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Trends on current and forecasted aircraft hybrid electric architectures and their impact on environment

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A B S T R A C T
Climate change is the megatrend that will have the biggest impact on the development of sustainable air transportation in near future. Aviation is expected to triple its proportional share of a Paris compatible 1.5 °C budget, declared by UNFCCC Agreement for global temperature through 2050 under current international policies. Basket of measures proposed by ICAO to keep the temperature change under this limit, including aircraft technology (up to 25%) and operation improvement (up to 9%) for fuel burn reduction by engines and new revolutionary architectures of the aircraft, deployment of sustainable alternative fuels (over 40% of fuel burn reduction), market based measures (ICAO CORSIA) as pushing system for more quick and efficient implementation of the first three, etc. Pioneering sustainable technology is allowing the civil aviation sector to embrace the next generation of aviation through electrification and alternative fuel sources. Electric propulsion is proposed as one of the revolutionary technology changes in aviation, which should be assessed on possible contribution in reaching the climate change goal and one of the environmental goals of the EU strategic document Flightpath 2050. Existing potential and forecasted progress for More Electric Aircraft concept is showing quite limited reduction in fuel burn and emission. Full electric or hybrid propulsion may provide essential reduction, but in considered time frame it is looking to be very possible for implementation in groups of General Aviation, Urban Air Taxis and Regional Aircraft first of all. More than 90% of GHG emissions from global commercial aircraft operations are generated by Large Commercial Aircraft, so research to reduce commercial aircraft emissions will be most useful if it focuses on technology applicable to them.

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1. Introduction
Besides safety, environmental protection is a major issue to be considered in air traffic management and aircraft operation. Among the environmental problems there are global and local issues exist, that is why ICAO Environmental Policy during last decade consists of the two separate parts at least — “General provisions, noise and local air quality” and “Climate Change” [1]. In subject of climate change control the recorded total CO2 aviation emissions are approximately 2% of the global greenhouse gas (GHG) emissions (international aviation accounts for about 1.3% of total global CO2 emissions, other part - domestic aviation), which is rising on 3–4% annually due to traffic and appropriate fuel consumption growth. Accordingly the international aviation is expected to triple its proportional share of a Paris-compatible (declared by UNFCCC Agreement in Paris, 2015) 1.5 °C budget for global temperature rise through 2050 under current international policies and “doing nothing” in technology development of the aviation sector. Paris Agreement calls upon all the States to maintain global warming at 2 °C in the middle of this century, compared with pre-industrial levels, and perform maximum efforts to keep the temperature rise even within 1.5 °C. Results of all last researches show the impossibility to reach these goals with evolutionary approach for aircraft design development — mostly concentrated on improvement of fuel consumption by engines, improvements in aerodynamics and weight reduction of the aircraft. A very new ICAO Standard on CO2 emission of the aircraft — both “being in production” and “new designs” — must contribute essentially to global aviation GHG emission reduction (it is realized in vol. III “Aeroplane CO2 Emissions” to Annex 16 “Environment Protection” to ICAO Convention [2] – the world’s first global design certification standard governing CO2 emissions for any industry sector), but

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concerning only the evolutionary path of the technologies in new aircraft designs and operation. Among the revolutionary expected changes in aircraft design are the concepts of full electric (FEA) and hybrid electric (HEA) aircraft, both concepts are relative to aircraft engine thrust production. These FEA and HEA concepts will compete with sustainable aviation fuels (SAFs) implementation in aviation sector, including biofuels and hydrogen. Hydrogen and fuel cell technology has undergone significant development in the last decades, industry technology outlook and expert interviews consider an optimistic and achievable forecast of the performance of H2 powerplant components for aircraft over the next decade. Other pathways to reach this aspirational goal — aviation sector development within 1.5 °C of global temperature rise — are still not foreseen today completely, a number of possibilities are under investigation and assessment. In real consideration the availability of SAFs are expected between 5 and 10 Mt annually, due to their production prognosis in following decade, but to solve the climate task completely in 2050 — its production should be around 300 Mt to cover the needs of aviation sector only. In this article the competitiveness of electric aircraft (with so called e-fuels) with imminent designs is considered, SAFs and hydrogen fuels are mentioned as possible future scenarios only.

