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Emerging Aviation Technologies – Progress in the Electrification of Aircraft

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Abstract

The aviation industry is constantly faced with new challenges that drives a steady evolution as well as revolutionary new solutions. Not only the enormous growth of global passenger and freight traffic, but also environmental and climate protection measures are constant innovation drivers. The European Commission has set substantial targets in its "Flightpath 2050" [1] guide to be able to meet these challenges is the future as well. The project PARE (Nr. 769220) addresses each of these goals to make a comprehensive assessment of present state but also projections of future developments and recommendation of measures.

It is uncertain that the given environmental targets in "Flightpath 2050" will be achieved without consideration of pioneering technologies. In the wake of the emerging electrification in the automotive sector, new drain concepts for the aerospace industry such as hybrid or all electric propulsion are in the focus of attention.

In a general statement, two approaches for electrification in aviation can be observed. The conservative approach aims at a successive replacement of hydraulic, pneumatic, and mechanical components by electrical system solution, which is often referred to a more electric aircraft. However, the more revolutionary approach would be hybrid propulsion or even full electric propulsion. To reach a sufficient range of the electric planes besides a high lift over drag ratio(L/D) which depends on the aircraft design and a high battery mass fraction (mbatt/m), where m is the total airplane mass (mempty + mpayload + mbattery) especially a high specific battery energy is required. The possible increase of the specific energy is in a roadmap given which is addressing also the expected commercialization time of the battery.

Caused by the today still insufficient specific battery energy for regional traffic (500 – 100 km) hybrid-electric airplanes are mostly preferred compared to all-electric planes.

1. Introduction

There is observed an enormous growth of global aviation passenger (see Figure 1) and freight.

In relation to that RPK increase also the CO2 emissions will be increased (see Figure 2). For the year 2019 is expected that the civil aviation, as a whole, emits around 927 mio. tonnes of CO2, which is roughly 2% of the global man-made carbon emissions.

With this 2 % the civil aviation is ranked worldwide on place 17 of the CO2 emitters. Nevertheless, the aviation industry takes the matter very seriously.

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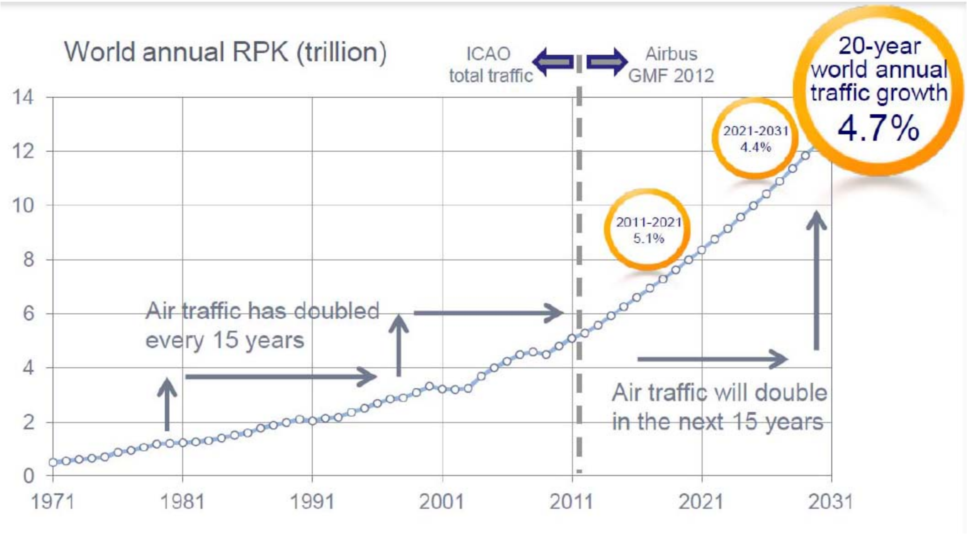

Figure 1: Expected growth of air traffic in Revenue Passenger Kilometers (RPK) [1]

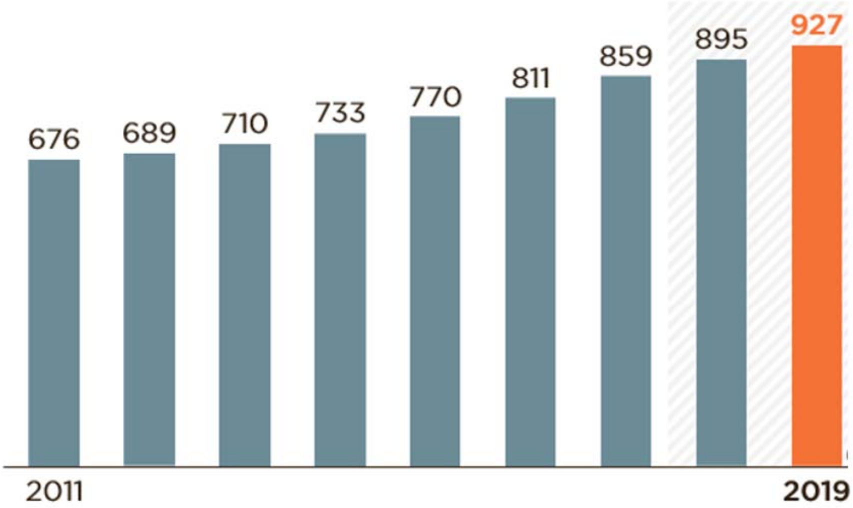

Figure 2: Air plane based CO_2 emissions in million tons based on IATA and ATAG data

E.g. has the International Civil Aviation Organization (ICAO) in February 2017 adopted the first ever global CO2 certification standard for new aircraft. The standard sets limits to the CO2 emissions from aircraft in relation to their size and weight. Another instrument is CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) which was introduced by the ICAO in order to have a carbon neutral revenue tonne-kilometer (RTK) growth. This will be achieved by the fact that airlines finance CO2-reducing climate protection projects worldwide, which compensates the emissions from aviation on a commensurate scale. Also, the European Commission has set substantial targets in its "Flightpath 2050" [2] guide to be able to meet these challenges in the future.

