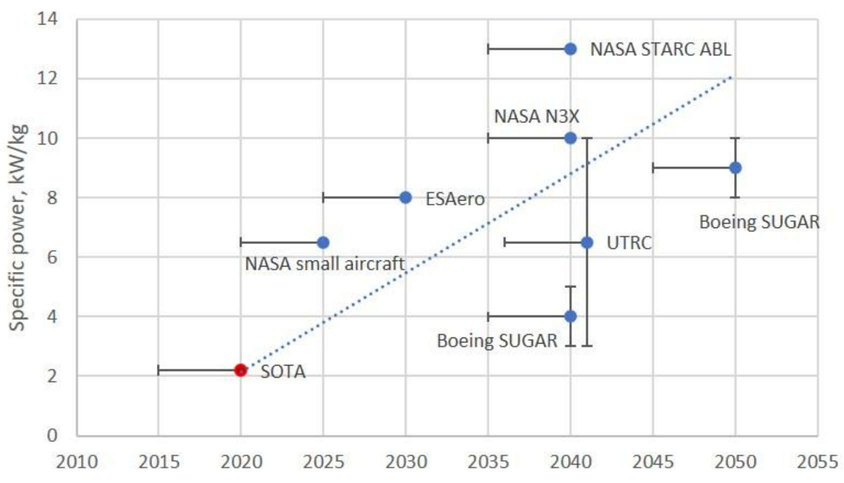



Figure 6: Trend of electric drives specific power. Reproduced from [6].

### 4.1.3 Batteries

**Batteries** are electrochemical cells that store chemical compounds holding a voltage difference between the electrodes. The battery (which usually is made up of several individual cells in series) provides electric energy with a chemical reaction when the electric circuit at its poles is closed. Electrochemical cells convert the energy stored in the chemical bonds directly into electricity, without producing heat or thermal energy as an intermediate stage of the energy conversion process. Because of this, electrochemical cells are not subjected to the Carnot limitations, hence their efficiency as energy in releasing energy can be very high. The total chemical energy that may be converted to electric energy is equal to the exergy of the electrode materials [21]. A fundamental parameter is the equivalent specific energy, which determines how much energy can be stored per mass unit. Jet fuel stores about 13,000 Wh/Kg, while current batteries are below 250 Wh/Kg. For regional hybrid-electric turboprop specific energies higher than 500 Wh/kg, ideally 800 Wh/kg, are needed. For an all-electric system, the required specific energy may be around 2,000 Wh/kg, if the actual design range are to be kept [6, 17, 21, 22]. Although additional improvements are foresighted, it is unlikely that an electrochemical cell or a super capacitor may achieve more than 1,500 Wh/Kg, while even 500 Wh/Kg within year 2035 seems optimistic. Current trends in battery technology concern Lithium-Ion, Lithium-Sulphur, and Lithium-Oxygen cells. Expected achievements by year 2035 *at cell level* are reported in Table 3.

| **Parameter** | **Unit** | **Li-Ion** | **Li-S** | **Li-$O_{2,open}$** | **Li-$O_{2,closed}$** |
|---|---|---|---|---|---|
| Specific Energy | Wh/kg | 250-350 | 600-700 | 800-1500 | 600-1200 |
| Specific Power | W/kg | 500-600 | 350-500 | 300-400 | 300-400 |
| Energy Density | Wh/l | 600-800 | 300-350 | 1000-1700 | 1000-1600 |
| Charge/Discharge efficiency | % | 90-95 | 70-90 | 60-85 | 60-85 |
| Cycle life # | cycles | 1,000-3,000 | 1,000-2,500 | 500-1,000 | 500-1,000 |
| Degree of Discharge | % | 70-90 | 90-100 | 70-90 | 70-90 |
| Lifetime | years | 7-15 | 7-14 | 5-10 | 5-10 |
| Cost ($ 2010) | $/kWh | 250-350 | 250-500 | 400-800 | 300-700 |
| Uncertainty | - | low | medium | High | High |

Table 3: Trends in future batteries at cell level by year 2035 [23].

While theoretical specific energy is much higher than those reported, in practice the attained value will be significantly lower, because of the added weight of current collectors, electrolytes, separators, battery cases, and terminals. Furthermore, the requirement to simultaneously achieve long cycle life, low cost, and acceptable safety greatly increases the complexity of the overall challenge. **Lithium-ion batteries** currently dominate the market in both consumer electronics and electric vehicles. Batteries can be scaled to meet power and energy requirements for aviation, as lithium-ion battery systems with power capability greater than 10 MW and energy storage capacity greater than 10 MWh have already been demonstrated in stationary energy storage for electric utility applications [6]. The maximum theoretical specific energy that can be obtained by chemical reaction is about 550 Wh/Kg. As regards safety, Li-ion batteries have proven to be susceptible to thermal runaway, a process where in which the heat from a failing cell causes itself and surrounding cells to fail, thereby generating more heat. In conditions like overcharging, the high local temperatures can release oxygen from the cathode. If the oxygen reacts with the flammable organic electrolyte there is a serious risk of combustion and even explosion. The **lithium-sulphur** combination is being investigated to increase the specific energy of lithium batteries. The practical application of Li-S batteries is hindered by very low life cycle and low efficiency that does not permit the full extraction of the chemical energy. Both of these drawbacks could be overcome by the application of nano-structures and graphene at the electrodes [23]. The **lithium-air** technology is the most promising concept for Li-ion batteries. It is forecasted a value of 1,500 Wh/kg at cell level by 2035. Similar to the Li-S battery, Li-Air cells have problems with safety, low charge and discharge rates, poor energy efficiency and limited life cycles. In *open-cycle* processes, the mass of the battery is theoretically reduced thanks to the fact that one of the compounds (the oxygen) is already present in the air. On the other hand, the mass increases (equal to + 0.2 g/Wh) while discharging, due to the additional oxygen bounded to the electrodes. At high altitudes, the oxygen must also be compressed to counteract its lower density at ambient conditions. A *closed-cycle* process eliminates the need for the oxygen separator, compressor, and purifier, but a pressure vessel is needed to keep the oxygen at the desired pressure value, yielding to a non-trivial safety issue. This is complicated by the difficulty of cooling or heating the battery within the vessel. The forecast provide better achievements for the open-cycle case [23].

### 4.1.4 Fuel cells

**Fuel cells** convert the chemical energy in a fuel into electrical power without any combustion. Since a fuel cell can be continuously fuelled to produce electric power, it can be represented as a power conversion unit (hence its contribution to aircraft powerplant performance can be evaluated in W/kg). The exhaust from fuel cells is totally carbon-free if hydrogen is used as the fuel. However, if a hydrocarbon fuel is used, the exhaust still contains $CO_2$ in direct proportion to the amount of fuel consumed, but there are no $NO_X$ or particulate emissions [6]. Fuel cells are similar to batteries, but they are open thermodynamic systems which may operate without stop. They are continuously supplied with fluid fuels and oxidants, their electrodes are not part of the reaction process and, hence, do not need to be regenerated or recharged. In general, the oxidant is air at sea level pressure, while the fuel is hydrogen or a hydrocarbon. Fuel cells produce a maximum voltage of the order of 1 V, therefore higher values of the output voltage are achieved by having several fuel cells in series, or *stacks*. Typically, fuel cells are in stacks of 20-30 units, which provide operational voltages close to 30 V [23]. The **Proton Exchange Membrane** (PEM) fuel cells operate at 80°C to 120°C and require pure hydrogen as the fuel. This type of fuel cell works perfectly when replacing the APU as it provides multiple advantages when small-sized (e.g.: water generation). However, when sized for primary propulsion, these advantages turn into low efficiency of 55 to 60% in combination with the low operating temperature making the cooling particularly challenging. Current PEM fuel cells have specific power around 100 W/Kg, depending on flight time and assuming a constant electric power [14]. An entire PEM fuel cell system may achieve more than 320 Wh/kg. **Solid oxide fuel cells** (SOFC) operate at 750°C to 1000°C and can use a variety of hydrocarbon fuels, including jet fuels. Current SOFC power systems have a specific power of less than 100 W/kg compared to about 1,000 W/kg for internal combustion engines. SOFCs are being developed for both large-scale stationary power applications (more than 100 kW) and small-scale (1 to 10 kW) APUs and residential applications. **Hydrogen fuel cell** (HFC) are a near-zero emission solution as the only output of fuel cells is water vapour, the impact of which can be minimized through careful aircraft operation. Implementing this technology may lead to a 90% climate impact reduction, with 15% more weight and 5% more cost 5% per available seat kilometre [15]. However, the use of hydro-carbon, both as hydrogen storage for a PEM or fuel for a SOFC, should be avoided if a significant abatement of the aircraft emissions is wanted. Because of their low specific power, fuel cells are competitive only for small aircraft and yet they would be better installed in a hybrid system with a battery or other power sources to boost the power during transient manoeuvres, while the fuel cell supplies a nearly constant load [14, 24, 25, 26, 27, 28]. Fuel cells will be attractive if the entire electrical energy generation system provides a comparable or superior performance with future batteries specific energy (say 600 Wh/kg by 2035) and specific power, with equal safety.

## 4.2 Aero-propulsive interactions

Improvements in aerodynamics have direct impact on the whole aircraft performance. From the beginning of aeronautics up-to-date, researches in the aerodynamic field are pushing the aircraft technology to ever improved performance. An improvement in terms of aerodynamic can be achieved by both upgrading current designs and adopting innovative technologies, by keeping in mind that such an introduction should not only guarantee a positive impact on main performances but should also contribute strongly to product cost and operability. In the following paragraphs, a selection of the most promising technologies is done.

### 4.2.1 Tip-mounted propeller

Wingtip vortex can be mitigated installing a propeller at the wing tip. The main impact of propeller slipstream on wing performance is to increase the speed downstream of the propeller. A first simple assumption that can be done is that only the speed component normal to the propeller plane is increased. However, this assumption neglects the swirl in the propeller slipstream, whose interaction with the tip vortex of the wing causes a variation of induced drag, even more than the increase in axial speed. In general, the induced drag can be approximated accordingly to Eq. (1) and this is due to the wing finiteness. Reducing the induced angle, induced drag is reduced. As shown in Figure 7, the presence of the wing causes a decrease in the angle of attack related to the induced downwash speed. The induced angle of attack due to the wing, also called downwash angle, $\alpha_{i_w}$ can be approximated as in Eq. (2). The effect of the increase in axial speed (red arrow in Figure 7) due to the presence of the propeller is shown. The variation of the axial speed causes an upwash effect counteracting the downwash due to the wing. The actuator disk theory drives the estimation of the axial induction factor at the propeller disk as a function of the thrust-to-weight ratio and the diameter of the propeller, as indicated by Eq. (3). Finally, the axial speed induced by the propeller $V_p$ is given by Eq. (4).

$$C_{Di} = C_L \alpha_i \tag{1}$$

$$\alpha_{i_w} = \frac{w_w}{V_\infty} = \frac{C_L}{\pi A R e} \tag{2}$$

$$a_p = \frac{1}{2}\sqrt{1 + \frac{8}{\rho\,\pi\,V_\infty^2}\frac{T_p/W}{D_p^2/W}} - 1 \tag{3}$$

$$V_p = a_p V_\infty \tag{4}$$

Beyond the axial induction, the flow rotation due to the propeller slipstream must be also accounted, as shown in Figure 8. Assuming a certain rotation direction of the propeller, the tangential induction is a measure of the ratio between the propeller angular speed, Ω, and the angular speed induced on the flow downstream of the propeller, ω, and it can be used to estimate the vertical speed due to the slipstream. The tangential induction due to propeller can be computed through Eq. (5). The tangential speed, $w_{swirl}$, perceived in the propeller slipstream is a function of the tangential induction, the tangential speed of the tip of the propeller and the propeller radius, and it can be computed through Eq. (6). Finally, the induced angle can be computed accordingly to Eq. (7).

$$a_{p_t} = \frac{\omega}{2\Omega} = \frac{1}{2} - \sqrt{\frac{1}{4} - \frac{V^2}{\Omega^2 R_p^2}\left(1 + a_p\right)a_p} \tag{5}$$

$$w_{\text{swirl}} = a_{p_t}\Omega R_p \tag{6}$$

$$\alpha_i = \tan^{-1}\left(\frac{w_w + w_p + w_{swirl}}{V_\infty + V_P}\right) \tag{7}$$

It is clearly understandable that, properly rotating the tip propeller in the opposite direction respect to the tip-vortex (inner-up direction), it is possible to reduce the induced angle of attack and so the induced drag. Numerical and experimental analysis clearly confirm the induced drag reduction due to the tip propeller.

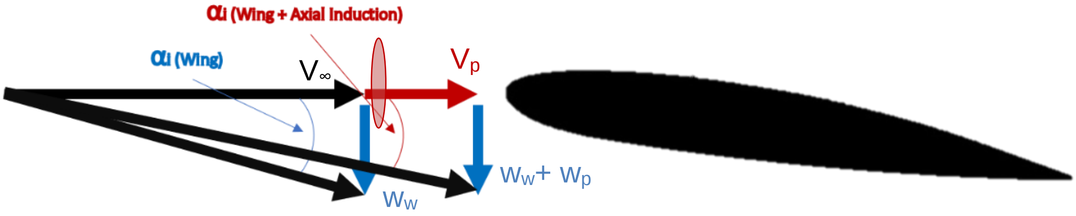



Figure 7: Induced angles due to wing and actuator disk.

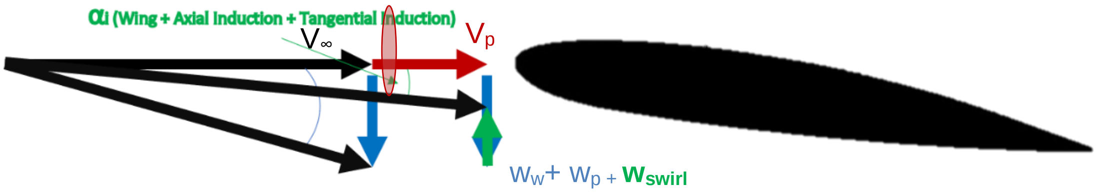



Figure 8: Induced angles due to wing and rotating disk.

In 1969 Snyder and Zumvalt [29] proposed that aircraft can be designed using propellers at the wingtips in such a way that the lift-to-drag ratio (L/D) can be varied by changing the effective aspect ratio in flight. An experimental program testing a wing with propellers mounted at the wingtips has shown that the use of a propeller at the wingtip, turning in the direction opposite to that of the wing vortex, shifts the trailing vortex core outboard, decreases the wing drag coefficient, increases the maximum lift coefficient and increases the effective aspect ratio. The main results were summarized in terms of lift coefficient, drag coefficient and effective aspect ratio ($AR_e$) as function of vortex rotating direction and number of revolution per second, as shown in Figure 9. Figure 10 shows the benefit of counter-vortex rotating propeller on efficiency, $AR_e$ and lift curve slope. All points plotted correspond to 175 or 188 revolution per second and a thrust coefficient $T_c$ equal to 0.42 or 0.6. To generalize the results and make them useful, a general curve on the induced drag effect has been drawn. Here, the parameter $\Delta C_{Di}/C_L^2$ has been evaluated for various values of $\mathfrak{N}$ d/b, where $\mathfrak{N}$ is the difference between rotor speed and windmilling speed, d is the propeller diameter and b is the wing span. It was found that $\Delta C_{Di}/C_L^2$ varies with the cube root of $\mathfrak{N}$ d/b. This relation is also shown in Figure 10.

| Configuration | Eff. Aspect Ratio $Ae_w$ | Vortex Span $b_v$, ft. |
|---|---|---|
| Dummy Spinner, No Propeller | 6.45 | 8.25 |
| Stationary Impeller | 6.32 | 8.42 |
| Impeller, Counter-Vortex Rotation, N = 175 r.p.s. | 10.35 | 8.93 |
| Impeller, Vortex-Rotation N = 175 r.p.s. | 5.34 | 7.42 |
| Propeller, Windmilling, N = 175 r.p.s. | 5.73 | 8.33 |
| Propeller, Counter-Vortex Rotation, N = 175 r.p.s. | 10.1 | 8.42 |
| Propeller, N = 50 r.p.s. | 4.0 | 7.42 |

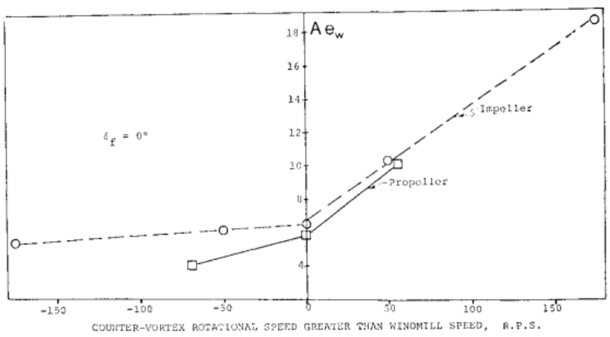



Figure 9: Variation of effective aspect ratio caused by rotor speed, Re = 6.7E5 [29].

Difficulty (or impossibility) of trimming the aircraft for One Engine Inoperative (OEI) operation, and aeroelastic problems created by the changing of the torsional moment of inertia of the wing and the interaction of bending and torsional modes of flutter or vibration are drawbacks that could be partially overcome with new technologies, design, materials, and powertrain strategies.

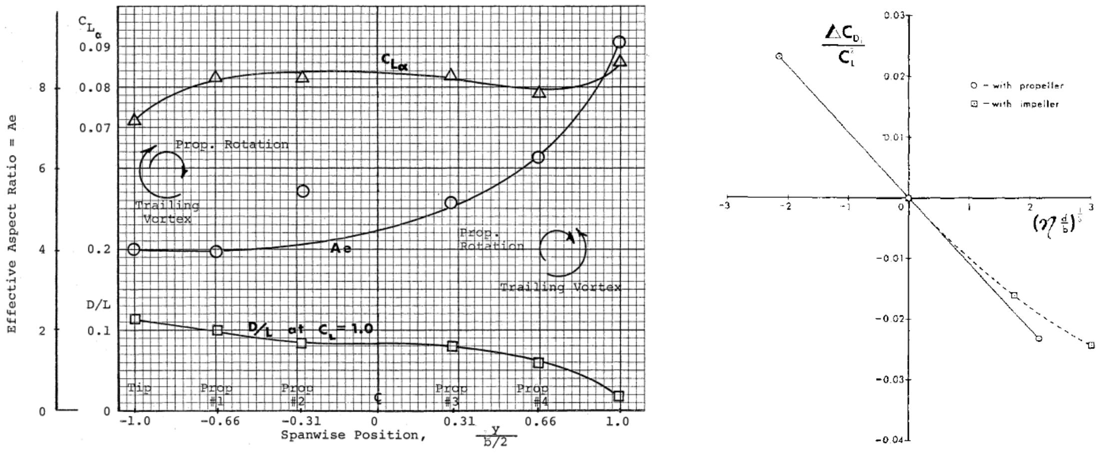



Figure 10: Left: Four-blade tip propeller effects on a wing with AR = 8, Re = 6.7E5, $T_C$ = 0.42 or 0.6. Right: Effect of propeller speed and size on induced drag coefficient [29].

In 1989 at NASA a wing-tip pusher propeller on a wing-body configuration with an AR = 6.10 was analysed in NASA Langley wind-tunnel facility [30]. Tests were done at M = 0.70 and Re = 3.82E6, within −2 to 4 degrees of angle of attack. Main results are shown in Figure 11, where a drag reduction of about 20 drag counts for the counter-rotating wing-tip pusher propeller is achieved, in the range of low values of lift coefficient.

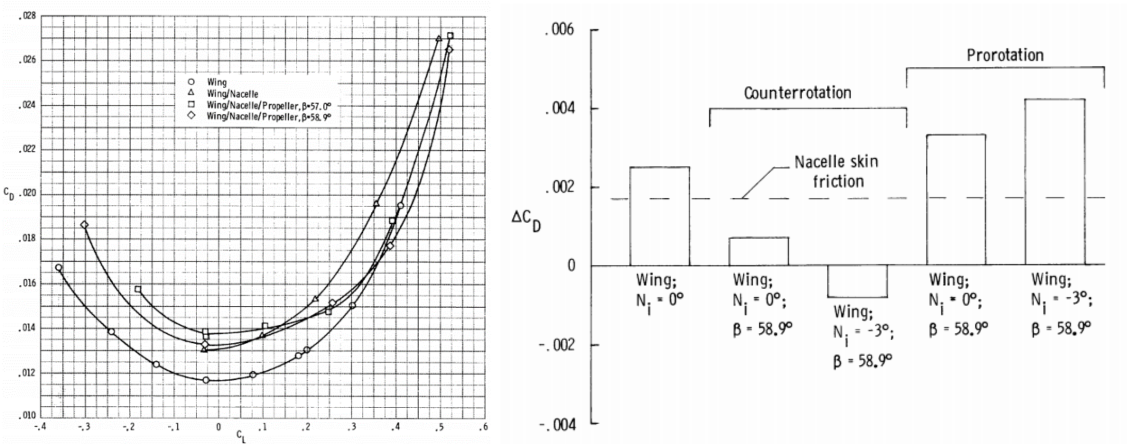



Figure 11: Left: Vortex-propeller interaction on drag coefficient versus lift coefficient for 0° incidence. Right: Delta drag with respect to the isolated wing for counter- and pro-rotating wing-tip pusher propeller; M = 0.7, Re = 3.82E6 [30].

In the last decade, NASA X-57 program has investigated also the effects of tip-propeller on the X-57 Maxwell aircraft (see also paragraph 5.2.10). A lot of numerical studies were performed, highlighting potential benefits of a tip mounted engine, useful in whole flight phases, reducing the induced drag. Some NASA’s CFD numerical analyses are shown in Figure 12, for a region of lift coefficients and power settings that are in the vicinity of the steady-state cruise condition. The efficiency difference can be inferred by the relative difference between the unpowered (solid) and powered (dashed) cases in these figures. Results have shown an average drag reduction in the range of 20-40 drag counts, slightly dependent on the solvers and transitional models [31], in line with what shown at NASA for pusher wing-tip propeller [30].

