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THE WHOLE TRUTH ABOUT ELECTRIC-POWERED FLIGHT FOR CIVIL TRANSPORTATION: FROM BREGUET TO OPERATIONAL ASPECTS

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ABSTRACT:

The decades-old idea of electric-powered commercial flight has re-emerged along with high expectations for greener air transportation. To what extent can electric aircraft reduce the energy and environmental footprint of aviation? How should they look like and how does their operation compare to conventional jet aircraft? What technologies are needed, and which of them are already in place? This paper goes back to basics and analyses critically some of the unresolved challenges that lay ahead. Current commercial operations are examined and the short-term effects of electrification are identified. Fundamental components, basic design and operating concepts are analysed to highlight unavoidable constraints that seem often overlooked. These limitations are illustrated with a conceptual study of a full-electric FAR/CS-23 commuter and realistic estimations of its performance. It becomes clear that electric propulsion alone will not fulfil the expected goals, but it might be one more step on the way.

1. INTRODUCTION

Civil air transportation stands on the crossroad between rising global air traffic, over-compensating fuel efficiency improvements and the rising social and politic will to reduce greenhouse gas emissions to limit global warming. While only contributing with ca. 2-3% of the global human-made CO_2 emissions, air transportation stands in the focus of political and social discussions in Europe like no other sector, followed by automotive and electric power production. Aeronautics suffered already its reputation as *the* high-tech technology leader industry in central- and northern-Europe which might in future also hamper the capability to attach youngsters to work within this field (pilot and engineering shortage).

There are numerous political commitments to reduce future greenhouse gas emissions on national, regional and world-wide alliances such as Sweden's climate goals [1], Europe's Flightpath 2050 [2] and UN's sustainability goals [3].

Following the strategy of electrification from the automotive sector, there is a never-before-seen trend of claiming the electric aircraft as the solution to reduce the aerospace greenhouse gas emissions. This enthusiasm in electrification the propulsion system – which by the way can be also found on system- and subsystem level of existing aircraft starting with the bleed-less system design of the Boeing B-787 and the partly electric driven actuation systems on the Airbus A380 and A350 – enables new technologies such as *distributed electric propulsion* (DEP). In turn, these new technologies offer new possibilities and open markets by introducing new concepts of air transportation, namely *electric propelled vertical take-off/landing* (eVTOL) vehicles. A significant part of the public, the media, and even political actors are placing extremely high expectations on these vehicles. The *urban air mobility* (UAM) revolution is expected to solve today's transportation problems in crowded urban areas while being environmentally friendly; neglecting, however, that the installed power in these vehicles (between $500\ kW$ and $1MW$) may be just serving one to four passengers.

This paper focuses on the possibilities and challenges of full-electric civil air transportation for carbon emission reduction. For the sake to simplify the analysis, hybrid solutions – which might offer a good balance between the characteristics of conventional jets and electric propulsion systems – are not part of this investigation.

2. CIVIL AIR TRANSPORTATION TODAY

It is sometimes proclaimed by stakeholders and the media that the upcoming generation of electric-powered aircraft, despite their eventual range limitations, will bring a significant benefit to the energy and environmental footprint of civil air transportation. But, first of all, how does civil air transportation look like nowadays? How, where, and how much do we fly? How significant would any change be? The following section aims to shed some light on this matter.

2.1. Transport Volume and Flight Distance

There is no universal indicator of air transport activity. Two of the most descriptive figures are usually the number of operations (departures) and the productivity, where the latter can be expressed in revenue-passenger-kilometres $[RPK]$ or, including all kinds of payload, in revenue-payload-kilometres $[kg-km]$. From the logistic point of view, focusing excessively on the number of flights can be deceiving as some segments seem to be more significant than what they are. Figure 1 shows the number of flights according to their stage length (great-circle distance) and aircraft class for all reporting U.S. air carriers and operations to, inside, and from the U.S. during the year 2017; as provided by the U.S. Department of Transportation [4]. The data shows that the twin-jet class dominates the market by number of flights already for stage lengths of $200\ km$ and above. Turboprop operations lose significance after $500\ km$, piston-engine aircraft after $200\ km$, and vertical-lift operations are negligible even for the shortest routes. According to departure numbers, the very-short range segment may seem a fertile ground for the electric commuter business; however, this data also reveals a hinder: it gives an idea of how many flights cycles air carriers need to survive in the short-range business. As it will be explained later, the future electric aircraft will not be economically suitable for fast battery cycling.

Coming back to the logistic problem of air transport, both business volume, energy consumption and emissions are more correlated to the payload exchange than to the number of flights. Figure 2 was elaborated with the same data from 2017 [4] and it shows the amount of revenue-payload flown (including passengers, cargo and mail) along with the distance over which it was transported. It is clear that the dominance of the twin-jet class here is absolute, turboprops are less significant than what departures suggested, and both piston and vertical-lift operations are negligible even for the shortest routes. This data also reveals some interesting details: the big piece of the cake, about 60%, was transported over a distance of $2000\ km$ or below, which scales almost linearly to approximately 30% at $1000\ km$ or below. About 12% was carried up to $500\ km$, and this amount falls to about 4% for the first $300\ km$. Hence, despite the large volumes in the short-medium range, the low end of the short-range segment is much less significant: we can observe a large number of departures for a relatively modest volume of revenue-payload which is mostly provided by twin-jet operations at high-subsonic flight speeds.