2. Assessment of necessary reductions of aviation impact on environment

To keep the climate change within Paris requirements to global temperature all the states and responsible economic sectors should begin their radical reduction of the GHG emissions now — during the current and following decades — and in a second half of XXI century to achieve a global balance between man-made emissions and natural and again man-made carbon sinks that absorb and store these gases (such as main natural absorbers — the oceans, forests and soils, and new technologies to utilize these emissions). In fact, this means the need to completely phase out fossil fuels by 2050 in any sector, including energy and transportation sectors first of all, and the transition to 100% usage of renewable energy sources, with aviation sector in the list of key players. As part of that global authority decision, the ICAO, as a responsible international board in management of aviation sector, set a sector-specific target that CO2 emissions from civil aviation in 2050 should be at or below 2020 level [3] (Fig. 1, the data compiled from Ref. [2]). Looking on a number of possible scenarios [6], the mostly optimistic long-term aircraft fuel efficiency of 1.37% is significantly lower of ICAO’s desired goal of 2% [1] — it means that evolutionary technology improvements may cover only around two-thirds of the necessary fuel consumption reduction per annum. ICAO (by its Committee on Aviation and Environment Protection — CAEP) even has identified the number of technology, operational and organizational measures that can contribute to reductions of CO2 emissions (so called ICAO’s basket of measures) more effectively: aircraft related technologies and standards to stimulate their implementation; improved air traffic management and aircraft operation (first of all fuel burn reduction per flight will be reached due to more direct cruise flights and more efficient vertical profiles in air traffic management); development and deployment of SAFs [4]; market-based measures (MBM) — global and regional [5]. First two — aircraft technology and operation — will contribute to fuel burn reduction as a primary goal and to CO2 emission reduction consequently only on one-third necessary volume in relation to aviation GHG emissions 2020 range (Fig. 1). A currently predefined by UNFCCC Agreement 1.5°C pathway in ICAO environment protection policy (coordinated by the CAEP and realized by the member states) would expect global emissions of CO2 and its equivalents to peak by around 2020 and decline thereafter, and necessitate negative emissions by around the mid part of the 21st century. Global MBM implementation in accordance with ICAO Standard requirements [5] must intensify aircraft technology and operation improvements, including revolutionary approach to them from one side, it must intensify SAFs development and deployment from other side, including their higher regional specification in accordance with natural possibilities around the world (scenarios assessment in Fig. 1 are grounded on and would require for high availability of bioenergy feedstocks around the world with a substantial expansion of the agricultural sector, complementarily a complete shift in aviation from petroleum refining to SAF production).

The results in Fig. 1 are presented for international aviation only, domestic aviation is not included, but it is also essential in contribution to total aviation CO2 emission. For example, in 2010 approximately 65% of aviation fuel was consumed by international aviation, of course other 35% - in domestic flights. This proportion between international and domestic air transportation is foreseen to be more or less stable in two-three decades, with quite small growth to nearly 70/30% accordingly by 2050 because of expected higher demand on international transportation and planned technology improvements inside the aircraft fleet (due to current CAEP analysis).

The global trends presented in Fig. 1 were developed by the ICAO CAEP in the context of a long-term forecasting, which are coordinated by two groups of experts — Forecast and Economic Analysis Support Group (FESG) and Models and Databases Group (MDG) inside the basic ICAO/CAEP task “Global Environmental Trends”, which are developed cycle-by-cycle for a range of flight operation scenarios for the assessment of future local air quality and aircraft noise exposure in/around airports, global aircraft fuel burn and GHG (mostly net CO2 emission) emissions trends. In 2015 international aviation (passenger and freight traffic combined forecasts) consumed approximately 157 Mt of fossil fuel (resulting in ~500 metric Mt of CO2 emissions), and by 2045 it is expected that despite an anticipated increase of 3.3 times in international air traffic, fuel consumption is projected to be increased over the same period by 2.2–3.1 times only, depending on the technology and ATM scenario [2,7]. By latest 2019 annular assessment, an international aviation consumed over 200 Mt of fuel for the reached 38.9 mln of flights performed globally [8], resulting in ~600 Mt of CO2 emissions. Baseline scenario (compiled and assessed by CAEP/11 meeting in 2019 — a blue line on the top of Fig. 1) includes the operational improvements necessary to maintain current operational efficiency levels only, but not covering any sufficient changes in technology beyond those available in current (2015) production aircraft. Global fuel consumption and CO2 emission projections in Fig. 1, so as air traffic and aircraft fleet as the basic values for this forecasting, can be changed dramatically by a wide range of impacting factors such as instabilities in fuel prices and in global economic conditions — every crisis not only put down the operational and economic data in aviation sector (Fig. 2 [26]), but shifted (with any kind of delay in reaching the goal) the prognostic curves from pre-crisis trends. The impact of COVID-19 crisis is still under the development, its recovery path is not understanding completely to today’s situation. In further text the COVID-19 impact is not considered.

Other scenarios under ICAO/CAEP expertise include fuel burn improvements of ~1% per annum for all aircraft entering the fleet after 2010, and 0.57% per annum for all aircraft entering the fleet beginning in 2015 out to 2050 (low aircraft technology and CAEP/9 Independent Expert (IE) operational improvement). The ~1% is slightly lower than the 1.3% cited in the latest CAEP/11 Independent Experts (IE) Review for single aisle aircraft [8]. The IE panel was tasked with providing goals for fuel burn, noise, and emissions in the mid-term (2027) and the long-term (2037) for four classes of
aircraft: business jets (BJ), regional jets (RJ), single-aisle aircraft (SA) and twin-aisle (TA).

Attention was concentrated on SA and TA aircraft, which overwhelmingly contribute in a fleet and have the largest environmental impact as a consequence (Fig. 3). For 2027, the potential fuel burn reductions attributable to the new propulsion technologies have been estimated to be about 5% for SA and about 6% for TA aircraft. For 2037, an extra 5% fuel burn reduction might be obtained. Improvements in aerodynamic performance of an aircraft (defined by lift-drag ratio) are also different — for TA 15% higher than for SA aircraft currently. Further aerodynamic performance improvements can be reached by the use of laminar flow: for smaller aircraft (usually fly slower and have less sweep) BJ, RJ and even SA with natural laminar flow and hybrid laminar flow (requiring suction) for the TA aircraft. Reducing aircraft empty mass is vital — advanced composites possible savings of 8% for the SA and 4% for the TA aircraft. Taking under consideration other aircraft mass reduction technologies (2–4% for SA and TA) the empty mass savings for global fleet are in the range 2–4% for 2027 and 8–10% for 2037.