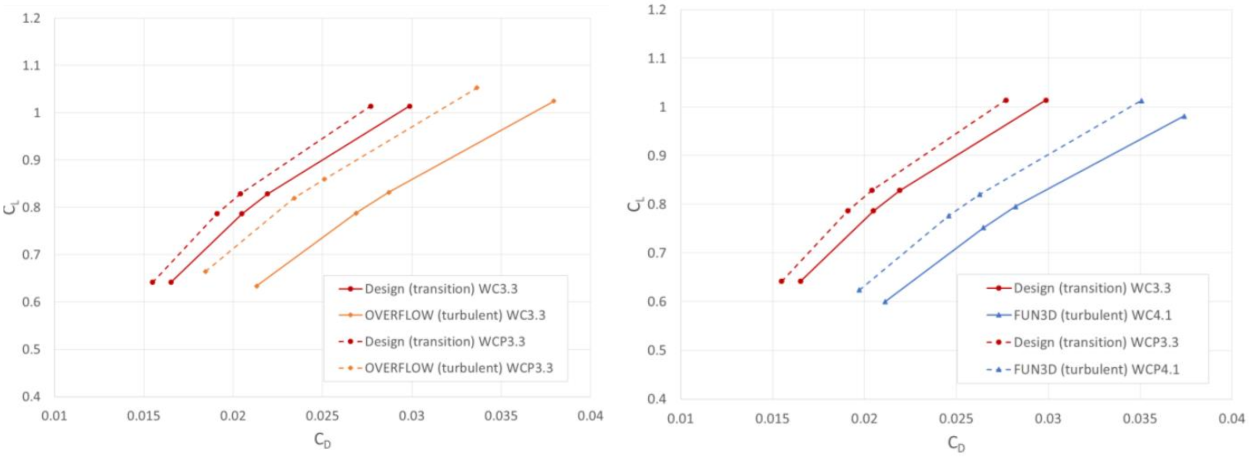



Figure 12: Drag Polar Comparison of Power-On (WCP) and Power-Off (WC) Wings, AR = 15, V = 150 kt, h = 8,000 ft [31].

At Technical University of Delft, several numerical and experimental studies have been conducted in the last two decades on the wing-tip-propeller, especially on low-and-medium aspect ratio wing from 3 up to 6.2 [32, 33, 34]. In one of the last research, they experimented conventional wing mounted configuration, versus wing-tip-mounted propeller configuration. The majority of the measurements discussed in this paper were taken at a freestream velocity of $V_1$ = 40 m/s. As expected the results showed a drag reduction when increasing the thrust setting level and the lift coefficient, leading to a drag reduction of about 30 up to 60 drag counts in conditions that are typical for general aviation small regional aircraft, with a $C_T$ range of 0.1-0.2 of cruise and with a lift coefficient equal to 0.5 (see Figure 13 and Figure 14).

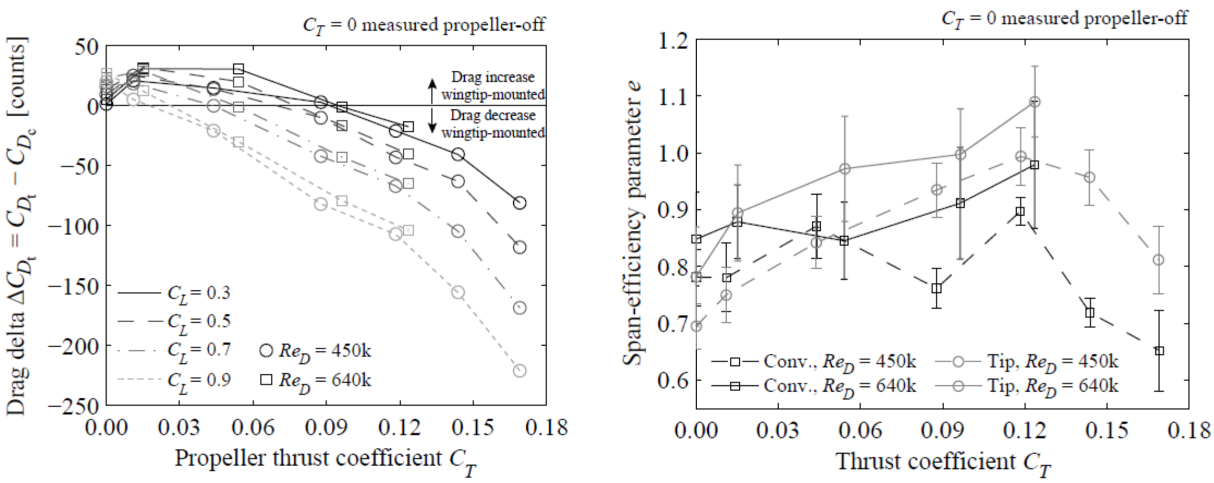
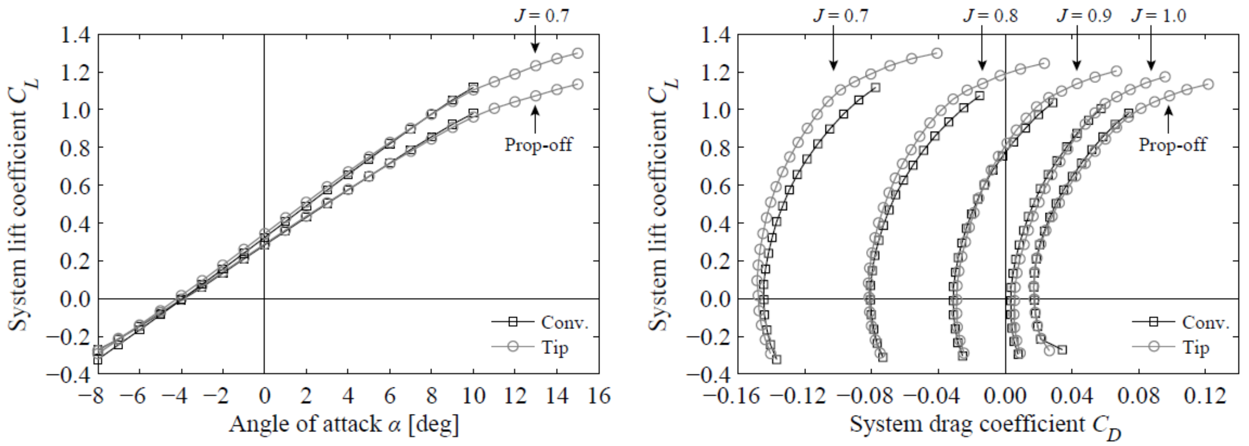



Figure 13: Left: Drag benefit of wingtip-mounted configuration compared to conventional configuration. Right: Effect of propeller thrust setting on the span-efficiency parameter [34].




**a) Lift polar** **b) Drag polar**

Figure 14: Lift and drag polars of the conventional and wingtip-mounted configurations, including propeller forces [34].

Della Vecchia et alii [7] studied the effects of high-efficiency tip-propeller on the Tecnam P2006T wing, varying the diameter and the thrust level in the range of typical cruise settings. They confirmed the previous results that a high-efficiency propeller (i.e. $\eta_p > 0.8$), allows smaller drag reduction than low efficiency propeller, improving the axial component than the available thrust. Moreover the numerical analyses show that, for a given propeller characteristics, decreasing the diameter, the drag reduction decreases, in the whole range of lift coefficient, while increasing the thrust level the drag reduction increases (see Figure 15). This behaviour is due to the variation of RPM, which must increase with decreasing diameter to provide the same level of thrust. Results globally show that, in the typical cruise attitude of the Tecnam P2006T, a drag reduction of about 10-15 drag counts can be attained for a propeller diameter equal to 1.78 m (the same propeller diameter installed on the aircraft).

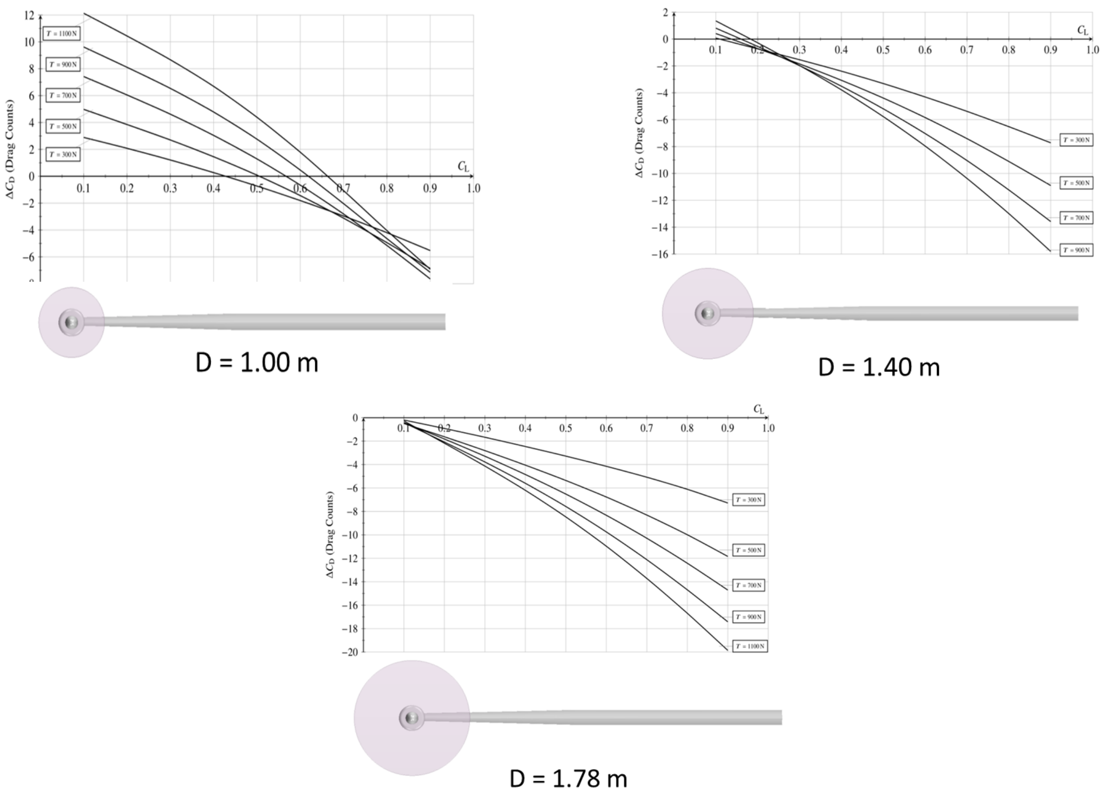



Figure 15: Drag reduction due to high-efficiency tip-propeller, AR = 8.47, M = 0.23, Re = 6.9E6 [7].

At University of Naples Federico II, high-fidelity Navier-Stokes analyses have been performed on a typical 40-passenger regional turboprop wing, to evaluate the tip-mounted propeller impact, by varying the thrust level and the propeller diameter. High-efficiency propellers, suitable for cruise and climb performance, designed accordingly minimum-induced-loss procedure, have been used to obtain required thrust, changing the number of revolution opportunely. Results are shown in Figure 16 in terms of wing drag reduction versus lift coefficient, for several thrust settings, propeller diameter and RPM (which means $C_T$). For a given thrust value, what usually happens is that when decreasing the propeller diameter (i.e. increasing the $C_T$) the drag reduction increases. Increasing the thrust level from 4000 N up to 12000 N (three times more), the drag reduction increases of about 4-5 times.

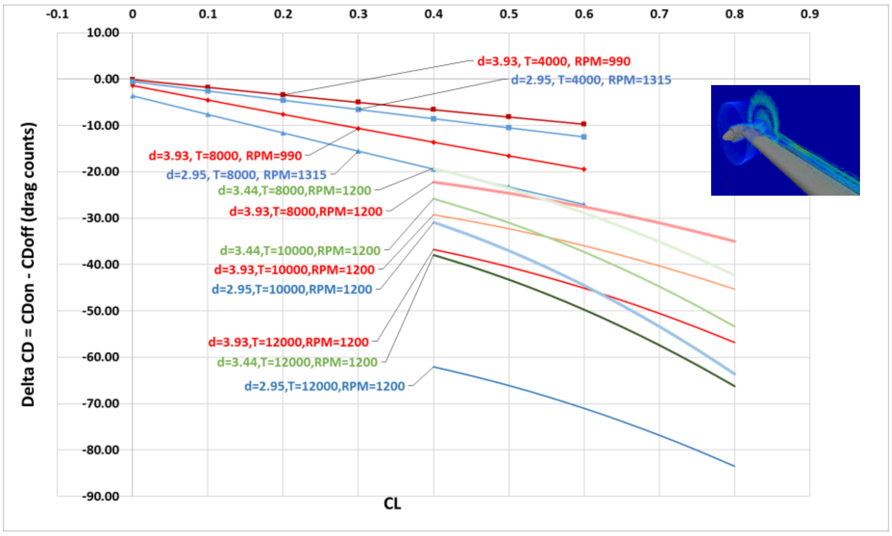



Figure 16: Wing drag improvement due to the propeller tip-mounted on an AR = 11 wing, with M = 0.48, Re = 15E6, Thrust T in Newton.

### 4.2.2 High-lift propeller

DEP system can be incorporated into the airframe to augment high-lift capabilities at low speed. The high-lift propellers must be properly designed, aiming to improve the wing-blowing. According to Patterson [35], to improve the axial velocity and so the high-lift capability, a near-uniform axial velocity must be produced aft of the propeller. One popular example is the NASA X-57 Maxwell, which is based on the fuselage of a Tecnam P2006T and reconfigured with a much smaller wing than the baseline aircraft. The smaller wing is achievable for this design due to the high lift provided by an array of 12 small electric propellers distributed along the leading edge of the wing during the take-off and landing phases of flight. The purpose of having these distributed propellers is to increase the dynamic pressure, hence the lift, over the wing at low speed [9]. The propellers are positioned on the nacelles in an alternating fore- and aft-staggered pattern for the high-lift blown wing. Preliminary results have shown a maximum achievable lift coefficient of about 4.3, almost double with respect to the unblown wing. Analyses were performed also to evaluate the effect of the rotation direction of each propellers, highlighting how co-rotating propellers were better than counter-rotating propellers, as shown in Figure 17. In 2016 NASA prepared and tested a DEP high-lift propeller testbed, highlighting a good agreement between numerical and experimental data (scattered results). The lift augmentation was about double with respect to the unblown solution, increasing from about $C_L = 2.8$ up to $C_L = 6$ (see Figure 18).

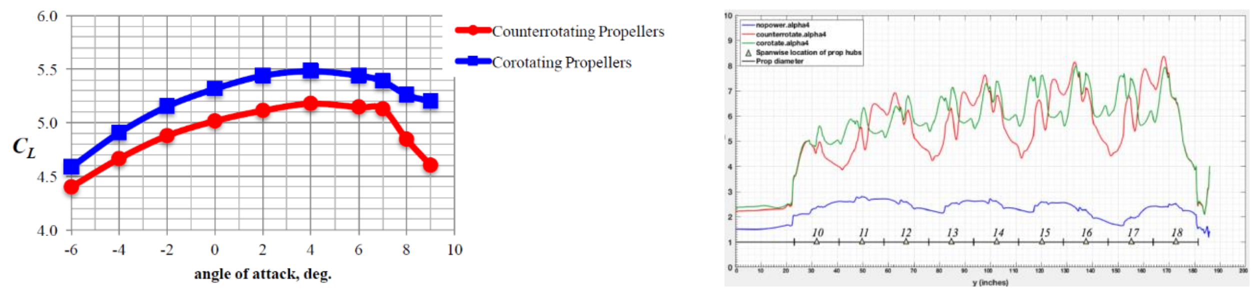



Figure 17: Left: Effect of propeller spin direction on span loading for the blown, high-lift wing (40° flap). Right: Effects on the span loading at α = 4°. Conditions are: V = 73 mph, M = 0.096, Re = 1.0E6, T = 60°F, h = 2,300 ft and 300.6 Hp (16.7 Hp/prop, 6,147 RPM) [36].

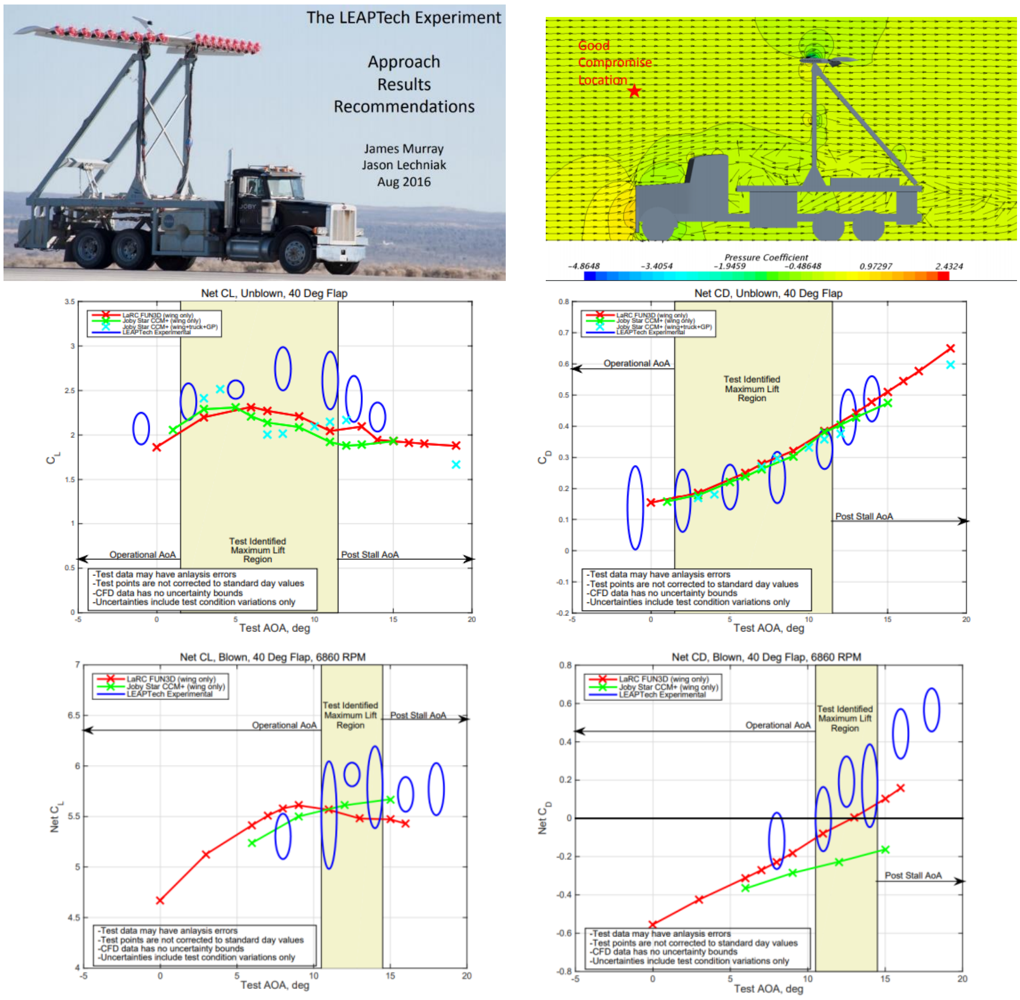



Figure 18: Top: Nasa high-lift propeller testbed, experiments and numerical. Mid: Unblown, prop removed, flaps at 40°. Bottom: Blown, flaps at 40°, 6,860 RPM [37].

Della Vecchia et alii evaluated the wing high-lift propellers effect on the Tecnam P2006T baseline wing, splitting the same available power of 200 Hp through several distributed propellers, considering 120 hp needed for cruise tip-mounted propellers [7]. Results show a reduced lift increment at about 1.0-1.5 due to small engine power, reduced blowing area and conventional propellers used for high-lift. Moreover, a key aspect is the propeller/chord ratio, $d_p/c$ = 0.42, which was half respect to the NASA X-57 Maxwell, $d_p/c$ = 0.9 (see Figure 19 and Figure 20).

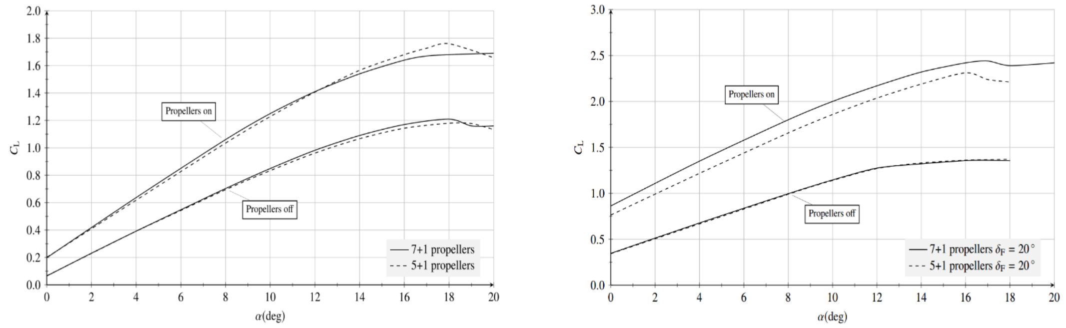



Figure 19: Tecnam P2006T’s wing lift coefficient at M = 0.08 and Re = 3.3E6. Left: Clean configuration. Right: Flapped configuration [7].

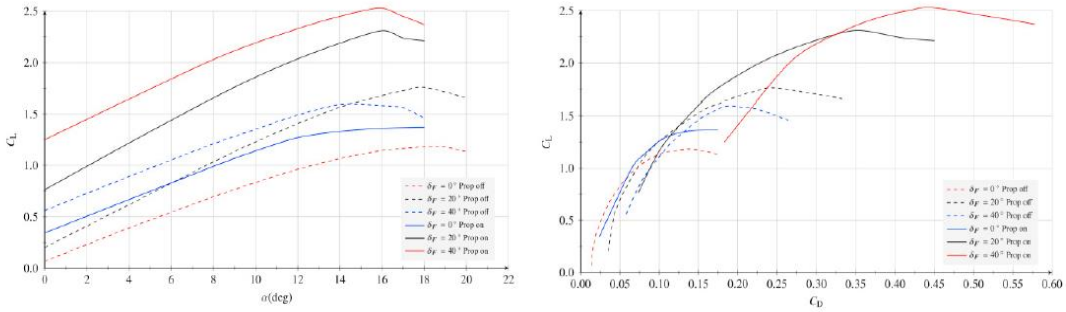



Figure 20: Tecnam P2006T wing, Results of 5+1 propeller configuration for CL and CD, with high-lift propeller and nacelles, M = 0.08, Re = 3.3E6 [7].