Airlines have continued to improve their fuel efficiency performance. A historical overview about the engine fuel consumption and the aircraft fuel burn per seat is given in Figure 3.

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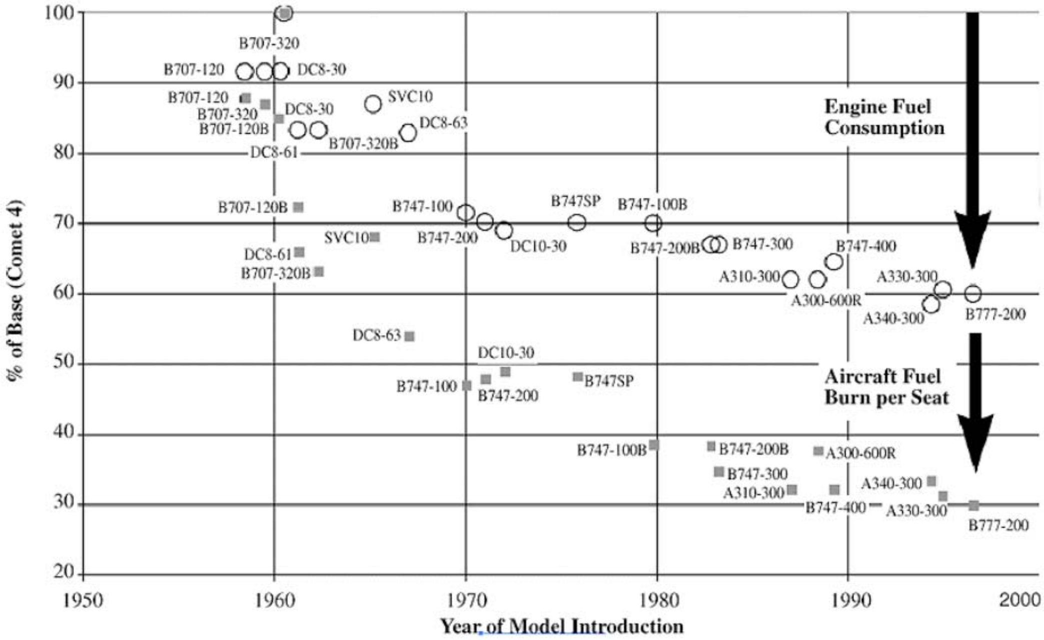

Figure 3: *Historical data on aircraft fuel-burn [3]*

In 2016 the fuel efficiency for total system-wide services amounted to 35.28 litres per 100 RTK, an improvement of 10.2% compared to 2009. So, the aircrafts emit less and less carbon dioxide.

The reasons for this lies in modern technology as well as in new and, above all, lighter materials. In many cases, such a high degree of energy efficiency has been achieved that it can no longer significantly increased. Therefore, ideas and concepts for completely new aircraft and the power train are being developed, which have little in common with conventional large aircraft.

2 European activities

In Europe the importance of aviation was early recognised and the EU commission has addressed this question and worked out the report “European Aeronautics: A vision for 2020” which was published in January 2001. Besides the report an Advisory Council for Aeronautics Research in Europe (ACARE) was establish for the development and maintaining a Strategic Research Agenda (SRA) that would help to realize the goals of the Vision 2020 to meet society's needs for aviation as a public mode of transport as well as noise and emissions reduction requirements in a sustainable way. Important documents were were initiated by ACARE as e.g. creating innovative air transport technologies for Europe (CREATE)[4]. However, this CREATE report showsthat between 2000 and 2010 a number of boundary conditions changed what ACARE forced to extend its view towards 2050. The New Vision, Flightpath 2050, was released in March 2011 and based on that a Strategic Research and Innovation Agenda (SRIA) was elaborated by ACARE during 2012 and successively renewed [5]. 23 main system attributes are addressed by ACARE (Table 1).

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Table 1: Overview of the main system attributes

1. Emissions
2. Energy efficiency
3. Impact on ethical considerations
4. Safety concerns
5. Security concerns
6. Low scale factor
7. Pilotability
8. Ease of adoption/spread of idea
9. Scientific credibility
10. Degree of required scientific/technological innovation
11. Travel cost
12. Time effectiveness
13. Quality advances
14. Cost advances
15. Novelty/radical content
16. Direct relevance to future air transport
17. Partnering needs
18. Availability of incubation resources
19. Mainstream funding availability
20. Industrial focus in the past
21. Credibility of incubation goals
22. Credibility of incubation project plan
23. Credibility of budget for applying project plan

Different EU projects support the ACARE activities and its 23 Flightpath 2050 goals. An important project is PARE – "Perspectives for Aeronautical Research in Europe" (Nr. 769220) in the fraemwork of the EU Horizon 2020 programme, which performs an assessment of the rate of progress relative to these 23 system attributes goals and respective provision of recommendations. Along its 3 years of implementation, PARE will create a group of yearly progress reports on the perspectives for aeronautical research in Europe.

