HDI Global Specialty SE

Technical Study
Electric Aviation in 2022

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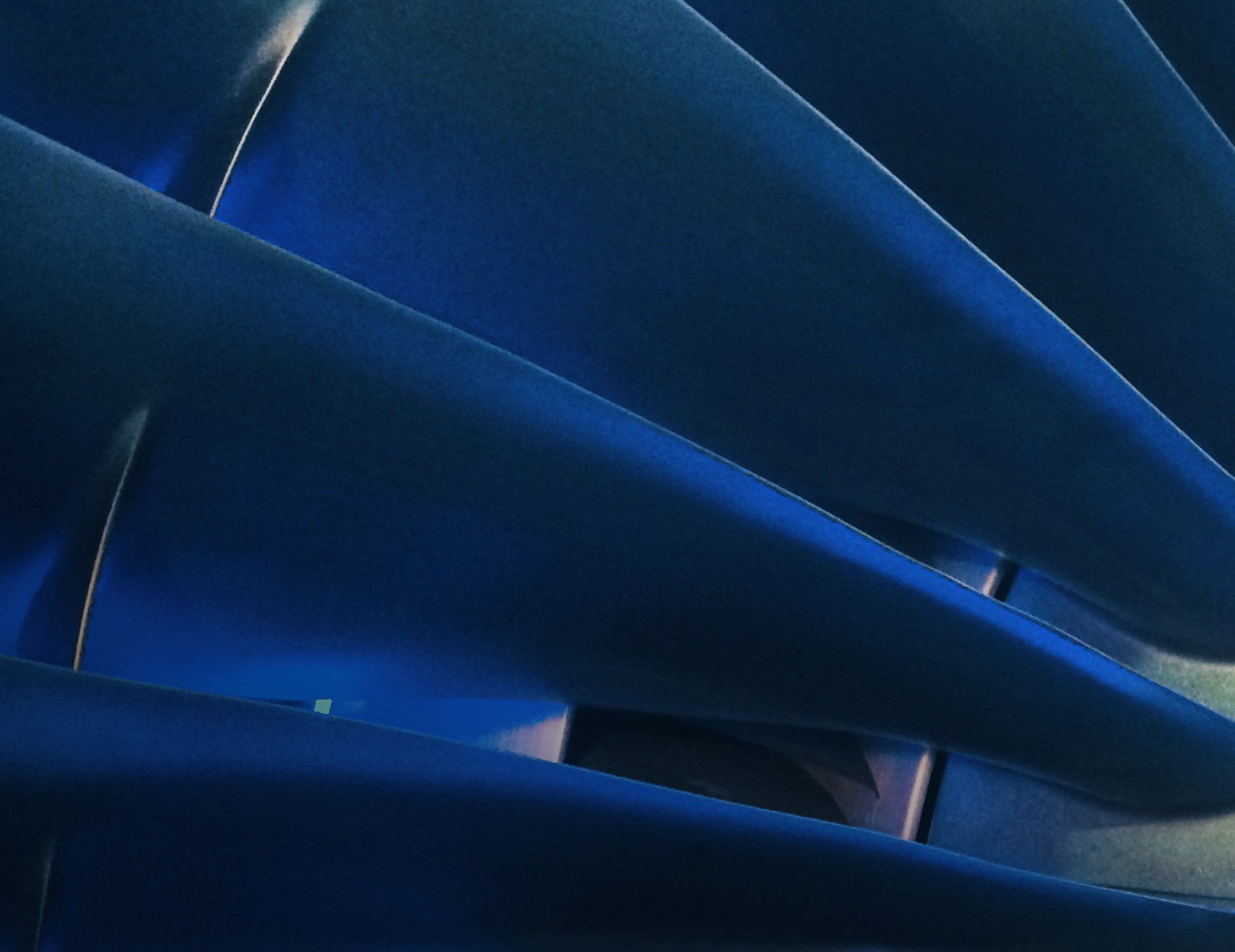
on behalf of all HDI Global Specialty Aviation offices

Contents



Introduction

This study, performed on behalf of all HDI Global Specialty Aviation branches, presents a comprehensive literature review on the state of electric aviation development in April 2022. At present there are few insurers offering dedicated electric aircraft policies. Some insurers however cover the few electric aircraft currently on their books via existing General Aviation policies. As this new revolution in aviation gathers pace it is increasingly clear that appropriate insurance policies may need to be considered.

