VOLTAIR - THE ALL ELECTRIC PROPULSION CONCEPT PLATFORM – A VISION FOR ATMOSPHERIC FRIENDLY FLIGHT

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Abstract

"VoltAir" – The all-electric transport concept platform is being presented. VoltAir is a technological vision by EADS Innovation Works for aero propulsion without CO_2 or water emissions during flight. Applying ultra-high capacity battery systems and high density electric motors in an energy efficient airframe, all-electric passenger transport could become reality in future air traffic.

1 Introduction

Europe's vision for aviation, as presented in the European Commission's report Flight Path 2050 [1], sets very ambitious targets for reducing aircraft emissions. These goals include a reduction of CO_2 emissions by 75%, NO_x by 90%, and noise levels by 65% compared to the year 2000. At the same time, the world air traffic is expected to double within the next 15 years. Between these conflicting priorities of traffic growth on the one hand and climate protection on the other, radical new approaches in terms of airframe design and propulsion systems are necessary on a long term basis to accomplish both ambitious goals.

Dealing with a similar challenge, the car industry recently initiated extensive research programs to develop an alternative propulsion concept to market readiness: the electric powertrain. The past years have shown significant improvements in the key technologies, namely high-capacity electric energy storage, efficient energy transmission and power management, as well as light-weight electric motors. As a result, electric cars are reaching reasonable ranges for daily use and first automakers announced the introduction of electric cars in high-volume production.

Anticipating ongoing investments and a growing market for electric vehicles within the next years, the question arises whether the technology of electric propulsion could also become feasible for commercial air transportation. With the expansion of renewable energy sources decided and heavily subsidized in many countries, electric power could evolve into a sustainable enabler of zero emission transportation in the future. Thus, substituting at least a fraction of the predicted growth in air traffic with electric propulsion aircraft would contribute significantly to reach the target emission goals. However, because of its higher specific weight, electric propulsion is not viable for transport aircraft based on today's technology level. Since weight is a much stronger cost and design driver for air vehicles compared to ground vehicles, further improvements in the electric propulsion system weight are necessary to realize aircraft with reasonable mission capabilities.

Predictions for the development of the main components of an electric powertrain have been published in several technology roadmaps. In this report, these predictions are summed up and weight trends for potential future electric aircraft propulsion systems are presented. The weight impact due to electric propulsion, as well as limits in payload and range capability are shown in preliminary design of electric turboprop-category aircraft. Finally, an energy efficient aircraft configuration is proposed as a mean to mitigate the weight impact and extend the limits for electric propulsion aircraft: the VoltAir concept platform.

2 Components of the Electric Powertrain

2.1 Storage of Electric Energy

One of the biggest challenges for potential electrically propelled aircraft is the storage of a large amount of electric energy at low volume and low weight. In principle, various technologies including fuel cells are possible candidates for energy storage. Since water emitted by fuel cells also affects the heat balance of the atmosphere at certain altitudes (e.g., by cirrus clouds), only rechargeable battery systems are considered for energy storage in this paper.

Boosted by the large demand in automotive applications and mobile electronic devices, high-density batteries have achieved impressive advances in their capabilities during the last decade, improving:

- gravimetric energy density Wh/kg;
- volumetric energy density Wh/l;
- gravimetric power density W/kg;
- cycle stability; and
- operational safety

Today's state of the art rechargeable batteries reach an energy density in the range of 100-200 Wh/kg and 250-400 Wh/l for Li-Ion systems at good cycle performance [2] [3]. For special applications, up to 350-380 Wh/kg have been demonstrated with a Li-S system, e.g., in the long endurance UAV "Zephyr", though with a limited number in recharging cycles [3]. Regarding power density, some Li-Ion cells optimized for high power output reach up to 1800 W/kg [4].

Comparing the energy density of today's batteries with conventional aircraft fuels shows the main challenge of battery powered aircraft. Kerosene is, providing 94.5 kWh/m³ and 12.5 kWh/kg, one of the highest energy density fuel available. Taking into account the efficiency of a conventional power train including internal combustion engine, still one third of the fuel energy (~ 4 kW/kg) is available at the propulsor unit (fan, propeller, etc.).