The first PARE report (Year 1) [6] is divided in the following chapters:

Chapter 1 - Introduction and Set of Recommendations
Chapter 2 - Meeting Societal and Market Needs
Chapter 3 - Maintaining and Extending Industrial Leadership
Chapter 4 - Protecting the Environment and the Energy Supply
Chapter 5 - Ensuring Safety and Security
Chapter 6 - Prioritizing Research, Testing Capabilities and Education
Chapter 7 - Long Distance Air Travel
Chapter 8 - Emerging Aviation Technologies
Chapter 9 - Cooperation Beyond Europe's Borders
Chapter 10 - Attracting Young Talent to Aeronautics
Chapter 11 - Increasing the Participation of Women in Aerospace

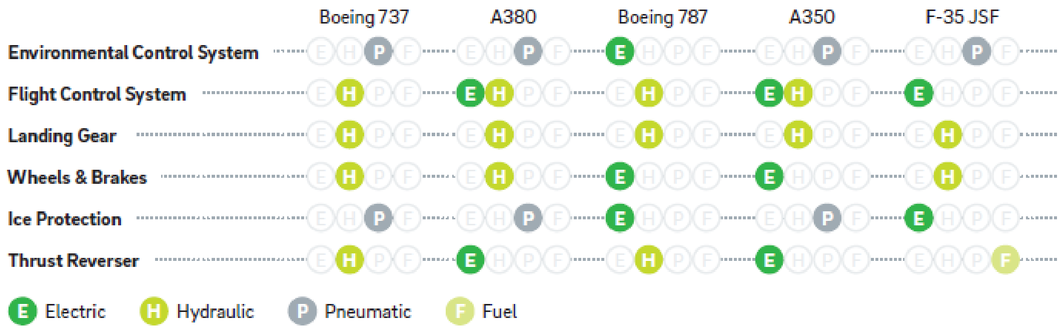
A high priority of the above given 23 main system attributes are efficiency and associated with this also emissions (CO_2, NO_x, noise). The emissions goals for 2050 in relation to 2000 are 75% CO_2 emission reduction, 90% NOx reduction and 65% aircraft noise reduction.

To address these both attributes evolutionary ways are treaded but also revolutionary ways. The latter way is described in Chapter 8 - Emerging Aviation Technologies of the PARE report. Although there is still a bright future in development of conventional propulsion systems especially to power long-range, large-payload and high-speed aircrafts, the focus within this chapter is on electric propulsion in several forms, including solar powered aircraft, battery or fuel-cell driven propulsion, and the use of gas turbines as generators of electricity.

3 Aircraft electrification

3.1. Electrification of airplane components

Many components/systems of conventional aircrafts such as actuation, de-icing, and air-conditioning are related to mechanical, hydraulic and pneumatic sources of power, which were extracted via different ways from the aircraft engines. About 5% of the engine's total output is consumed for such non-propulsive systems. But the hydraulic and pneumatic systems have often suffered from a lack of reliability and high maintenance costs. Miles of complex and heavy pipes and ducting running throughout an aircraft. Leaks in both systems are often difficult to locate, sometimes hard to trace and time-consuming to repair. Well-designed electrically powered systems do not suffer from many of the shortcomings inherent in hydraulic, pneumatic and also mechanical systems. Therefore, more and more electrical systems have replaced the conventional sources of power, starting in 1967 with the Boeing 737 with electrical cabin equipment, avionics, landing gear actuation, etc. This concept is now popularly known as the More Electric Aircraft (MEA). "Fly by Wire" (FBW) systems, electrically actuated thrust reverser, hybrid electro-hydraulic actuation systems for wing and tail flight control surfaces, electrically-powered environmental control (air-conditioning) system, electrically actuated brakes etc. were introduced later – see Figure 4 .



	Boeing 737	A380	Boeing 787	A350	F-35 JSF
Environmental Control System	P	P	E	P	P
Flight Control System	H	E H	H	E H	E
Landing Gear	H	H	H	H	H
Wheels & Brakes	H	H	E	E	H
Ice Protection	P	P	E	P	E
Thrust Reverser	H	E	H	E	F

E Electric H Hydraulic P Pneumatic F Fuel

Figure 4: Penetration of electrical systems by aircraft type (F-35 Joint Strike Fighter: military plane from Lockheed Martin)[7]

The higher electrification leads to reduced weight, greater reliability, lower maintenance costs and increased efficiency and finally to lower emissions. Still evolutionary changes are expected in the future , implemented through step-by-step adoption towards electrically-powered equipment in additional aircraft systems [7].

In most cases the electrical energy is generated via the aircraft engine. During ground operations, however, the engine is not switched on and the power is supplied via cable or during taxiing by APUs (Auxiliary Power Unit). The APU has an efficiency of < 20 % and emits noise and CO_2, NO_x. A PEMFC driven APU does not have these disadvantages[8].

In airplanes the primary electrical system incorporates also batteries, which are mainly used during preflight to power up the electrical system and to start the APU and/or the engines. Once started, the APU or engine(s) drive generators which then power the electrical circuits and recharge the batteries. Some electrically powered fixed equipment such as the Emergency Locator Transmitter (ELT), Cockpit Voice Recorders (CVR) and Flight Data Recorders (FDR), will have their own dedicated batteries

3.2. Electric propulsion

3.2.1 Electric propulsion concepts

In general, there are existing three electric propulsion concepts – see Figure 5.

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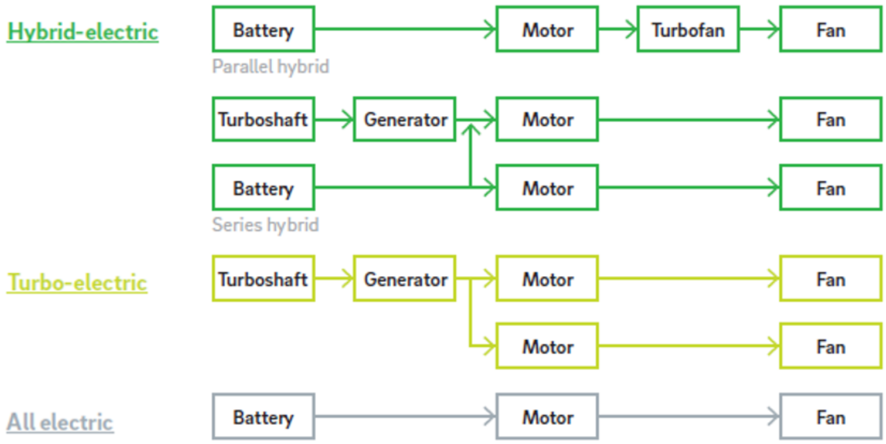


Figure 5: Scheme of electrical propulsion architectures [7]

Hybrid-electric: Additional electric energy can be used for acceleration and in times of high-power demand; bi-directional flow of power is possible. The hybrid architectures could be in parallel or in series. In this configuration the fossil driven turbine supports the battery in acceleration phases (take-off, climb) and can also to increase the flight time.