The future fleet composition was derived using an appropriately calibrated passenger aircraft retirement function. In comparison with decade 2010–2020 (~20,000 aircraft fleet globally) a total of about 56,000 new aircraft will be needed by 2040 to accommodate the predicted demand, ~65% of which will be for growth, and the remainder will replace current aircraft (Table 1).

As with the previous fuel burn analyses, this analysis considers the contribution of: new aircraft technology, improved air traffic

Fig. 1. ICAO CAEP trends in fuel burn (left axis of ordinate) and net CO₂ emissions (right axis of ordinate) from international aviation.

Fig. 2. 9/11 and global financial crisis had a U/L-shaped impact on air transport (the data for United States).
management, and infrastructure use. While in the near term (2010–2020), fuel efficiency improvements from aircraft design and operational improvements are expected at level of the predefined 2020 targets (Table 2 shows the reached fuel efficiency by new aeroplanes implemented in operation during last years), they are projected to accelerate in the medium term (i.e., 2020 to 2030, see in Table 3 [26] and Fig. 4).

Under the most optimistic Scenario “Optimistic Aircraft Technology and CAEP/9 IE Operational Improvements” (initially considered as 1.5% fuel efficiency improvement per annum for all aircraft entering the fleet out to 2050) the international aviation fuel efficiency, expressed in terms of volume of fuel per RPK, is foreseen to improve at an average rate between 1.29% and 1.37% per annum to 2045 with extrapolation to 2050 (Table 3 and Fig. 4). This indicates that ICAO’s aspirational goal of 2% per annum fuel efficiency improvement is unlikely to be met by 2050 if the evolutionary approach will be considered alone.

More than 90% of fuel burn and appropriate CO2 emissions from global commercial aircraft operations are generated by large aircraft (TA and SA airplanes with board capacity to transport over 100 passengers). Newer jet aircraft (RJ and SA airplanes with board capacity to transport over 80% of the fuel savings for last generation of aeroplanes are due to improvements in their propulsion systems), – up to 20% more fuel efficient than the previous one. For example, if to look on most popular aircraft in operation for passenger transportation the Boeing 737, it took to the skies for the first time in 1967 (it was Boeing 737–100), carrying on board 124 passengers over the distance 2775 km with a total payload around 13 tones. A current most popular version the Boeing 737–800 is carrying on 48% more passengers, flying 119% farther with a 67% increase in payload, while burning 23% less fuel—or 48% less fuel on a per-seat basis. Boeing 737 MAX is ~20% more fuel efficient than its predecessor – it is usual for new generation of RJ and SA aeroplanes, TA designs even reached 25% of fuel efficiency improvement (for example in comparison of Airbus 350 or Boeing 787 to Boeing 767). It is a kind of evolutionary technologies’ improvement, which is still character for current and next decade of aircraft design development.

In Fig. 1 the contribution of technology improvements in fuel burn (fuel burn reduction scenarios) are realized through implementation of a new aeroplane CO2 emissions standard, its aim is to implement more fuel efficient technologies into new manufactured aeroplane designs. It is quite similar to the number of other ICAO technology standards like for engine emissions to control local air quality of the airports and for aircraft noise of the aircraft to manage noise around the airports. The CO2 standard [16] was developed for the aeroplane as a whole, it includes the contributions of all the technologies associated with the aeroplane propulsion, its airframe aerodynamics and structures (their reduced weights due to usage of new light materials first of all) of aeroplane designs. The CO2 standard is applied to subsonic jet and turboprop aeroplanes that are the new types from 2020, as well as to aeroplane type designs still in production in 2023 and undergo a change. The aeroplanes in production that do not meet the standard can no longer be produced from 2028 (a production cut-off for them), unless the designs are modified to comply with the standard.

By 2050, the contribution of cumulative GHG emissions from international aviation is forecasted between 2.8% to 5.3% against the 2.0°C budget scenario, and the projected annual emissions in 2050 could lie between 1.8 and 6.6% of global GHG emissions under the RCP4.5 scenario prepared and assessed by IPCC (global mean surface temperature change at the end of the 21st century projected within 1.8°C [9]). Scenario RCP4.5 (Fig. 5) is an intermediate IPCC forecasting between a stringent mitigation scenario RCP2.6 and a scenario allowing for very high GHG emissions RCP8.5 among all 4 Representative Concentration Pathways (RCPs) in the latest IPCC’s 5th Assessment Report [9].

Table 1

| Number of aircraft in operation | Decades | 2010 | 2020 | 2030 | 2040 |
|--------------------------------|--------|------|------|------|------|
| % total                        |        | 151.4| 214.1| 286.5|
| % replaced                     | 27.1   | 70   | 96.9 |
| % for growth                   | 51.4   | 114.1| 186.5|
| % number of replaced/number for growth | 65.5   | 62   | 65.5 |
which was the basis of the current emission reductions strategy (Figs. 1 and 5, Table 3), which also left the 2050 ambition open, setting a range of 80–95% cuts, but in practice mostly working towards the lower end of that range. Considering that global temperatures have already risen at least 0.8°C and GHG concentrations are increasing rapidly aviation (international and domestic) must decarbonise itself by 2050, so as all the impacting sectors in general. Meeting the goals of the Paris Agreement will require rapid near-term emissions reductions.