For that reason, manned battery powered aircraft are currently limited to small aircraft and short ranges, for example, the "Pipistrel Taurus G4" or eGenius. Both aircraft demonstrated a 200 miles range carrying two pilots in the NASA funded "Green Flight Challenge". [5]

Aiming for commercial air transport, battery systems with much higher energy density are necessary to achieve reasonable payload-range capabilities. While state of the art batteries are constantly improving in incremental steps, fundamentally different storage concepts are envisaged for the mid- to long term future. Among these, open-cycle battery systems like Zinc-Air and Lithium-Air are currently being tested with Li-Air yielding the highest theoretical available storage density. This cell type uses free oxygen from the atmosphere (or from a storage device) to oxidize the lithium to lithium-oxide or peroxide:

$$2Li + O_2 \longrightarrow Li_2O_2; \; G_0 = -145 \; kCal \quad (1)$$

The theoretical specific energy of this reaction is 5200 Wh/kg including the mass of the oxygen [3]. This value will be significantly reduced on cell level due to further required elements like electrolytes, housing, etc. A schematic view of a Li-Air battery system is shown in Figure 1.

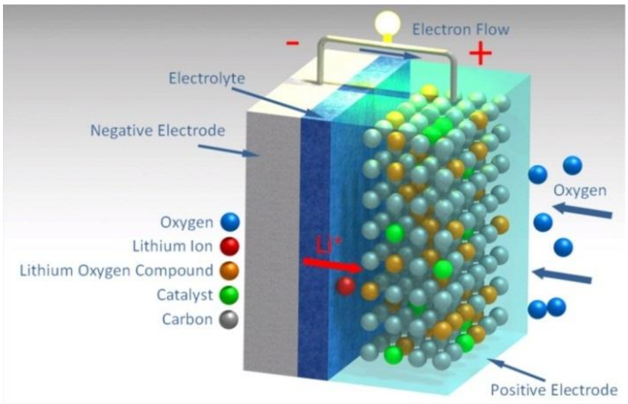

Figure 1, Lithium-Air Battery

In contrast to conventional batteries, Li-Air systems are constantly gaining weight by accumulating oxygen during discharge.

Considering the reaction chemistry this mass increase can be estimated as follows:

- Reaction Potential Li_2O_2: 3.1 V
- Faraday constant: 96485 C/mol
- Specific mass O_2: 0.016 kg/mol

For Li_2O_2 follows:

$$\Delta m = \frac{0.016\frac{kg}{mol}\cdot 3600\frac{C}{Ah}}{3.1V\cdot 96485\frac{C}{mol}} = 1.92\cdot 10^{-4}\frac{kg}{Wh} \qquad (2)$$

The energy density of Li-Air systems (discharged, including oxygen) is predicted to reach values between 750 and 2000 Wh/kg on cell level. Visco predicts 1000 Wh/kg [6], Girishkumar 1700 Wh/kg [2], Johnson up to 2000 Wh/kg. Johnson also predicts the power density to be in the range of 400 to 640 W/kg [7]. Market readiness is considered in the timeframe 2030 [8].

While the values cited here are based on the battery cell level, additional weight for cooling, cell monitoring and power control has to be taken into account for the whole battery system. In battery systems of hybrid/-electric cars today, the cell itself only accounts for around 40% of the whole system weight [3]. Assuming further weight optimization potential for airborne applications and a higher cell weight share for larger battery systems, a 50% weight share for the cell and 50% for the systems is assumed for further calculations.

2.2 Electric Motors

In electric propelled aircraft, the electric motor substitutes the combustion engine and converts the electric power delivered by the batteries into mechanical shaft power to run the propeller/ or fan propulsor. Obviously, the motor should feature a high power density to minimize weight and a high efficiency to minimize losses and cooling requirements.

Due to the fact that electric motors have been used largely in stationary, ground based applications, cost was the predominant design driver in the past. Only when the car industry asked for compact and low weight electric motors for hybrid and e-mobility vehicles, the research and development for high power density electric motors was intensified. Aiming for this demand, e.g., Remy Motors Inc. is offering its HVH 250 series motors with up to 7-8 kW/kg (excluding additional components for cooling and power control) at 300 kW peak power in the speed range of 3000 to 4000 RPM [9].

