Electric Aircraft

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Introduction

Electric aircraft hold tremendous potential to improve emission, noise, and operating economics across a range of different applications in support of the aviation industry's goal of achieving net-zero CO_2 emissions by 2050. In this section, we will draw from the industry's state-of-the-art research and flight demonstrations to illustrate the technology challenges and opportunities, and how it intersects with Sustainable Aviation Fuel (SAF) that will be necessary for achieving net zero. The following sub-sections are organized to introduce these key elements including enablers for electric aircraft operations.

Emission and Economics of Electric Aircraft

The exciting development of electric aircraft has been referred to as "the Third Revolution in Aviation"[1]. The first revolution was the Wright brothers' very first successful powered flight, the second one, the invention of jet propulsion which allowed us to fly faster and farther. The growth of aviation that followed introduced the big carbon emission problem. The advent of electric aircraft propelled by clean electricity marks the dramatic transformation to zero carbon emission for aviation, and the "third revolution". The benefit from this revolution goes well beyond the emission reduction.

The operation of these revolutionary electric aircraft already demonstrated significant cost savings. For example, the energy cost of the two-seat Pipistrel aircraft (Figure 1) per hour is at 0.9 € while a conventional Cessna two-seat aircraft C152 commonly used for training is approximately $34 (pre-Ukraine war estimate), which is equivalent to 34X that of the Pipistrel Alpha Electro[2]. An estimate of the per hour total operating cost for the C152 vs the Alpha Electro is approximately 3.6:1; that is, the conventional two-seat fossil fuel propelled aircraft is almost *fourfold more expensive* to operate than the equivalent two-seat electric aircraft ! In March 2022, the aviation industrial conglomerate Textron, parent company of Cessna, decided to underwrite the expansion and success of electric aviation for commercial use with its acquisition of Pipistrel.

By April 18, 2022, Textron completed acquisition of Pipistrel for a cash purchase price of €218 million. This deal will dramatically accelerate the development, deployment and adoption of electric aircraft.

FIGURE 1: Pipistrel Electric Aircraft

In the span from 2016 to 2022, there have been over 300 Electric Aircraft projects and up to 200 electric aircraft start-ups around the world, similar to the renaissance of aviation period in the early 1900's. The overall electric aircraft service domain is loosely referred to as "Advanced Air Mobility" (AAM), which covers the "Urban Air Mobility" (UAM) and part of "Regional Air Mobility" (RAM). electric aircraft for UAM are primarily equipped with vertical lift

1 *"Could electric airplanes propel a third revolution in aviation?"* Miles O'Brien, PBS News Hour, May 26, 2021. https://www.pbs.org/newshour/show/could-electric-airplanes-propel-a-third-revolution-in-aviation

2 *"Alpha Electro, the first serially produced electric trainer",* Tine Tomažič, AIAA-IEEE Conference, Aug, 2020.

capability, also referred to as eVTOL (electric Vertical Take-Off and Landing), while the RAM electric aircraft take advantage of the runway to gain momentum (hence less energy demand) for take-off and landing, and are referred to as eCTOL (C for Conventional) or eSTOL (S for Short). The eVTOLs operate similar to rotorcraft and require heliports (or "vertiports") in urban environment. Examples of eVTOLs include projects from Joby, Volocopter, Lilium, Archer, EHang, Wisk, and many more. In contrast, eCTOLs and eSTOLs are fixed-wing aircraft that can use the massive number of existing airports, transforming the regional travel due to the unprecedented economic and environmental benefits. These electric aircraft are developed in several start-ups and OEMs, e.g. Airbus, Ampaire, Electra.Aero, Heart Aerospace, MagniX (with Eviation), Rolls Royce Electric, VoltAero, ZeroAvia, etc. NASA's white paper on RAM[3] outlined how the application of electric aircraft will dramatically increase the accessibility and affordability of regional travel while building on the extensive and underutilized US local airports.

Electric Aircraft Innovation – Challenges and Opportunities

Aviation has witnessed the shift toward "more electric aircraft" since the introduction of Boeing's 787 in 2011. For the traditional airplane, power is extracted from the engines in two ways to power other airplane systems: one, the generators are driven by engines to create electricity (e.g., to power avionics system); second, a pneumatic system "bleeds" air off the engines to power other systems (e.g., hydraulics). The B787's more electric aircraft approach uses electric instead of the pneumatic system and provides much more efficient power generation and distribution for use and reduces systems weight, including the adoption of a higher capacity electric energy storage system (ESS e.g., Li-ion battery). The evolutionary change towards more electric aircraft for large transport aircraft such as the B787 is a very slow process. However, the significant technology development and adoption of ground Electric Vehicles (EV) in the last decade has made the electric aircraft more feasible. In addition to the relevant technological advances, the economy of scale and new supply base growth have driven down the component systems cost tremendously. These potentially common component systems include, e.g., electric motors and inverters which when operating together in an electric aircraft are defined as the "electric engine[4]" (e-engine) and ESS (battery or fuel cell) instead of the conventional "fuel system". Three key challenges and opportunities are highlighted here.