At University of Naples Federico II, the aerodynamic effects of high-lift propellers on a typical 40 passengers regional aircraft have been numerically analysed, varying the number of blown propellers, the thrust per propeller, the flap settings, blowing on the same wing area (Figure 21). High-lift propellers were designed for each configuration according to MIL theory. Figure 22 shows the main achieved results: generally speaking, for a given reference wing, increasing the number of high-lift propellers leads to a increment of maximum lift coefficient, an increment in drag coefficient and a increment in the pitching moment. This behaviour slightly change by deflecting a conventional flap: as it can be seen in Figure 22 (top), the flap deflection promotes the trailing edge separation, reaching maximum lift coefficient increment ever before with a lower number of high-lift propellers. Conversely, drag coefficient increment exhibits a minimum in a certain range of $T/(D^2V^2)$, meaning a certain number of high-lift propellers. Not negligible is the pitching moment increment due to high-lift propellers, as shown in Figure 22.

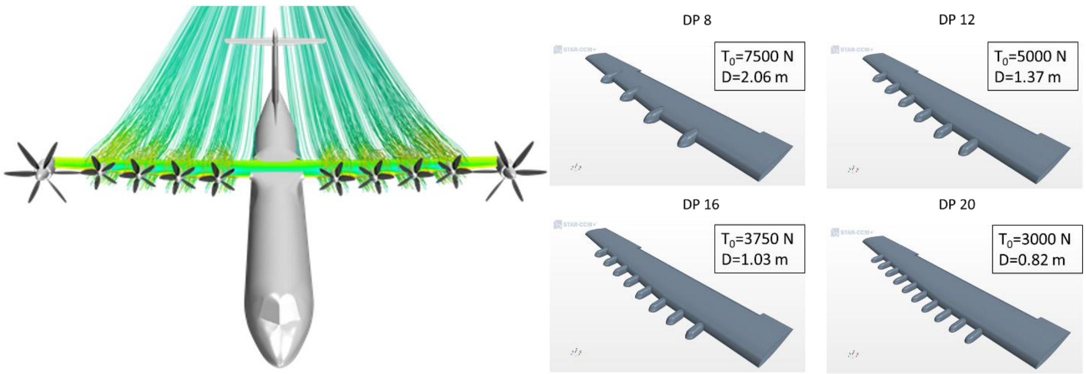



Figure 21: Left: High-lift propellers on a typical 40 passengers regional turboprop wing with AR = 11.07, M = 0.15, Re = 7.6E6. Right: DEP 8, DEP 12, DEP 16 and DEP 20 configurations; $T_0$ is the thrust per propeller.

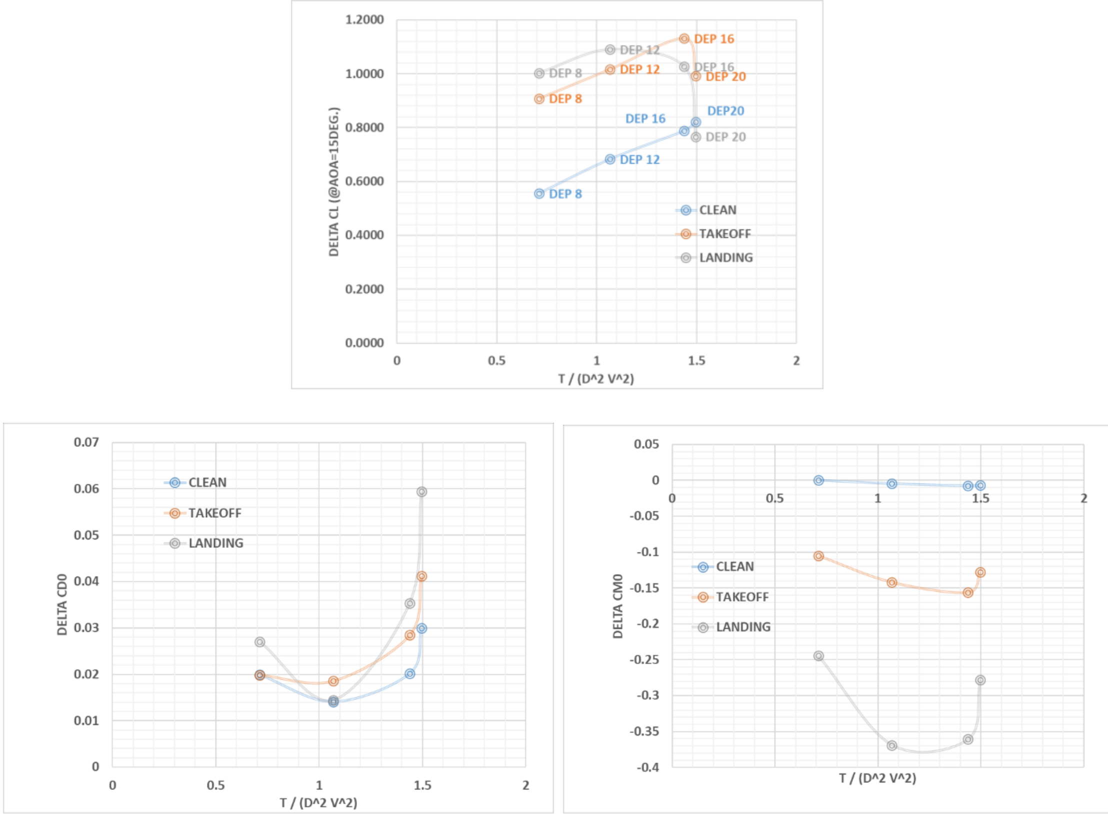



Figure 22: Variations with respect to an isolated wing, of high-lift propeller on a typical 40 passengers regional turboprop wing, AR = 11.07, M = 0.15, Re = 7.6E6. DEP 8, DEP 12, DEP 16 and DEP 20 configurations are considered. Top: Delta CL (lift coefficient at α = 15°), Bottom left: Delta CD0 (zero lift drag coefficient). Bottom right: Delta CM0 (pitching moment coefficient at α = 0°).

All the results on high-lift propellers highlight how promising this technology could be. The main key factors to take into account in the design stage are the followings:

1) The operative speed must be as lower as possible to obtain the maximum benefit;
2) The thrust levels must be as much as possible;
3) The propeller diameter over the chord ratio $d_p/c$: must be as much as possible;
4) The propeller design must have an axial induction as much constant as possible;
5) The propeller-high-lift device interaction must be carefully taken into with high-fidelity methods.

Finally it is highlighted here that aircraft with distributed propulsion may employ differential thrust as a mean to reduce or eliminate the vertical tail and be still compliant with regulations, although aero-propulsive interactions and system robustness must be carefully investigated, while different safety criteria could be applied [38, 39, 40, 41].

### 4.2.3 Boundary Layer Ingestion

The primary benefit associated with boundary layer ingestion (BLI) is the potential for reduction in energy usage due to ingestion of the thin, low-momentum air region at the aircraft surface, known as the boundary layer. The ingestion of this low-momentum air leads to an increased propulsive efficiency and can also lead to wake-filling benefits when the air is re-energized and used to reduce the velocity deficit and turbulent mixing losses in the wake. For these reasons, BLI propulsors are located at the end of the fuselage (in the case of an annular BLI concept) or on the top of the trailing edge lifting surface (which is the case of DEP concepts, which deal with distorted inflow, as shown in Figure 23). BLI can reduce the required propulsive power by 4% to 8% [42, 43]. Several conceptual DEP aircraft aim to take advantage of BLI. First among these is the N3-X aircraft (see also paragraph 5.1.4), where the large fuselage boundary-layer provides an excellent opportunity to take advantage of BLI. Studies were performed to incorporate the effects of BLI in the propulsion system design for the BWB aircraft, and additional work has been done to investigate the potential for incorporating a boundary-layer ingesting crossflow fan into the N3-X propulsion system. Experimental and numerical work has also been performed to assess the effects of BLI on propulsion system performance and inlet distortion problems. Finally, the Lilium aircraft propulsion systems (see also paragraph 5.2.8) also utilize BLI as a performance improving mechanism [44].

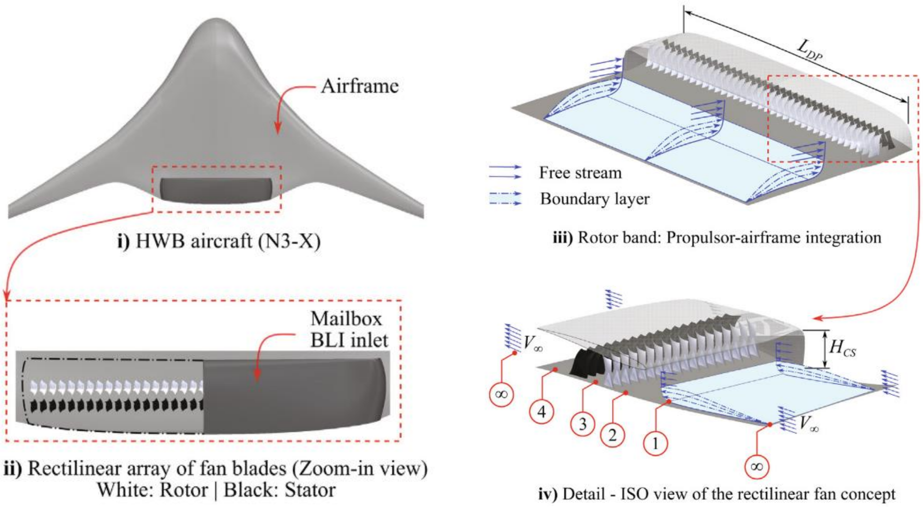



Figure 23: Distributed boundary layer ingestion concept [43].

Numerical and experimental analyses show a potential propeller efficiency improvement, hence propulsive thrust, due to a fuselage tail mounted propeller (Figure 24) used as BLI device. It is demonstrated that the required power for BLI is lower than the required power without BLI. Experimental results at TU Delft [45] performed on different architectures (see Figure 25) show a net-force benefit of about 9% benefit in case of wake ingestion (WI) and 18% for BLI; moreover a 11% propeller efficiency improvement for WI and a 21% increase for BLI configurations have been measured, with respect to free-stream propulsor configuration, taking an advance ratio of 1 (see Figure 26).

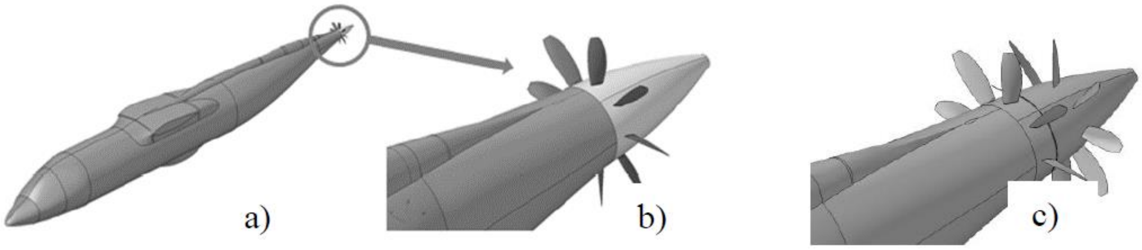
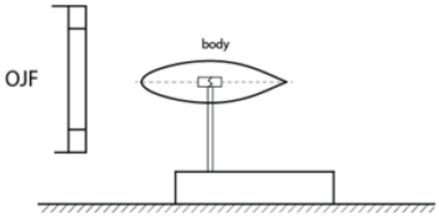
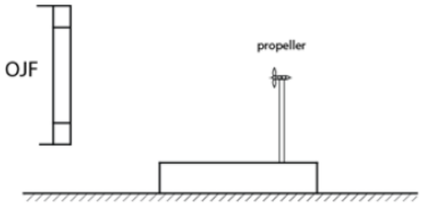


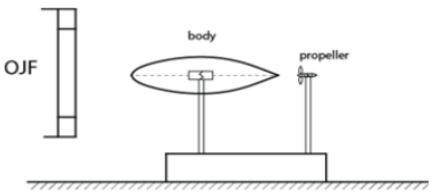

Figure 24: Example of fuselage-tail-mounted propeller.



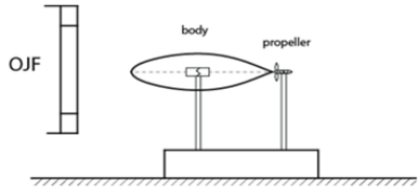

(a) Isolated Body




(b) Free-stream Propulsor



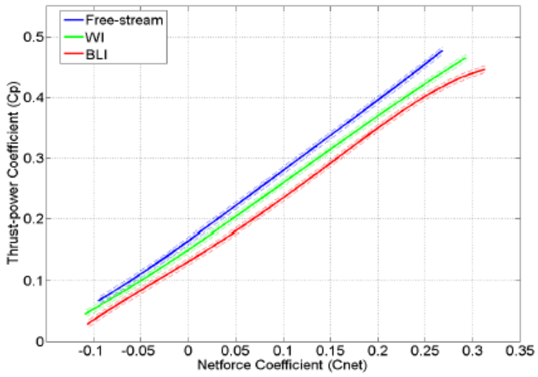

(c) Wake Ingestion



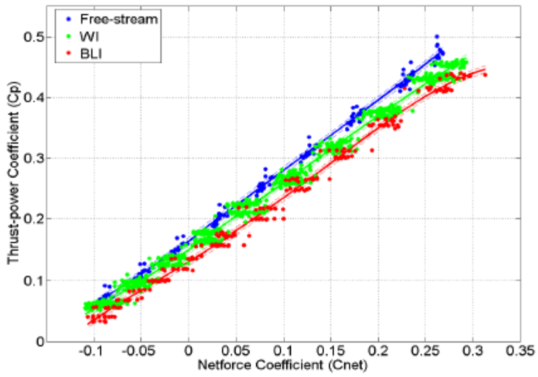

(d) Boundary Layer Ingestion

Figure 25: TU Delft configurations practiced for the experiment [45].

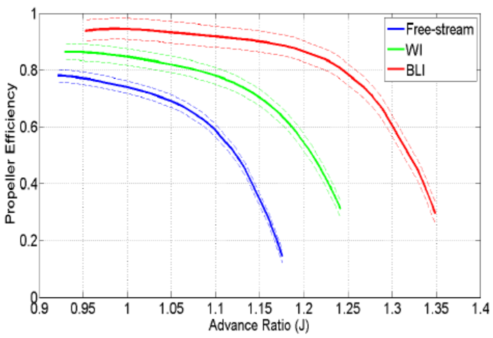
$$C_{(net-force)} = \frac{T - D_{body}}{q \times s} \qquad \eta_{propeller} = \frac{TV_\infty}{P_{shaft}} = \frac{TV_\infty}{2\pi \times Tor \times RPS}$$



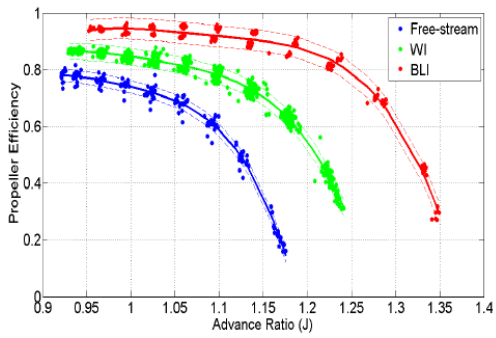

(a) $C_{(net-force)}$ vs. Cp for Various Configurations




(b) $C_{(net-force)}$ vs. Cp for Various Configurations with Observations




(a) Propeller Efficiency for Various Configurations




(b) Propeller Efficiency for Various Configurations with Observations

Figure 26: TU Delft Main results of tail propeller BLI [45].

# 5 Hybrid Aircraft Design Projects

The experimental history of electric aviation dates back to over a century ago, on 8 October 1883, when the Tissandier brothers demonstrated the world's first electric-powered flight of a dirigible aerostat [46, 47]. In the same years, a dirigible powered by an electric motor, **La France**, successfully flown in 1884 by Charles Renard and Arthur Constantin Krebs, performed the first full round trip flight with a landing on the starting point [48]. About a century later, In the 1980s and 1990s, NASA devoted itself to the study of solar aircraft with very high aspect ratios. This experimental heritage has produced unmanned high-altitude long-life (HALE) systems such as **QinetiQ / Airbus Zephyr**, which is discussed in more detail in paragraph 5.2.3. Although they are applicable in the case of UAVs, solar cells generally do not justify the weight and additional strength in manned applications, even at low speeds and power levels [49]. The first manned electric aircraft was the **Brditschka MB-E1** whose first flight on 21 October 1973 took less than 10 minutes but proved that electrically manned flight was possible [50]. From that moment on, thanks also to the constant technological developments of motors and batteries, an ever-increasing number of electric or hybrid-electric concepts began to appear. However, the demanding requirements related to weight and range have prevented larger aircraft from trying to adopt these new solutions. However, electrical power demand has been steadily increasing as a result of the electrification of conventionally pneumatic and hydraulic accessory systems. The most electric airplane today is the Boeing 787 with electric power demand in the order of 1.5 MW and voltages of up to ±270 Volts. As power levels continue to increase, so too does the need for higher power density motors, generators, and power electronics capable of reliably handling associated loads. The use of advanced ceramic-based semiconductors, packaging methods, thermal management, and manufacturing techniques becomes necessary in order to cope with the required power levels [51]. This section is intended to collect general information on some of the most important European or international projects currently under development or recently canceled. Section 5.1 presents projects that are still in the research or experimental phase, or that have failed for some reason. Section 5.2, on the other hand, reports successful projects that have passed a Technology Readiness Level (TRL) of 6, i.e. for which at least a scale prototype has been built and has served to demonstrate all enabling technologies in industrially relevant environment [52]. All the projects studied are indexed here in Table 4 and Table 5.

| Project | Type | Category | Passengers | Paragraph |
|---|---|---|---|---|
| Airbus E-Fan X | Hybrid-Electric | Large Commercial Aircraft | 100 | 5.1.13 |
| Ampaire Eco Otter SX | Hybrid-Electric | Regional Aircraft | 19 | 5.1.13 |
| Ampaire TailWind | Electric | Business Aircraft | 9 | 5.1.13 |
| Bell Nexus | Electric | eVTOL | 4 | 5.1.13 |
| Boeing SUGAR Volt | Hybrid-Electric | Large Commercial Aircraft | 154 | 5.1.1 |
| DLR/BHL CoCoRe | Hybrid-Electric | Regional Aircraft | 19 | 5.1.13 |
| DLR EXACT | Full-Electric | Regional Aircraft | 19 | 5.1.13 |
| e.SAT Silent Air Taxi | Hybrid-Electric | General Aviation | 4 | 5.1.2 |
| Heart Aerospace ES-19 | Electric | Regional Aircraft | 19 | 5.1.13 |
| Joby Aviation | Hybrid-Electric | Regional Aircraft | 11 | 5.1.3 |
| NASA N3-X | Turbo-Electric | Large Commercial Aircraft | 300 | 5.1.4 |
| NASA PEGASUS | Hybrid-Electric | Regional Aircraft | 48 | 5.1.5 |
| NASA STARC-ABL | Turbo-Electric | Large Commercial Aircraft | 154 | 5.1.6 |
| ONERA AMPERE | Hybrid-Electric | Business Aircraft | 4 - 6 | 5.1.7 |
| ONERA DRAGON | Hybrid-Electric | Large Commercial Aircraft | 150 | 5.1.7 |
| Uber Elevate | Electric | eVTOL | ≤ 4 | 5.1.8 |
| UTAP Project 804 | Hybrid-Electric | Regional Aircraft | 30 - 50 | 5.1.9 |
| VoltAero Cassio | Hybrid-Electric | General Aviation | 4-10 | 5.1.10 |
| XTI Tri-Fan 600 | Hybrid-Electric | eVTOL | 5 | 5.1.11 |
| Zunum Aero ZA10 | Hybrid-Electric | Business Aircraft | 12 | 5.1.12 |

Table 4: List of the electric or hybrid-electric aircraft with TRL<6 mentioned in this document.

| Project | Type | Category | Passengers | Paragraph |
|---|---|---|---|---|
| Airbus CityAirbus | Electric | eVTOL | 4 | 5.2.1 |
| Airbus E-Fan | Electric | General Aviation | 2 | 5.2.2 |
| QinetiQ/Airbus Zephyr | Electric | UAV | 0 | 5.2.3 |
| Ampaire 337 EEL | Hybrid-Electric | General Aviation | 5 | 5.2.4 |
| Eviation Alice | Electric | Business Aircraft | 9 | 5.2.5 |
| IFB Stuttgart eGenius | Electric | General Aviation | 2 | 5.2.6 |
| Lange Antares 20E | Electric | General Aviation | 1 | 5.2.7 |
| Lilium Jet | Electric | eVTOL | 5 | 5.2.8 |
| MagniX eBeaver | Electric | Regional Aircraft | 6 | 5.2.9 |
| MagniX eCaravan | Electric | Regional Aircraft | 5 | 5.2.9 |
| NASA X-57 Maxwell | Hybrid-Electric | General Aviation | 2 | 5.2.10 |
| Pipistrel Alpha Electro | Electric | General Aviation | 2 | 5.2.11 |
| Pipistrel Panthera | Hybrid-Electric | General Aviation | 2 + 2 | 5.2.12 |
| Pipistrel Taurus Electro G2 | Electric | General Aviation | 2 | 5.2.13 |
| Rolls-Royce ACCEL | Electric | General Aviation | 1 | 5.2.14 |
| Siemens/Diamond DA36 E-Star | Electric | General Aviation | 2 | 5.2.15 |
| Siemens/Extra 300LE | Electric | General Aviation | 2 | 5.2.16 |
| Volta Volaré DaVinci | Hybrid-Electric | General Aviation | 2 + 2 | 5.2.17 |

Table 5: List of the electric or hybrid-electric aircraft with TRL>6 mentioned in this document.

## 5.1 Ongoing research project

### 5.1.1 Boeing SUGAR Volt

The Boeing SUGAR (Supersonic Ultra-Green Aircraft) is a NASA contract awarded to Boeing for research into subsonic commercial aircraft technology to meet the agency's future environmental and efficiency goals by 2050. SUGAR is a series of turbofan concepts all sized for 154 seats. They allow a comparison on the same 900 nmi reference mission between a hybrid-electric aircraft, the **Boeing SUGAR Volt**, and several turbofan aircraft embodying different innovative technologies, starting from the classical tube-wing baseline (SUGAR Free). A refined version based on 2030 foreseen technologies (Refined SUGAR), a blended wing body concept (SUGAR Ray) and a high aspect ratio strut-braced tube-wing concept (Sugar High) were also designed. Finally, SUGAR Volt (Figure 27) is a version of the Sugar High with parallel hybrid-electric propulsion replacing the traditional powerplant architecture. SUGAR Volt uses a parallel hybrid electric propulsion system that can improve fuel efficiency, reducing noise and greenhouse gas emissions.