Substantial reduction of CO2 in aviation sector may be achieved with SAFs implementation (Figs. 1 and 5, Tables 3 and 4) [4], in combination with market-based measures [5], which are considered as an important instrument for pushing SAFs into the air transportation market. The values for RCP4.5 in Table 3 are higher than the same values for expected aircraft flight fuel efficiency put in forecasting by CAEP, but once again they are not enough to reach the 2% annular reduction technology goal defined by ICAO Policy [1].

The modeling assessment shows that up to 100% of jet fuel demand in international aviation sector could be met using SAFs in 2050, providing neutral carbon growth of aviation during the period 2020–2050. SAFs are considered as biofuels first of all, since 2008 six types of biofuel for aviation production pathways have been certified up-to-date, and other pathways are in the qualification process, utilising a variety of feedstocks worldwide including non-crop sources such as waste oils, waste gases and municipal wastes. Projects to produce SAF providing at least a 70% life cycle carbon savings compared to fossil fuel are presently under

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Table 2
New aeroplane types recently entered the market.

| Aeroplane category | Previous Generation (reference) | New generation (latest deliveries) | Entry into service | Fuel saving to reference |
|--------------------|---------------------------------|-----------------------------------|--------------------|--------------------------|
| RJ                 | ATR/CRJ, E-Jet                  | MRJ, E-Jet E2                     | 2020               | 20–24%                  |
| SA                 | A320/B737                       | A220/A320neo/B737 MAX             | 2016/2017          | 20%                     |
| TA                 | B767                            | A350/B787                         | 2015/2011          | 20–25%                  |
|                   | A330/A380/B777/B747-8           | A330neo/B777X                     | 2018/2019          | 14–20%                  |

Table 3
International aviation's contribution in CO2 global emission for ICAO and IPCC scenarios.

| Scenario                           | Basic description                                      | Contribution in the given year, % | 2010 | 2020 | 2030 | 2040 | 2050 |
|-----------------------------------|--------------------------------------------------------|-----------------------------------|------|------|------|------|------|
| CAEP 2019 [7]                     | ICAO/CAEP Optimistic scenario                           | 1.00                              | 1.29 | 1.37 | 1.37 | 1.37 | 1.37 |
| ICAO current goal [1]             | ICAO Policy, long term goal – global temperature rise 2 °C | 2.00                              | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| ICAO aspirational goal [1]        | ICAO Policy, long term goal – global temperature rise 1.5 °C | >2.00                            | >2.00 | >2.00 | >2.00 | >2.00 | >2.00 |
| RCP4.5 [9]                        | Baseline including fleet renewal                        | 1.28                              | 2.02 | 2.89 | 4.18 | 6.58 | 6.58 |
|                                  | Carbon neutral growth from 2020                         | 1.28                              | 1.97 | 1.80 | 1.74 | 1.78 | 1.78 |

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Fig. 4. Fuel burn metrics for aircraft in operation and the ICAO/CAEP IE technology goals: CAEP/9 – for midterm at 2020 and long-term at 2030; CAEP/11 – for midterm at 2027 and long-term at 2037 (metric value is equal to 100 to the point when new age SA and TA – Boeing-737 and Boeing-747 – were delivered to the market).
development elsewhere in the world. They will be able to reduce net global life-cycle CO₂ emissions from commercial aviation immediately because they are drop-in fuels, so they are compatible with existing aircraft and system infrastructure — therefore they can be used without any modification to present aircraft. They are qualified for use in up to a 50% blend with fossil fuel, with the potential for higher blends in future. In comparison with conventional jet fuel the combustion of equivalent amounts of the SAFs is also producing lesser amounts of other harmful emissions, such as sulfur oxides and particulate matter.

Based on the analysis assumptions, if enough SAFs were produced in 2050 to completely (up to 100%) replace fossil jet fuel, it would reduce net CO₂ emissions in aviation sector up to over 60% (also shown in Fig. 1, green area). For analysis shown in Fig. 1 the SAF availability was calculated including around ten different groups of feasible feedstocks around the world [4] for: various crops, agricultural and forestry residues, waste fats, oils and greases, microalgae, urban solid waste. The complete replacement of fossil jet fuel would require one-two hundreds of new biorefineries to be deployed every year during the next three decades, which may cost around 15 … 60 bln dollars annually with simplest assessment. These amount and cost calculations include in consideration the potential total global production and an average life cycle assessment values of the SAFs based on their share that contribute to each scenario in consideration currently. These values show obviously that investment and commercial scale up barriers exist, also significant uncertainties still exist in predicting the contribution of SAFs into climate change radiation forces till 2050.

3. New technology requirements for next aircraft generation

The world aerospace industry is a big success story and now again an air transportation system is in a period of great change and generational shift. During last decades the importance of aircraft efficiency has increased with the rise in jet fuel prices first of all [11] — due to high fuel prices different aircraft concepts have been taken into consideration, including the usage of varied fuel types [12,13], but also the usage of more electricity.