For aircraft propulsion, the required shaft power is about an order of magnitude higher than for the high power density motors described above. Scaling up motors like the HVH 250 to the MW class leads to unfavorable trends related to physical sizing laws. The ratio of outer (cooling-) surface to internal motor volume is getting worse with growing motor size, which hampers efficient heat dissipation. In ground based applications like power plant generators, this issue is addressed using “oversized” conductor cross sections to minimize ohmic heat losses, at the cost of a bulky and heavy motor layout.

Superconductivity could be a key technology for light-weight and high-power electric motors, suitable for airborne applications. Replacing copper-, aluminum- and iron-based conductors on the rotor or even the stator with superconducting materials, the magnetic flux density can be increased significantly at less weight and almost zero losses. The main drawback of this technology is that superconducting materials required operating temperatures of below 5 K (low temperature superconductors, LTS), or 80K (high temperature superconductors, HTS) respectively. The required cryogenic cooling system partly offsets the weight advantage of the lighter motor. However, in this case the physical sizing laws mentioned above are in favor of bigger motors, since the motor surface and hence the heat in-leak grows slower than the motor volume and power.

Superconducting motors in the MW class have been demonstrated by for ground based [10] and airborne [11] applications. Masson and Luongo proposed preliminary motor designs for distributed propulsion systems in airborne applications [12] [13]. Based on their results, Buysschaert addressed weight trends for superconducting motors including cryogenic cooling system [14]. His results indicate that superconducting motors could match the power density of turbo-shaft engines with 8 kW/kg at low speeds (3000 RPM) and exceed 25 kW/kg at high speeds (20000 RPM).

Since propellers of turboprop aircraft operate in the range of 1000 to 1200 RPM, a reduction gearbox between motor and propeller is necessary. Plecner provides a method for gearbox weight estimation, depending on gear-ratio and maximum propeller torque [15]:

$$m_{gb}[lb] = (\tau \cdot 0.0174 + 45lb) \cdot (0.118/GR)^{0.5} \quad (3)$$

Assuming a propeller speed of 1200 RPM, the gear ratio is defined and the propeller torque can be calculated depending on the mechanical shaft power. The resulting weight trends for the HTS motors with and without reduction gearbox are shown in Figure 2.

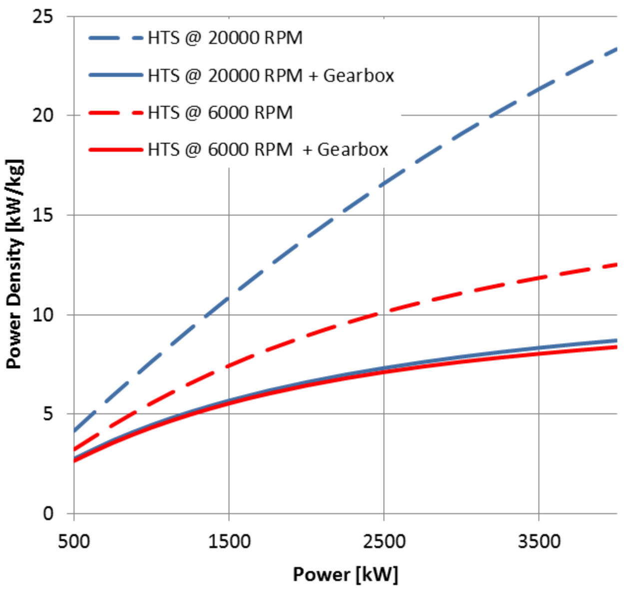

Figure 2, HTS Motor Weight Trends

2.3 Power Management and Distribution

For power distribution across the electric powertrain and aircraft subsystems, voltage type (AC or DC), voltage level, and conductor material have to be chosen to match safety requirements at minimum weight. Furthermore, the overall powertrain architecture must include sufficient redundancy to maintain airworthiness after a failure of any system component.