Figure 27: The Boeing SUGAR Volt concept [credits to Boeing].

From Phase I of the project, it emerged that the SUGAR Volt was the only one, among all the concepts considered, to allow at least a 70% reduction in fuel compared to SUGAR Free, consuming 28% less than SUGAR High. On the other hand, the reduction in noise emissions was estimated to be only 1 EPNdB compared to SUGAR High [53]. This value is limited by the fact that the SUGAR Volt features podded engines in a near-classical configuration and does not take full advantage of the design space enlarged by hybrid-electric powerplant, which would allow greater effective shielding as highlighted by Moore and Fredericks [54]. Table 6 summarizes the main technical characteristics of the SUGAR Volt as presented in the Phase I Final Report [53].
In Phase II the following suitable technologies were identified: Liquefied Natural Gas (LNG), hydrogen, fuel cell hybrids, battery electric hybrids, Low Energy Nuclear (LENR), Boundary Layer Ingestion (BLI), unducted fans and advanced propellers. Combinations of all these were selected and quantitatively analyzed, and in the end the best performing architecture was identified to be the one that uses LNG, a fuel cell topping cycle, an unducted fan, and an electric motor augmenting fan shaft power. It would allow a reduction of 64.1% in fuel burn and 59.8% in total energy required for the mission [55].

| Parameter | Value |
|---|---|
| Target EIS year | 2035 |
| Powerplant Architecture | Parallel Hybrid-Electric |
| Battery Energy Density | 750 Wh/kg |
| Thrust (M = 0.25, S/L) | 2x 17,300 lbf |
| Number of Passengers | 154 |
| Wing Area | 1,500 $ft^2$ |
| Aspect Ratio (Effective) | 27 |
| Maximum Take-Off Weight | 70,307 kg |
| Fuel Weight | 6,486 kg |
| Design Range | 3,500 nmi |
| Cruise Mach Number | 0.7 |
| Block Fuel / Seat (900 nmi) | 15.3 kg |

Table 6: Characteristics of the Boeing SUGAR Volt concept [50, 53].

### 5.1.2 e.SAT Silent Air Taxi

The **Silent Air Taxi** (SAT) is a 5-seat aircraft currently being developed by e.SAT GmbH in Aachen (see Figure 28). The project was launched in 2015. The maiden flight is scheduled for 2022 and the aircraft's certification is pursued for 2024. The SAT features an innovative boxwing and a hybrid-electric drivetrain allowing short take-off distances [56]. Aero-acoustically optimized design and ultra-low noise fans are the means by which the SAT strives for acoustic emission levels that become indiscernible from urban background noise at a distance of just 100 m, increasing passengers' comfort and reducing environmental footprint. The small aircraft flies with four passengers and a pilot, has a range of up to 540 nmi, and a cruising speed of over 160 kt. The aircraft will need less than 1,300 ft runway for take-off and landing, which will allow it to fly to 95 percent of all German airports and airfields.


Figure 28: Rendering of the e.SAT Silent Air Taxi [credits to e.SAT GmbH].

The SAT features an innovative box-wing, an evolution of Prandtl's wing concept. Its advantages consist mainly in a proven reduction of induced drag [57, 58, 59]. The electric-hybrid propulsion system avoids oversizing the engines and allows them to work at their optimum operating points in take-off, climb and during cruise flight ensuring high overall efficiency. Other peculiarities and specifications of the Silent Air Taxi are shown in Table 7.

| Parameter | Value |
|---|---|
| Target EIS year | 2024 |
| Powerplant Architecture | Hybrid-Electric |
| Power (Take-Off) | 2x 335 Hp |
| Number of Passengers | 4 + 1 |
| Wing Span | 10 m |
| Maximum Take-Off Weight | 1,600 kg |
| Design Range | 540 nmi |
| Cruise Speed | 162 kt |
| Take-Off Field Length | < 1,300 ft |
| Landing Field Length | < 1,300 ft |

Table 7: Characteristics of the e.SAT Silent Air Taxi [56, 60].

### 5.1.3 Joby Aviation

**Joby Aviation** is an American venture-backed aerospace company, founded in 2009 and headquartered in Santa Cruz, CA. In 2016, Alex Stoll and Gregor Veble Mikić from Joby Aviation [10] presented the results of a conceptual study on a thin-haul aircraft benefiting from the effects of distributed electric propulsion. A number of promising distributed electric propulsion concepts are considered in this study: wingtip propeller installation to improve propulsive efficiency; distributed fixed-pitch foldable propellers along the wing to allow for reduced wing area for a given stall speed equal to 67 KCAS (i.e. reduced cruise drag); a propeller mounted at the tip of the vertical tail to provide additional thrust during takeoff and climb and ameliorate yaw trim issues potentially arising from a wingtip propeller configuration in the event of a single wingtip motor or propeller failure (the tail installation reduces scrubbing drag relative to a conventional fuselage installation). A series hybrid powertrain was employed for the electric propulsion designs, such that shorter routes can be operated on battery power alone, while longer routes can be operated with a range extender. A modern turbodiesel and an advanced recuperated turbogenerator are both considered as valid range extenders. Specifications chosen for the advanced aircraft concepts are listed in Table 8.

| Parameter | Value |
|---|---|
| Target EIS year | 2025 |
| Powerplant Architecture | Series Hybrid-Electric |
| Number of Passengers | 11 |
| Fuselage Length | 11.7 m |
| Cabin Width | 1.48 m |
| Maximum Payload | 1,090 kg |
| Design Range | 400 nmi |
| Maximum Cruise Speed | 180 - 325 kt |
| Take-Off Distance | 2,000 ft |

Table 8: Specifications of the Joby Aviation's advanced concepts [10].

Based on the route profile of Cape Air and similar airlines, two missions were selected: a 400 nmi flight and a 100 nmi flight. The electric aircraft designs perform the 100 nm flight on battery power alone, but employ a generator as a range extender for the 400 nm flight. The cruise speed for the 400 nmi flight was varied from 180 KTAS to 325 KTAS to evaluate the impact of this parameter on other metrics, with the 100 nm flight flown at the most economical speed. Both the 400 nm and 100 nmi flights are accompanied by a 67 nmi IFR reserve. The cruise altitude for the 100 nmi mission is set to 8,000 ft. The cruise altitude for the 400 nmi mission is a design variable and pressurization is employed for altitudes greater than 10,000 ft. A longitudinal static margin of 25% was specified, with the assumption that the battery packs can be opportunely installed to allow the requisite center of gravity to be achieved in a typical loading scenario. A payload of 2,400 lb (1,090 kg) including pilot was specified for the 100 nmi mission, to be decreased for the 400 nmi mission. Three different designs were selected for the analysis (Figure 29). A first configuration, named **Conventional** (**C**), has two modern conventional wing-mounted propellers similar in layout to the Cessna 142. A **Three-Motor** (**3M**) configuration employs wingtip propellers and a tail propeller. Finally, the **High-Lift Propellers** (**HLP**) configuration employ wingtip propellers and DEP for increasing the wing loading. All three designs use the same fuselage geometry so that passenger accommodation is consistent, and are built with composite materials.

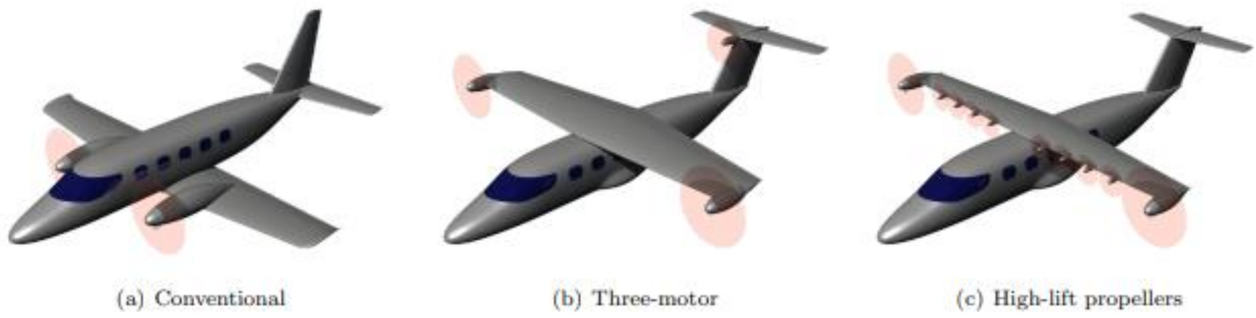



Figure 29: Illustrations of the advanced concept configurations by Joby Aviation [10].

Their results suggest that the configurations examined in this study present an advantage in operating costs over conventional aircraft, in addition to assumed noise and emissions advantages. The process of optimizing operating costs has led to the specifications reported in Table 9, where the three concepts studied are compared with the Tecnam P2012.

| Parameter | Tecnam P2012 | Value (C) | Value (3M) | Value (HLP) |
|---|---|---|---|---|
| Fuel Capacity | 620 l | 216 | 174 | 167 |
| Battery Capacity | 0 | 0 | 262 kWh | 231 kWh |
| Engine Power | 522 kW | 370 kW | 173 kW | 169 kW |
| Cruise Power | 429 kW | 250 kW | 249 kW | 233 kW |
| $CL_{max}$ | 2.3 | 2.6 | 2.6 | 3.2 |
| Aspect Ratio | 7.2 | 12.7 | 7.2 | 11.9 |
| Wing Span | 13.6 m | 14.1 m | 11.6 m | 13.3 m |
| Maximum Take-Off Weight | 3,452 kg | 3,017 kg | 3,597 kg | 3,506 kg |
| Wing Loading | $ 1.8 | $ 1.5 | $ 1.8 | $ 1.8 |
| Unit Cost (million) | $ 3.74 | $ 3.01 | $ 2.76 | $ 2.77 |

Table 9: Comparison of turbodiesel-powered advanced concepts for V = 180 kt and over 400 nmi [10].

Figure 30 shows that the electric aircraft are lower in battery + energy + fuel costs, but are heavier, so it is difficult to assess how attractive these designs are compared to the conventional designs by these metrics alone. Specific trade studies (see Figure 31) revealed that for the 400 nm flight, at every choice of the speed, the advanced concepts are lower-cost than the reference aircraft. The HLP configuration is similar to the 3M configuration at low speed, but gradually become more competitive as the speed increases. All the advanced concepts, being designed for a higher wing loading and lower maximum range, require less power than the reference aircraft, and the electric designs require less power than the conventional designs due to the ability to supplement the engine power with batteries. The authors also highlight that the sensitivity of the weighted cost to increasing battery pack energy density from 400 Wh/kg to 500 Wh/kg is relatively small, but that such a result may not be generalized to a generic thin-haul aircraft. As final result, the high-lift propellers configuration presents an operating cost advantage in most cases, especially at high design speeds with the turbodiesel range extender option.

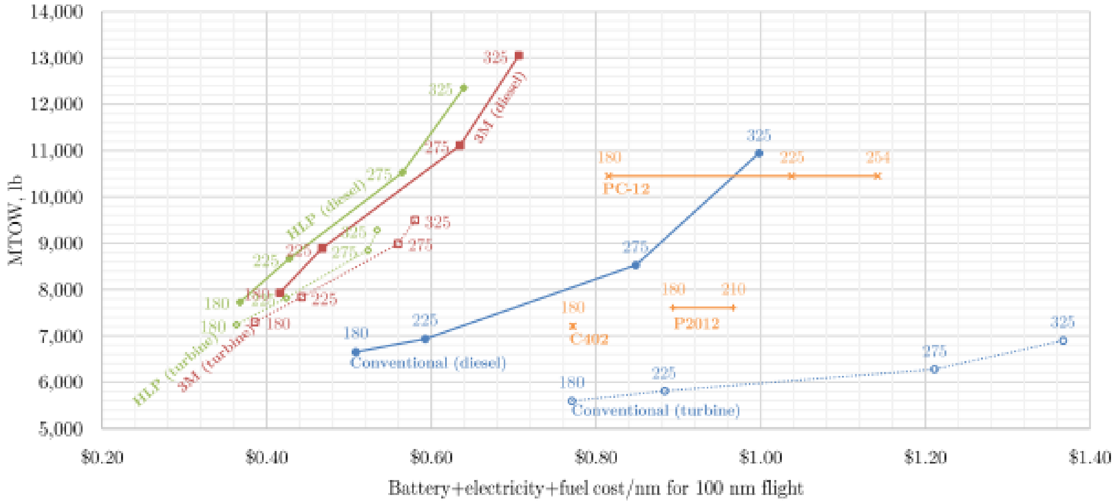



Figure 30: Energy cost versus maximum take-off weight for concepts optimized for range of 400 nmi and speed variable from 180 kt and 325 kt, compared to reference aircraft at indicated cruise speeds [10].

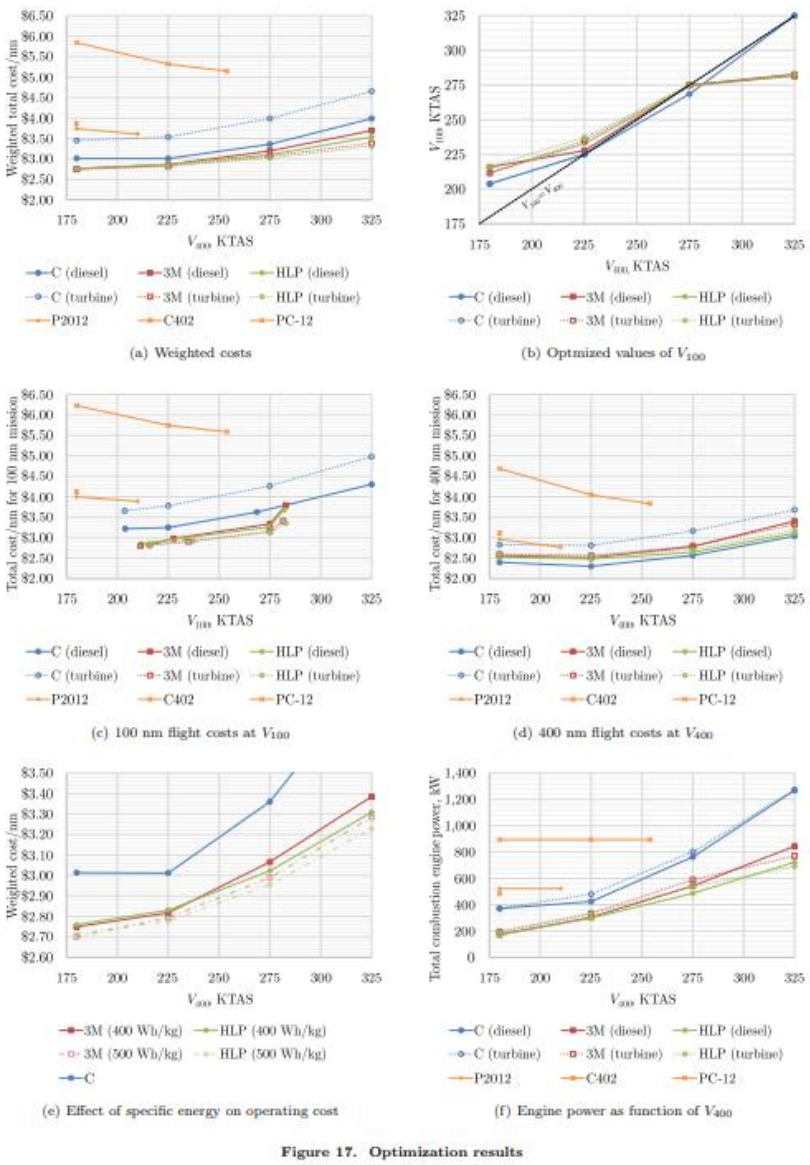



Figure 31: Optimization results for advanced concepts by Joby Aviation [10].

### 5.1.4 NASA N3-X

The **NASA N3-X** represents the largest electric transport aircraft design ever seriously studied. This innovative aircraft sets itself the challenge of integrating multiple disruptive technologies: hybrid wing-body; Boundary Layer Ingestion (BLI); 4 MW fan motors at 4,500 RPM; 30 MW generators at 6,500 RPM; 99% efficient electric machines with power density of 16.4 kW/kg; 99.0% efficient cryogenic power converters [61]. NASA claims a 72% reduction in fuel consumption compared to the B777-200LR, used as the reference baseline sharing the same TLARs as the N3-X [16, 62]. Predictions for landing and take-off $NO_X$ are estimated to be 85% less than the Tier 6 - CAEP/6 standards. Two variants of the N3-X were examined for certification noise and found to have ICAO Chapter 4 cumulative margins of 32 and 64 EPNdB [63].


Figure 32: The NASA N3-X Concept [credits to NASA].

The baseline N3-X Turboelectric architecture includes two turboshaft engines mounted on each wingtip, which drive cryogenically cooled superconducting electrical generators. At the wingtips, the engine exhausts disrupt the vortex and effectively lower the total induced drag. Each engine is associated with a pair of isolated generators with a dedicated power converter. The variable AC voltage of the generators is first converted to DC, then reconverted back to AC to power the superconducting electric propulsor motors [64]. The 12 fan modules are positioned in a single continuous nacelle near the trailing edge of the upper fuselage, where they ingest the boundary layer flow and significantly contribute to drag reduction (Figure 33). No drag penalty due to nacelles is expected due to the absence of conventional pylons. More specifications about the NASA N3-X are listed in Table 10. The project aims to achieve a technological readiness level (TLR) of 6 by the year 2025.

| Parameter | Value |
|---|---|
| Target EIS year | 2045 |
| Powerplant Architecture | Turboelectric |
| Number of Passengers | 300 |
| Maximum Take-Off Weight | 226,796 kg |
| Fuel Weight | 34,473 kg |
| Design Range | 7,500 nmi |
| Cruise Mach Number | 0.84 |

Table 10: Characteristics of the NASA N3-X concept [16, 50, 61].


Figure 33: The NASA N3-X with turboelectric distributed propulsion [62].

### 5.1.5 NASA PEGASUS

The Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (**NASA PEGASUS**) concept is a hybrid electric regional aircraft designed to satisfy both hybrid and purely electric missions [65]. Figure 34 shows a rendering of the concept aircraft. PEGASUS' electric and hybrid-electric powertrains are strategically positioned to provide greater aerodynamic advantages. PEGASUS uses parallel electric-hybrid thrusters on the wingtips to decrease downwash effects, reducing the energy required to maintain flight in all phases. Two mid-span electric thrusters with folding propellers and an unducted tailcone pusher propeller provide additional thrust and increased aerodynamic benefits during the take-off and climb phases. The inner propellers on the wing are able to fold in mid-flight to reduce the effects of the windmill while cruising. Recent research within the project suggests that the additional electric thruster at the aircraft tail may provide a benefit due to boundary layer ingestion. The PEGASUS concept was designed to fly a 200 nmi electric only mission or a 400 nmi parallel hybrid electric mission (see also Table 11). The specific energy of the battery utilized for PEGASUS modeling was assumed to be 500 Wh/kg. The entry into service is planned for 2030.


Figure 34: NASA PEGASUS concept [credits to NASA/Langley Research Center].

The 48-passenger ATR 42-500 was chosen as the baseline vehicle for the development of the new aircraft. The year 2030 PEGASUS uses the same conventional airframe as the ATR 42-500, but the two turboprop engines are replaced with parallel hybrid electric powertrains [66, 67]. For this purpose, a modification has been made to the PW127E in order to obtain an updated hybrid-electric version of the same. Reduced power versions of the model were also created in order to reproduce and study different degrees of hybridization for the new concept. Studies by Antcliff and Caprisan [67] have claimed that the PEGASUS concept could reduce both the gross weight and the required total energy for the flight mission compared to the reference aircraft by relying on the advanced technologies introduced. On the other hand, the study did not address whether there was a total energy saving compared to a conventional turboprop.

| **Parameter** | **Value** |
|---|---|
| Target EIS year | 2030 |
| Powerplant Architecture | Parallel Hybrid-Electric |
| Battery Energy Density | 500 Wh/kg |
| Propeller Diameter | 4 m |
| Max Take-Off Weight | 24,000 kg |
| Fuel Weight | 410 kg |
| Number of Passengers | 48 |
| Design Range | 200-400 nmi |

Table 11: Characteristics of the NASA PEGASUS concept [50, 67].

### 5.1.6 NASA STARC-ABL

A key priority for NASA Aeronautics is investing in electrified aircraft propulsion technologies for their potential to reduce fuel consumption, emissions, and noise for commercial airplanes [68]. Because of the high technological barriers of the N3-X, NASA sought to develop a concept which would be feasible in the nearer term [69]. The **NASA STARC–ABL** concept under development by ASAB (see Figure 35 and Table 12) aims to bridge the gap between current jet fuel-powered aircraft and future all-electric vehicles. It has more moderate fuel burn benefits and fewer passengers when compared to the N3-X, but not relies as heavily on disruptive technologies. The STARC-ABL is a 150-passenger class commercial transport with a traditional wing-fuselage configuration combined with a turboelectric powerplant architecture.

Figure 35: The NASA STARC-ABR concept [credits to NASA/Langley Research Center].

Two traditional jet engines are mounted under the wings, which also contain electric generators. NASA uses 96% efficient electric machines with a power density of 13.6 kW/kg, a 2.6 MW tailcone thruster motor rotating at 2,500 RPM, and 1.4 MW generators at 7,000 RPM, and claims 7-12% fuel burn savings for 1,300 nmi mission. Electrical power is sent to the tail, where an all-electric propulsor benefits from boundary layer ingestion (BLI). In the NASA STARC-ABL, this slow moving air flows through the tail-mounted engine and is sped up then released behind the airplane to reduce drag and improve fuel efficiency. The aircraft has many similarities to current, conventional designs, which reduces risks and maintains the high level of safety enjoyed by today's air travellers.

| Parameter | Value |
|---|---|
| Target EIS year | 2035 |
| Powerplant Architecture | Turboelectric |
| Static Thrust (S/L) | 2x 95503 N |
| Wing Area | 518 $ft^2$ |
| Take-Off Gross Weight | 60,495 kg |
| Operative Empty Weight | 36,505 kg |
| Number of Passengers | 154 |
| Design Range | 3,500 nmi |
| Cruise Mach Number | 0.7 |
| TSFC | 3.66 N/(kg*h) |

Table 12: Characteristics of the NASA STARC-ABL concept [16, 50, 70, 71].