### Table 4

| Measures                                    | CO₂  | Change in non-CO₂ | Assumption considered                                                                 |
|----------------------------------------------|------|-------------------|---------------------------------------------------------------------------------------|
| Market-based measures, ICAO CORSIA [5]       | ✔    | ✗                 | 1.5% efficiency improvement per year for new aircraft entering the fleet.              |
| Technology improvements [6] and CO₂ Airplane Standard [10] | ✔    | ![image](https://via.placeholder.com/150) | Electric taxing systems                                                             |
| Operational improvements [6]                | ✔    | ![image](https://via.placeholder.com/150) | Removing constraints on vertical and horizontal profiles flight                       |
| Lower C footprint SAF [4]                   | ✔    | ![image](https://via.placeholder.com/150) | RNAV routes, dynamic airspace configurations, ADS-B use                                |
| Carbon neutral synthetic fuels             | ✔    | ![image](https://via.placeholder.com/150) | 100% replacement with SAF.                                                            |

![image](https://via.placeholder.com/150) Fig. 5. Annual anthropogenic CO₂ emissions, used from Ref. [8].
Today ICAO is concerned with international aviation GHG emissions mostly – Volumes III [3] and IV [5] to Annex 16 are the latest ICAO standards for Environment Protection from civil aviation impact. Ambitious goals, unveiled by US NASA [14] with its N+3 goals or the European Commission with the Strategic Research Innovation Agenda (SRIA) – Flightpath 2050 [15] challenges and goals, are confronting the aviation community with new challenges in aircraft design and operation due to new technologies implementation (Table 5). Those goals are targeting significant power efficiency, emission and noise reductions for future aircraft designs, so the aviation sector is likewise under governmental and international pressure to reduce further the impact on environment significantly.

USA NASA has developed a 3-tiered goal structure for technology research with current aircraft at N’s generation. The generations N+1, N+2 and N+3 represent technologies which will be nearing maturity, i.e. roughly Technology Readiness Level 6 (TRL6) in 2015, 2020, and 2025 respectively. Technology Benefits for generation N+1 were reached in 2015 relative to a SA Reference Configuration (improvements for Boeing-737 and Airbus-320 families mainly, which were realized in their latest Boeing-737MAX and Airbus-320Neo versions); for noise the cumulative reduction on 20 EPNDB below ICAO Chapter 4, for NOx, emissions the reduction on 60% below CAEP/6 Standard, aircraft fuel burn decrease on 33% relative to a 2005 baseline. Their engines LEAP-1A and PW1100G-JM have significantly larger fan diameter and bypass ratio than their predecessors. A higher bypass ratio (PW1100G-JM has bypass ratio to 12:1, which doubles the same parameter for V-2500 – its predecessor) in turn increases the jet propulsion efficiency and reduces the fuel consumption. Radically new aircraft configurations are being developed for the time beyond 2030 (N+3 generation), including electric propulsion, because evolutionary approach is considered as not enough to reach the ambitious goals for ICAO, Europe and USA in Table 5.

This will include the benefits of changes to technology embedded onto aircraft, including the coming revolution in full-electric (use batteries and generators as the only power source on the aircraft, including for the propulsion) or hybrid electric power for aircraft and other offenders like the possibilities of urban air mobility vehicles. In this way an electrification of the aircraft has the potential to revolutionize the aviation industry as a whole, providing its less impact on environment.

Up to date a number of new programmes were launched globally for the four groups of the aircraft – General Aviation/Recreational Aircraft (GA), Urban Air Taxis (UAT, aircraft with vertical take-off and landing - VTOL), Regional/Business Aircraft (RA/BA) and Large Commercial Aircraft (LCA) [17]. All of them are the starting points in existing roadmap for electrification of the aircraft, as shown in Fig. 6, most of them are planned to entry in service in nearest decade 2020–2030, LCA of course later, but some of them are already commercially available even now. The first flights of RA/BA prototypes for 9–12 passengers are planned during 2020, with their type certification in between 2020 and 2022. In parallel a creation of regional electric network must begin between the airports located on flight distance close to 1000 km between themselves. LCA includes mainly the attempts of Airbus in cooperation with Rolls-Royce and Siemens focused on the development of hybrid-electric, SA aircraft – their jointly produced demonstrator E-Fan X is planned to fly at 2020 (which will be obviously impacted by global COVID-19 crisis). In nearest plans of the biggest EU low-cost Airline EasyJet is to implement these aircraft within the next decade. UAT/VTOL aircraft also have made significant progress over past years. For example, Chinese and German (but NASA, Bell Helicopters and Embraer contributed into development and design) electric UAT/VTOL has been entered for testing during 2017–2018, so final commercial product may fly into the market even within a year-two (once again with correction on COVID-19 crisis).