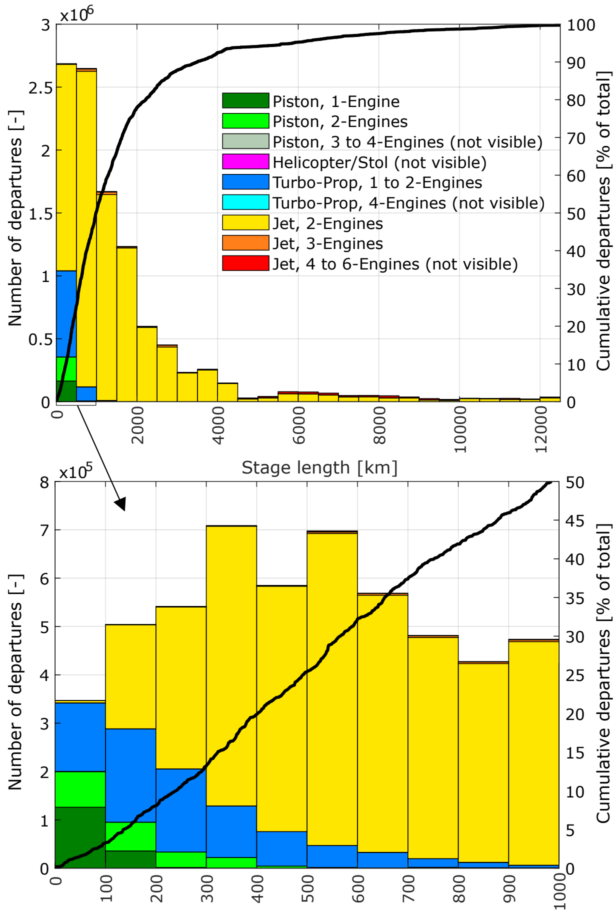

Figure 1. Departures by stage length for passenger and cargo flights to, inside, and from the U.S. during 2017. Black solid line represents the cumulative fraction of the total. Raw data from [4].

2.2. Energy and Environmental Efficiency

The next question is: how much are we *paying* for transporting all these payload volumes? How efficient is it? Approaching the logistic problem from the environmental point of view and disregarding speed, energy efficiency can be understood as a measure of productivity delivered (revenue-payload-kilometre) per unit energy consumed or environmental cost. Hileman et al. [5] name this metric *Payload Fuel Energy Efficiency* (PFEE). It is slightly modified here to ease the comparison to usual electric energy figures by expressing the cost in terms of kWh instead of MJ.

The same source [4] provides also information on reported fuel consumption during real operations for a wide range of aircraft types and missions during the last decades. The samples were considered sufficient to elaborate a yearly fleet-wide average efficiency index taking into account the total distribution

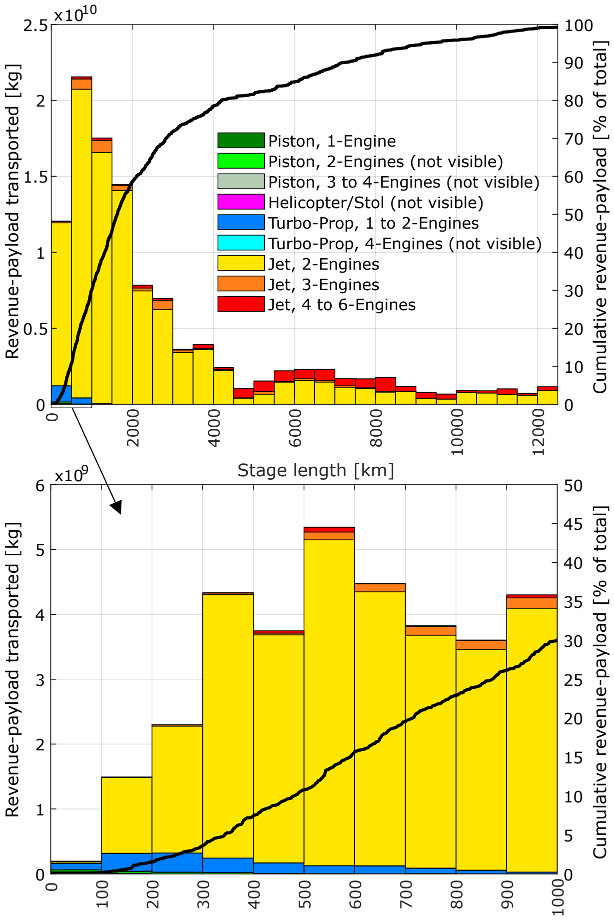

Figure 2. Revenue-payload by stage length for passenger and cargo flights to, inside, and from the U.S. during 2017. Black solid line represents the cumulative fraction of the total. Raw data from [4].

of passenger and cargo flow, flight hours and load factors. Fuel consumption was translated into energy consumption following the same assumptions as in [5], i.e. accounting the total chemical energy spent in the mission from block to block and not taking into account the energy spent in *well-to-tank* processes. The energy and environmental footprint caused by well-to-tank processes is not negligible, especially if comparing to an electric-propulsion scenario; however, these processes are difficult to quantify due to large geographical variations and lack of transparent information. See Edwards et al. [6] for more information on these processes in a European context.

Figure 3 shows the resulting evolution of the fleet-wide energy efficiency along with the relative change in total revenue-payload-distance achieved during the last two decades. According to these estimations, aviation is not only transporting more than ever but also more efficient than ever before. Two of the factors that may have contributed to this improvement are the introduction of more fuel-efficient aircraft and the general increase in load factor for passenger flights. Note that the latter has a significant effect and that it is independent of the propulsion technology used. To put it into perspective, the average fleet-wide energy efficiency in 2017 was approaching that of a typical utilitarian car ($6\ l/100km$) with two occupants on-board while being one order of magnitude faster over large distances. Although transportation speed is not included in this efficiency metric, it plays an important role in productivity and it should be taken into account when comparing aviation to other means of transportation.