Turbo-electric: The kinetic energy of a turbo shaft is transformed into electric energy via a generator to drive multiple, distributed fans, with the fans driven by electric motors. This configuration gives the aircraft designer complete freedom over the number and location of the propulsive fan(s), potentially leading to more efficient designs with higher propulsive efficiency.

All electric: One, or multiple, fans are driven by electric motors with energy stored in a battery or generated in fuel cells. Besides these both power sources theoretically also sophisticated systems as power cables connect to a ground-based supply or microwave energy which has been beamed from a ground-based source.

All three electrical airplane propulsion architectures have similarities in the automotive industry, and in many ways, aerospace is following the path already set in the automotive sector.

Although for the time being in short and middle term the focus is on the hybrid-electrical architecture caused by the relatively low specific battery energy there are also development activities for shorter distances (air taxi) based on the all-electric version.

3.2.2 All-electric architecture

As already above mentioned the both main power sources for propelling all-electric planes are batteries or/and fuel cells. The following Figure 6 shows the principal routs of fully airplane electrifications.

In case A and B the fuel cell is mainly a PEMFC. If, however, the PEMFC uses kerosene, methanol or bio fuels as fuel a reformer for the generation of hydrogen reach gases is necessary. These fuels, however, could be used directly without an external reformer in high temperature fuel cell (MCFC, SOFC) (case C). In principle also a redox-flow battery is a choice for the electrification (case D), but for practical applications its specific energy is with about 25 Wh/kg too low. The case E shows the electrification with a battery. In the case E the energy is fixed and given by the size of the battery. For cases A – D the energy is given by the amount of the fuel (H_2, kerosene, methanol, bio fuel, or redox-flow electrolyte). The most promising practical cases are A (H2 PEMFC) and E (battery). Both systems are beneficiaries from strong developments of the car industry, but therefore they are limited today to 100 kWh and 100 kW class.

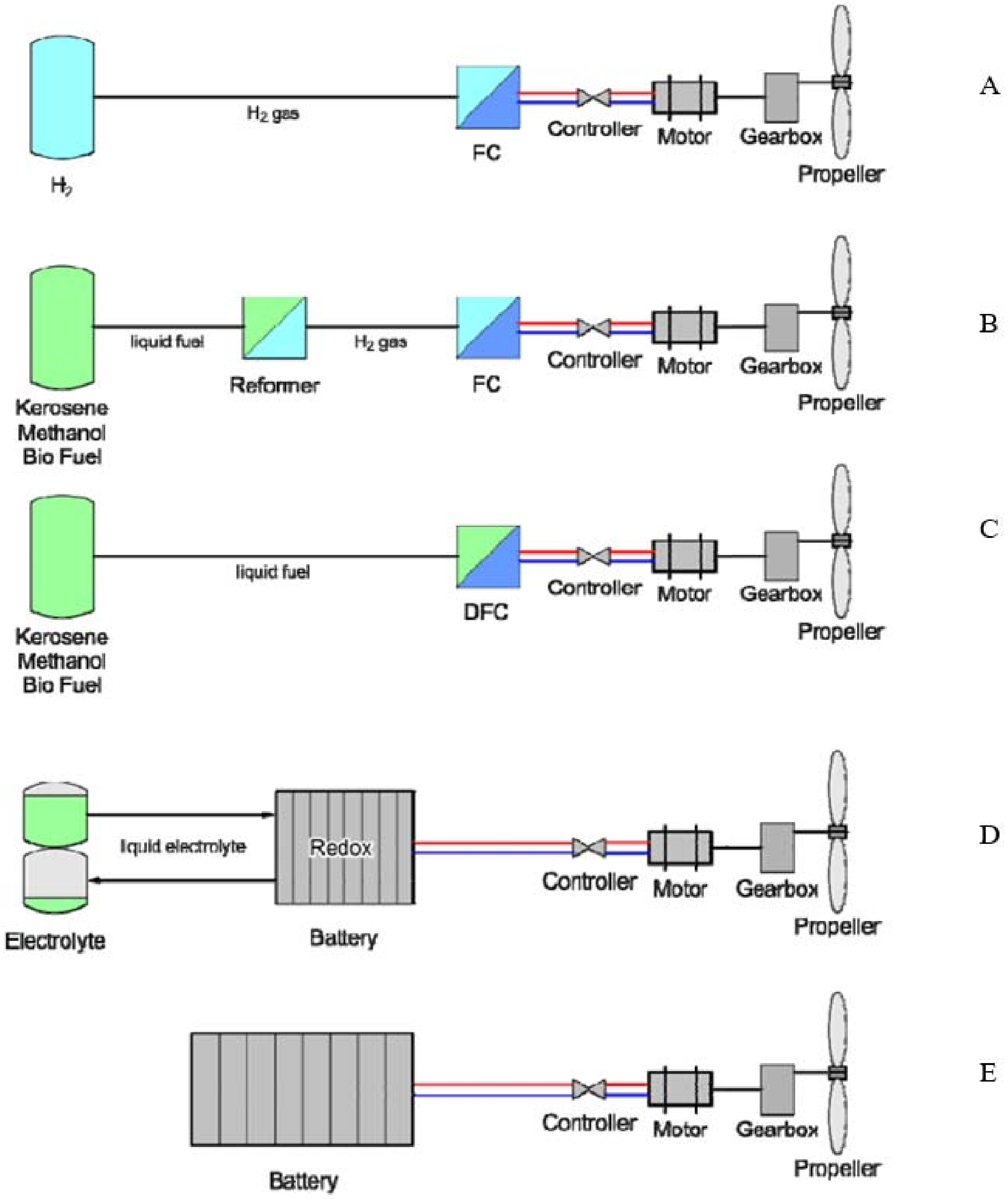
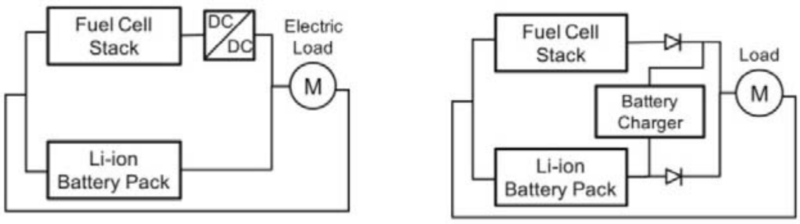