### 5.1.7 ONERA AMPERE and DRAGON

In the last decade, ONERA started exploratory studies to investigate potential new key technologies and concepts that could participate in answering societal need for on-demand mobility. On this basis, ONERA started in 2013 a CARNOT funded project, called **AMPERE** *(Avion à Motorisation réPartie Électrique de Recherche Expérimentale)*, dedicated to increase maturity of Distributed Electric Propulsion and Electric Ducted Fans (EDF). TLARs for a new electric concept, compliant with CS23’s constraints, were derived from a market investigation, and consisted in a 4 to 6 seats small business aircraft, able to cover ranges from 400 to 500 km (216 to 270 nmi) in about 2 hours at low cruise altitude, up to 10,000 ft above mean sea level. Starting from these, two different concepts were drawn at conceptual levels and their renderings are shown in Figure 36. EDF increase aerodynamic lift in low speed conditions, giving some STOL capabilities and improving aerodynamic and propulsive efficiency, yaw and roll control, and potentially also noise emissions. The propulsive system was provided with 40 electric ducted fans. However, to be compliant with regulation constraints, flight performance analysis has shown that only 32 operational EDF are required (Figure 37). The EDP array spans 60% of the wing. The motors’ position reduce loss of energy related to friction, through ingestion of the boundary layer. No complex Environmental Control System is required due to flight level [72].


Figure 36: Two different concepts studied within the ONERA AMPERE project. Left: Three-surface configuration with EDF along the wing trailing edge. Right: High-wing configuration with EDF along the wing leading edge [credits to ONERA].

Figure 37: ONERA AMPERE’s optimized high-wing concept with 32 EDF [credits to ONERA].

With reference to the high-wing concept, further details are herein reported. During the take-off, an electric power of 400 kW is required under the assumption of an electric motor efficiency of 97 % and an engine power unit efficiency of 95 %. A required energy of 500 kWh has been estimated to be necessary for the 400 km mission. A multi-disciplinary approach revealed that Polymer Exchange Membrane Fuel Cells (PEMFC) supplied with pressurized hydrogen at 700 bar are the more promising solution, for the considered TLAR, in order to provide the electric power (both for propulsion and systems). Each fuel cell unit system is designed to provide a power of 40 kW sufficient to supply 4 EDF (10 kW each), except two fuel cell systems providing 44 kW to supply also on-board equipment. A power density of 1.8 kW/kg has been assumed for fuel cells (226 kg in total). The addition of a battery pack is only necessary for instantaneous power demand in the most critical phases. To reduce the weight, a High Voltage Direct Current (135 V) distribution is chosen between fuel cell/battery stack and EDF. This choice reduces the number of power conversion steps and wires. Considering an energy density of 300 Wh/kg, a weight of about 133 kg was calculated for battery packs. Figure 38 shows the weight breakdown in the form of a pie chart (Left) and a representation of the propulsive architecture (Right). It is organized in 10 clusters of 4 EDP each, where each cluster is controlled by a single fuel cell so that, in case of failure of one cell, only a small fraction of the total thrust (10 %) is lost. However, it is possible to control each EDP individually which allows reconfiguration of the overall electric propulsion system in case of single EDP failure (only 1/40 total thrust is lost in this case). Finally, Table 13 lists TLARs, assumptions and sizes of the AMPERE [72].


Figure 38: Left: Estimated MTOW breakdown for the high-wing concept aircraft. Right: Fuel cell/battery clusters and corresponding EDFs (one color for each cluster).

| Parameter | Value |
|---|---|
| Powerplant Architecture | Series Hybrid-Electric (with EDF and PEMFC) |
| Power (Take-Off) | 670 Hp |
| Battery Capacity | 40 kWh |
| Battery Specific Energy | 300 Wh/kg |
| Fuel Cell Specific Power | 1.8 kW/kg |
| Number of Passengers | 4 - 6 |
| Wing Span | 14.5 m |
| Length | 20.8 m |
| Height | 2.93 m |
| Maximum Take-Off Weight | 2,400 kg |
| Design Range | 216 - 270 nmi |
| Cruise Altitude | < 10,000 ft |

Table 13: Technical characteristics of the ONERA AMPERE (High-Wing configuration) [72].

As batteries improve, the craft could grow from six seats to 50, and range will increase to be competitive with smaller Boeing and Airbus aircraft [73]. A wind-tunnel powered mock-up of one of ONERA's concept-planes (the high-wing configuration) has been designed and manufactured to be tested in ONERA's L2 facility located at Lille Center, in order to capture DEP behavior for aerodynamic assessment and flight control law definition [72].

Based on the knowledge gained by ONERA thanks to the studies mentioned above, and to complete its understanding of this aero-propulsion layout, ONERA decided in 2018 within the European Programme Clean Sky 2 to investigate distributed propulsion also for high speed applications. The research concept was identified as **DRAGON** (*Distributed fans Research Aircraft with electric Generators by ONERA*) and is herein shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**.


Figure 39: The ONERA DRAGON concept [credits to ONERA].

As today’s airplanes used around the world by airlines fly at a cruise Mach number of about 0.8, ONERA decided to assess the benefits and issues associated with the integration of high speed distributed propulsion on a 150 passenger aircraft with a 1,200 nmi range. In 2019 Schmollgruber et alii [74] conducted detailed disciplinary analyses. A redundant hybrid-electric architecture was selected, with all sources (turboshaft and generator) connected to the power management units (PMUs) via AC cabling. PMUs consist of a bus and converters to send direct current to the inverters located near each electric motor. The number of electric motors (fixed at 40 as a starting point), as well as turboshafts and generators, are open options to be optimized. The preliminary layout, shown in Figure 40, has only 2 turboshafts in the rear fuselage, with electric motors and fans located at the wing trailing edge, the inverters in the leading edge area (used as anti-icing devices), PMUs in the front cargo bay (so that the large number of cables can run through the wing) and the fuel tank in the rear cargo hold area of the fuselage. DRAGON doesn’t meet all airlines requirements in terms of operational flexibility, highlighting the fact that it should be considered as a technology demonstrator.

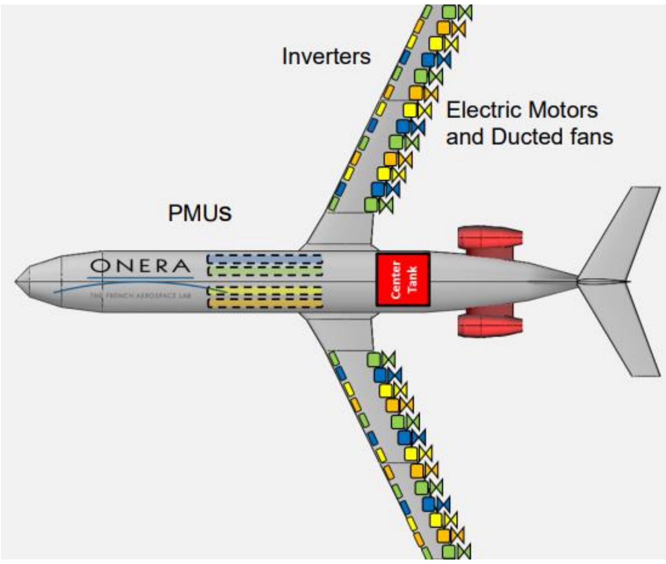



Figure 40: Preliminary layout for DRAGON. The number of electric motors is not still optimized [74].

Preliminary analyzes have shown that, assuming a moderate technological scenario for 2035, it is possible to obtain an advantage over the reference conventional aircraft only for ranges below 1,100 nmi. However, in order to be competitive, a design range of 2,750 nmi had to be fixed, which motivated the researchers to carry out more detailed analyzes published in January 2020 [75]. Figure 41 proposes a preliminary cross-redundant architecture which results from redundancy choices considering failure scenarios, and an optimization of electrical systems' power and weight. A parametric analysis considering the same design leads to a turboshaft power equals to 12.2 MW with a thermal efficiency of 44.2 % for take-off (TO) conditions. From an aerodynamic point of view, 2D and 3D led to an overall good design. A Finite Element model of the DRAGON wing was used to estimate the weight, highlighting the benefits of distributing masses along the span with respect to bending moment. No flutter risk was identified for DRAGON [75]. In conclusion, a 7% reduction in fuel burn with respect to a conventional 2035 reference aircraft was calculated with reference to a DRAGON configuration featuring 26 ducted fans (Table 14).

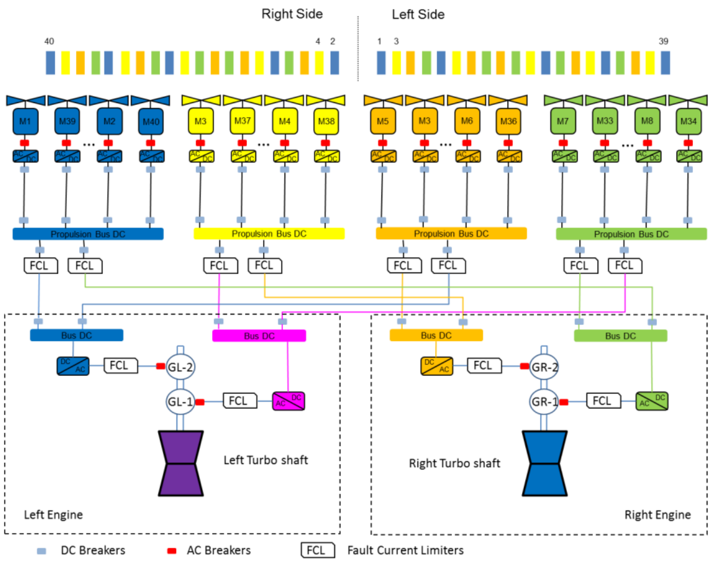



Figure 41: DRAGON's preliminary cross-redundant powerplant architecture diagram [75].

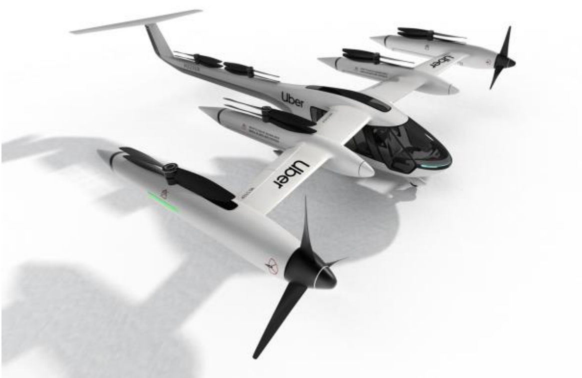
| Parameter | Value |
|---|---|
| Target EIS year | 2035 |
| Powerplant Architecture | Hybrid-Electric (with EDF) |
| Turboshaft Power | 2x 16,360 Hp |
| Number of Passengers | 150 |
| Wing Surface | 121.44 m$^2$ |
| Maximum Take-Off Weight | 67,860 kg |
| Design Payload | 13,608 kg |
| Fuel Weight | 11,540 kg |
| Design Range | 2,750 nmi |
| Cruise Mach Number | 0.78 |
| Cruise Altitude | 33,000 ft |
| Cruise Efficiency | 17.19 |

Table 14: Technical characteristics of the DRAGON's concept featuring 26 ducted fans [75].

### 5.1.8 Uber Elevate

With the spread of large-scale ridesharing services, several companies such as Uber are designing new, more efficient and faster solutions consisting of air travel, which would have the advantage of bypassing congested ground traffic by soaring above it. **Uber Elevate** is developing shared air transport between suburbs and cities, and also within cities. Uber is working closely with federal and local policymakers to develop an offering that is safe, quiet, and environmentally friendly, and that extends the range of existing transportation options [76]. The first planned step is to launch fleets of small full-electric VTOL (eVTOL) aircraft in Dallas, Los Angeles and Melbourne in 2020. Commercial operations are projected to begin in 2023. The Uber Elevate’s concepts fundamentally rely on the advantages provided by distributed electric propulsion. A network of distributed Skyports is being planned to enable Uber Air operations [77]. Uber Elevate’s top level requirements include 130 kt cruise speed, 50 nmi design range, a 3-hour sprint of 25-mile trips, and capacity for one pilot and 4 riders with a maximum payload weight of 445 kg [78]. Certified vehicles must be able to perform a safe vertical landing even in the event of a critical failure. There is also the aim to achieve acoustic emissions that are 15 dB quieter than existing light helicopters. Vehicles are expected to charge for less than 7 minutes during 3-hour sprint windows and less than 15 minutes otherwise. Due to the limited size of airports in urban environments, the maximum size of the aircraft must not exceed 50 ft and the height must not exceed 20 ft. Requirements are summarized in Table 15. Four reference models based on Elevate vehicle requirements have been studied [79, 80, 81, 82]. They are shown in Figure 42.


(a) eCRM-001




(b) eCRM-002

(c) eCRM-003


(d) eCRM-004

Figure 42: eVTOL reference models for the Uber Elevate concept [credits to Uber Elevate].

| Parameter | Value |
| --- | --- |
| Target EIS year | 2023 |
| Powerplant Architecture | Full-Electric (with DEP) |
| Number of Passengers | 4 + 1 |
| Wing Span | < 15.2 ft |
| Length | < 15.2 ft |
| Height | < 6.1 ft |
| Payload Weight | 444.5 kg |
| Design Range | 50 nmi |
| Cruise Speed | 130 kt |
| Cruise Altitude | 1,500 ft |
| Take-Off and Landing | VTOL performances |
| Rate of Climb | 500 ft/min |

Table 15: Uber Elevate’s technical requirements [78].

### 5.1.9 UTAP Project 804

United Technologies Corporation (UTC) was an American multinational conglomerate, merged with the Raytheon Company in April 2020 to form Raytheon Technologies. In 2019 it expanded as United Technologies Advanced Projects (UTAP), uniting Pratt&Whitney, Collins Aerospace and United Technologies Research Center to carry out **Project 804** for the development of a regional turboprop with parallel hybrid-electric powerplant architecture (Figure 43). The name represents the straight-line mileage between Pratt&Whitney's research group in Montreal and Collins Aerospace's site in Rockford, Illinois. The X-plane is built on the basis of a mid-size regional turboprop, the Dash 8-100, with the original power system replaced on one side with 1 MW engine plus 1 MW electric motor, delivering a total power of 2 MW in a 50/50 split during take-off. The engine has been downsized and optimized for cruising, allowing to get some fuel savings while keeping the battery size manageable as well. Moreover, in-flight energy recovery can mean even more efficient performance. The hybrid-electric propulsion system will be mounted in a modified nacelle, and is expected to provide a total fuel savings of at least 30% during an hour-long mission [51, 83]. The battery, its power management system, and the power electronics will be installed in the cabin. The hybrid-electric system increases the aircraft Operating Empty Weight, and the aircraft's fuel capacity is reduced by about 50% to allow for the electrical equipment and energy storage. This gives the new aircraft a range of approximately 600 nmi (as compared to the base 1000 nmi range). Table 16 summarizes the main aircraft's specifications. Given that 99% of this airframe's missions are shorter than 500 nm, and considered the highest propulsive efficiency, the tradeoff is justified both technically and economically [51]. UTAP will invest $50 million in a high-voltage laboratory in Rockford called "The Grid", a 25,000 $ft^2$ test bed for future electric power systems. The idea was to test the electrified Dash 8 and make it fly by 2022, but Raytheon has recently announced that it will slow down the work on Project 804, citing pandemic, although it remains committed to advancing electric-aircraft technologies [84].

Figure 43: UTAP Project 804's proposed demonstrator [credits to UTAP].

| Parameter | Value |
|---|---|
| Target EIS year | 2022 |
| Powerplant Architecture | Parallel Hybrid-Electric |
| Engine Power (Right Side) | 1,340 Hp |
| Motor Power (Right Side) | 1,340 Hp |
| Engine Power (Left Side) | 2,680 Hp |
| Number of Passengers | 30 - 50 |
| Design Range | 600 nmi |

Table 16: Main technical specifications of the UTAP Project 804 [51].

### 5.1.10 VoltAero Cassio

The **VoltAero Cassio** is a family of hybrid-electric aircraft being developed by the French startup company VoltAero. Key characteristic of the Cassio is the in-house series/parallel hybrid-electric module integrating a cluster of electric motors with a high-performance internal combustion engine that serves as the range extender. From full electric to full rechargeable hybrid, it adapts its operating mode to the flight profile and mission requirement. In May 2020 VoltAero revealed that Cassio will be offered in three versions, each sharing a high degree of modularity and commonality [85]. First, a 4-seat configuration, named the **Cassio 330**, is planned to be delivered by the end of 2022 and will be provided with a hybrid-electric power of 440 Hp given by a 200 Hp thermal engine and three 80 Hp electric motors on the same shaft, moving an aft propeller framed in a twin-boom high tail. A second version, the **Cassio 480**, will have 6 seats and a propulsive power of 640 Hp deriving from the combination of a 400 Hp thermal engine plus three electric motors providing 80 Hp each. The last version, the **Cassio 600** promises to carry 10 passengers with a total power of 800 Hp [86]. The 4-seater production version (Figure 44) relies on STOL performances. The Cassio 480 serves as short-haul regional aircraft covering up to 320 nmi thanks to the thermal engine which serves as range extender. Finally, the heavy hybrid Cassio 600 serves as medium-haul regional aircraft (see also Table 17). The powertrain is currently being validated on VoltAero's flight test aircraft named "Cassio 1", a modified Cessna 337 Skymaster with two front electric motors. VoltAero also claims a 4 dBA lower noise than comparable aircraft during operations, and no noise during ground taxi thanks to an electrically-driven nose wheel. Emissions saving of 20% are attainable in full hybrid mode.


Figure 44: Artist’s impression of the VoltAero Cassio 330 [credits to VoltAero].

| Parameter | Value (Cassio 330) | Value (Cassio 480) | Value (Cassio 600) |
|---|---|---|---|
| Target EIS year | 2022 | 2023 | 2024 |
| Powerplant Architecture | Hybrid-Electric | | |
| Maximum Power | 440 Hp | 640 Hp | 800 Hp |
| Number of Passengers | 4 | 6 | 10 |
| Maximum Take-Off Weight | 2,500 kg | < 5,000 kg | |
| Design Range | 110 nmi | 320 nmi | 650 nmi |
| Cruise Speed | 200 kt | | |
| Take-Off Distance | < 1,800 ft | | |
| Landing Distance | < 1,800 ft | | |

Table 17: Technical specifications of the VoltAero Cassio [85, 86].

### 5.1.11 XTI Tri-Fan 600

The **XTI TriFan 600** (Figure 45) is an electric VTOL aircraft designed by Denver-based XTI Aircraft Company. The project was started as crowdfunding initiative in August 2015. Work on a 65% scale model of the aircraft powered by a single HTS900 turboshaft engine, began in June 2017 and was completed in late 2018. In 2019, it was ground-tested to validate the electric motors, battery systems, ducts, propellers, flight controls, systems and instrumentation. After its flight in May, it conducted multiple controlled hovers [87]. The completion of the first full-scale prototype is expected by 2021. The aircraft has already received over 80 orders from customers, and the XTI Aircraft Company plans to enter the market by 2023.

Figure 45: The XTI TriFan concept [credits to XTI Aircraft].

The XTI TriFan 600 is a 6-seat, hybrid-electric, fixed-wing airplane that uses three ducted fans to power the aircraft. The two ducted fans in the wings, hosting two 335 Hp electric motor each [88], pivot to enable the aircraft to transition from hover to forward flight and back again for landing. In July 2019, the 1,100 Hp class GE Catalyst was selected to power three generators in the hybrid-electric propulsion system. No gear boxes or drive shafts are connected to the engine. The TriFan also incorporates thin-film photovoltaic solar cells capable of providing sufficient energy for ground operations. The aircraft, made of carbon-fiber composites, weighs 5,300 lb, can reach a height of 29,000 ft in 11 min and is designed to fly up to 300 kt over a distance of 670 nmi in VTOL, but the range can be extended to 1,200 nmi when operating from a runway [88]. Three battery packs assist the aircraft during take-off, and are recharged during the flight. XTI Aircraft claims 40% lower CO2 emissions and 50% less noise due to hybrid-electric propulsion [89]. Further details on the XTI TriFan, its powerplant system and its technical specifications are shown in Figure 46 and Table 18.

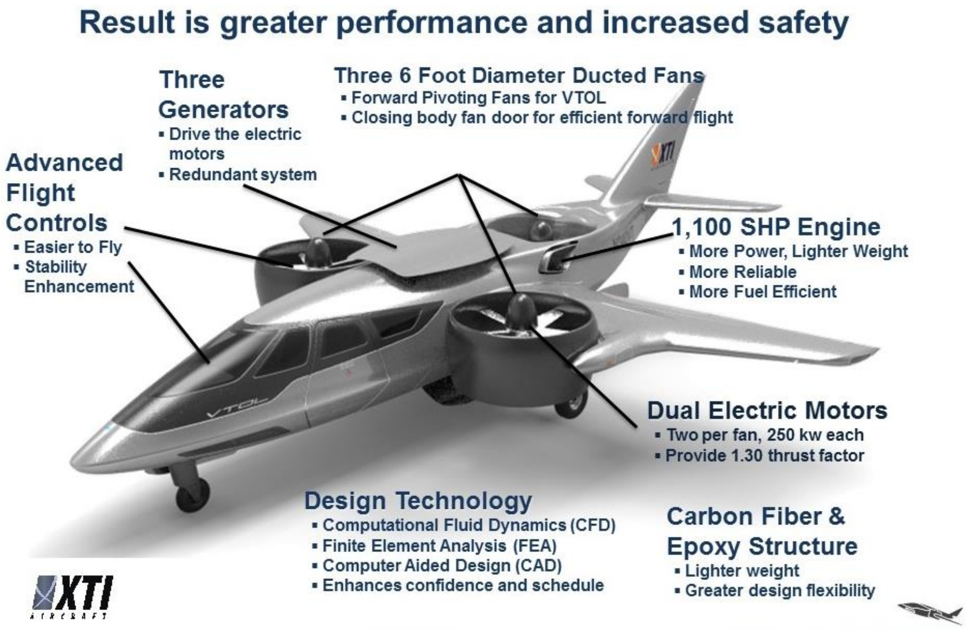



Figure 46: Technical details on the XTI TriFan 600 [88].

| Parameter | Value |
|---|---|
| Target EIS year | 2023 |
| Powerplant Architecture | Hybrid-Electric |
| Engine Power | 1,100 Hp |
| Ducted Fan Diameter | 6 ft |
| Number of Passengers | 5 + 1 |
| Wing Span | 11.5 ft |
| Length | 11.8 ft |
| Maximum Take-Off Weight (VTOL) | 2,404 kg |
| Maximum Take-Off Weight (STOL) | 2,858 kg |
| Empty Weight | 1,588 kg |
| Maximum Range (VTOL, pilot only) | 670 nmi |
| Maximum Range (STOL, pilot only) | 1,200 nmi |
| Maximum Cruise Speed | 300 kt |
| Maximum Cruise Altitude | 29,000 ft |
| Take-Off and Landing | VTOL performances |
| Rate of Climb | 2600 ft/min |

Table 18: Technical specifications of the XTI TriFan 600 [89].