4. Aircraft electrification nowadays

During last few decades the need for more energy-efficient aircraft promoted the More Electric Aircraft (MEA) concept [18] (a concept is known since 1940s, if to be correct). MEA is a new generation aircraft that is equipped with more electrical (and more energy power sources onboard the aircraft) systems to minimize non-propulsive power systems, such as mechanical, hydraulic, and pneumatic systems first of all. One of the main advantages of this system is that it provides better starter/generator systems. MEA enables a more efficient cruise flight, leading to some fuel savings as well as more efficient use of the aircraft’s engine as a thrust and power generator. There is better power availability through the flight envelope due to the shifting of power extraction from high spool to low spool, improving engine operability during the flight. This has resulted in a reduction of aircraft weight, usage of less fuel, and consequently in emission reduction, leading to a low cost of ownership and increased reliability of the aircraft. A parallel process in recent years exists, which is contributing to the success of the MEA concept implementation – aircraft of various types have become increasingly complex, generating vast amounts of data through countless parameters especially since the Boeing-787 and Airbus-380/350XWB were coming in operation. Optimized aircraft performance, reduced operating & maintenance cost, and increase in aircraft deliveries are some of the drivers for the MEA market across the world. The MEA market is expected to grow over 10 bln USD in next decade, at a compound annual growth rate over 7% during this period.

Consistent upward trends in the electrification of aircraft

| Table 5 Environmental goals in policies of ICAO, EU and USA on Research and Development. |
|---------------------------------|---------------------------------|---------------------------------|
| Environmental impact            | ICAO Policy Goals [1]           | EU ACARE Goals (FP2005 till 2050) [15] | US FAA and NASA Goals (NSTC2010 [16] and CLEEN II [16] till 2035) |
| Noise                           | Limit or reduce the number of people affected by significant aircraft noise | Perceived noise emission of flying aircraft is reduced by 65% | 52 dB reduction relative to cumulative margin of ICAO/FAA Stage 4 noise limit (a 25-year goal, by enabling N+3 aircraft and engines) |
| NOx emissions                   | Limit or reduce the impact of aviation emissions on local air quality | 90% reduction in NOx emissions | 80% reduction in NOx emissions (for cruise relative to 2005 best in class and for LTO relative to ICAO CAEP/6 standard) |
| Greenhouse gas emissions and fuel energy consumption | Limit or reduce the impact of aviation greenhouse gas emissions on the global climate: a reduction in net aviation CO2 emissions of 50% by 2050, relative to 2005 levels | 75% reduction in CO2 emissions per passenger kilometre | 60% reduction in Aircraft Fuel/Energy Consumption (CO2 emissions per passenger kilometre) relative to 2000 best in class |
onboard systems is observed during the whole aviation, especially jet, history, as shown in Ref. [19]. Currently commercial aircraft were implementing MEA features more or less stepwise, their latest examples are the Airbus 380/350 and the Boeing-787 (Table 6) with highest electrical power generating capacity on the board in a fleet today. Boeing-787 is nearly 1 MW in total [20], which is twice as much as that of the Boeing-777, single generator power rating raised on ~10 times during the jet aviation history (in particular between Boeing-707 and Boeing-787).

During the last 50 years the average annular rise of onboard electricity production is about 10 kW. The necessity of using an electric storage battery started the practice of accompanying it with a DC generator, first of low current and voltage capacity, later of 50-A 12-V rating and of 200-A 24-V output, etc. [21]. Most of existing and previous aircraft were/are still DC powered (current generators are 3–4 times less weight, Table 7, that is important for their onboard installations), but the generators are not the only electricity sources on board of the aircraft.

The on-board Auxiliary Power Unit (APU, they are generally located at tail sections of the aircraft) also produces energy to power the various onboard systems, not only supplying the energy necessary to start the engines before flight, when the aircraft is on the ground. In some specific cases APU can also be used in flight. Among the drivers for aircraft electrification are not only the reduced emissions — global and local, but also the huge potential for more energy-efficient aircraft, including their new architectures and use cases (like UAT/VTOL aircraft mentioned before), also new supply base in the aerospace industry with facilitated access for new entrants. Increasing aircraft speed and size are ground for increase of required electric power, of higher reliability and power density, so in AC generation was observed in aircraft [22], providing some advantages in comparison with DC generation. In terms of power density the AC generators are lighter and smaller. The standard values of voltage level 115/200 V and frequency of the current 400 Hz have been made mandatory for use at the end of 1950s and remained to this day.

There is a pressure for the airlines to be able to cope more efficiently with the increased number, capacity and complexity of energy-consuming systems on board an aircraft; improve the comfort, health, and safety of the passengers; and mitigate the global impact of aviation on the environment. The key challenge in technology in electricity production and storage is to be able to provide all of this at a lower cost than before. Taking in mind the importance of the (empty) aircraft weight the most important parameters for their onboard systems are specific energy (Wh/kg) for energy storage and specific power (kW/kg) for electrical components. Today mass energy density for the best batteries (~200 Wh/kg), the specific energy of the batteries with economically acceptable payload-range characteristics — 400–500 Wh/kg — is expected roughly in 2025 for N+3 generation aircraft.

A conventional engine has two responsibilities during aircraft flight: propulsion as a primary function, and a power plant for the secondary systems power source as a subsidiary function. Specifically, the engine will be an important factor not only for the conventional role of high efficiency and low emission, but also for optimization between the propulsion system and electric power system because a MEA integrates power management into the electric power generated by engines (Table 5). In addition, the MEA will also have to consider the importance for optimization of the aircraft in integrated management by advancing management of fuel burns and the thermal control system, optimization of engine control and information sharing with the entire aircraft, and the integration of flight control [23].