Aviation is some years behind other forms of transportation such as the automobile where a transition away from internal combustion towards electric vehicles is already underway. Nevertheless, the number of experimental electric aircraft has steadily increased over the last decade since the first flight of a two-seat electric aircraft, the Taurus Electro, in 2011 [1].

The outlook on electric aviation in 2022 is exciting with over 200 different aircraft under development worldwide [2] (Figure 1), many of which are of non-conventional design. Not only this, new aviation services are being considered that do not fit into the existing aviation framework. Many of these new electric aircraft and services are targeting certification and entry into service before the end of this decade.

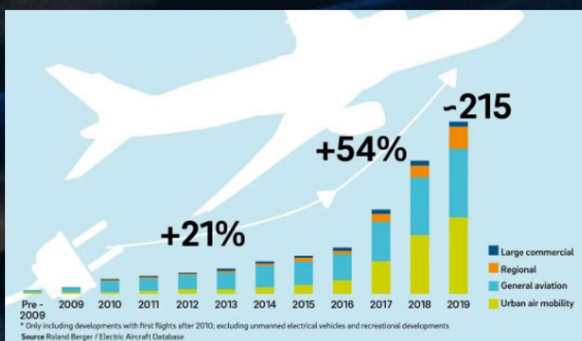


Figure 1 – Known electrically propelled aircraft developments as of 2019 [2].*

Introduction *continued*

This paper is organised over seven sections as follows:

- **Section I** presents the key technologies required for electric aviation, and other associated technologies such as hybrid systems and autonomy.
- **Section II** describes electric aircraft design architectures, applications, associated infrastructure, and concepts of operation.
- **Section III** discusses key hazards applicable to electric aircraft.
- **Section IV** presents several new players in the electric aviation market that are developing aircraft, some of whom are also expected to operate commercial services in the near future.
- **Section V** discusses the work being put into electric aviation by established aerospace organisations.
- **Section VI** provides an overview of the current regulatory environment and electric aircraft certification.
- **Section VII** describes the present insurance standpoint including coverage availability and policy development.

A summary of the findings of each section above is given in the conclusion. The remainder of this introduction focuses on two of the main driving forces behind the development of electric aviation; the first of which, Urban Air Mobility, is set to become a major application of electric aircraft.

The second major driving force is decarbonisation, which as shown by the recently held COP26 in Glasgow (November 2021) will play a significant role in aviation and many other industries over the coming decades.

Urban Air Mobility

The development and operation of new classes of small, fully electric aircraft targeted specifically at flight operations in and around major urban metropolitan areas is commonly referred to as *Urban Air Mobility* (UAM) [3]. Such a concept, depicted in Figure 2, has historically been visualised through science-fiction as the futuristic metropolis where people commute to work in 'flying cars' or *Urban Air Taxis* (UAT). Making these ideas a reality is now closer than most people realise thanks to the progress made in electric energy storage and propulsion technologies. Certain technological and regulatory / operational hurdles remain before UAM can move from experimental prototypes to active commercial services. Nevertheless there are multiple projects under development that aim to translate this vision into reality by the mid 2020's. A more detailed description of the UAM concept of operations is given in section II and examples of aircraft under development are presented in section IV.

Figure 2 – A vision of Urban Air Mobility [4].