Figure 6: Principal routs of fully airplane electrifications[9]

But there are also hybrid power source systems possible, as shown in Figure 7 with and without a DC/DC converter



a Conventional hybrid system.

b Direct hybrid system.

Figure 7: Conventional (a) and direct (b) FC-Battery hybrid system [[10]*]*

The main difference between batteries and fuel cells from the application point of view is the relation between power and energy. In case of batteries[1] energy and power are related linearly, in case of FCs energy and power could be chosen independently of each other. The FC power is given by the FC stack and the FC energy mainly by the fuel tank, which has a relatively low mass. This has a decisive influence on the mass of the system. For lower energy/operating time demand batteries are preferred caused by their smaller system mass, at higher energy/operating time demand FC systems have a smaller mass with regards to batteries (Figure 8).

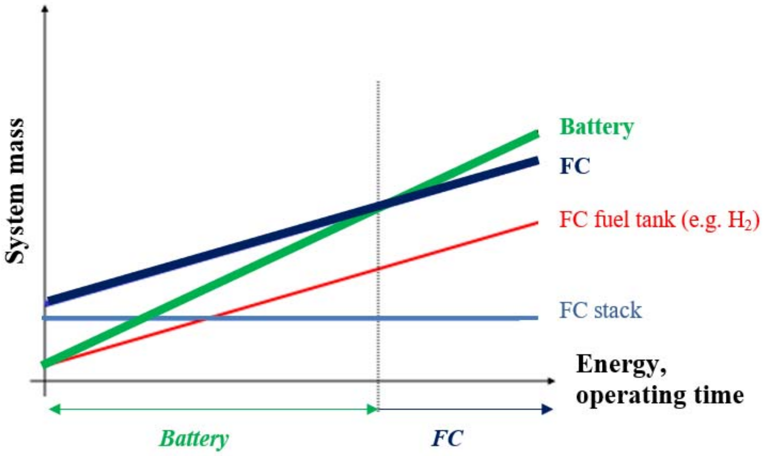


Figure 8: Schematic connection between mass of battery and FC systems vs. energy /operating time

Especially in case of batteries with low specific energy, as lead-acid batteries (PbA), the battery mass/volume must be strongly increased to reach a certain flight range, the battery mass/volume – range relation reaches a logarithmic ratio. In case of fuel cells, where the energy is mainly given by the H_2 tank the FC mass/volume – range relation has a linear progression. This is shown in Figure 9 for EVs, but this is valid also for electric airplanes. Therefore, larger flight timer or larger planes designate FC system as the technology of choice. .

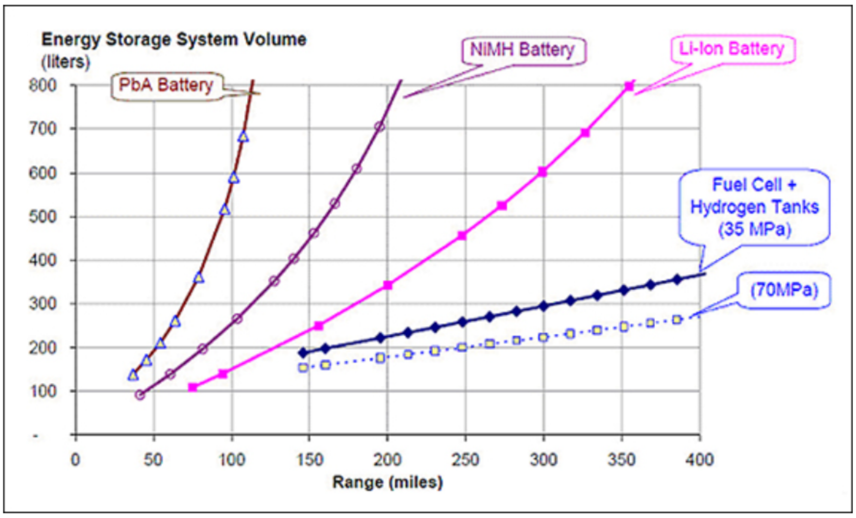


Figure 9: Driving range of electric cars as a function of different energy storage/conversion systems [11]

For fuel cells in aviation application one has to consider also the use of waste products – water, water vapor, heat and oxygen-depleted air for fuel tank inerting and cargo bay fire suppression.