The Boeing 787 is the most electric aircraft currently in operation [20], its electricity is produced by six generators onboard: two on each engine and two on the APU. It has two alternators for each of its two engines, Table 5. The electricity generated on the LCA Boeing 787 supplies its large air conditioning compressors, as well as the cabin pressurization system (an electrically-powered system of environmental control of the aircraft), the electrically actuated brakes and the wing de-icing system (electro-thermal ice production).

Table 6

|                     | Boeing 787 | Airbus A380 |
|---------------------|------------|-------------|
| No. of engine       | 2          | 4           |
| No. generator per engine | 2    | 1          |
| Generator rating   | 250kVA     | 150kVA      |
| Generating output voltage | 230 V AC | 115 V AC   |
| No. generator per APU | 2     | 1          |
| Generator rating per APU | 225kVA | 120kVA     |

Fig. 6. Trends of possible aircraft hybrid architectures at different installed power.

8
protection scheme, in which several heating blankets are bonded to the interior of the protected slat leading edges. Furthermore, although the 787 has a relatively conventional hydraulic system, the pressure within the system is generated by electrically-powered hydraulic pumps. Withdrawal the pneumatic bleed leads to more efficient engine usage in flight due to reduced overall airplane level power requirements — the airplane does not implicate as much power off the engine during main part of flight, as a result it doesn’t need as much fuel onboard. The corresponding predicted improvement in fuel consumption of the Boeing 787 at cruise conditions is in the range of 1–2% — quite efficient result for now. As a general result the 787 Dreamliner is cleaner, quieter and more efficient that any aircraft in operation nowadays: total reduction in fuel burn and CO₂ is close to 20% (MEA concept is not a single contribution to this value), its engines are cleaner for NOₓ (28% below CAEP/6 limits) and a noise footprint on 60% smaller than the same existing analogue with the same flight mass.

The next significant contribution to MEA concept was done with the Airbus 380 including the installation in its design of an electrically actuated thrust reverser, along with hybrid electro-hydraulic actuation systems for wing and tail surfaces. Airbus has baseline electro-hydrostatic actuators to flight controls, dictated by big size of this aircraft — much larger control surfaces than in previous generations, thus A380 would have required much higher hydraulic power provided with more system design elements and fluid, consequently rising the weight and complexity for Airbus 380. The introduction of electrically powered actuators allows to more efficiently segregate power distribution channels and to save weight — a weight was reduced on of ~1500 kg within short-medium range aircraft market is possible by employing these radical new technologies: DEP could lead to about 15–20% fuel reduction for SA, further 3–5% (and thus CO₂ reductions) is looking feasible for BLI (a dominant radical aircraft configuration nowadays). Future long-term radical aircraft configurations for passenger SA and TA aeroplanes are optimized for the integration of HEP systems on their boards.

Large turbofans powering long-range LCA are already highly efficient, making it hard for electrification to buy its way onto aircraft. Aeroplane propulsion concepts under research range from advanced ultra-high bypass ratio turbofans to open rotor engine and further to HEP. The open rotor engine is expected about twice the diameter of current turbofans (~4.50 m), their greatest promise of delivering a further 15% fuel burn improvement. Unfortunately in terms of noise this design has no nacelle to attenuate the noise generated by the rotating blades. But clean, quiet, reliable electric propulsion could find a place relatively easily in short-range GA. And the middle range RJ could prove fertile for HEP. Industry thinks in classes of aircraft, from short-range UAT through short-haul RJ to long-range TA requiring many orders of magnitude more energy (Fig. 6).

**An Electrical Propulsion (EP)** is a potentially revolutionary new approach in comparison to the evolutionary MEA trend, which, if adopted widely, would transform large segments of the aerospace industry, affecting not only propulsion, but also aircraft systems, and leading to radically new aircraft architectures. New electric motors to drive aircraft engine fans should be light in weight, with much higher specific power than shown in Table 7 for current aircraft systems, while being of very large-scale and very high performances for driving (Table 8). Their current technology does not meet the necessary power and weight requirements, new innovative solutions are expected in near future as necessary. EP and power systems solutions, known currently, are distinguished between different architectural approaches, mainly in three domains (Table 8): HEP (parallel hybrid, series hybrid, series/parallel partial hybrid); Turboelectric (TEP – FEP and Partial TEP) and FEP (or All electric). These EP concepts are not dependent on advances in battery technologies, but their synergistic benefits achieved through aircraft—propulsion integration may provide for them both more advantages, for example like using in DEP system (Table 8).

Both of them, MEA and EP, are approaching an idea of low emission aircraft, sometimes even to the new architectural approach of Ultra Low Emission System (ULES) used for air transportation, which should cover:
Electrical energy storage, including synergy with airframe (any kind of hybrid architecture); Fully integrated power management and control (including Flight Control System); Integrated utilities like Environmental Control System, Landing Gear and Avionics.

Two core areas of the ULES are the “Propulsion and Power Generation” and “Power Management, Distribution, Transmission and Control”, they are identified as priorities for FEP aircraft.