Minimizing electromagnetic interference and saving cable weight, DC voltage is proposed for a main bus transmitting electric power from the battery system to the motors. Due to its low specific weight and good conductivity, aluminum is chosen as conductor material for the main bus. Allowable current densities for this type of conductors are taken from DIN standard 43 670. The electric current required to transmit a certain power is directly related to the transmission voltage. In order to keep the electric current and thus the conductor weight as small as possible, a high transmission voltage is needed. The limiting factor is the risk of electric arcing, which is increasing with altitude due to the lower air density [16]. While the actual suitable voltage level is depending on the detailed conductor design, a transmission voltage of 1 kV DC is assumed for further calculations. In this "low voltage" category, the International Electrotechnical Commission (IEC) considers the risk of electric arcing to be low.

For motor power and speed control, a converter/ inverter module is necessary to connect the motor to the DC distribution system. Motor converters today reach power densities around 11 kW/kg, while weight improvements by using new semiconductor materials and cryogenic cooling are anticipated. Masson [12] projects a factor three in potential weight reduction. In the context of this paper, a power density of 20 kW/kg is assumed.

3 Modeling of Electric Propulsion Aircraft

3.1 Sizing Methodology

For the evaluation of the performance and limitations of future electric propulsion aircraft, the electric powertrain as described above is integrated in preliminary aircraft design. The structural weight of the aircraft main components as well as the aerodynamic performance is modeled using methods according to Torenbeek **[17]**. The propulsive efficiency of the propeller is determined using a momentum-theory based approach **[18]**.

As outlined in the last chapter, the most promising battery technology being investigated today is the Lithium-Air battery. Since this type of battery is gaining mass during discharge, the aircraft weight continuously increases during the flight mission, which hast to be taken into account for the calculation of the mission energy demand. For this reason the design mission is separated into short time segments (few minutes) and the actual mass, lift and drag coefficient, required thrust and consumed energy are calculated for each segment. This procedure is outlined in Figure 3.

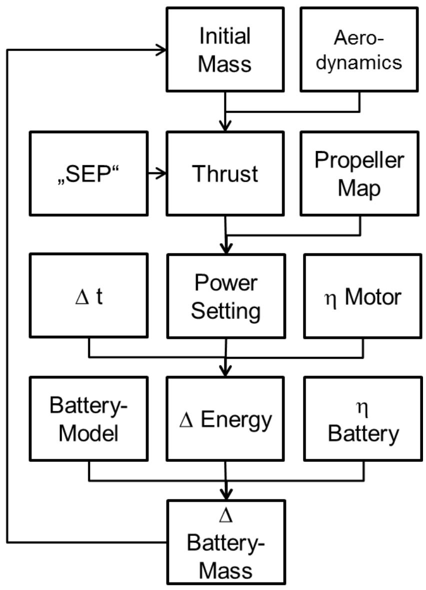

Figure 3, Modeling of Battery Weight Gain

The required size of vertical and horizontal tail is determined by a tail volume method according to Raymer **[19]**. The wing loading and the required installed power are determined with respect to the field and cruise performance requirements, as well as the CS 25 certification standards (second segment and missed approach climb gradient). In order to find an optimal design point where all requirements are met, a matching chart approach is used as suggested by Loftin **[20]**.

3.2 Results for Electric Propulsion Aircraft in Conventional Configuration

3.2.1 Electrified Turboprop-Category Aircraft

In a first step, an aircraft in conventional configuration is being sized with an electric powertrain. Using turboprop category aircraft as the reference, the design requirements resulting from certification standards and the mission requirements are as follows:

- Payload 68 PAX
- Range 900 NM
- Design Speed 500 km/h
- TOFL/ LFL 1300 m
- Second segment climb gradient (OEI) 2.4 %
- Missed approach climb gradient (OEI) 2.1 %

On the basis of these requirements, a preliminary aircraft design is performed using a parametric sizing code implemented in a numeric environment. In Figure 4, the resulting matching chart for wing loading and power-to-weight ratio is shown and the critical design constraints can be identified: for the considered electric aircraft, the landing field length and the takeoff field length are critical to determine the design point. In contrast to gas turbines, the power provided by electric motors is independent of the air density. Hence the full installed take-off power is available also in high level cruise and the cruise requirement becomes uncritical (given that the battery system is able to deliver the required power). In the case of the aircraft considered, also the second segment climb and missed approach climb are less stringent compared to the TOFL and LFL requirements.