An important parameter for the all-electric fly is the flight range (R), which is given by

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[1] Exception: Redox-flow battery

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$$R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{batt}}{m} \qquad \text{(equation 1)}$$

with g - gravity acceleration [m/s²]

So, the flight range is mainly determined by

- Specific battery energy [Wh/kg] (E*)
- System efficiency from battery to propulsive power (η_{total}), which is about 75 %
- Lift over drag ratio which depends on the aircraft design (L/D), which is about 10…15 for larger commercial aircrafts.
- Battery mass fraction (m_{batt}/m), where m is the total airplane mass (m_{empty} + $m_{payload}$ + $m_{battery}$). By light weight electrical machines and construction materials m_{empty} can be reduced.

Based on equation 1 the flight range is given for different L/D values (40 related to sailplanes, 10 to general aviation aircrafts), different battery mass fraction (m_{batt}/m), and specific battery energies at η_{total} = 75 % - see Figure 10.

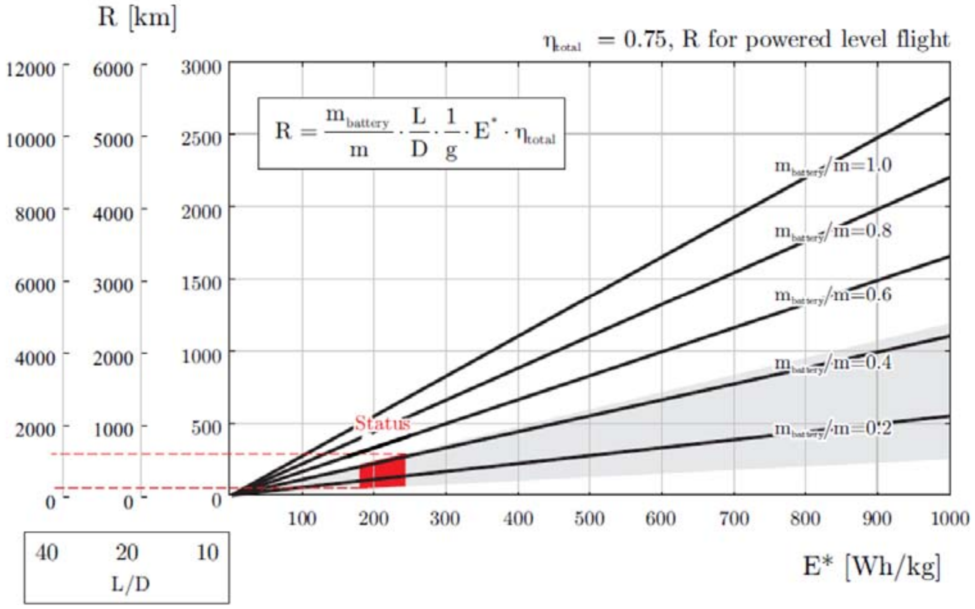

Figure 10: Range (R) vs. specific battery energy (E), different ratios of lift over drag (L/D) and battery mass fraction [9]*

This figure shows the relatively low range for general aviation aircrafts (L/D ≈10) with practical battery mass fraction (m_{batt}/m) of 0.2 …0.4 for specific battery energies of 180 … 250 Wh/kg. Decisive for a range increase to 250… 500 km is the increase of the specific battery energy to about 500 Wh/kg (see chapter 4)

As long this specific battery energy is not reached only hybrid-electric planes could fly in this range region or the battery is charged during the fly via PV panels.

The first electrically powered aircraft, an airship, was constructed in 1883 by the French G. Tissander, who attached a Siemens electric motor to power the airship propeller. One year later the battery-powered La France was introduced by A. Krebs and Ch. Renard, both French military officers. La France was the first fully-controlled airship which was able to return to its starting point in good weather conditions.

The first manned electric plane of the modern area was the MB-E1 based on the fully certified motor glider HB-3 with minor modifications to carry batteries and electric motor proposed by F. Militky and build by the Austrian manufacturer H. Brditschka in 1973 – see Figure 11. The 10 kW e-motor was provided by BOSCH and the 100 V, 24 Ah Ni-Cd batteries by VARTA. The max. fly time of MB-E1 was about 10 min.

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Figure 11: First electric plane MB-E1[12]

Selected newer developments are as follows:

The US company Zunum Aero plans in cooperation with Boeing and JetBlue a hybrid electric drive system for 12-passenger, with 550 km/h; first flights will be 2020/21.

The three French aerospace companies Airbus, Daher and Safran are developing a hybrid-electric plane based on the Turboprop-Einmot Daher TBM with the name EcoPulse (5 passengers). The combustion engine drives the main rotor on the fuselage of the aircraft. The electric motors drive six smaller propellers attached to the wings – three on each side; iIn 2022 will be the first flight. Airbus is also developing with Rolls-Royce and Siemens the Airbus E-Fan X as a hybrid-electric airline demonstrator.

EasyJet plans together with Wright Electric a nine-passenger all-electric aircraft prototype that will fly next year with about 500 km range.

The Slovenian company Pipistrel offers a tiny two-seat, all-electric Alpha Electro for approximately $137,500. It is intended for the pilot training market with a flight time of one hour. The Chinese Liaoning Ruixiang RX1E-A is used also for pilot training, the flight time, however, is 2 hours. The price is about $150,000.

There are also many developers of flying taxis, which are mostly electric vertical take-off and landing (eVTOL) aircrafts normally with a range between 50…100 km and partially larger. Examples are the German company Lilium with their Lilium Jet with 36 all electric engines and max. 300 km in one hour. Other developers are and Rolls-Royce, Even Aston Martin, Vertical Aerospace, Karem Aircraft, and Urban Aeronautics.

Exceptionally is the all-electric ALICE plane of the Israeli company Eviation with 9 + 2 seats, ultra light, all-composite airframe as well as one main pusher propeller at the tail and two pusher propellers at the wingtips driven by Siemens engines. A range + IFR reserve of 1,000 km is reached by a 900 kWh Li-ion battery which surpassed together with a proprietary Al-air system (as primary battery probably for the IFR reserve) the specific energy of 400 Wh/kg. The battery weight takes up 65% of the aircraft's weight. Eviation is expected to begin first deliveries in two years.