### 5.1.12 Zunum Aero ZA10

In October 2017, the startup Zunum Aero formally launched the development of a 12-passenger hybrid electric business aircraft designed to Part 23 rules (Figure 47), the **Zunum Aero ZA10**, funded from Boeing and JetBlue. The concept was based on a serial hybrid-electric powerplant architecture realized by means of a range extender, that is a fuel-based auxiliary power unit driving a generator designed to charge the aircraft battery [90]. The battery mass was estimated to be below 20% the maximum take-off weight, and the maximum power delivered by the engines amounted to 1 MW. CO2 emissions are claimed to be below 0.14 kg per Available Seat Mile, and the sideline noise level perceived on the runway is 65 EPNdB. The operative cost would be comparable to the Bombardier Q400 for distances of 250-350 nmi and 3-to-5 times cheaper than similar-sized Pilatus PC-12 and Beechcraft King Air [91]. Table 19 contains further specifications of the ZA10. Its Safran turbogenerators and batteries were each designed to initially provide about half the power required. The battery pack energy density would be upgraded regularly, to increase the range from 610 to 870 nmi between 2020 and 2030. The evolving batteries would be certified every two years, in line with their short cycle lives at high utilization rates [92]. To date, Zunum Aero's prospects of flying the ZA10 in the near future appear to have vanished due to serious financial troubles, which began when Boeing backed away from the company.

Figure 47: The Zunum Aero ZA10 Concept [credits to Zunum Aero].

| Parameter | Value |
|---|---|
| Target EIS year | 2020 |
| Powerplant Architecture | Series Hybrid-Electric |
| Engine Power | 2x 670 Hp |
| Number of Passengers | 12 |
| Maximum Take-Off Weight | 5,000 kg |
| Fuel Weight | 363 kg |
| Design Range | 610 nmi |
| Cruise Speed | 340 mph |
| Cruise Altitude | 25,000 ft |
| Take-Off Distance | 2,200 ft |
| Landing Distance | 2,500 ft |
| Rate of Climb | 1600 ft/min |
| Operative Cost | 8 cents / seat mile |

Table 19: Characteristics of the Zunum Aero ZA10 Concept [50, 90].

### 5.1.13 Other Projects

This paragraph concludes the section with projects that are still in their embryonic stage or that have been cancelled. As less information is available for the aforementioned aircraft, it was decided to collect it in the form of a single text. The projects shown here are sorted alphabetically. In late 2017, Airbus, Rolls-Royce and Siemens announced a partnership to build a hybrid electric aircraft known as the **Airbus E-Fan X** (Figure 48). Initially scheduled to fly by 2030, the project was cancelled due to the global Covid-19 pandemic [93]. The testbed was a BAe 146, and one of its four Lycoming ALF502 turbofans was to be replaced by a Siemens 2 MW (2,700 Hp) electric motor, adapted by Rolls-Royce and powered by its AE2100 turboshaft, controlled and integrated by Airbus with a 2 tonnes battery [94]. Siemens aimed to achieve a significantly higher power density level than the Extra 330LE's 5.2 kW/kg. Rolls-Royce's challenge was to apply its experience of gasturbine and generators to industrial and naval applications in the aeronautical field, while Airbus had to manage an electric propulsor that was 30 times larger than its first demonstrator, the E-Fan. In less than three years, E-Fan X has successfully achieved its main initial goals: it launched and tested the possibilities and limitations of a serial hybrid-electric propulsion system in a demonstration aircraft, acquiring valuable information to develop a roadmap more focused on how to move towards decarbonising aviation. It also laid the groundwork for the future adoption and regulatory acceptance of alternative-propulsion commercial aircraft [95].

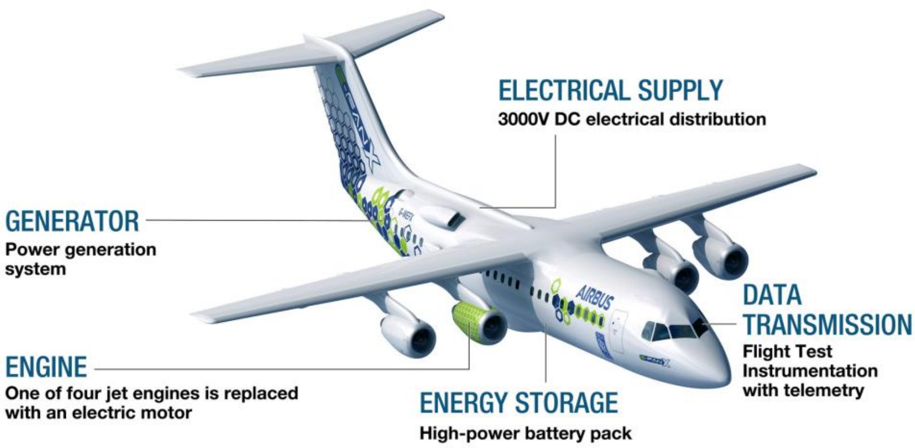



Figure 48: The Airbus E-Fan X [credits to Airbus].

Ampaire is an early-stage California-based start-up, with the goal of solving the problems of high operating costs for short-haul airlines and reduce emissions. In collaboration with NASA through multiple contracts, Ampaire is validating the capabilities of electrified aircraft with its biggest vehicle, the **Ampaire Eco Otter SX** (Figure 49). It constitutes a low-emission 1 MW variant of the De Havilland Canada DHC-6 Twin Otter turboprop, used worldwide as a regional airliner, cargo hauler, and bush plane, as well as in a variety of specialized operations from surveillance to parachute launch. The Eco Otter will be hybrid-electric and is expected to have a maximum take-off weight of 6,530 kg (908 kg more than the Twin Otter) [96], standing within the limits of FAA's Part 23 aircraft category. Its ability to carry 19 passengers (or a 1,915 kg payload) for over 200 nmi makes the concept economically feasible. Ampaire aims at a fuel saving of between 20 and 30%, and a reduction in maintenance costs between 10 and 25% [97].

Figure 49: Artist-s impression of the Ampaire Eco Otter SX [credits to Ampaire].

The **Ampaire TailWind** (Figure 50) [98] concept is an ultra-efficient configuration in the 500 kW class, featuring an aft boundary layer ingesting thruster in an all-electric (TailWind-E) or series hybrid (TailWind-H) configuration [99]. The airframe is designed for a maximum take-off weight of 4,536 kg and wing loading of 225 kg/m$^2$. An air scoop supports cooling and potential flow control for lift enhancement [100]. Both the TailWind-E and the TailWind-H (designed for longer flights) configurations have a high-aspect-ratio wing, ducted propeller fan, retractable gear and an extremely clean design [101]. Ampaire is currently developing the initial revolutionary concept which should be achievable by 2028. However, Ampaire has taken a pragmatic approach to take immediate action to reduce the environmental cost of aviation by first developing and selling a plug-in hybrid aircraft, the Ampaire 337, also called EEL (see paragraph 5.2.4 to gain more insight).


Figure 50: The Ampaire TailWind concept [credits to Ampaire].

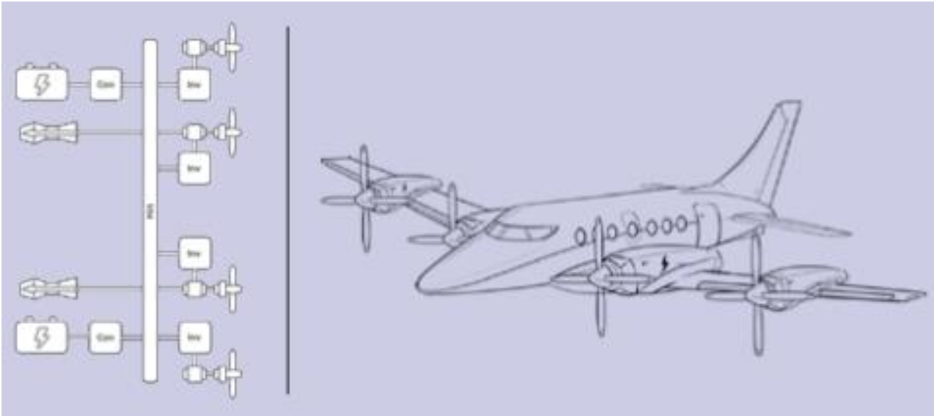
Suitable for transporting material goods or paying passengers, the winged VTOL **Bell Nexus** concept (Figure 51) [102] offers a quiet and comfortable means of urban transport, representing a faster alternative to personal cars. The first design of the Nexus was unveiled in January 2019 in the form of a full-scale model at the Consumer Electronic Show (CES) in Las Vegas, Nevada. Equipped with three fans that rotate clockwise and three that rotate counter-clockwise to balance the torque generated by the aircraft, the Nexus 6HX will have dimensions of approximately 12 m x 12 m with a gross weight of approximately 2,721 kg, and will be able to carry 4 passengers and a pilot. The powertrain architecture is of the serial hybrid-electric type, based on a turbine engine that drives an electric generator, producing DC electricity. This electricity is then distributed to the six tilt-rotors (all 2.4 ft in diameter) through a redundant power control system. Each fan has a direct drive electric motor, eliminating the need for a gearbox and replacing the connecting shafts of a traditional helicopter with cables. The fan blades are able to start and stop quickly, which translates into time savings during loading and unloading operations. The aircraft's rotors and ducts are also responsible for a noticeable improvement in controllability of the aircraft's pitch, roll, and yaw. The battery in the Nexus, produced by Electrical Power Systems, is being built with lithium-ion based cells that are contained in a pack with a battery management and safety system [103]. Recently, at CES 2020, a new full-electric version expanding the Nexus family has been unveiled by Bell [104]. The new version will have a range of about 50 nmi, less than the 130 nmi of the hybrid-electric 6HX. The maximum speed for both versions will be around 150 mph [105]. Prototypes of the Bell Nexus are currently under development.

Figure 51: Artist's impression of the Bell Nexus. Left: Series Hybrid-Electric Nexus 6HX. Right: All-Electric Nexus 4EX [credits to Bell].

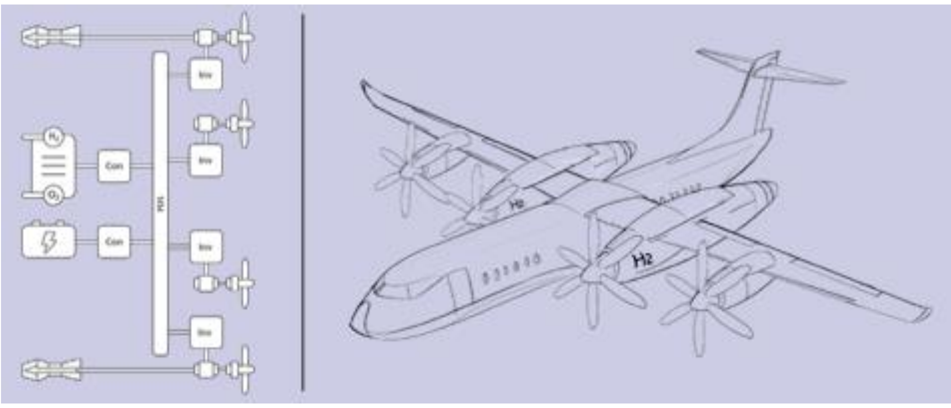
The German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) is conducting research into hybrid-electric aircraft, with the conviction that it could constitute an important building block for future aviation. DLR has teamed up with Bauhaus Luftfahrt to work on the **CoCoRe** (Cooperation for Commuter Research) project, which examines the possibilities and potential for hybrid-electric 19-seater aircraft. On the other hand, researchers' market analysis revealed that 83% of the commuters currently in service are employed on shorter routes [106]. The idea is to extend the application of hybrid-electric solutions also to the commuter class (with 19 seats) following the past successful projects on small aircraft. This study has revealed that pure-electric propulsion systems can be used to reduce emissions from this class of aircraft on short, frequently flown routes over distances of up to 190 nmi, suitable for air taxi connections in medium-sized cities. Examples of such routes within Germany include Mannheim to Berlin, Bremen to Berlin and Münster to Leipzig. The configuration investigated by the DLR (Figure 52) is based closely on the 19-seater Dornier Do 228 and, in particular, the British Aerospace Jetstream 31. In their design, the researchers focused on modifying the landing gear nacelles, which were extended above the wings to accommodate easily replaceable battery packs. This allows to place the weight of the batteries (2,000 kg) exactly where it is most convenient during take-off and landing - directly above the landing gear. The weight of the batteries, compared to the maximum take-off weight of 8.6 tonnes, involves the main limitation for the range in compliance with CS23's standards. The range can be extended to over 540 nmi by using two range extenders (gas turbines) that can be coupled to and decoupled from the propellers [106]. The range extenders also enable longer fully electric flights, as the battery does not have to be used for reserves: if the aircraft needs to divert to a more distant alternative airport, fuel reserve allows it to cover the necessary additional distance without any need to oversize the batteries. Currently, the main limitation encountered by researchers is the high price of batteries in relation to their low longevity, in the order of 1000 charge / discharge cycles, which together with low carbon dioxide prices makes the concept not yet economically comparable with conventionally powered commuter aircraft.

Figure 52: Conceptual DLR CoCoRe's 19-seater aircraft [credits to DLR/BHL].

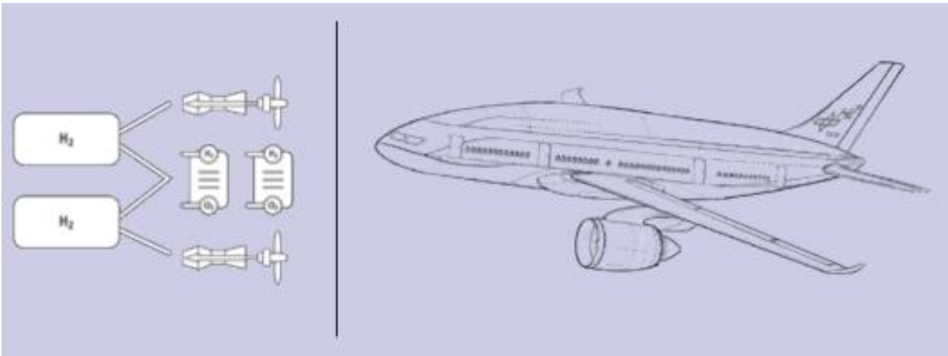
Since January 2020, 45 researchers from 20 DLR institutes have also been working together on the Exploration of Electric Aircraft Concepts and Technologies (**EXACT**) project [107]. The aim is to develop an aircraft with at least 70 seats that can cover a distance of 2000 km (1080 nmi) by 2040. The team is developing models for climate impact, noise, and product and energy lifecycles. Reductions in emissions are already possible by mixing conventional kerosene with synthetic fuels. However, these new fuels are currently only available in small quantities and are disproportionately expensive. The EXACT project will also investigate propulsion systems that burn hydrogen directly, which could remove some intermediate steps and reduce the costs of power-to-liquid fuels as it avoids having to produce and transport them using fossil fuel. On the other hand, the volume of hydrogen represents a major design obstacle. As an alternative, batteries will need to be able to be charged, stored and recycled. Hybrid-electric propulsion systems are fundamentally different from their conventional counterparts and will place completely new demands on aircraft structures, raising problems and perplexities about the realization of the principle of commonality. A first concept is characterized by a 19-seater with completely battery-powered propulsion system, with 4 wing thrusters, capable of flying for up to 108 nmi (200 km). Additional fuel is carried exclusively in case of emergencies. A second concept is represented by a medium-sized, short-haul aircraft with a range of over 1,000 nmi with reduced carbon emissions, relying on a clever combination of several propulsion technologies, i.e. hydrogen fuel cells powering the aircraft at ground, batteries supplying the on-board electric systems and hydrogen gas turbines providing the necessary thrust for take-off. One last, larger concept carrying 150 passengers over 1,000 nmi uses fuel cells when taxiing on the ground, gas turbines burning synthetic fuels for faster cruising flight, and the combination of both systems to produce enough thrust for take-off [108]. All three configurations are represented in Figure 53.



(a)



(b)



(c)

Figure 53: DLR EXACT's aircraft concepts with associated propulsion systems. (a) Full-electric 19-seater commuter aircraft. (b) Medium-sized, short-haul aircraft powered by hydrogen fuel cells, hydrogen gas turbines and batteries. (c) 150-seat large commercial aircraft powered by fuel cells and synthetic fuels [credits to DLR].

In September 2020, Swedish Gothenburg-based start-up Heart Aerospace, founded in 2018 by Anders Forslund, unveiled its all-electric regional aircraft named the **Heart Aerospace ES-19** (Figure 54) [109]. The aircraft is a 19-seat airliner with an operational range of 400 km (217 nmi). The company is planning to certify the aircraft by the year 2026, under the EASA's CS-23 standards. Initially, the aircraft is expected to offer point-to-point transportation between Scandinavian cities, before expanding operations to the rest of the world. The ES-19 will be able to land and take off on runways as low as 2,640 feet, allowing the aircraft to use airports much closer to urban centers. The aircraft is expected to have a top speed of 215 knots and a cruise speed of 180 knots. Its reliable electric motors would reduce maintenance costs by 90% compared to existing turboprops and intelligent electronic monitoring would reduce inspection needs. The company also aims for 50-75% lower energy costs and lower noise levels than conventionally powered aircraft, also thanks to the benefits of aero-propulsion interaction connected with its four wing-mounted propellers. Heart believes that its conventional aluminium-fuselage, fixed-wing aircraft will be relatively simple to certify [110].

Figure 54: The Heart Aerospace ES-19 concept [credits to Heart Aerospace].

## 5.2 Research project with TRL>6

### 5.2.1 Airbus CityAirbus

The **Airbus CityAirbus** (Figure 55 and Table 20) is a full-electric 4-seat multicopter vehicle demonstrator that focuses on advancing remotely piloted electric vertical take-off and landing flight. In 2015, a feasibility study confirmed the design's operating costs and that it could meet safety requirements. Full-scale testing of the ducted propeller drivetrain was completed in October 2017. To date, the scale model of CityAirbus has made more than 100 test flights demonstrating the aerodynamic configuration of the full-scale prototype, which conducted its maiden flight in May 2019 (see Figure 55) [111]. The concept has a capacity of four passengers, ideal for aerial urban ridesharing and for flying between fixed routes between critical transit hubs. CityAirbus has a multi-rotor configuration that includes four carbon fiber ducted high-lift propulsion units. Its 8 fixed-pitch propellers are driven by 8 Siemens SP200D (130 Hp, direct-drive) electric motors at around 950 rounds per minute, producing low acoustic impact. CityAirbus has the advantage of being autonomous and remotely piloted through advanced control systems. Type certification and commercial introduction are planned for 2023 [112].

Figure 55: The Airbus CityAirbus [credits to Airbus].

| Parameter | Value |
|---|---|
| Target EIS year | 2023 |
| Powerplant Architecture | Full-Electric |
| Battery Capacity | 110 kWh |
| Driving propellers | 8x 130 Hp |
| Number of Passengers | 4 |
| Wing Span | 8 m |
| Height | 8 m |
| Propeller Diameter | 0.85 m |
| Maximum Take-Off Weight | 2,200 kg |
| Maximum Flight Time | 15 min |
| Cruise Speed | 65 kt |
| Take-Off and Landing | VTOL performances |

Table 20: Characteristics of the Airbus CityAirbus [111, 113]

### 5.2.2 Airbus E-Fan

Airbus Group Innovations created an innovative concept for a new generation of electric training and general aviation aircraft: The **Airbus E-Fan** (Figure 56). The project originated during the 2011 Paris Air Show. Design of the E-Fan began in late 2011, and the technological demonstrator made its first public flight in April 2014. The prototype was realized by VoltAir, an Airbus subsidiary. The E-Fan demonstrator aircraft was produced with carbon-fiber composite materials. The engines provide 32 kW each via eight-blade ducted fans, are nearly noise-free, and produce zero greenhouse gas emissions contributing to global reduction in aviation's environmental impact. The landing gear consists of a retractable fore and aft wheel, and a fixed wheel under the wings. The main wheel is electrically-driven by a 6 kW engine which enables the E-Fan to taxi without thrust from the aircraft's engines, and also contributes to the acceleration during take-off. The Lithium-ion Kokam 18650 batteries that power the motors are housed in the wing's inboard section, providing an endurance of more than 100 minutes. The batteries can be completely recharged in one hour and can be quickly replaced. An on-board electrical network supplies power to the avionics and radios via a converter. A backup battery is provided for emergency landing [114]. See Table 21 to gain more insight about the E-Fan's technical features.

Figure 56: Artist's impression of the E-Fan [credits to Airbus].

| **Parameter** | **Value** |
|---|---|
| EIS year | 2017 |
| Powerplant Architecture | Full-Electric |
| Battery Energy Density | 207 Wh/kg |
| Battery Weight | 167 kg |
| Maximum Power | 2x 40 Hp |
| Number of Passengers | 1 |
| Wing Span | 9.45 ft |
| Length | 6.67 ft |
| Height | 2 ft |
| Maximum Take-Off Weight | 590 kg |
| Cruise Speed | 86 kt |
| Maximum Endurance | 1 h 45 min |

Table 21: Characteristics of the Airbus E-Fan 1.0 [114, 115].