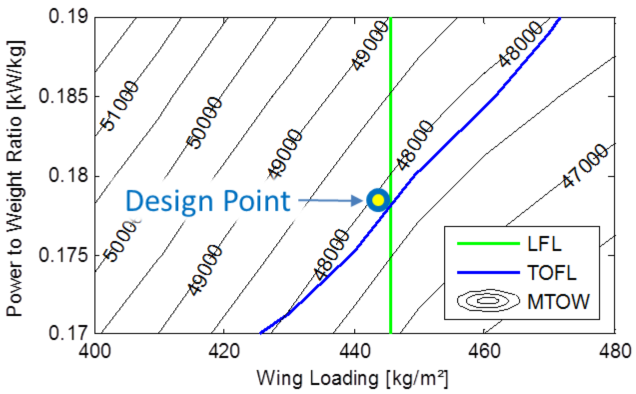

Figure 4, Electric Aircraft Matching Chart

While wing loading (444 kg/m²) and power-to-weight ratio (0.18 kW/kg) are in the typical range of turboprop aircraft, the weight penalty caused by the electric powertrain is significant.

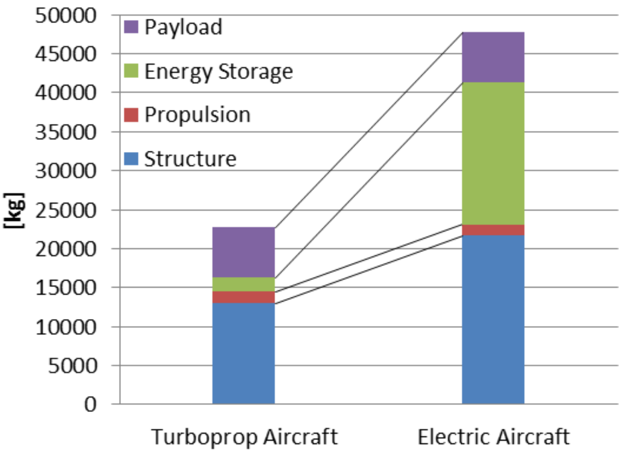

Figure 5, Weight Comparison

With 18 tons, the 1000 Wh/kg battery system is roughly 10 times heavier than the fuel of a corresponding aircraft with conventional propulsion. Yet, matching the field performance requirement, a large wing area of 107 m² and 8500 kW installed motor power are necessary. In total, the maximum gross weight of the electrified aircraft almost doubles compared to the reference aircraft, reaching 47,740 kg. A weight breakdown of the main components is shown in Figure 5, a three side view of the electric aircraft is shown in Figure 6.

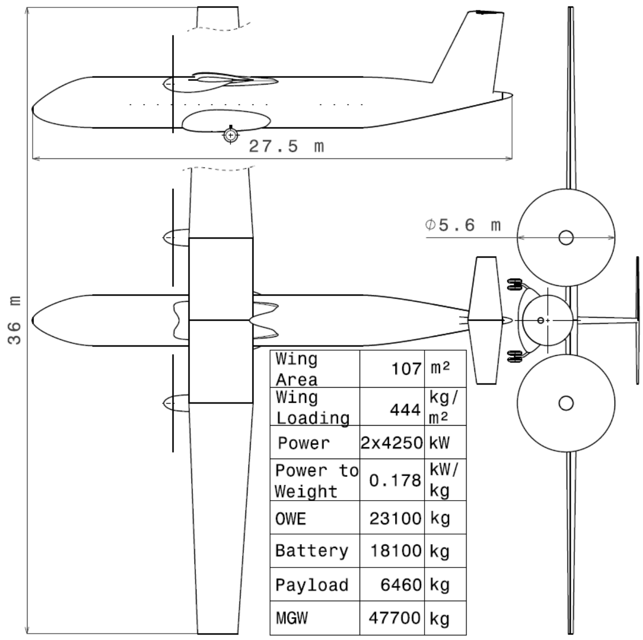

Figure 6, Electric Aircraft Three Side View

3.2.2 Design Space Exploration

After the assessment of a single point design for an electric propulsion aircraft was presented in the last section, the design space for payload and range is explored in the following section. Therefore, the cabin size and payload is varied from 23 to 95 passengers and the design cruise range from 500 to 1300 NM. For various combinations a preliminary design is performed, using the same sizing methods and technology assumptions as for the single point design in the last section.