Figure 12: Model of the all-electric airplane ALICE [[13]*]*

By May 2019, Roland Berger counted almost 170 electric aircraft programs in development, anticipating over 200 by the year end, with a majority of urban air taxi.

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3.2.3 Solar powered aircrafts

Solar powered aircrafts offer the ultimate promise of environmentally clean operation for long periods of days, months or years. They are alternative to satellites, operating at an altitude of about 20 km, well below the satellite orbits above 200 km. They could loiter in a desired geographical region as a much cheaper alternative to geostationary satellites. The lower distance of solar powered aircraft to receivers and users on the ground compared with satellites would enable lower emission power and less atmospheric signal degradation by staying below the ionosphere.

Solar panels are the electricity generator. Under the assumption of a solar radiation of 1.4 kW/m^2 at 20 km altitude a propulsive power of 2 MW will require a wing area of at least 140 m^2 panel area covered with solar panels. The relatively high power allows a speed up to 120 km h^{-1}, which is necessary to keep a geostationary position even at stratospheric winds with max. 200 km h^{-1}.

Also round the globe flight or long-time flights by solar powered aircrafts are possible. They solar powered planes are used either as unmanned platforms for sensors or manned for demonstration and leisure The first manned fly was 1979 the Mauro Solar Riser. In the same year Bryan Allan successfully crossed the English Channel with his Gossamer Albatross. Later NASA (Pathfinder, Pathfinder Plus, Centurion, and Helios) and also Airbus/Siemens have developed prototypes. The Solar Impuls in the beginning of the 2010th was a new milestone. The Solar Impulse 2 has had a wingspan of 72 m, 270 m² PV panels and 4 x 41 kWh Li-ion batteries (164 kWh, 633 kg, 2e60 Wh/kg) ultra-high energy NMC batteries from Kokam.

Figure 13: Solar powered aircraft Solar Impuls 2

The circumnavigation of the earth with 42,438 km and in summarized 23.25 days was done 2015/16 in 17 stages. The longest leg was with 7,212 km and 117 h from Japan to Hawaii. During that fly the plane's batteries were overheated and it was assumed that they got damaged. But it was impossible to rule out capacity loss or battery damage in Hawaii. For safety reasons the Solar Impulse batteries were replaced with new ones. Later it was found out that the batteries were undamaged, with only a small decrease in the battery capacity.

For night propulsion the electrical excess energy generated during daytime has to be stored by conventional batteries or by a hydrogen accumulator (electrolyser, H_2 store, fuel cell). The storage system decision depends inter alia on the necessary energy for the night and the available room for H_2 storage. The later speaks for hydrogen accumulators in case of zeppelins.

4 Batteries

As in Figure 10 shown, the range of the electric plane is determined besides the L/D ratio and the battery mass fraction especially by the specific energy of the battery.

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As high energy batteries come into question only the Li-battery. The specific energy of the Li-ion battery is today in the region of 150 … 250 Wh/kg. There are, however, further developments under the way, which will lead to an increase of the specific energy:

- Increase of the Ni-content and therefore higher specific energy in NMC ($LiNi_{1-x-y}Mn_xCo_yO_2$) cathode mass from 33 % (NMC111), 50 % (NMC523) and 60 % (NMC622) to 80 % (NMC811) or 90 % (NMC90.50.5). Problems in the moment are a reduced thermal stability

- Use of Si-anodes in composite with graphite. Problems in the moment are a reduced lifetime.

- Li-Sulfur batteries. Problems in the moment are a low lifetime, a high self-discharge and a low power.

- All solid-state batteries with a metallic Li anode. Problems in the moment are the low lifetime and a low power.

- Li-air batteries. Problems in the moment are a low electrical efficiency, low power and low lifetime.

Before these batteries will be produced the given problems must be solved. This., however, takes time. The timeframe for the introduction of the different generation of Li and their expected specific energy is given in Figure 14.