The most interesting now group of aircraft — SA/LCA and RJ (with PAX capacity over 100) is expected to be started for designing and testing close to 2040, thus to expect for their essential contribution to solve the strategic task provided by neutral carbon growth scenario. Wright Electric has announced its intention to build a 150-seat electrically-propelled aircraft (expected full-electric, if batteries will be available, otherwise of hybrid-electric architecture) within a decade to compete with the smaller members of the Airbus-320 and Boeing-737 families [24]. So, new technologies for high specific energy batteries are looking dramatically important as for revolutionary new all-electric architectures, so as for successful solution of more strategic task — to satisfy the declaration of 1.5—2.0 °C budget for global temperature through 2050, which is mostly looking to be covered in aviation sector by SAFs. Despite the losses in converting the energy contained in jet fuel into useful thrust, the energy density advantage of jet fuel remains a factor of 6—8 times higher than the 500 Wh/kg batteries.

Considering a time span up to 2035, correspondent to +15—20 years in Fig. 6, one can see how FEP is expected to be employed only in GA and in some UAT/VTOL applications, while partially EP would be needed to power UAT and RJ propeller-driven airplanes. Turbfan aircraft would at most benefit from assisted electric power, provided that a trade-off could be made between engine mass increase and fuel consumption, noise and pollutant emissions decrease; only MEA tendency is thus expected. Taking in mind the contribution of BJ, RJ and turboprops in total fuel consumption it is looking obviously not enough to concentrate on electrification of these groups only.

Moving to a larger time span, up to 2050 (+30 years in Fig. 4), one may expect to have advanced enough batteries necessary to enable FEP even to SA/LCA, for example for the standard 200—300 PAX aircraft, at first step for SA type. In Fig. 7 one may find that a gap for CO₂ emission reduction during this time period — 2035—2050 may be covered, at least partly, by EP aircraft.

This possibility to extend this technology to large aircraft by 2050 is affected by heavy uncertainty and requires large improvements in terms of power-to-weight ratio of electric motors and electro-mechanical conversion, cooling systems, wiring and, of course, on batteries. Taking year 2000 as a reference, as considered by Flightpath 2050 program [15], it can be expected an improvement due to HEP-mobility starting around 2025, with fuel saving around 25—30% per flight due to advanced turbofan studies, while further improvements are subjected to really large uncertainties.

### 6. Conclusions

The electrification of air transportation is considered currently as one of evident consequences among the technological consensus solutions to reduce in fossil fuel consumption in aviation sector, which also means the reduced emissions: as in terms of GHG, so as for usual LAQ emission inside airport area — NOₓ, CO, HC and PM.

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**Table 8**

Requirements for electric aircraft architectures (complementary to Fig. 6, main data used from Ref. [25]).

| Aircraft propulsion type | Electric system performances | Battery capacity |
|--------------------------|------------------------------|------------------|
|                          | Power capability, MW         | Specific power, kW/kg | Specific energy, Wh/kg |
|                          | BJ/GA | RJ/SA | TA | BJ/GA | RJ/SA | TA | BJ/GA | RJ/SA | TA |
| Parallel HEP             | <1    | 1 … 6 | still not studied | >3 | >3 | still not studied | >250 | >800 | still not studied |
| FEP                      | <1    | 1 … 11 | not feasible yet | >6.5 | >6.5 | not feasible yet | >400 | >1800 | not feasible yet |
| TEP Motor Generator      | <1    | 1 … 3 | 4 | >6.5 | >6.5 | >10 | not applicable |
| APU for LCA generator    | generator 0.5 … 1 | >3 | | | | | still not studied |

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**Fig. 7.** Potential for fuel consumption and CO₂ emission reduction in aviation sector by aircraft with electric propulsion.
The use of power from onboard batteries eliminates the aircraft operational emissions for all-electric architectures and reduces emission from hybrid electric ones. Existing potential and forecasted progress for MEA concept is showing quite limited reduction in fuel burn and emission. EP may provide essential reduction, but in considered time frame it is looking to be very possible for implementation in groups of GA/RA, Urban Air Taxis (first of all with vertical take-off and landing) and RJ/BJ first of all. Over 90% of GHG emissions in global aviation sector are generated by LCA (TA and SA airplanes with more than 100 passengers onboard), so research to reduce commercial aircraft emissions will be most useful if it focuses on technology applicable to these LCA. But for this group the uncertainties in reaching the effective values in specific energy for energy storage and specific power for electrical components are looking huge, TRL for them is quite small currently. Wright Electric has announced its intention to build a 150-seat electrically-propelled aircraft (expected full-electric, if batteries will be available, otherwise — of hybrid-electric architecture) within a decade to compete with the smaller members of the Airbus-320 and Boeing-737 families [19,20]. So the gap between the evident scenario of technology/operational improvements for the aircraft with evolutionary architectures and neutral carbon growth scenario, which is required by 1.5—2.0 °C budget for global temperature through 2050, is mostly looking to be covered by SAFs. Since SAFs is a global issue, not linked solely to aviation, but also to other types of transport and economical sectors (competition with other sectors for biomass will be expected), strengthening the partnership between the aviation and energy sectors will be necessary. The technical feasibility of SAFs usage in aviation was proven and commercial aviation has already sent a number of strong signals that should the quantities of biofuels needed for the industry be produced sustainably, at right place, with concurrent price, there would definitely be a strong demand for these fuels.

The one more advantage for aircraft with EP, not analyzed in an article — evident reduction in noise generation by aircraft, which in combination with complete elimination of fuel and emission in flight may provide further quick steps forward in progress of full and/or hybrid electric aircraft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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