In Figure 7, the resulting maximum gross weight for each combination is plotted over payload and range. Convergent designs are found up to an aircraft gross weight of around 60 to 70 tons. Above this limit, the growth in propulsion system weight and the related growth in aircraft size lead to an escalation in the aircraft sizing process and no convergence is reached. The location of this limit in the design space is depending on the technology level of the propulsion system, mainly the energy density of the battery. With higher energy density batteries available, the battery weight decreases and the limit in the design space is shifted toward higher transport capacities. In Figure 8, the impact of different battery system energy densities is shown. It is found, that a minimum of 1000 Wh/kg is necessary to match the design missions of the majority of commercial turboprop class aircraft in service today. If the available battery technology is limited to 750 Wh/kg, only small turboprop aircraft like ATR 42 are feasible with electric propulsion.

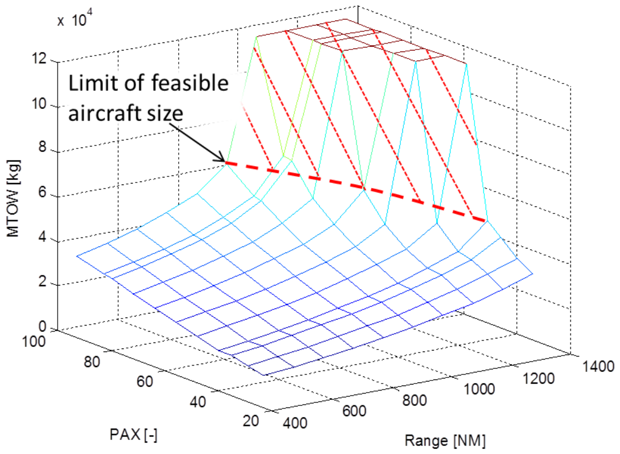

Figure 7, Aircraft Weight Results (1000 Wh/kg Battery System)

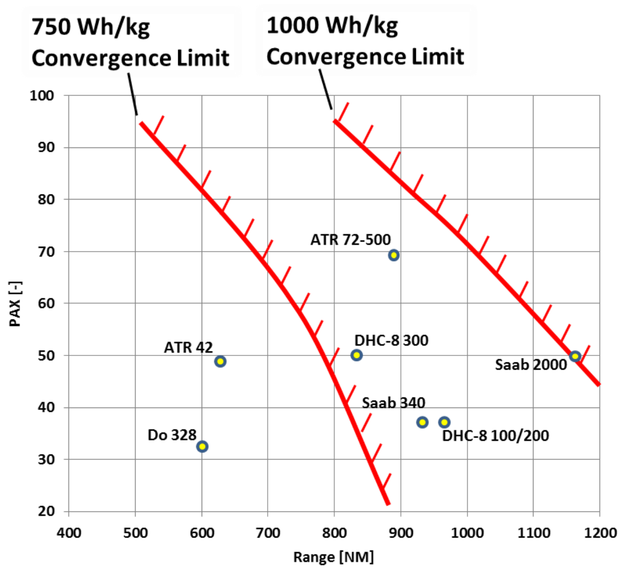

Figure 8, Design Limits for Electric Aircraft

3.3 Results for a high efficient configuration VoltAir

While in principle physically feasible, the weight penalty of electric propulsion aircraft compared to today's conventional aircraft is substantial, as results have indicated so far. These penalties could be reduced by more sophisticated battery systems with higher energy density than predicted for Li-Air cells. Tough, no such battery system is in sight today and even to achieve the values predicted for Li-Air is ambitious. Another approach to reduce the weight penalty is to minimize the inflight energy consumption using a highly efficient airframe design and an energy optimized flight profile. The VoltAir concept platform presented hereafter addresses this solution.

A promising and effective approach to reduce aircraft drag and hence reduce energy consumption is the laminar flow technology. High subsonic aircraft require complex active flow control systems to achieve laminar flow on the wing due to high Reynolds numbers, wing sweep, and gaps at the leading edge due to high lift devices. Hence, laminar flow was yet only utilized for small aircraft. By contrast, the low flight speed of turboprop aircraft, unswept wings and the absence of leading edge high lift devices favors the use of laminar flow. On this basis, laminarity can be maintained for about 50-60% of the wing chord length by proper airfoil shaping alone **[21]**. Figure 9 shows the limits of laminar flow due to shaping (natural laminar flow) and the operating point of a typical turboprop aircraft wing.