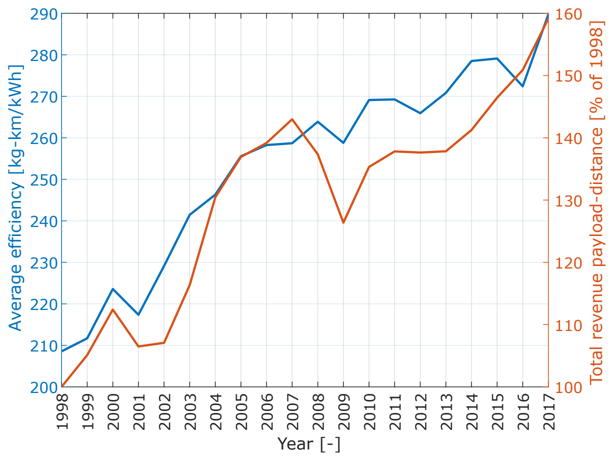

Figure 3. Evolution of the fleet-wide energy efficiency and total revenue payload-distance during the last two decades. Estimated from data by [4] including passenger and cargo flights to, inside, and from the U.S.

The available information on reported fuel consumption for operations during 2017 was also used to develop a model for average energy efficiency for each stage length segment. This model was then applied to the operations dataset to obtain an estimation of the total energy consumption for each segment. The result is plotted in fig. 4 together with the distribution of departures and revenue-payload-kilometres from figures 1 and 2. Moreover, energy consumption could also be associated with emission of pollutants. For instance, Hileman et al. [5] consider a proportional correlation with CO_2 of $263\ g/kWh$, or approximately $313\ g/kWh$ considering the entire *well-to-wheel* cycle. Nevertheless, uncertainties related to the proportionality of the emissions of different pollutants and the added effects of high-altitude operations make it difficult to establish a straightforward relationship [7, 8].

In any case, fig. 4 illustrates that associating directly the number of flights or payload-distance to energy consumption can be misleading. If in a hypothetical near-future, we were to enforce all commercial flights under $500\ km$ (about 25% of the departures and 10% of the payload) to be performed with full-electric aircraft, we would shift about 5% of the total energy consumption. It seems plausible to achieve a similar or greater impact with more straightforward and immediate measures, such as enforcing the retirement of the oldest long-range aircraft in existing fleets.

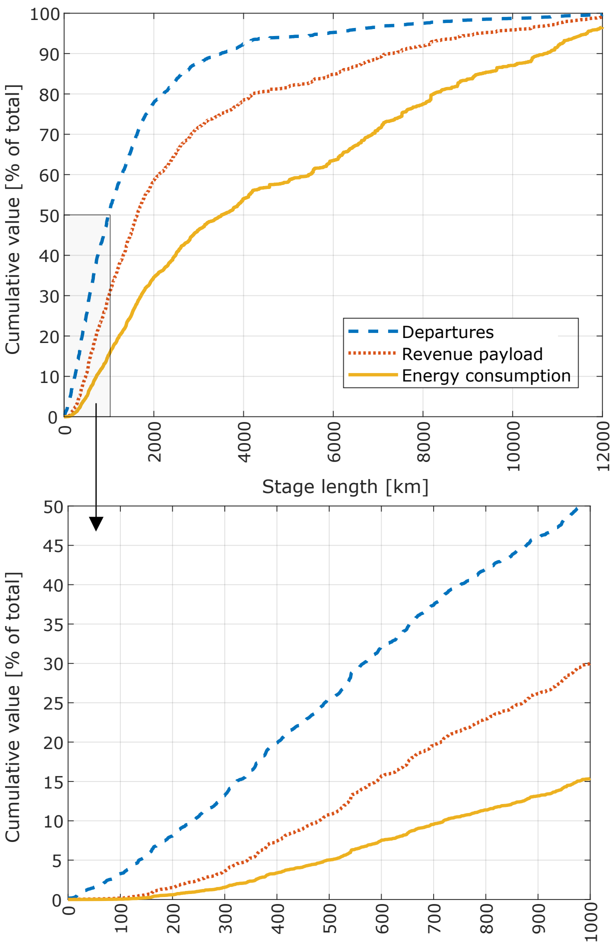

Figure 4. Distribution of number of departures, revenue-payload, and estimated energy consumption according to stage length for passenger and cargo flights to, inside, and from the U.S. during 2017. Elaborated with data from [4].

3. RANGE AND PAYLOAD CAPACITY

Both concepts use the concept of stockpiling to make the mission. The kerosene fuelled aircraft has the advantage that it a) takes the oxidizer oxygen "for free" and "just in time" from the ambient air and b) discharges the burned fuel in form of emissions into the atmosphere. The electric aircraft, however, has to carry the whole "fuel" battery weight over the total distance. The consequences are severe and cannot be only expressed as a higher MTOW but are influencing the whole performance of the aircraft. Figure 5 shows the large operational difference between conventional and full-electric aircraft.