Introduction *continued*

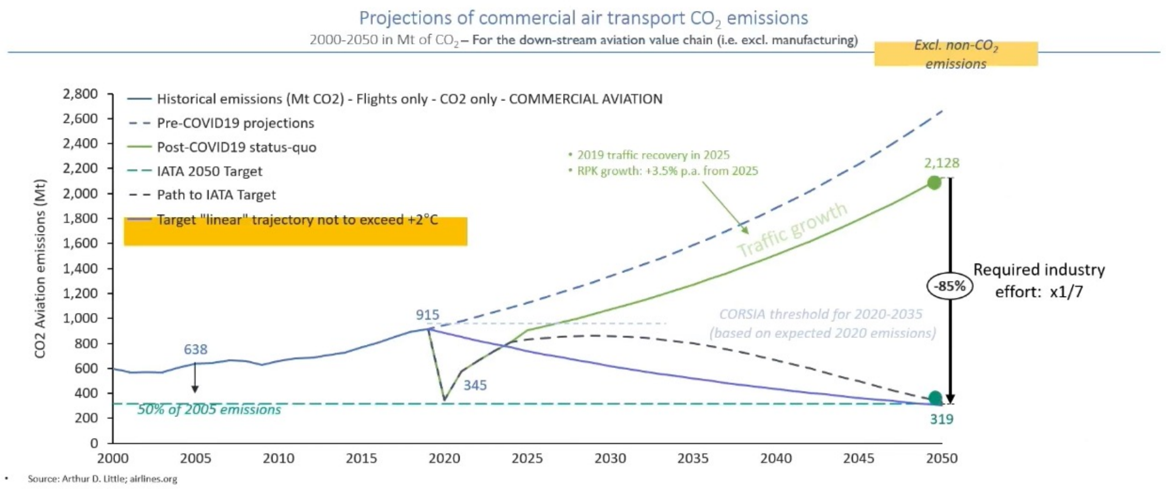


Figure 3 – Projection of commercial air transport CO2 emissions [6].

Decarbonisation

In 2019 air travel accounted for 2.5% of global CO2 emissions [5], however if the growth in worldwide traffic resumes following a post-Covid recovery (Figure 3) and other sectors get cleaner as quickly as some experts predict, aviation's share could rise significantly.

As shown in Figure 4 below, projections suggest aviation's share of global CO2 emissions could increase to 10% and possibly as much as 24% by 2050 unless significant technological change occurs [7]. While some airlines have started offsetting their contributions to atmospheric carbon, a more radical approach will likely be required if the aviation industry is to follow other sectors in the drive towards decarbonisation. This decarbonisation is necessary if the world is to avoid dangerous climate temperature increase, as highlighted at COP26.

Without significant technological changes being made, future growth of the aviation industry is seen as unsustainable given tightening restrictions on emissions. As such, decarbonisation is a major driving force behind the development of electric aviation (both all-electric and hybrid-electric).

For medium and large airliners (>100 passengers) efforts in the near-term are likely to be directed towards Sustainable Aviation Fuel (SAF) and/or *synthetic* aviation fuel, while in the medium and long-term there is expected to be a push towards hybrid-electric, liquid hydrogen, and all-electric propulsion. For smaller aircraft (<50 passengers) the transition towards electric propulsion is possible in the near to medium-term. Further discussion of the technologies enabling this decarbonised future are discussed in section I.