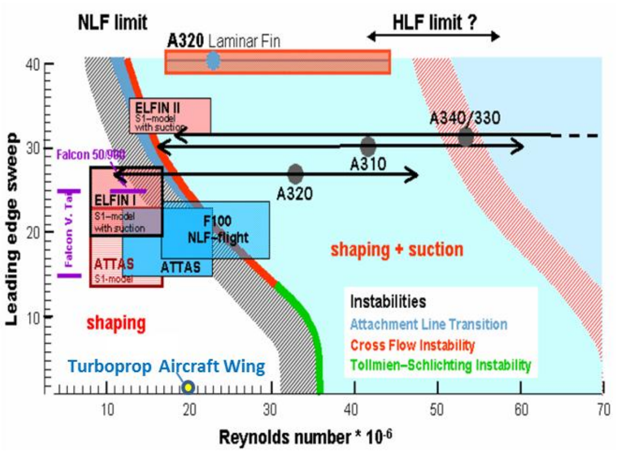

Figure 9, Limits of Laminar Flow [21]

While general conditions on a turboprop aircraft wing are in favor of laminar flow, the installation of propellers in front of the leading edge eliminates any chance for laminarity on a large portion of the wing. This problem can only be solved if the conventional configuration of turboprop aircraft is abandoned and a different concept for propulsion integration is found that does not disturb the flow field of the wing. A possible solution is the pusher configuration that was successfully demonstrated in various designs in aviation history. While easily applicable for small aircraft and UAV's, the installation of the propellers at the tailcone of a large passenger aircraft hampers the ability for take-off rotation. The required propeller ground clearance interferes with the rotation scrap angle, as shown in Figure 10. To avoid this issue, a 6-abreast fuselage cross section is chosen instead of a typical 4-abreast layout, leading to a wider and shorter fuselage. This configuration provides several advantages:

- Due to the shorter fuselage, the propeller clearance at take-off rotation is increased.
- The wing can be integrated in a low wing configuration with the wing box in the under floor as in standard narrow-bodies.
- The landing gear can be stowed within the fuselage under floor, eliminating the need for an additional wheel-bay fairing.
- The lower slenderness ratio of the fuselage provides more useful volume, facilitating the integration of bulky battery installations.
- The lower slenderness ratio provides better structural efficiency and hence lower weight. **[17]**
- The propellers ingest and accelerate low momentum fuselage boundary layer air, increasing propulsive efficiency. **[22]**

Further adding a shroud around the propeller(s) accounts for:

- Increased static thrust for improved take-off performance **[18]**
- Increased longitudinal and yaw stability
- Propeller noise shielding

The geometrical considerations regarding propulsion integration are displayed in Figure 10, a graphic of the VoltAir configuration is given in Figure 11.

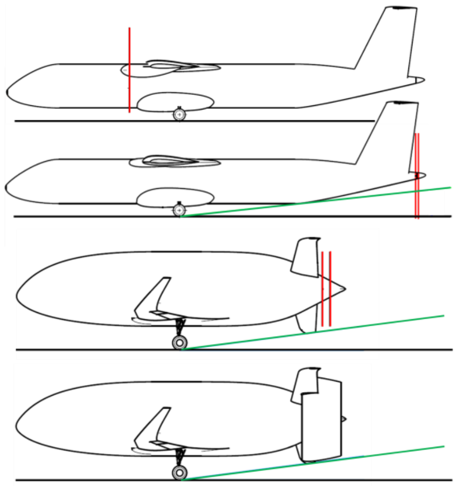

Figure 10, VoltAir Propulsion Integration

While the proposed configuration in general is also suited for a combustion engine based propulsion system, some integration aspects speak in favor of an electric propulsion train: The configuration requires the engines to be buried inside the fuselage. In contrast to electric motors, gas turbine engines need extensive heat shielding, fire protection and air intake provisions, complicating the integration in the rear fuselage. With the motor/ propeller unit at the rear of the aircraft, a counter weight in the forward fuselage is necessary to avoid a strong backward shift of the center of gravity. For the electric aircraft, the battery packs can provide that functionality, given that there is no or only little mass change during discharge (depending on the battery type).