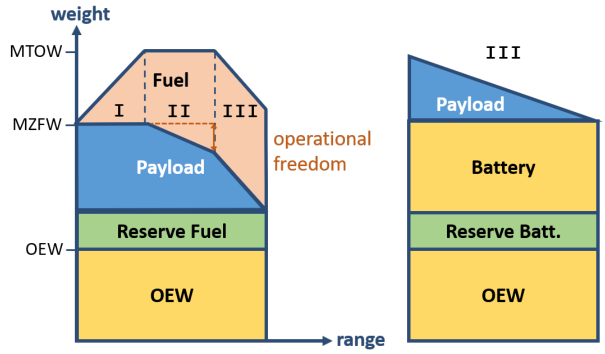

Figure 5. Comparison of a conventional fuelled (left) and a battery-powered aircraft (right) (axis not to scale!).

3.1. Basic Range Remarks

The cruising range of an aircraft (neglecting climb and descend) can easily be estimated with help of the so-called Breguet range equation, mostly known (since ca. 100 years) in the following notation for jet-engine aircraft:

$$R = v_{cruise} \cdot L/D \cdot 1/TSFC \cdot \ln\left(\frac{W_{initial}}{W_{final}}\right) \tag{1}$$

Thus, range is a direct result of the aircraft's aerodynamic quality (L/D), the overall propulsion system efficiency (expressed by the term *thrust specific fuel consumption* (TSFC)) and the weight fuel weight fraction $\left(\frac{W_i}{W_f}\right)$. Within these three classical aircraft design domains, namely aerodynamic, structure (weight) and propulsion have been significant advantages achieved in the past which partly have been scarified by a high cruise velocity (often Mach 0.82) and extended range of new aircraft types (thus too large and too much structure).

In the case of a full-electric aircraft with its constant mission weight (emptied batteries are not thrown overboard or become lighter with their *state-of-*

charge (SOC)), the Bregue equation becomes:

$$R = E \cdot \frac{M_{batt}}{M_{total}} \cdot 1/g \cdot L/D \cdot \eta_{total} \tag{2}$$

Thus the all-electric aircraft range is a direct consequence of the mass effective battery pack energy density (expressed in $[Wh/kg]$) and the battery pack weight fraction. While the formula is very simple, it is an eye-opener to play around with the values and see directly the consequences; the reader is encouraged to do so on the interactive Breguet range equation online calculator by Ferrier [9].

Besides the weight penalty and the lack of operational flexibility, it can be observed in a classical sizing- (or constraint-) diagram that some design factors become predominantly hard to meet; for instance: required runway length for take-off and landing (at MTOW!), approach speed, increased energy requirements (due to the constant maximum weight) for reserves (missed approach, detour to alternate, loiter...).

3.2. Fuel to Battery Comparison

Often, battery and kerosene fuel energy densities are compared directly with or without including an estimated propulsion drive train efficiency, e.g. see Equation 3. This, however, neglects the abovementioned operation difference - usually, the empty batteries are not thrown overboard (due to economic, environmental and safety issues).

$$\begin{aligned} absolute: \rho_{E,batt} &= 250[Wh/kg]; \\ relative \rho_{E,batt} \cdot \eta_{elec} &= 250[Wh/kg] \cdot 90\% = 225 \\ absolute: \rho_{E,JetA} &= 11,950[Wh/kg]; \\ relative \rho_{E,JetA} \cdot \eta_{jet} &= 250[Wh/kg] \cdot 30\% = 3585 \end{aligned} \tag{3}$$

$$\begin{aligned} relative: \frac{\rho_{E,JetA}}{\rho_{E,batt}} &\approx 50 \\ absolute: \frac{\rho_{E,JetA} \cdot \eta_{elec}}{\rho_{E,batt} \cdot \eta_{jet}} &\approx 16 \end{aligned} \tag{4}$$

One alternative expression of the energy to weight ratio is in terms of its own lifting capacity, stated in a virtual altitude that the fuel can lift itself in a fixed gravity world:

$$\begin{aligned} \rho_{E,batt} &= 200[Wh/kg]- > 92[km] \\ \rho_{E,JetA} &= 11,950[Wh/kg]- > 4385[km] \end{aligned} \tag{5}$$

4. ELECTRICAL (PROPULSION) SYSTEMS

Similar to the problematic of how to compare jet engines with shaft power delivering engines, also a direct comparison of electric (shaft-power delivering) motors and jet engines is not trivial and requires to consider the operation point (especially the cruise Mach number) into the comparison.

4.1. Electric Motor

Compared to jet-engines that deliver thrust for the sake of propulsion, electric motors deliver (shaft) power to some kind of a propeller or fan. The direct comparison of an electric aircraft with an "equal" jet aircraft is therefore not possible. In a extremely simplified model, with the basic definition of induced drag and the assumption of a constant parasite drag C_{d0} and constant thrust- or power-specific fuel or energy consumption (for the jet engine resp. the electric motor), the following relationship for the best fuel economic cruise lift coefficient applies:

$$\begin{aligned} jet\ engine: C_{L,min(T)} &= \frac{1}{3} \cdot C_{D0} \\ elec.\ motor: C_{L,min(P)} &= 1 \cdot C_{D0} \end{aligned} \tag{6}$$

So, there is a natural speed disadvantage for electric aircraft if the parasite drag is not reduced in some unrealistic way[1].

Neglecting the speed (and therewith the cost and utilization disadvantages), electric driven propeller/fans offer the following advantages compared to jet engines:

Pro1 $\eta_{elec,motor}$ ambient temperature independent
⇒ Free choice to choose suitable flight altitude.

Pro2 Efficiency and power density are rather independent of the engine size
⇒ Designers freedom to split-up and place the propulsion system (DEP).