Today's state-of-the-art commercial lithium batteries are ~50X heavier than aviation fuel. Even accounting for the much lower losses through an e-engine leaves a ~25X net energy weight disadvantage. However, an e-engine weighs a lot less than a combustion engine. ARPA-e's ASCEND project seeks to extend this advantage leading to 12 kW/kg for an e-engine compared to a MW-class gas turbine at ~3 kW/kg[5], or 4X the power-to-weight performance! Additionally, there is a rapid development in solid-state batteries (SSB), which will reach 4X higher energy density and power density, substantially surpassing the performance, safety, and processing limitations of Li-ion batteries. It is estimated that these SSBs will become commercially available in 2030's in the electric vehicles and aircraft market respectively.[6] Some eVTOLs, (hybrid) eCTOLs and eSTOLs such as Ampaire's 9-seat Eco Caravan and Outlander with compelling emission reduction and meaningful range performance of up to 500+ miles are already on the horizon to enter service by 2025.

The hydrogen fuel cell is another energy storage system (ESS). It is an electrochemical device that converts hydrogen directly into electricity supply for the e-engine while releasing heat and water. Boeing's hybrid-electric and fuel-cell demonstrator flew in 2007 for approximately 20 minutes on energy from the fuel cell ESS. However, Boeing "does not envision that fuel cells will ever provide primary power for large commercial airplanes"[7]. It should be noted

3 *"Regional Air Mobility: Leveraging Our National Investments to Energize the American Travel Experience",* Kevin Antcliff et. al., April 2021, https://ntrs.nasa.gov/citations/20210014033
4 *"Taxonomy, Architecture, Safety, Endurance Testing",* SAE E-40 Electrified Propulsion standard publication, ARP8689, Q1, 2023.
5 *https://arpa-e.energy.gov/technologies/programs/ascend*
6 "*Solid-State Batteries: The Technology of the 2030s but the Research Challenge of the 2020s",* Faraday Insights, Issue 5: Feb 2020. https://faraday.ac.uk/wp-content/uploads/2020/04/Faraday-Insights-5_Updated.pdf
7 "*Boeing makes history with flights of Fuel Cell Demonstrator Airplane",* Tom Koehler, Boeing Frontiers, May 2008, https://www.boeing.com/news/frontiers/archive/2008/may/ts_sf04.pdf

that the hydrogen supply for the fuel cell requires storage tank(s). The electric vehicles and truck industry uses a 700 bar compressed hydrogen gas tank. Even at 700 bar, the volumetric energy density of hydrogen will take 7X more volume to store the hydrogen for the equivalent mission. The placement of such fuel tank would not be inside the conventional wing, but more likely in the fuselage which would reduce the passenger load capacity unless new airframe configuration is applied.

The second key challenge is unique to the aerospace industry, as it is a highly regulated industry for an important reason, safety. All the new (and retrofit) electric aircraft must be type certified for air worthiness by regulatory bodies, e.g. FAA and EASA. With over 200 projects of new electric aircraft (or even a fraction of them) going to the regulatory bodies for certification, the regulators will have not only a resource issue but also knowledge and experience issue which is necessary to address the gaps of existing standards and rules. In 2022, the FAA's Center for Emerging Concepts and Innovation (CECI) that leads the early certification stages for electric aircraft has 8 program managers and already ~70 projects in the pipeline.[8]

The Pipistrel two-seat "Velis Electro" is the world's first electric aircraft to receive a Type Certificate from EASA in June 2020, approved for pilot training in Day Visual Flight Rule operations. The knowledge and experience gained from the Pipistrel's certification activities have been used to develop the Special Condition SC E-19 "Electric/ Hybrid Propulsion System" to further enable electric aircraft certification projects. In the US, the FAA also released Special Conditions for e-engine Airworthiness in October 2021. These Special Conditions are based on a new American Society for Testing and Materials standard and are a mix of 14 CFR Part 33 standards and special conditions applicable to the magni250 and magni500 model engines from MagniX that applied for the type certificate in April 2019. Due to the more integrated airframe and propulsion system of the electric aircraft, it is not clear at this point how different the certification process would be compared to the conventional one for "airframe" (e.g. Part23 or CS23) vs. "engines" (Part33 or CS-E). A certain outcome is that there will be more "Special Conditions" going forward.