First deliveries were at that time expected at the end of 2017 or early 2018. A series hybrid-electric version of the E-Fan with a 50 kW range extender, called the **E-Fan 1.2**, was also designed and its prototype was shown in October 2016. The success of the E-Fan technology demonstrator led to the definition of 2-seat and 4-seat production versions, designated **E-Fan 2.0** and **E-Fan 4.0**. The E-Fan 2.0 had to be a fully-electric battery-powered training aircraft with improved energy density of battery cells, and its first flight was scheduled for 2017. The E-Fan 4.0 version was a training and general aviation aircraft with its on-board electrical energy supplemented by a combustion engine that recharges the batteries to extend the flight endurance to 3.5 h. The first flight of the E-Fan 4.0 was planned for 2019 [116]. Both projects were dropped when also production of the E-Fan was cancelled, in April 2017, when Airbus decided to concentrate on the design of a hybrid-electric regional jet aircraft, the E-Fan X [117] (see also paragraph 5.1.13).

### 5.2.3 Airbus Zephyr S

The Airbus Zephyr (Figure 57) is a series of leading solar-electric stratospheric Unmanned Aerial System (UAS) originally designed by the British company QinetiQ in 2003 and currently under development by Airbus Defence and Space. Different levels of payload capability are possible, with incremental performance levels [118]. In 2010, a Zephyr 7 flew uninterrupted for 14 days. A new variant, the **Airbus Zephyr S** (or Zephyr 8) was unveiled at the Farnborough Air Show 2018. It has a wingspan of 82 ft and weighs less than 75 kg [119] (see also Table 22). In July 2018 it achieved a flight endurance record of nearly 26 days. The Zephyr S is powered by two solar-powered electric motors. The solar energy is generated by a combination of solar cells and Amprius lithium-sulphur batteries. Each motor drives a two-bladed propeller mounted on the wings. Zephyr relies on solar energy, with secondary batteries charged in daylight to power overnight flight. Its Z-shaped morphing wing is helpful for increasing flight endurance. As claimed by Airbus, it is the only HAPS (High Altitude Platform Station) to have demonstrated day/night longevity in the stratosphere [119]. Zephyr can support a wide range of payload capabilities, including Electro Optical, Infrared, Hyper spectral, Passive Radio Frequency (RF) Radar, Synthetic Aperture Radar (SAR), Early Warning, Lidar and Automatic Identification System (AIS). Zephyr has wide visual payload coverage of 20 by 30km footprint which enables it to provide a range of continuous surveillance as well as high resolution imagery and video capture for intelligence gathering.

Figure 57: The Airbus Zephyr [credits to Airbus].

| Parameter | Value |
|---|---|
| First Flight | 2018 |
| Powerplant Architecture | Full-Electric |
| Battery Energy Density | 435 Wh/kg |
| Battery Weight | 24 kg |
| Motor Power | 40 Hp |
| Number of Passengers | 0 |
| Wing Span | 22.5 m |
| Maximum Take-Off Weight | 61 kg |
| Maximum Payload | 5 kg |
| Cruise Altitude | 70,000 ft |
| Maximum Endurance | 26 days |

Table 22: Technical specifications of the Airbus Zephyr S [118, 119, 120].

### 5.2.4 Ampaire 337 EEL

The **Ampaire 337 EEL** (Figure 58) is a Cessna 337 Skymaster with its rear, 210 Hp piston engine replaced with Ampaire's proprietary electric-propulsion system. It represents a test bed for the development of a fully electric aircraft. ARPA-E (Advanced Research Projects Agency - Energy), a branch of the U.S. Energy Department, has entrusted Ampaire to develop the new six-seats aircraft for deploying advanced technologies as a new platform for the development of scalable technologies and certification processes [121]. It makes possible to test new power distribution systems, high power electronics, inverters, electric motors, propellers, ducted fans, batteries, fuel cells, and even high-efficiency combustion engines in a real flight environment. A 50 to 70 % reduction in fuel costs and a 25 to 50 % saving in maintenance costs are expected with Ampaire’s hybrid-electric configuration.


Figure 58: The Ampaire 337 EEL. Left: The First Prototype (2019). Right: Second prototype (2020) with batteries moved into a belly capsule [credits to Ampaire].

The hybrid prototype held its first test flight on 6 June 2019, ahead of its certification and entry into service scheduled for 2021 [122]. Test flights were performed on commuter routes operated with Cessna Caravans by Hawaiian Mokulele Airlines. A second prototype was launched in September 2020 [123]. With this second prototype, limited to one pilot and two passengers, Mokulele Airlines will test the connection of Maui's airports. The Electric EEL is powered by a conventional combustion engine (a 310 Hp Continental IO-550) and a 270 Hp-capable electric motor, limited in this application to 160 Hp. The prototype was originally configured with the electric motor in place of the stern motor, but in October 2019 the configuration was changed with the piston engine in the rear position and the electrical system in the forward. The batteries were moved out of the cabin into a belly capsule. Currently, the maximum payload is 204 kg or 3 passengers over a design range of 200 nmi (Table 23) [121]. US start-up Personal Airline Exchange has already ordered 50 EEL examples plus an option for a further 50 units.

| Parameter | Value |
|---|---|
| Target EIS year | 2021 |
| Powerplant Architecture | Parallel Hybrid-Electric |
| Number of Passengers | 4 + 1 |
| Maximum Payload | 204 lb |
| Cruise Speed | 120 kt |
| Design Range | 200 nmi |

Table 23: Characteristics of the Ampaire 337 EEL [121, 123].

### 5.2.5 Eviation Alice

Eviation is an Israel-based firm developing the **Eviation Alice** 9-passenger concept. The Eviation team aims to certify the first all Fly-By-Wire FAR 23 aircraft, with an airframe structure 95% made of composite materials and propulsion based on innovative technologies [124]. Since compactness of electric motors enables wingtip propulsion, the Eviation Alice uses two wingtip-mounted pusher propellers which counter vortex rotation and reduce drag. In addition, a third tailcone propeller offers boundary-layer ingestion benefits. Wingtip propellers also help the overall yaw controllability of the aircraft, and the tailcone propeller grants safely powering in case of wingtip emergency. A V-Tail configuration characterizes the tail plane, and the cabin is unpressurized.

Figure 59: The Eviation Alice [credits to Eviation].

In February 2018, a scale UAV model was flown to validate the aerodynamics and flight controls. Kokam was selected to supply Li-Ion batteries to power the full-scale prototype [125]. Eviation selected Siemens as supplier for its three 350 Hp (cruising power) electric motors, and MagniX 375 Hp Magni250 electric motors as an alternative option [126]. In 2019 Eviation teamed up with Embry-Riddle Aeronautical University (ERAU) to launch a research and development programme at ERAU's campus in Prescott, Arizona. The program would focus on performance analysis, validation and testing, along with preliminary design and sub-scale testing of future electric design concepts [127]. A full-size static Alice was exhibited at the Paris Air Show in June 2019 (Figure 59). List price was announced to be $ 4 million per plane [128]. By October 2019, over 150 Alice aircraft had been ordered by two American companies. With 260 Wh/kg cells, the 920 kWh battery capacity is initially estimated to give the design a range of 540 nmi at 240 knots and 10,000 ft (Table 24), but the company has anticipated to increase these performances as battery technology improves. The weight of the batteries currently constitutes about 60% of the maximum take-off weight. Claimed operative costs are 3-5 times lower than for a turboprop aircraft, with a penalty on flight speed. Alice is designed from the ground up for regional commuters. Being electric, a drastic reduction of vibrations and interior noise typical of similar aircraft is expected.

| Parameter | Value |
|---|---|
| Target EIS year | 2022 |
| Powerplant Architecture | Full-Electric |
| Battery Specific Energy | 260 Wh/kg |
| Battery Capacity | 920 kWh |
| Maximum Power | 3x 350 Hp |
| Number of Passengers | 9 + 2 |
| Length | 13.2 m |
| Wing Span | 16.1 m |
| Height | 4.2 m |
| Maximum Take-Off Weight | 6,350 kg |
| Design Range | 540 nmi |
| Cruise Speed | 260 kt |
| Cruise Altitude | 10,000 ft |
| Service Ceiling | 12,500 ft |
| Take-Off Field Length | 3,000 ft |
| Operative Cost | 200 $/h |

Table 24: Characteristics of the Eviation Alice [50, 124].

### 5.2.6 IFB Stuttgart eGenius

The two-seat battery-powered **IFB Stuttgart eGenius** (Figure 60) is a manned electric airplane developed by the Institute of Aircraft Design at the University of Stuttgart [129]. Its first flight was in May 2011 on the airfield of Mindelheim-Mattsies, Germany. The e-Genius has been developed for the practical testing of alternative propulsion and energy storage technologies. Most of the airplane was built by a team of students between October 2010 and May 2011. Instead of the modification of a conventional aircraft, the configuration of e-Genius has been completely re-designed and optimized for the electric propulsion system. The special feature is the big, slowly rotating propeller that is mounted in the vertical stabilizer. The aircraft has a maximum range of more than 400 km by using a fuel equivalent to 1.3 l per 100 km. The area behind the sitting pilots offers enough space for the four lithium-ion battery packs [129]. Since 2015, the developers have been testing a series hybrid-electric version of the eGenius, with a range extender in a pod underneath the right wing that can be added or removed easily from the aircraft (Figure 61). The aircraft is completely manufactured of carbon-fibre composite materials and equipped with a retractable landing gear. Other technical characteristics and performances are listed in Table 25. The aircraft participated in the Green Flight Challenge of the Comparative Aircraft Flight Efficiency (CAFE) in the summer of 2011 in Santa Rosa, California, finishing second and winning the Lindbergh Prize for the quietest aircraft [130]. The goal of the competition was to find a two-seat aircraft which can fly a minimum range of about 175 nmi at a minimum speed of 87 kt while using less fuel than 85 km/l.

Figure 60: The IFB Stuttgart eGenius [credits to the University of Stuttgart].

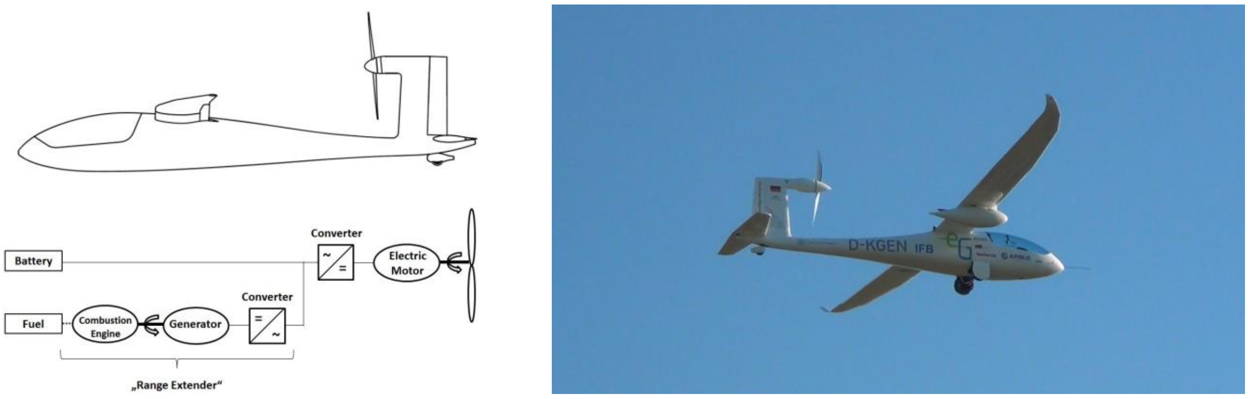



Figure 61: The IFB Stuttgart eGenius with range extender [credits to the University of Stuttgart]

| Parameter | Value |
|---|---|
| First Flight | 2011 |
| Powerplant Architecture | Full-Electric |
| Battery Specific Energy | 204 Wh/kg |
| Battery Capacity | 58 kWh |
| Motor Power | 2x 80 Hp |
| Number of Passengers | 2 |
| Length | 8.1 m |
| Wing Span | 17 m |
| Propeller Diameter | 2.2 m |
| Maximum Take-Off Weight | 950 kg |
| Design Range | 243 nmi |
| Endurance | 3 h 30 min |
| Cruise Speed | 90 kt |
| Maximum Speed | 150 kt |
| Service Ceiling | 20,000 ft |
| Climb Rate | 787 ft/min |
| Take-Off Distance (over 50 ft) | 1,475 ft |

Table 25: Characteristics of the IFB Stuttgart eGenius [49, 129].

### 5.2.7 Lange Antares 20E

In 1999 a new electric powered airplane entered the market, the **Lange Antares 20E** motor glider. Today it holds the distinction of being the first manned fixed-wing aircraft to have received certification, released by EASA in August 2006. The first flight took place in 2003. Lange Aviation claims excellent soaring performance, extremely sensitive controls and good handling qualities for its Antares 20E, as well as low noise levels, low maintenance costs and high reliability [131]. Its 57 Hp EM42 brushless external rotor motor, rotating at 1,500 RPM, is the first electric motor to be officially approved by the European Aviation Authority EASA. The Antares can boast a high availability thanks to a maximum charging time of nine hours and a charge cycle controlled via SMS. As a result of propeller optimization, the Antares 20E can boast a climb rate of more than 800 ft/min during initial climb, up to more than 10,000 ft (see also Table 26). The Antares 20E is equipped with a battery-system based on lithium-ion cells of type SAFT VL41M (with 72 cells), chosen because of their great capability for high-current and their very high cyclic durability.


Figure 62: Lange Antares 20E [credits to Lange Aviation GmbH].

| Parameter | Value |
|---|---|
| First Flight | 2003 |
| Maximum Power | 57 Hp |
| Number of Passengers | 1 |
| Aspect Ratio | 31.7 |
| Wing Span | 20 m |
| Fuselage Length | 7.4 m |
| Fuselage Height | 1.6 m |
| Empty Weight | 475 kg |
| Maximum Take-Off Weight | 660 kg |
| Best Glide Ratio | 56 |
| Maximum Speed | 151 kt |
| Maximum Climb Rate | 866 ft/min |
| Maximum Climb Altitude | 11,155 ft |

Table 26: Technical features of the Lange Antares 20E [47, 50, 131, 132].

### 5.2.8 Lilium Jet

The **Lilium Jet** is a German VTOL electrically powered personal air vehicle designed by the Munich-based start-up Lilium GmbH. The aircraft is being engineered to the requirements of EASA's SC-VTOL regulations (2019) [133] and their Associated Means of Compliance (2020) [134], in order to be certified by EASA in Europe and the FAA in the United States.
The 36 all-electric engines are integrated into the wings to reduce drag and optimize efficiency, while their ducted design provides a noise shielding advantage over open rotors. This enables a noise footprint that is low enough to allow inner city operations [135]. Twelve engines are mounted on the front wing, and the remaining ones are mounted on the rear wing. Their ducted design provides a significant efficiency advantage over open rotors by blocking the formation of tip vortices. Propellers and engines are each installed in twelve tiltable wing parts. These drive-carrying "flaps" are rotated downwards for vertical launch; at the transition to the horizontal position, forward thrust is generated. Distributed vectored thrust allows for precision control of the aircraft, making tail, control surfaces and also oil circuits and gearboxes superfluous. This enables a weight saving and makes the aircraft simpler and faster to design, reducing both maintenance and operative costs. The main target performances of the Lilium Jet are listed in Table 27.

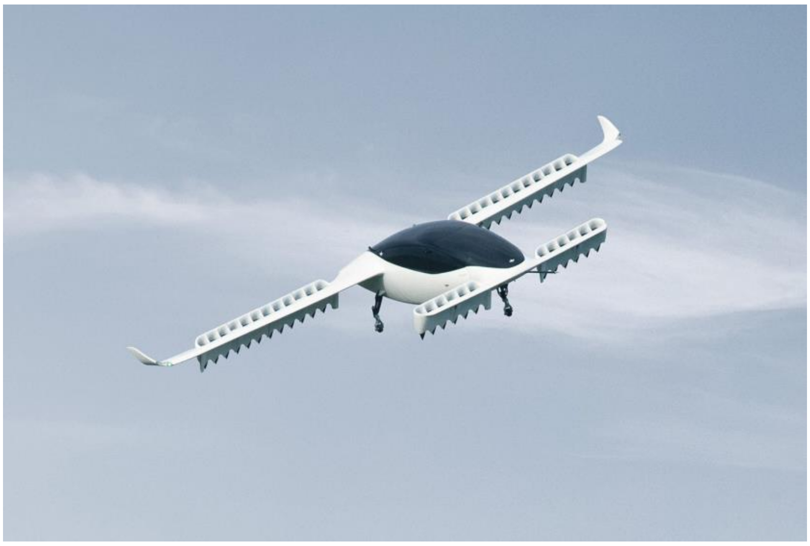


Figure 63: The 5-seater prototype of the Lilium Jet [credits to Lilium GmbH].

| Parameter | Value |
|---|---|
| Target EIS year | 2025 |
| Powerplant Architecture | Full-Electric (with DEP) |
| Number of high-lift propellers | 36 |
| Number of Passengers | 4 + 1 |
| Design Range | 162 nmi |
| Maximum Flight Time | 60 min |
| Cruise Speed | 162 kt |
| Take-Off and Landing | VTOL performances |

Table 27: Top Level Requirements of the Lilium Jet [135, 136].

The Lilium Jet engine has been fully developed and customized in Lilium's in-house sound laboratory, and contains innovative liner technology thanks to which the aircraft will be inaudible from the ground when flying above 1,300 ft. The target is to obtain 7 times less acoustic emissions than a helicopter at take-off. On the ground, the aircraft will move using separate electric motors, allowing it to be as quiet as a typical electric car. The company originally conceived the basic electric jet concept in 2013. A first full-scale 2-seater technology demonstrator, named "Eagle", was used to complete a series of unmanned test flights in April 2017. The current test aircraft (Figure 63) is a full-scale 5-seater prototype that first flew in May 2019. Flight tests are currently being performed to prove the design of the Lilium Jet and its technologies. More than 100 different ground and flight tests saw the aircraft travel at speeds exceeding 54 kt, turn at bank angles of up to 30 degrees and climb and descend vertically at rates of 500 ft per minute. The goal is to finalize serial aircraft development, certification and industrialization by 2024. The Lilium GmbH also plans to found an air taxi service for urban air mobility with the Lilium Jet [137].

### 5.2.9 MagniX eBeaver and eCaravan

MagniX is an electric motor manufacturer headquartered in Redmond, Washington. To date its two main products are the *Magni250* and the *Magni500*, plus the 170 kW multi-application inverter called *magniDrive* used to run both motors. The Magni250 provides a power of 375 Hp turning at 1,900 Hp, and in April 2019 it was selected as an alternative option for powering the Eviation Alice [126]. The Magni500 offers 750 Hp at 1,900 RPM and weighs 133 kg [138]. As of 2019 MagniX has partnered with Harbor Air to electrify its entire fleet. In doing so, MagniX has the opportunity to develop retrofitted versions of historic sailplanes serving as testbed for its latest generation motors. As of 2019 MagniX has partnered with Harbor Air to electrify its entire fleet. The first converted aircraft was a DHC-2 Beaver re-named the **MagniX eBeaver** (Figure 64, left side and Table 28), in which the original 450 Hp Pratt & Whitney R-985 Wasp Junior had been replaced with the Magni500. The prototype first flew for only 10 minutes on 10 December 2019 in Vancouver, Canada. In collaboration with AeroTec, MagniX also works on a retrofitted version of the 208B Cessna Grand Caravan, called the **MagniX eCaravan** (Figure 64, right side and Table 28). Powered by a Magni500, it first flew on 28 May 2020 at Moses Lake, WA, becoming the world's biggest ever all-electric commercially-focused aircraft [138, 139]. The Magni500 on the eCaravan receives power from a 750V lithium-ion battery system weighing roughly one tonne. Current batteries will allow to carry up to 5 passengers for a range of only 100 miles, hence MagniX is studying alternative technologies, including lithium-sulfur batteries and hydrogen fuel cells [140].


Figure 64: Left: The MagniX eBeaver. Right: The MagniX eCaravan [credits to MagniX].

| Parameter | Value (eBeaver) | Value (eCaravan) |
|---|---|---|
| Target EIS year | 2022 | 2021 |
| Powerplant Architecture | Full-Electric | Full-Electric |
| Motor Power | 750 Hp | 750 Hp |
| Number of Passengers | 6 | 5 |
| Design Range | 87 nmi | 87 nmi |

Table 28: Characteristics of the MagniX eBeaver and the MagniX eCaravan [138, 139, 141].

### 5.2.10 NASA X-57 "Maxwell"

The **NASA X-57** (Figure 65) was announced by NASA during the 2016 AIAA Aviation and Aeronautics Forum Exposition [142]. Research on the X-57 began as part of the Convergent Aeronautics Solutions project of NASA Aeronautics Research Mission Directorate's Transformative Aeronautics Directorate program, with flight demonstrations performed as part of the Flight Demonstration Concepts project in the Integrated Aviation Systems program. Nicknamed "Maxwell" in honor of the Scottish physicist James Clerk Maxwell, it is an experimental aircraft based on the aerodynamic advantages of distributed propulsion. It features 14 electric motors that rotate propellers integrated into a newly designed wing. NASA Aeronautics researchers intend to use the Maxwell to show that electric propulsion can make planes quieter, more efficient, and more environmentally friendly. The X-57 is studied and designed as part of NASA's SCEPTOR (Scalable Convergent Electric Propulsion Technology Operations Research) project starting from a baseline represented by the Tecnam P2006T twin-engine light aircraft.
Four incremental demonstrations ("Modifications") are utilized to mitigate risk throughout the SCEPTOR project [143]. As a part of Modification I, in 2015 the Leading Edge Asynchronous Propeller Technology testing (LEAPTech) performed the ground validation of the DEP system, on the Rogers Dry Lakebed at Edwards Air Force Base in California [37]. The tests, carried out on an experimental electric wing named the Hybrid Electric Integrated Systems Testbed (HEIST), validated that the airflow from the distributed 18 motors generated more than double the lift of the unblown wing. In Modification II the focus shifted to the electrical retrofit of the baseline and to the validation of batteries, engines and instrumentation. Distributed electric propulsion including nacelles was developed, manufactured and tested in Modification III. The P2006T was therefore retrofitted with 14 electric motors: 12 internal propellers located on the leading edge provide additional thrust during take-off and landing and 2 larger motors (98 Hp) on the wing tips are used for primary propulsive power in all other flight phases [9, 50]. Finally, Modification IV consists of flight tests aimed at optimizing the acoustic footprint, the control robustness at low speeds, and at delivering the X-plane in its final configuration.


Figure 65: Artist's concept of the X-57 Maxwell [credits to NASA Langley].