Pro3 Excellent efficiency over wide operation range (RPM and power)
⇒ Operational freedom; good efficiency already at low power settings required for economic cruise velocities.

Other frequent named advantages of electric propulsion are reduced maintenance costs, enhanced reliability (both to be shown), enhanced lifetime, weight savings, simpler system architecture, reduced complexity (reduction of parts and especially reduction of rotating parts) and safety improvements (absence of fuel, uncontained engine failure, risk of fire, no hot components).

Main challenges – apart from the low *technology readiness level* (TRL) for aircraft propulsion – are

[1] Actually, parasite drag consists mainly of form-drag and friction-drag and it scales with the aircraft size (wetted area) and the frontal area. Therefore, it is sensitive to aircraft volume and hence it scales with volumetric fuel energy density.

the thermal control of all power electric components, the magnetic fields including the *electromagnetic compatibility* (EMC) and *electromagnetic interference* (EMI) issues, and insulation problems for higher (DC) voltage systems due to arching. The latter topic is closely related to the electric motor size and current limitations on the electric cables. For applications exceeding 1 MW, superconducting components are seen as a essential technology, with the first superconductive electric motor already available since 2018 [10].

4.2. Battery

The choice and performance of the energy carrier is one of the most critical aspects for the feasibility of electrically powered aircraft. It is therefore one of the most polemic topics. The ground transportation industry is already basing its electrification process on the use of rechargeable electric battery cells for energy storage or energy buffering onboard vehicles. Thanks also their popularity in consumer electronics, this type of electric batteries have seen a tremendous improvement and this technology is nowadays perceived at user-level as reliable and relatively safe. Electric batteries, in their latest chemistries, seem to be also the preferred choice for the first generation of commercial electric-powered aircraft, although they are not necessarily the only option. See Misra [11] for more information on this topic.

Rather than a detailed discussion on the state-of-the-art chemistries and performance, the aim is here just to remark certain critical aspects of electric battery integration that are often overlooked or misunderstood. Perhaps the most important of these is the value of specific energy that can be used for sizing and performance estimations. For lithium-ion (Li-Ion) cells, the current commercial state-of-the-art, specific energy is often mentioned to be somewhere between 200 and $300\ Wh/kg$, with even higher values occasionally reported in special experiments under very particular discharge conditions. The step between these reasonable values and the useable performance in "real-life" operation is unfortunately large. Beyond the additional weight for packing individual cells in a manageable pack and adding monitoring, thermal and safety systems, there is also a significant amount of energy that cannot be used for nominal commercial operations.Figure 6 describes conceptually the main factors that should be taken into account when assuming a battery specific energy at *system-level*, understanding system-level as one or several battery packs fully integrated on the aircraft including all installation features [12].

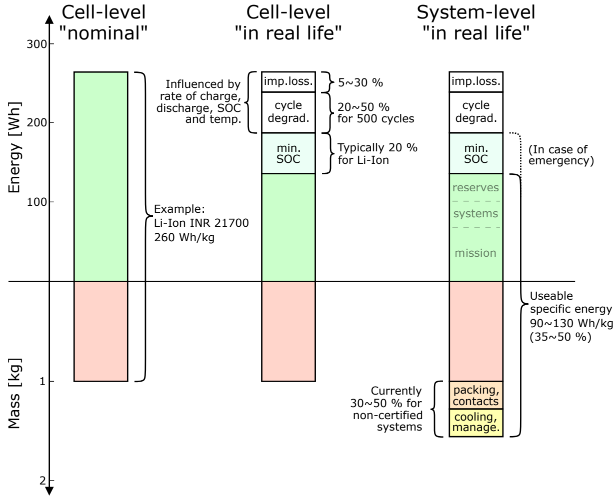

Figure 6. Conceptual representation of the adverse factors affecting the specific energy value of a typical state-of-the-art battery, from its individual-cell form to "real-life" use integrated in a commercial aircraft. Values are merely indicative.

The mass and volume overhead for battery packs can be observed in readily available electric road vehicles such as the Mercedes EQC (believed to be $123\ Wh/kg$ for full-depth discharge) and Tesla Model 3 (best in its class, with estimated $157\ Wh/kg$ from $247\ Wh/kg$ cells in full-depth discharge [13]). However, it is unclear if these values include the mass of installation or integration elements and the liquid cooling system. In any case, it is expected that eventual airworthiness, crashworthiness, environmental protection, and general safety requirements for the use of these batteries in commercial aviation will increase, rather than decrease, the mass and volume overheads observed in road vehicles.

4.2.1. Safety and Degradation Margins

Regarding the useable energy, it is often forgotten that the nominal energy values given for commercial cells correspond to a full-depth discharge cycle, i.e. from 100% SOC to the minimum acceptable voltage (often between 2.5 and $3.0\ V$ for Li-Ion cells) and under a light load. Typical cells using this chemistry see their cycle life directly correlated to the depth and rate of the discharge cycles. For regular use in commercial service, discharge cycles should be ideally as small as possible, and never exceed 80% depth (20% SOC remaining from a full charge) if the battery is expected to endure at least 500 cycles with acceptable performance. This means that at least 20% of the energy cannot be considered useable in nominal missions, although it may remain available for emergency situations if the battery is discarded afterwards (see fig. 6).