The third challenge area is in the eco-system readiness for enabling the electric aircraft operation, e.g. clean energy availability and distribution to the plug-in electric aircraft for charging. This eco-system includes stakeholders such as airports from an infrastructure and operations perspective, airlines who may need to modify their existing process on ground and flight routing to take advantage of the electric aircraft capabilities, and the energy industry which could be the supplier, on-site storage, or distributors for the energy management. While all RAM airports are already powered by electricity, most are directly from the grid which may not have complete renewable sources for the electricity. These infrastructure feasibility considerations and recharge strategies for electric aircraft operations have been reported in several studies.[9,10]

Infrastructure and Flight Demonstrations

Electric aviation offers a great opportunity to better integrate airports as "energy hubs" into both urban and rural transit networks, providing clean energy and charging to local communities (e.g. charging buses overnight), and grid storage plus resiliency to power outage for critical infrastructure. Examples of airport solar farms include New Zealand's Christchurch airport[11] which will provide 150 MW to power the airport and local communities, Japan's Kansai airport with largest solar farm in Asia at 11.6 MW, UK's Glasgow airport at 15 MW, and the US Chattanooga airport that has already been operating at 100% on-site solar energy at 2.64 MW. Other forms of renewable energy for airports include for example UK's East Midlands Airport wind farms, Sweden's Stockholm Arlanda airport[12] using

8 SAE AeroTech 2022 Digital Summit, FAA CECI.
9 *"Power optimized battery swap and recharge strategies for electric aircraft operations",* Cedric Y. Justin et. al., Transportation Research Part C 115 (2020) 102605, Elsevier journal. https://doi.org/10.1016/j.trc.2020.02.027
10 Connected Places Catapult, Zero Emission Flight Infrastructure (ZEFI) programme in collaboration with the Department for Transport. https://cp.catapult.org.uk/project/zero-emission-flight-infrastructure-preparing-uk-airports-for-zero-emission-aircraft/?utm_campaign=zefi-&utm_source=linkedin&utm_medium=roadmap-and-blueprint-
11 https://renewablesnow.com/news/new-zealand-airport-plans-150-mw-solar-park-as-part-of-wider-project-764032/
12 https://www.swedavia.com/arlanda/environment/#

FIGURE 2: Ampaire's Hybrid Demonstrator, Electric Eel

biofuel, wind, and other renewable sources, which are stored in the world's largest thermal energy storage unit, an "aquifer" underground that provides 8MW power. The European Marine Energy Centre is collaborating with Highlands and Islands Airports Limited (HIAL) in Scotland to decarbonise heat and power at Kirkwall Airport through green hydrogen technology.

Electrifying aviation at airports to date includes plugging planes into gate power for Auxiliary Power Unit, electric taxi to the runway, as well as electric tugs and ground equipment. Moving forward, this means investing in development and scaleup, from adoption of electric trainer aircraft to integrating the plug-in (hybrid) electric aircraft. This is where the demonstration projects such as 2ZERO (Towards Zero Emission Regional Aircraft Operations) and SATE (Sustainable Aviation Test Environment) sponsored by the Future Flight Challenge program of Innovate UK are extremely valuable as the public and the private sectors' are brought together to solve the systems problem collaboratively. Ampaire's participation on these projects allowed us to work together with HIAL, Exeter, and Newquay airports and chart the course of aviation electrification roadmap. In August 2021, the hybrid demonstrator "Electric Eel" (Figure 2) was able to achieve the longest non-stop flight of 418 nautical miles in UK, at a 38% reduction to fuel emission. A mobile charger was used for the demonstration flights, which incorporates the standard plug-in interfaces both on aircraft and to the airport energy outlet with advanced coordination. This Eel demonstrator is a hybrid of independent parallel architecture, which is not optimized. We estimate that for an optimized parallel hybrid electric aircraft using sustainable aviation fuels (SAF) (at 50% blend) for the combustion engine, it can achieve 90% emission reduction with today's technology. As batteries and electronics improve, smaller planes can move to all-electric and larger planes can convert to hybrids over time, using a combination of SAF and clean electricity.

If we want to mitigate climate change, decarbonizing aviation is a must — electric aviation needs to be an important part of the solution. But launching the electric aircraft operations widely will require the combined vision and focus of both the public and the private sectors. This must be a collaborative effort joining the creativity of the private sector and the long-term perspective and decarbonization goals of the public sector. The time to act is now. By building a strong foundation to support the electric aircraft development and infrastructure for enabling the electric aircraft, we can achieve something truly revolutionary in our industry!