Table 29 reports some of the most relevant features of a recent revision of the concept. The use of DEP allows to accelerate the flow of air on the wing at low speeds, constituting a high-lift system that enables a 2.5x reduction in the wing area as compared to the original aircraft, and a shift of the condition of maximum efficiency aerodynamics to a higher speed. The wingtip-mounted cruise propellers entail a further efficiency increase connected to the interaction with the wingtip vortex.

| Parameter | Value |
|---|---|
| Target EIS year | 2020 |
| Powerplant Architecture | Full-Electric (with DEP) |
| Number of high-lift propellers | 12 |
| Battery Specific Energy | 130 Wh/kg |
| Number of Passengers | 2 |
| Wing Area | 6.20 $m^2$ |
| Wing Aspect Ratio | 15.0 |
| Wing Loading | 2,155 $N/m^2$ |
| Take-Off Gross Weight | 1,361 kg |

Table 29: Characteristics of the NASA X-57 "Maxwell" concept [9, 50].

NASA's SCEPTOR hopes to validate the idea that distributing electrical power to a number of motors installed on the wing in this way could result in a fivefold reduction in the energy required for a private plane to fly at 175 mph. Additionally, the X-57 "Maxwell" will be powered only by batteries, eliminating carbon emissions and leading to a further threefold reduction with respect to the piston engines. Finally, as electric motors are quieter than traditional piston motors, the X-57's electric propulsion technology is expected to significantly reduce aircraft noise.

### 5.2.11 Pipistrel Alpha Electro

The Pipistrel Alpha Trainer is a Slovenian 2-seat, single-engine light-sport aircraft intended specifically for flight training, whose production started in 2012. In 2015 Pipistrel introduced an electric version called the **Pipistrel Alpha Electro** (Figure 66), certified under the EASA's CS-23 standards. From the outside, the Electro is much quieter than its gasoline-powered version. It has a useful load of 172 kg, short take-off distance, and an endurance of one hour plus a 30-minute reserve (Table 30). Up to 13% of energy is recuperated on every approach, increasing operations range. Instead of 35 kg of fuel, it has 106 kg of Li-Po cells. The battery pack is dual-redundant and designed to be either quickly replaceable within minutes or charged in less than one hour thanks to the Pipistrel's Battery Management technology. The in-house 80 Hp electric motor only weighs 20 kg. The two-blade fixed-pitch propeller is made of wood with composite protection [144, 145].

Figure 66: The Pipistrel Alpha Electro [credits to Pipistrel USA].

| Parameter | Value |
|---|---|
| First Flight | 2015 |
| Powerplant Architecture | Full-Electric |
| Battery Specific Energy | 200 Wh/kg |
| Battery Capacity | 21 kWh |
| Engine Power | 80 Hp |
| Number of Passengers | 2 |
| Wing Span | 10.5 m |
| Wing Aspect Ratio | 11.8 |
| Propeller Diameter | 18 m |
| Take-Off Gross Weight | 550 kg |
| Design Range | 75 nmi |
| Maximum Endurance | 60 min |
| Cruise Speed | 85 kt |
| Maximum Speed | 100 kt |
| Service Ceiling | 12,800 ft |
| Rate of Climb | 1,220 ft/ min |
| Take-Off Distance (over 50 ft) | 870 ft |

Table 30: Technical specifications of the Pipistrel Alpha Electro [144, 145].

### 5.2.12 Pipistrel Panthera Hybrid

The Pipistrel Panthera (Figure 67) is an all-composite, efficient 4-seat aircraft developed by Slovenian Pipistrel. It first flew in April 2013 and is planned to have a certification by 2022. The gasoline-powered version of the Panthera is featured by a 260 Hp Lycoming I0-540V-V4A5, with 200 kt cruise speed for over 1,000 nmi [146]. The goal of the project is to design an airplane that can be equipped with three different types of propulsion: a conventional version, already on the market; a series hybrid-electric version now under development (**Pipistrel Panthera Hybrid**); a future pure electric one (**Pipistrel Panthera Electro**). Instead of 4 seats as for the baseline aircraft, the two innovative versions have only 2 seats to allow the housing of the batteries. The hybrid concept was the result of the EU funded HYPSTAIR program. Both hybrid and electric models reduce the noise footprint by taking advantage of the pure-electric take-off. The hybrid powerplant, fed by Li-Po batteries, aims to allow the same range as the baseline (see Table 31).

Figure 67: The Pipistrel Panthera Hybrid [credits to Pipistrel].

| Parameter | Value |
|---|---|
| Target EIS year | 2020-2021 |
| Powerplant Architecture | Series Hybrid-Electric |
| Maximum Power | 268 Hp |
| Number of Passengers | 2 |
| Length | 8.2 m |
| Height | 2.2 m |
| Wing Span | 10.9 m |
| Wing Aspect Ratio | 10.5 |
| Take-Off Gross Weight | 1,315 kg |
| Design Range | 540 nmi |
| Cruise Speed | 155 kt |
| Cruise Altitude | 12,000 ft |
| Rate of Climb | 1,150 ft/min |
| Take-Off Distance (over 50 ft) | 2,155 ft |
| Landing Distance (over 50 ft) | 2,316 ft |

Table 31: Technical specifications of the Pipistrel Panthera Hybrid [146, 147].

### 5.2.13 Pipistrel Taurus Electro

The Pipistrel Taurus is a Slovenian 2-seat microlight glider designed and built by Pipistrel. The Taurus is capable of self-launching thanks to a propeller mounted on the rear fuselage and powered by a Rotax 503 piston engine. The Pipistrel Taurus Electro was announced in 2007, and entered into service in 2011 [148, 149]. This variant had a Sinedon 40 Hp electric motor replacing the piston engine. In 2011, Pipistrel introduced an updated version of the Taurus Electro, the **Pipistrel Taurus Electro G2** (Figure 68). It was powered by tailor-developed lithium batteries intended to allow for self-launching to an altitude of 6,500 ft, after which the engine is retracted and the aircraft can soar as a sailplane. Pipistrel claims that the Taurus G2 has been the first electric 2-seat in serial production on the market [150].

Figure 68: The Pipistrel Taurus electro G2 [credits to Pipistrel USA].

A more advanced version was introduced in 2011: The **Pipistrel Taurus G4** (Figure 69). Its most distinguishing feature is a twin-fuselage design, which brings the advantage of a favourable span-load distribution significantly reducing wing-root bending moment. This means a decrease in the structural weight of the aircraft, allowing the Taurus G4 to have an empty weight fraction (excluding batteries) of 42% of the total gross weight. Its battery system consists of three parallel-connected groups of 88 series-connected Li-Po cells, organized in 11 packs of eight cells each and providing a total capacity which exceeds 90 kWh. One battery group is installed in each fuselage, and one battery group is installed in the nacelle [49]. The 2-blade propeller provides 200 Hp rotating at 5,500 RPM. Taurus G4 Won NASA’s Green Flight Challenge competing against the eGenius in 2011. Table 32 offers a comparison between some of the technical features of Taurus Electro G2 and Taurus G4.


Figure 69: The Pipistrel Taurus G4 [credits to Pipistrel].

| Parameter | Value (Taurus Electro G2) | Value (Taurus G4) |
|---|---|---|
| First Flight | 2007 | 2011 |
| Powerplant Architecture | Full-Electric | Full-Electric |
| Battery Specific Energy | 169 Wh/kg | 180 Wh/kg |
| Battery Capacity | 7.1 kWh | 90 kWh |
| Motor Power | 40 Hp | 200 Hp |
| Number of Passengers | 2 | 2 + 2 |
| Length | 7.3 m | 7.4 m |
| Wing Span | 14.9 m | 21.3 m |
| Propeller Diameter | 1.6 m | 2.0 m |
| Maximum Take-Off Weight | 550 kg | 1,500 kg |
| Cruise Speed | 62 kt | 87 kt |
| Climb Rate | 610 ft/min | 885 ft/min |
| Take-Off Distance (over 50 ft) | 800 ft | 1,970 ft |

Table 32: Technical specifications of the Pipistrel Taurus Electro G2 and G4 [49, 50, 149, 150].

### 5.2.14 Rolls-Royce ACCEL

Half funded by the UK government via the Aerospace Technology Institute, the "Accelerating the Electrification of Flight" (**ACCEL**) program is aimed at designing, building, testing and commercializing a fully electric aircraft. The aircraft (Figure 70), dubbed "**Spirit of Innovation**", uses electric motors and controllers from YASA and aviation startup Electroflight [151]. The ambitious goal of the Innovation aircraft is to break the world record by becoming the fastest electric aircraft in the world and surpassing the 185.13 kt top speed of the Extra 330LE and aiming for speeds of over 260 kt (see also Table 33) [152]. The battery pack was designed and assembled for providing enough energy to fly 200 miles on a single charge. Its 6,000 liquid-cooled cells are packaged for maximum lightness and thermal protection. These drive a 750 V powertrain made up of three lightweight YASA 750R electric motors (weighing only 37 kg each) capable of providing a total of 500 Hp to the propeller at 2,400 RPM with increased stability and very low noise emissions. At maximum power the emission-free system delivers about 1,000 Hp. The airframe, especially designed for air racing, was developed from John Sharp's Nemesis NXT. Sensors will collect in-flight information across more than 20,000 points on the powertrain every second, measuring battery voltage, temperature and general performance metrics.


Figure 70: The Rolls-Royce ACCEL’s Spirit of Innovation [credits to Rolls-Royce].

| **Parameter** | **Value** |
|---|---|
| Target EIS year | 2020 |
| Powerplant Architecture | Full-Electric |
| Maximum Power | 1,000 Hp |
| Number of Passengers | 1 |
| Length | 7.0 m |
| Height | 7.3 m |
| Range | 174 nmi |
| Maximum Speed | 260 kt |

Table 33: Technical specifications of the Rolls-Royce ACCEL’s Spirit of Innovation [152].

### 5.2.15 Siemens/Diamond DA36 E-Star

The Diamond HK36 Super Dimona is an extensive family of Austrian low-wing, T-tailed, two-seat motor gliders currently produced by Diamond Aircraft Industries. The series started with the Hoffmann H36 Dimona in the early 1980s. Later members of the family added slightly greater span and improved the glide ratio by adding winglets. Developed by Siemens, EADS and Diamond Aircraft with the goal of reducing fuel consumption and emissions by up to 25% when compared to conventional aircraft, the **Siemens/Diamond DA36 E-Star** (Figure 71 and Table 34) was the first airplane to use a serial hybrid-electric architecture drive. The propeller is powered by a Siemens 94 Hp electric motor. Electricity is supplied by a small Wankel engine from Austro Engine with a generator that functions solely as a power source. A Siemens converter supplies the electric motor with power from the battery and the generator. Fuel consumption is claimed to be very low since the combustion engine always runs with a constant low output of 40 Hp. A battery system from EADS provides the increased power required during takeoff and climb, and is recharged during the cruising phase. A 40 Hp Austro Engines' Wankel rotary serves as generator, producing energy which is stored in batteries provided by EADS. The prototype first flew 8 June 2011 [153]. An improved version, named the **Siemens/Diamond DA36 E-Star 2**, had a new integrated hybrid drive system developed by Siemens, around 100 kg lighter than that of the predecessor model of 2011.


Figure 71: The Siemens/Diamond DA36 E-Star [credits to Diamond Aircraft].

| **Parameter** | **Value** |
|---|---|
| First Flight | 2011 |
| Powerplant Architecture | Series Hybrid-Electric |
| Maximum Power | 94 Hp |
| Number of Passengers | 2 |
| Length | 7.1 m |
| Height | 1.7 m |
| Wing Span | 16.0 m |
| Maximum Take-Off Weight | 798 kg |

Table 34: Technical specifications of the Siemens/Diamond DA36 E-Star [50].

### 5.2.16 Siemens/Extra 300LE

The **Siemens/Extra 330LE** (Figure 72) is a two-seat aircraft based on the German-built Extra 300L. It is constructed with light-weight materials and is suitable for 20-minute flights, including take-off, climbing and five minutes of full-throttle flight. Its all-electric drive system was five times larger than other systems available on the market, enabling it to provide a sustainable means of transportation with carbon-free emissions. Extra 330LE is powered by a 50 kg electric SP260D motor with a power output of 348 Hp [154]. The electric motor was developed by Siemens with support from Germany's Aeronautics Research Program (LuFo). The motor, turning the propeller at 2,500 RPM, has a maximum coolant inlet temperature of 90°C and an efficiency of 95%. The aircraft features two battery packs, each with 14 high-power Li-Ion battery modules with a capacity of 18.6 kWh. The Extra 330LE prototype was developed by Extra Aircraft in partnership with Siemens, MT-Propeller and Pipistrel and first flew in 2017 [155].


Figure 72: The Extra 300LE [credits to Extra Aircraft].

| Parameter | Value |
|---|---|
| First Flight | 2017 |
| Powerplant Architecture | Full-Electric |
| Maximum Power | 348 Hp |
| Motor Power Density | 5.2 kW/kg |
| Battery Capacity | 18.6 kWh |
| Number of Passengers | 2 |
| Length | 7.5 m |
| Height | 2.6 m |
| Wing Span | 8.0 m |
| Aspect Ratio | 5.9 |
| Maximum Take-Off Weight | 998 kg |
| Maximum Speed | 185 kt |
| Climb Rate | 2,300 ft/min |

Table 35: Technical specifications of the Siemens Extra 300LE [50, 154, 155, 156].

### 5.2.17 Volta Volaré DaVinci

Offering a high level of comfort, luxury and silence of the interior, the **Volta Volaré DaVinci** (Figure 73) was developed by the Oregon-based Volta Companies. The DaVinci is claimed to offer a much lower cost per passenger mile than any other aircraft in its class [157]. During take-off and climb (and for short cruising segments) the propulsive power is capable of being supplied by only batteries. While cruising, the range extension generator uses 100LL or automotive gasoline to recharge the battery packs in flight with a power of 180 Hp. The aircraft can be recharged on the ground in a few hours by connecting it to a normal 220V power supply (all adapters included) or by installing Hi-Flex solar wings. Alternatively, the series-hybrid drivetrain can be charged by common aviation fuel available at nearly any airport, which greatly increases the aircraft's versatility. The aircraft features a pusher-canard configuration, and the propeller behind the cabin allows to take advantage of boundary layer ingestion and safeguard a cleaner airflow on the wing. The series-hybrid drivetrain is provided with a Volta Aero Tech 300 Hp EViation Drive, a Range Extender and a 58 kWh Energy Storage System (ESS). According to Volta Volaré, the EViation Drive and the ESS deliver more torque and horsepower than any 20th century internal combustion engine and requires one-tenth maintenance, performing silently and with near-zero emissions [157]. Other technical specifications and performances are listed in Table 36.

| **Parameter** | **Value** |
|---|---|
| EIS year | 2017 |
| Powerplant Architecture | Series Hybrid-Electric |
| Engine Power | 300 Hp |
| Battery Capacity | 58 kWh |
| Number of Passengers | 2 + 2 |
| Wing Span | 9.5 m |
| Canard Span | 4.8 m |
| Height | 2.4 m |
| Take-Off Gross Weight | 1,724 kg |
| Empty Weight | 1,179 kg |
| Wing Loading (Landing) | 618 N/m$^2$ |
| Range at 55% with Generator | 1,000 nmi |
| Cruise Speed | 160 kt |
| Cruise Altitude | 12,500 ft |
| Maximum Speed (S/L) | 310 kt |
| Service Ceiling | 24,000 ft |
| Rate of Climb | 1,800 ft/min |
| Take-Off Distance | 1,400 ft |
| Landing Distance | 1,500 ft |

Table 36: Technical specifications of the Volta Volaré DaVinci [157].

Figure 73: The Volta Volaré DaVinci [credits to Volta Volaré].

# 6 Conclusions

The objective of identifying projects constituting the state of the art (SOTA) is the definition of an industrial and technological framework for the ELICA project. While listing the promising enabling technologies studied on other projects and the related characteristics, the comparison with ELICA top level aircraft requirements and considered technologies is a mandatory step to evaluate the competitiveness of the present project.

Since projects dealing with fuel-cell or hydrogen are still a minor portion of industrial projects, the characteristics of these technologies and the limits directly connected to their applications are not considered in the present conclusions except for two different considerations which would be sufficient to drive the future steps of ELICA if fuel-cell and hydrogen propulsive systems are considered.

The first consideration is that the high efficiency of fuel-cells would be an interesting objective for a close future, but it is not compliant with the scope of the present project which targets near zero emissions. On the other hand, hydrogen can be considered an interesting alternative but studies on these concepts are still at early stages due to security issues related to $H_2$ storage and combustion procedure. Thus, the second consideration deals with the severity of these issues, it could be necessary to further investigate these aspects before choosing this technology.

About the hybrid-electric technologies, the importance of the battery characteristics has been stressed in all the projects presented employing hybrid-electric propulsion, even more than the enhancement of e-motor drives characteristics. The relationship of battery energy density and the design range of these concepts is clearly shown in Figure 74. The conclusion stated by the figure is that long range aircraft are only possible when approaching to futuristic energy density of the batteries.

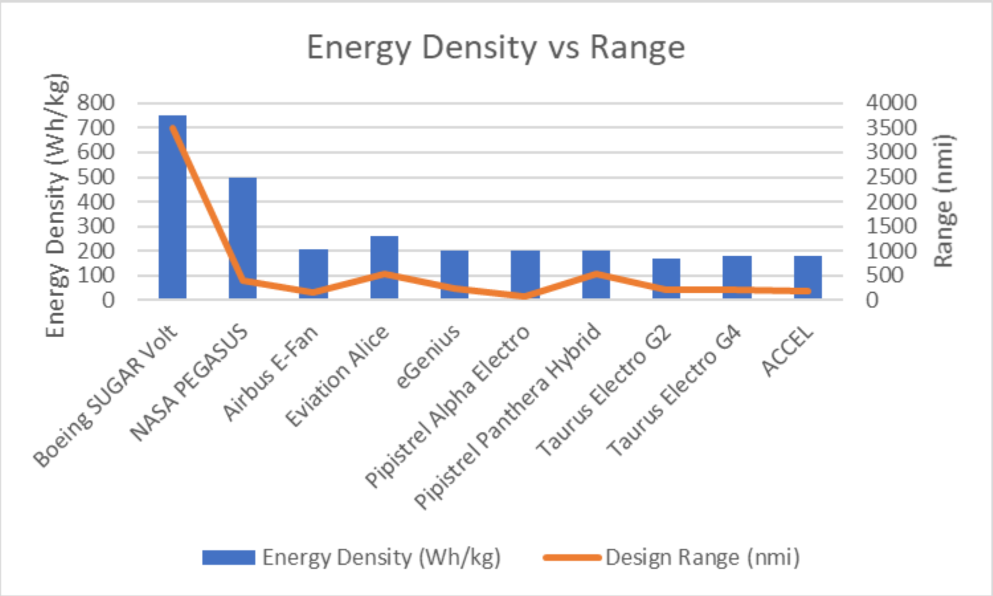



Figure 74 - Energy density and design range of different aircraft projects.

The energy density of batteries in case of design range higher than 200 nautical miles requires energy density higher than 250 Wh/kg, which can be considered a value compatible with the state of the art. This can be considered an acceptable range in case of small air transports, which are the scope of the present project, but also when coming to the typical mission range of commuter aircraft.

The requirements have been fixed in the previous documents and here reported in Table 37 to investigate the battery characteristics necessary to be compliant with TLAR. Since the design range is around 234 nautical miles, an energy density of about 250 Wh/kg is necessary. At the same time, high specific power and C-rate are required. A high value of the supplied power ratio, that is the quantity of power supplied by the e-storage with respect to the total power supplied, is synonymous of lower fuel burned, but also of maximum required power. This is way a high specific power and C-rate are also necessary.

Table 37 - T.L.A.R. identified for the ELICA project.

| Parameter | Value | Remark | Req. type | Source |
|---|---|---|---|---|
| Max. MTOM | 8,618 kg | *Certification limit* | Maximum | CS-23 |
| Payload | 2,000 kg | - | Optimum | D2.1 & Benchmark |
| Take-off distance total | 700 m | *Sea level, MTOM, ISA, Flaps 50%* | Maximum | Benchmark |
| Take-off field length | 1,000 m | | Maximum | D2.1 & Benchmark |
| Long range cruise speed | 375 km/h | - | Minimum | D2.1 & Benchmark |
| High speed cruise | 430 km/h | - | Minimum | Benchmark |
| Noise | 75 dB(A) | *ICAO Annex 16 Volume I* | Maximum | Benchmark |
| Design range | 435 km | *1,500 kg payload* | Optimum | D2.1 |
| Max. range | 1,400 km | | Minimum | Benchmark |
| Revenue/RPK | 0.5 €/RPK | *See D2.1 – revenue to allow ~10% margin* | Optimum | D2.1 |
| Certification basis | CS-23 | - | Fix | Benchmark |
| Flight conditions | VFR, IFR, FIKI | *Required for weather independent operations* | Fix | Benchmark |
| Powertrain | Hybrid | - | Fix | ELICA |
| Cabin layout | Modular approach for PAX & Cargo transport or special missions, high passenger comfort (e.g. upright walk) | | Fix | D2.1 & Benchmark |

Considering the technologies nowadays available, a Li-Ion battery seems to be interesting for both the cost and the lifetime, however, in case of aviation application, a Li-S would be more suited. In fact, it has a higher specific energy with respect to Li-Ion cells, but still a longer lifespan of $Li\text{-}O_2$ cells.

Table 38 - Different Battery Technologies.

| **Parameter** | **Unit** | **Li-Ion** | **Li-S** | **$Li\text{-}O_{2,open}$** | **$Li\text{-}O_{2,closed}$** |
|---|---|---|---|---|---|
| Specific Energy | Wh/kg | 250-350 | 600-700 | 800-1500 | 600-1200 |
| Specific Power | W/kg | 500-600 | 350-500 | 300-400 | 300-400 |
| Energy Density | Wh/l | 600-800 | 300-350 | 1000-1700 | 1000-1600 |
| Charge/Discharge efficiency | % | 90-95 | 70-90 | 60-85 | 60-85 |
| Cycle life # | cycles | 1000-3000 | 1000-2500 | 500-1000 | 500-1000 |
| Degree of Discharge | % | 70-90 | 90-100 | 70-90 | 70-90 |
| Cost ($ 2010) | $/kWh | 250-350 | 250-500 | 400-800 | 300-700 |

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