On the other hand, the cell degradation after a such number of cycles may reduce the available energy an additional 20% (or up to 50%, depending on how aggressive the charge and discharge cycles are). Unless it is accepted that the aircraft is assigned to shorter routes according to its battery health, this degradation should also be taken into account when designing the nominal mission. Bugga et al. [14] provides some examples of life-cycle performance of commercial cells tested for space applications. Note that those tests correspond to much lighter cycles than those expected for aircraft propulsion uses.

Furthermore, impedance losses will vary depending on battery health, temperature, and rate of discharge, where the latter is directly linked to the power demand. The mission should therefore be designed to not overstress the battery and to minimize energy losses in the form of heat during the climb phase, or otherwise the battery will need to be oversized accordingly. It is also necessary that a thermal management system not only evacuates the excess heat, but also maintains an acceptable minimum temperature during idling conditions and re-charge.

4.2.2. Future Battery Improvements

Battery technology has actually experienced a tremendous development during the last two decades. Today, there are commercially available Li-Ion cells in the format 2170 (or 21700) that have already a specific energy of $260\ Wh/kg$ while delivering a discharge rate of 1C (100% depth, according to the author's experiments). In the past, battery performance has increased by about $5\%/p.a.$. Current technology development forecasts are expecting higher values due to the R&D push by the automotive sector expecting $400-500\ Wh/kg$ cells in the 2022-2025 time frame [11]. For aviation applications, consider adding at least three years to the automotive timeline, making $500\ Wh/kg$ cells available around year 2028.

The maximum theoretical weight effective energy of today's technologies is limited to ca. $600-700\ Wh/kg$ so that for higher values such as $1000\ Wh/kg$ – which equals the mass specific (chemical) energy level of hydrogen peroxide (H_2O_2) [15] – would require some new kind of battery technology (e.g. Li-Sulfur).For aerospace applications, battery safety is also an important issue: the thermal runaway risk becomes more critical with rising mass (and volumetric) specific energy levels.

4.3. Power Electronics

Compared with all other forms of energy aboard an aircraft – namely hydraulic, pneumatic and mechanic power – is the outraging efficiency of power conversion of electric systems, bypassing the low thermodynamic efficiency of heat engines and enabling a control by adaption instead of restrictive throttling like in most cases in the other domains. The key enabler of such high-efficient electric power control has been the solid state power electronic components.

However, besides many advantages, there are certain bottlenecks that have to be addressed:

Con1 Power limitation:
due to maximum voltage and current levels

Con2 High currents:
limit of conventional cables; resistance losses

Con3 High DC voltages:
insulation (weight, volume, risks) and arching (switch design: complex, bulky and maintenance effort)

To overcome the first two disadvantages, superconduction is seen as a possible solution. A lot of enhancements have been achieved in this field in the past, ranging from material development to higher the superconducting temperature up to the first superconductor electric motor available at the market since 2018 [10]. Limitations are also set by field-strength of the electromagnetic fields caused by the huge currents. EMC is one of the critical design challenges that will require more attention to future *more electric aircraft* (MEA) or full-electric concepts. EMI caused problems in one of the first full-scale DEP ground tests during the LEAP Tech test campaign for the NASA X-57 Maxwell project (see [16]).

5. ALTERNATIVE CONCEPTS

The all-electric aircraft is only one possible more environmental friendly future setup. Other alternatives are:

1. Conventional design and the use of synthetic fuels/E-fuels or biofuels
2. Hybrid solutions with a wide variety of hybridisation (of power an energy)
3. Gas fuel driven aircraft: hydrogen, *liquified petroleum gas* (LPG) and *liquified natural gas* (LNG)
4. Fuel cell driven concepts
5. Other battery- or electric energy storing technologies such as liquid batteries, superconduct-

ors, etc.

6. Other just-in-time energy recuperation concepts or directed energy (from ground, mother-vehicle or space).

While the last option seems very unrealistic with nowadays technologies, the first alternatives of the listing above can be realized with nowadays technologies. Globally, there might be no best technology but there might be a best system architecture for each application, depending on the vehicles range, payload capacity and velocity.

5.1. Sustainable Liquid Aviation Fuels

There is a long list of synthetic fuel (synthetic kerosene) available (also denoted as E-fuels) which are being produced by a power-to-gas or a power-to-liquid process. First test plants are already in operation to create synthetic fuel out of electric energy and e.g. CO_2 and H_2O [17]. The problem of any power-to-X conversion are the moderated process efficiencies ranging between 0.53 to 0.7 depending on the process an type of materials [18].

6. APPLICATION EXAMPLE: ELECTRIC FAR/CS-23 COMMUTER AIRCRAFT

At this point of the discussion, it may be clear that the technical possibilities for introducing a successful commercial aircraft with full-electric propulsion in the short or mid-term are extremely limited. Beyond certain niche applications, it is also doubtful that sufficient business-cases exist in the very low-end of the air transportation market, at least without support from political actors and policy-makers. Nevertheless, in the near future, a logical first-attempt to balance the market demand for higher capacity and the technology limitations could consist of a small commuter aircraft certified under the FAR/CS-23 regulation.

Exploring the design of such an aircraft is an interesting exercise that reveals the architectural challenges and the performance figures that may be realistically expected in different battery-development scenarios. This case was studied here using typical conceptual design methods, low fidelity tools, and disregarding radical technologies or unproven concepts. The design aim was to maximize range for 19 light-travelling passengers and two crew, giving lower priority to flight speed and comfort. The main weight constraints and the relatively simple margin for design trade-offs are shown in fig. 7, assuming a mass of $95\ kg$ per person.