Figure 11, The VoltAir Configuration

In total, of the design aspects mentioned above sum up to a significant drag and weight reduction potential relative to the conventional electric aircraft addressed in the last chapter:

Zero lift drag:

- 60 % natural laminar flow wing: -15% **[17]**
- No wheel well fairing: -5% **[17]**

Induced drag:

- Addition of winglets: -10% **[23]**

Propulsive efficiency:

- Boundary layer ingestion: +5 % **[22]**

Empty weight:

- Low slenderness ratio fuselage: -12% **[17]**

The resulting 25% improvement in energy efficiency, the hence smaller battery and the related "snowball" sizing effects lead to a 30% reduction in maximum gross weight. Figure 12 shows the impact of the savings in a comparing mass breakdown.

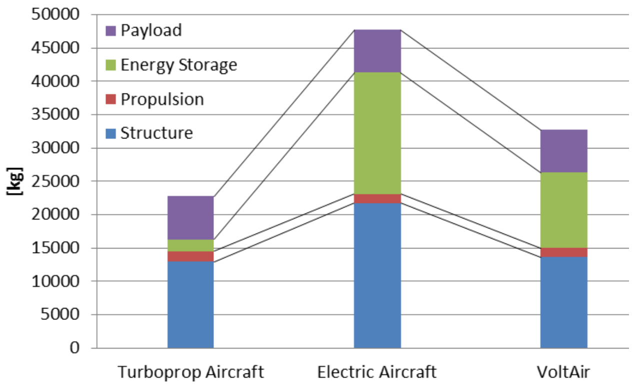

Figure 12, Mass Breakdown Comparison

Considering again at the design space for a VoltAir configuration, the limits for electric aircraft are shifted towards larger aircraft and longer ranges. As shown in Figure 13, typical payload/ range missions flown today can thus be realized with 750 Wh/kg battery systems, compared to 1000 Wh/kg, which are necessary for the conventional configuration.

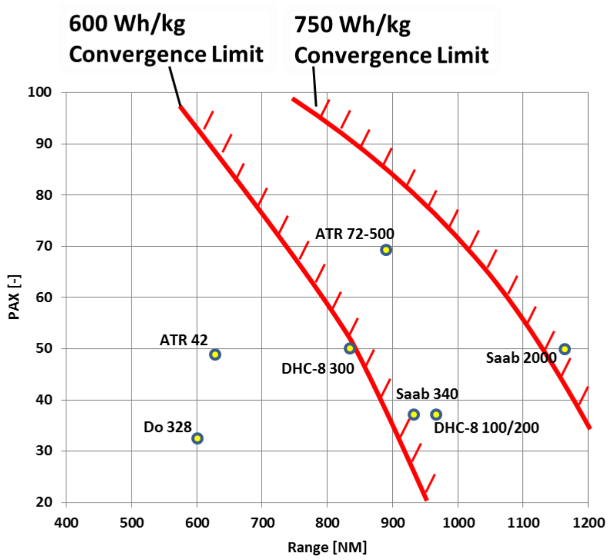

Figure 13, Design Limits for the VoltAir Configuration

4 Summary

In this report, the feasibility of future electric powered aircraft has been assessed. Using predictions for the components of an electric powertrain an electric propulsion system for propeller driven aircraft has been modeled. On the basis of superconducting electric motors and a battery system providing 1000 Wh/kg, a conceptual design of electric propulsion aircraft was presented. The weight of these aircraft reached roughly double the weight of today's turboprop aircraft for the same design mission. Further, a limit in electric aircraft size was identified, caused by a mass escalation of the propulsion system above an aircraft weight of 70 tones.

As a way to mitigate the weight penalties of electric propulsion aircraft, the VoltAir concept platform was proposed. Taking advantage of beneficial aerodynamic effects, a potential improvement of 25% in energy efficiency has been identified. On this basis, the limits for electric propulsion aircraft could be shifted towards higher transport capabilities.

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