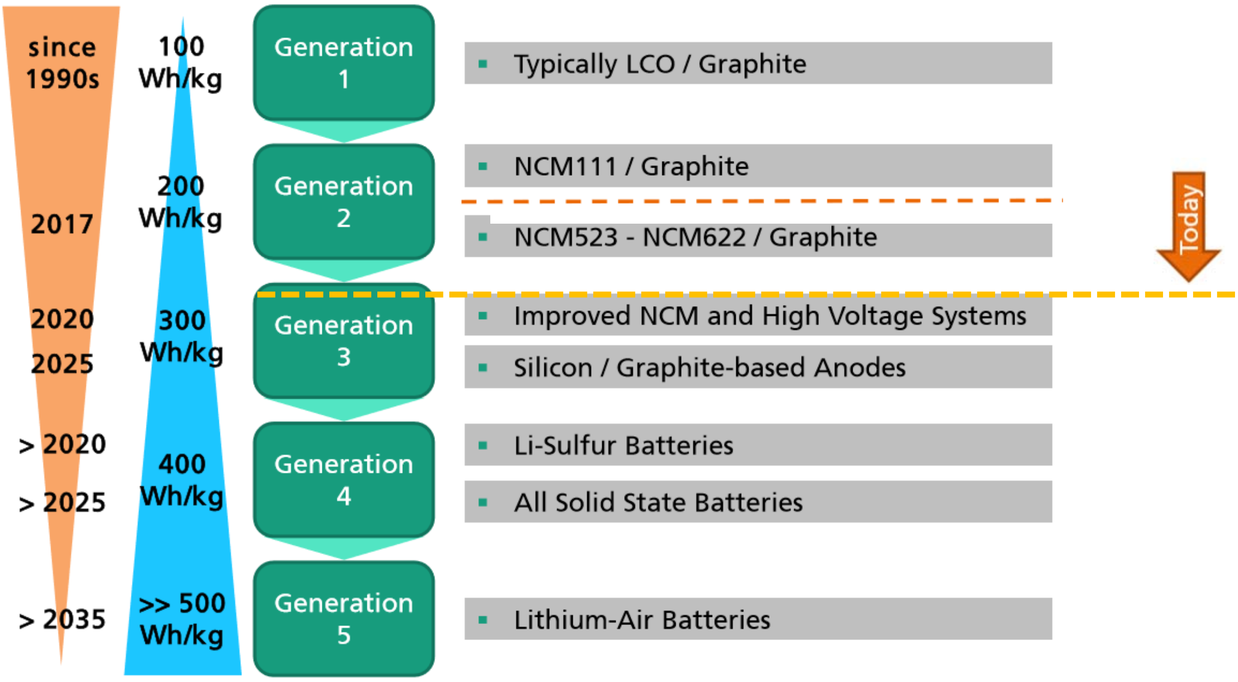

Figure 14: Roadmap for the introduction of new Li systems with higher specific energy [14]

For the aviation application of Li batteries the RTCA (Radio Technical Commission for Aeronautics) which acts as a federal advisory committee for the development of consensus-based recommendation has worked out the document DO-311A: *Minimum operational performance standards for rechargeable Li batteries and battery systems* in 2017. This document based on RTCA DO-311 (2008 version of *Minimum operational performance standards for rechargeable Li batteries and battery systems*), RTCA DO-347 (Certification Test Guidance for Small and Medium Sized Rechargeable Lithium Batteries and Battery Systems), RTCA DO-160 (environmental conditions and test procedures for airborne equipment), UL 1642 (Standard for Safety for Lithium Batteries), UL 2054 (Standard for Safety for Household and Commercial Batteries), UN Section 38.3 ("UN manual of tests and criteria), and IEC 62133 (Secondary cells and batteries containing alkaline or other non-acid electrolytes –Safety requirements for portable sealed secondary cells) cells, and for batteries made from them, for use in portable applications.

This document contains Minimum Operational Performance Standards (MOPS) for rechargeable Lithium battery systems to be used as permanently installed power sources on aircraft. Compliance with these standards is recommended as a means of assuring that the Lithium battery will perform its intended function(s) safely, under conditions normally encountered in aeronautical operations. These standards apply to the chemical composition, cell size, cell construction, cell interconnection methods within batteries, venting provisions, operational and storage environments, packaging, handling, test, storage and disposal of rechargeable Lithium batteries, installed separately or in avionics equipment aboard aircraft. The RTCA DO-311A is divided into section 1, which identifies battery categories by energy content, venting provisions, and architecture, section 2, which contains general, performance, safety, and environmental requirements and tests, and section 3 provides installation consideration in relation to the battery system design. The battery applications are related to the provision of power throughout the aircraft, including engine, APU starting, avionics, emergency, and other systems.

From the theoretical point of view also the Zn-air system would be worthy of discussion. But its low power and low cycle number exclude that system for the time being as secondary propulsion battery. But the Zn-air battery and also the Al-air battery can be used in its primary variant (not rechargeable) as reserve battery, which will be activated in case of emergency. This battery could be accepted also as IFR-reserve, which is related to instrument flight rules (IFR) as reserve for holding pattern or a flight to an alternate airport. But this primary battery can be used only once. Obviously, the electric ALICE plane of the Israeli company Eviation is using an Al-air primary battery as reserve battery.

5 Literature

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[1] Airbus Global Market Forecast 2012 – 2031. http://www.airbus.com/company/market/forecast/, [retrieved 25 September 2012]

[2] Flightpath 2050 Europe´s Vision for Aviation – Report of the High Level group on Aviation Research

[3] Henderson, S.C. and Wickrama, U.K. (1999) Figure 9-3 of 'Aircraft emissions: current inventories and future scenarios', in Penner, J.E., Lister, D.H., Griggs, D.J., Dokken, D.J. and McFarland, M. (eds) (1999) *Aviation and the Global Atmosphere: a Special Report of IPCC Working Groups I and III*, Cambridge University Press, Cambridge.

[4] https://www.acare4europe.org/sites/acare4europe.org/files/document/Create-Final-Report-October-2010.pdf

[5] https://www.acare4europe.org/sites/acare4europe.org/files/document/ACARE-Strategic-Research-Innovation-Volume-1.pdf

[6] https://www.pareproject.eu/publications

[7] Roland Berger GmbH, Report Aircraft Electrical Propulsion – The Next Chapter of Aviation? 2017

[8] M. Keim, J. Kallo, K.A. Friedrich, C. Werner, M. Saballus, F. Gores, Multifunctional fuel cell system in an aircraft environment: An investigation focusing on fuel tank inerting and water generation, Aerospace Science and Technology, 29 (2013) 330-338

[9] M. Hepperle, Electric Flight – Potential and Limitations, NATO Workshop Energy Efficient Technologies and Concepts of Operation STO-MP-AVT-209, 2012, DOI10.14339/STO-MP-AVT-209

[10] A. Nishizawa, J. Kallo, O. Garrot, J.; Weiss-Ungethüm, Fuel cell and Li-ion battery direct hybridization system for aircraft applications, J. Power Sources, 222 (2013) 294-300

[11] International Journal of Hydrogen Energy, 34 (2009) 6005-6020

DOI: 10.13009/EUCASS2019-851

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[12] AUSTRIAN WINGs - Österreichs Luftfahrtmagazin, 27.10.2017

[13] https://en.wikipedia.org/wiki/Eviation_Alice#/media/File:Eviation_Alice.png

[14] FhG IFAM, Li-battery roadmap