The million-dollar question is here "how big can

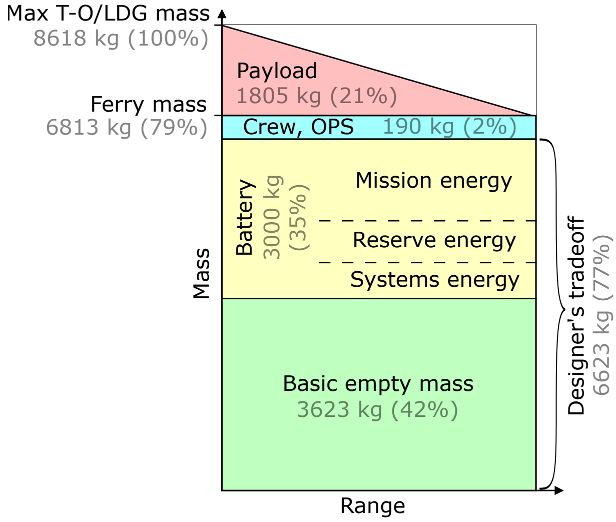

Figure 7. Conceptual mass-range diagram for a 19-passenger, CS-23-compliant fully-electric commuter aeroplane.

the battery mass-fraction be?". A quick weight analysis based on similar aircraft, typical on-board systems and equipment showed that a basic empty mass lower than $3600\ kg$ would be hardly realizable even in the case of non-pressurised cabin and extensive use of composites. This left a rather optimistic three-ton allowance for battery mass, ideally located near the motors to minimize power-distribution complexity and weight. Considering state-of-the-art Li-Ion battery cells and high-density packing, the total volume required by such battery would be at the lowest between 1.5 and $2\ m^3$, which is comparable to a full wet-wing or to four nacelles slightly larger than those of conventional turboprops. The mass of this battery would however induce significant inertial loads on the wing structure upon touchdown. In this exercise, it was necessary to introduce wing bracing struts to minimize structural weight while keeping a high aspect-ratio with optimal low-speed efficiency.

The concept converged into a high-wing, T-tail configuration with four $300\ kW$-class motors driving $2.8\ m$ propellers. While a twin-motor configuration would probably be more efficient, no $600\ kW$-class electric motor has been demonstrated in flight so far. The fuselage, seating two-abreast, was reduced to the minimum volume and cross-section that was practically possible. Aiming for operation on $1500\ m$ -runways, the wing loading was severely limited due to the high take-off and landing weight. These and other characteristics of interest are listed below:

$$\begin{aligned} W/S &= 270\ [kg/m^2] \\ T_{max}/W &= 0.48\ [N/N] \\ S_{wet}/S_{ref} &= 5.6 \\ AR &= 14.8 \\ L/D_{max} &= 21\ at\ M0.22 \\ L/D_{cruise} &= 17\ at\ M0.30 \end{aligned} \tag{7}$$

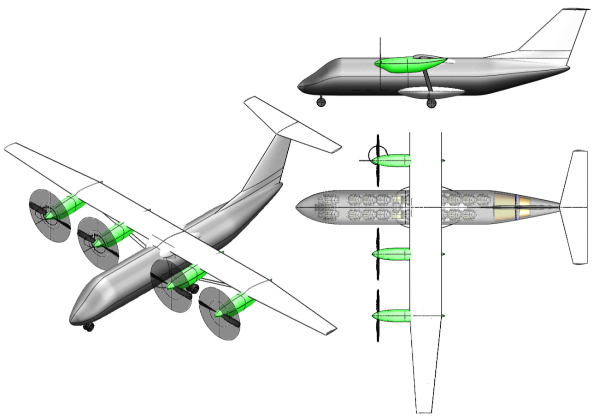

Figure 8. Representation of the evaluated concept, modelled in OpenVSP for visualization purposes.

6.1. Mission-Range Analysis

In the quest for maximum range and sacrificing all-weather operation, passenger comfort and speed, the optimum cruise was found at an altitude of $8000\ ft$ (also limit for unpressurised cabin) and Mach 0.30 (approximately $200\ kn$). Higher and faster cruise conditions could not overweight the energy invested in the climb phase for very short missions. Table 1 summarizes the simulations results obtained for different values of battery specific energy. Please note that these refer to useable specific energy at system level (see 4.2). An indicative value of what could be achieved with current technology is approximately $130\ Wh/kg$. Due to the relatively optimistic assumptions, these values should be seen just as a "theoretical maximum".

6.2. Key Enablers to Make it Work

While the design study above shows that it is possible to design a FAR/CS-23-compliant full-electric aircraft for short routes, depending on the available battery technology from an engineering point of view, it is questionable whether there is an sufficiently large market to operate such an aircraft economically. On ultra-short routes, there is usually a

Table 1. Range estimation for a 1 MW-class electric commuter with the mass characteristics of fig. 7. Full payload, max. continuous-power climb, cruise at FL080, M0.30, L/D = 17.

Useable specific energy at system-level $[Wh/kg]$	Energy fraction for reserves and systems $[\%]$	Max stage length $[km]$
130	40	180
160	40	340
200	40	540
300	35	1100
400	30	1700

direct competition with other transportation means such as trains, buses, car or ships. This can be the case for special locations with the absence of these competitors due to lack of infrastructure or difficult terrains such as mountainous regions, jungle and archipelagos, uplands and moors.