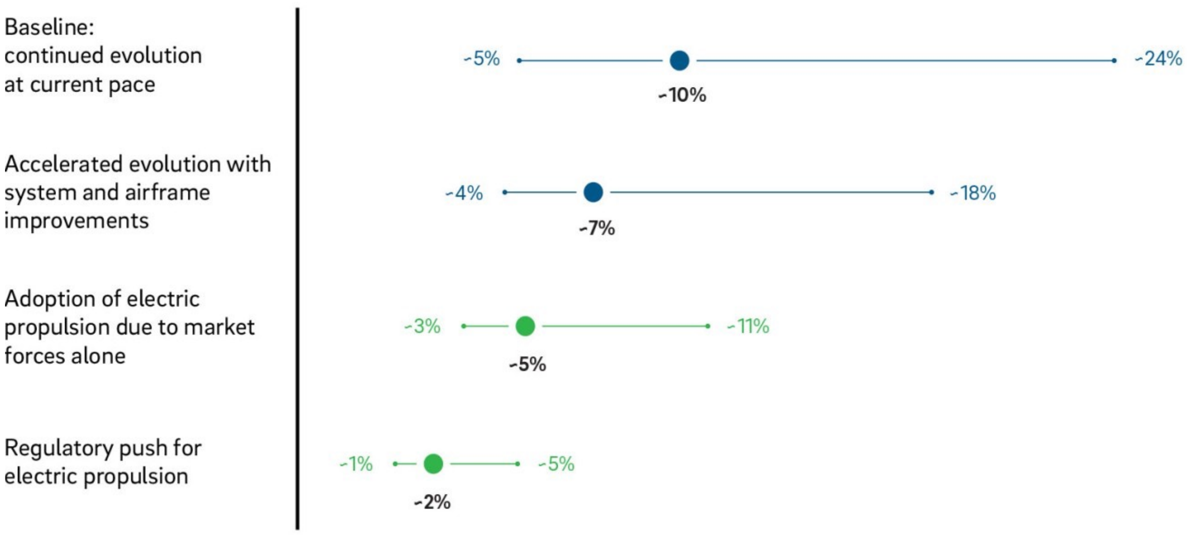


Figure 4 – Forecast aviation share of global CO2 emissions in 2050 depending on the underlying global emissions scenario [8].

I. Technology

As with most forms of electrified transportation the foundational technologies are electrical energy storage i.e. batteries, and propulsion i.e. electric motors. Both of these technologies have been in existence since the 19th century, however it is only in the last decade that sufficient progress has been made to enable commercially viable electric aircraft. This section takes a closer look at these two key technologies, compares electric propulsion to conventional propulsion systems, and explains how several related technologies are being developed in parallel.

I.1 Batteries

The battery is a method of energy storage, analogous to the liquid hydrocarbon-based fuel (Kerosene) stored in tanks on-board conventional aircraft. Whereas in a conventional propulsion system the energy stored in the fuel is converted via a thermodynamic cycle (i.e. combustion) to drive the engine, in an electric propulsion system the energy stored in the battery is converted via an electrochemical process into an electric current to drive the electric motors.

Batteries are composed of cells, which are the basic electrochemical unit. Each cell consists of the anode, the cathode, and the electrolyte as shown in Figure 5.

Many different battery chemistries are possible depending on the choice of materials used. Since the 1990's the Lithium-ion (Li-ion) battery has become one of the most ubiquitous types of rechargeable battery, primarily because of its high specific energy density amongst various other advantages. The specific energy density of a battery is the amount of energy that can be stored per unit battery mass, measured in Watt-hours per kilogram (Wh/kg). Passenger aircraft are particularly sensitive to specific energy density since they require a lot of energy to fly whilst keeping mass to a minimum.

The Li-ion battery is therefore the only battery chemistry available today that can be considered for the needs of electric aviation. The current state-of-the-art in commercially available Li-ion batteries have specific energy densities in the range of 250-300 Wh/kg [7]. For comparison the specific energy density of conventional aviation fuel is approximately 40 times higher at 12,000 Wh/kg [5] [9].

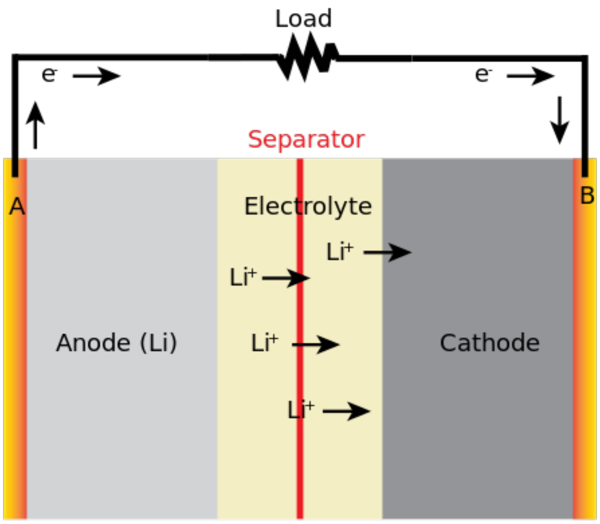


Figure 5 – Simplified diagram of a Lithium-ion cell in discharge.

The result of this disparity in specific energy density is that despite the relatively high energy density of current Li-ion battery technology, it is still much less energy dense than aviation fuel and therefore only capable at present of powering small aircraft over relatively short distances (typically <200 miles).

To be considered for larger aircraft with greater range, much higher specific energy densities are required that will only be achieved with significant technological progress in Li-ion and more advanced battery chemistries. UAM vehicles such as air taxis are feasible with today's or near-term technology at specific energy densities of 250 Wh/kg and above. Regional (i.e. short-haul) passenger aircraft with electric propulsion will not be feasible until specific energy densities of ~500 Wh/kg are reached, and as shown in Figure 6 this is not expected before 2030 [2] [7].