7. DISCUSSION

The authors doubt whether there is a big enough (niche-)market for a FAR/CS-23 commuter aircraft such as the one presented in this paper. But even in the case all short-range operations are switched towards all-electric aircraft, this represents only a small fraction of the total *available seat kilometres* (ASK) and at maximum 5% of the total energy spend today for air transportation. While this paper shows that it is technically feasible it seems questionable whether this can go along with a cost advantage with today's low fuel price. Additionally, many uncertainties come from the low TRL level of many components that have not yet been tested in flight in the required power category for larger aircraft.

7.1. Technology Coexistence

Technology development can be either a steady process, denoted as (design) evolution or a rapid change – imposed e.g. by a new technology – denoted as a revolution. Especially in aeronautics, the technology maturity process from low to high TRLs is a long-term and costly process. History shows that, even with vast investments, the slanted TRL-wave cannot be shortened significantly. In reference to its maturity state, the electrification of flight might actually be suffering from an excess of visibility and inflated expectations that may probably lead to a hard encounter with reality, as described by the so-called Gartner technology hype cycle [19], fig. 9.

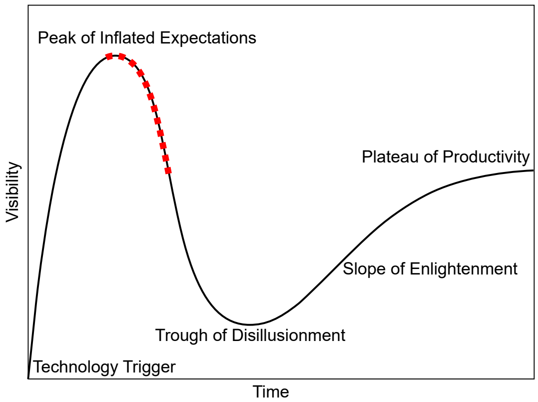

Figure 9. Gartner's technology hype cycle. Is electric-powered flight about to follow the red line?

7.1.1. Swedens Car Energy/Technology Mix

Example of mislead governmental aid is the automotive segment in Sweden: historically, the overwhelming majority had been petrol cars. Then in the 90s there was a great subsidy of Ethanol cars which more or less vanished when high-efficient Diesel cars were promoted as the best solution and Ethanol tax benefits vanished. Nowadays, exaggerated by the Diesel-gate happenings, electric and plug-in hybrid cars (or SUV's) are selling well beside Petrol cars that replace partly again the Diesel car market. The political (and society) render decisions to black-white or yes-no (technology) decisions (following technology hype described by Garner) where from a holistic environmental impact point of view a technology coexistence would be the best solution, selecting the propulsion technology an ""Behalf" of the application/use case, availability of raw material (e.g. environmental friendly/Co_2 neutral energy sources for Ethanol production e.g. from waste and forest industry residues in Sweden are limited)

In a similar fashion UAM is nowadays overhyped. Obviously, the emergence of UAM is backed by real technology evolvement (e.g. batteries, solid state electric devices, communication devices, etc.) but it's getting over-representative focus in academia an R&D investments which is a positive side of the medal (a lot of ongoing research on electrification) that comes alongside as an disadvantage for the financing of other research fields.

7.2. Technology Uncertainties

Largest uncertainty predicting the (short-range) performance of new full-electrical aircraft as the presented design study of a FAR/CS-23 compatible aircraft comes from the unclear way of how to handle the reserves in case of a full-electric aircraft. For short-range aircraft, the required reserves (for the alternate airport and loiter time) are the dimensioning requirement, respectively the residue range would not be sufficient for a commercial operation. Here, the aircraft community has together with the licensing authorities start the discussion how the reserves should be handled in case of a full-electric aircraft. Also, because of the low cruise altitude and flight velocity, operation and useable range are very prone by wind and weather; it is questionable whether this will be accepted by the passengers (comfort!), the crew (risk e.g. due to icing) and the operators (cancellation of flights). Together with a sound estimation of future battery technology advancements, including a reasonable time frame for technology adaption for aerospace applications will enable a precise study for possibilities and operation of future full-electric air transportation.

8. CONCLUSION

In this paper, it is shown that electric civil air transportation over relevant distances first becomes possible with significantly increased battery weight- and volumetric- energy densities.

While a direct comparison to jet aircraft is not possible, the main design impacts for the electric aircraft are the sizing for the fixed (higher) mass (landing distance!) and the required battery volume. The only positive effect here is that the designer is free to place the batteries because there is no change of the centre of gravity due to fuel-burn.

In order to design an aircraft for best energy efficiency, it is not enough to focus on only optimizing the overall propulsion system efficiency only, but the energy efficiency is a result of the total vehicle weight and the aerodynamic finesse (L/D) at cruise point. The design study revealed a (expected) high sensitivity between total mass and the battery weight specific energy, while the aerodynamic efficiency relates to the volume-specific energy density. So minimizing the required mission energy is necessary and not surprisingly the outcome of the design process is a slow and low flying aircraft. This result in turn can be validated with already existing full-electric aircraft, where perhaps the most advanced optimization from an energetic point of view is a motor glider Antares 20E which is in series production since 2003 [20]: extreme high L/D, low velocities and a low wing-loading, offering enough space for the batteries in the wing.

This paper should not be seen as a negation of the potential of electrification in civil air transportation, but rather as a call for keeping expectations at a realistic level and keeping in mind our ultimate goal: to create safer, greener, and cheaper aircraft; in this order. Electrification can play a more or less relevant role in different segments and systems, but it alone will not provide a paradigm shift towards our greener-aviation goals in the short-medium term. The natural advantages of former technologies, as well as the natural drawbacks of the new ones, should not be forgotten.

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