The specific energy density of a battery is the amount of energy that can be stored per unit battery mass, measured in Watt-hours per kilogram (Wh/kg).

There are other battery related limitations such as cycle life that also present obstacles to the adoption of electric aircraft, however the greatest hurdle to be overcome in the development of larger electric aircraft with longer range is specific energy density. Current indications suggest that the automotive manufacturers currently leading on battery development (Tesla etc.) would likely be satisfied with a specific energy density of ~350-400 Wh/kg. If so, aerospace developers may have to "take up the baton" to ensure new battery technology keeps getting investment beyond this point [7].

	First serial application in vehicles	Volumetric energy density[1] [Wh/L]	Gravimetric energy density[1] [Wh/kg]
Adv. chem.			
Potential Li air technology	2030	-	>500
Li-Metal/Solid state technologies			
Cathode: Ni-rich Anode: Li-Metal Electrolyte: Ceramic based structure	2025	>1,000	>400
Cathode: Ni-rich Anode: Li-Metal Electrolyte: Polymer based structure	2022	>1,000	>400
Cathode: Mn-rich Anode: Li-Metal Electrolyte: Stabilised "liquid"	2025	>1,000	>350
Adv. LiT formulations			
Cathode: Mn-rich Anode: Graphite (<85%)/Silicon (>15%)	2024	900-1,000	250-300
Cathode: Ni-rich/HV-Spinels Anode: Graphite (<90%)/Silicon (>10%)	2021	~900	250-300
Next gen LiT formulations			
Cathode: NCM721 Anode: Graphite (<90%)/Silicon (>10%)	2020	800-900	>240
Cathode: Advanced NCA Anode: Graphite (90%)/Silicon (10%)	2019	780-800	290-300
Cathode: NCM622-NCM811 Anode: Graphite (95%)/Silicon (5%)	2018	350-600	180-280
Current LiT formulations			
Cathode: NCA Anode: Graphite (95%)/Silicon (5%)	2014	650-690	230-260
Cathode: NCM523-NCM622 Anode: Graphite (100%)	2016	220-400	150-180
Cathode: NCM111-NCM523 Anode: Graphite (100%)	2014	220-250	150-160

Figure 6 – The Lithium-ion roadmap [7].

I.2 Electric motors

The electric motor is a simple machine that converts electrical energy into mechanical energy. Most electric motors operate through the interaction between the motor's magnetic field and the electric current in a wire winding to generate force in the form of *torque* (a rotational force) applied to the motor's shaft (see Figure 7) [10]. There are numerous different types of electric motor found in appliances, tools, industrial equipment, and forms of transportation (trains, ships, cars etc.). These range in scale from tiny motors found in watches to huge motors used to turn the propellers on ships.

One major benefit of the electric motor over other methods of producing rotational force such as the internal combustion engine is that they are very efficient. Typically electric motors are over 95% efficient while combustion engines are generally well below 50%. They are also comparatively lightweight, compact, mechanically simple, and can provide instant and consistent torque. In addition they can run on electricity generated by renewable sources and do not produce greenhouse gases. For these reasons electric motors are rapidly replacing the combustion engine in transportation and industry.

Electric motors for application to aviation must be designed with a high power-to-weight ratio, otherwise referred to as their specific power density (measured in kW/kg). Today's state-of-the-art motors can achieve specific power densities of 8-10 kW/kg [7], with companies such as magniX, Rolls-Royce (previously Siemens eAircraft), YASA, EMRAX, and Remy (acquired by BorgWarner in 2015) leading the way. Aviation-rated motors must be capable of continuous operation at cruise power and therefore thermal management (i.e. cooling) is also key.

Specialised types of motor such as the *brushless and radial-flux* motor provide various advantages over the basic motor design shown in Figure 7. One design of particular importance to electric aviation is the *axial-flux* motor. A comparison of this versus the more traditional radial-flux design is shown in Figure 8. The main advantage of the axial-flux design is increased power density and efficiency, making it especially well-suited for use in aircraft. Axial-flux motors have a short axial length meaning they can be used in applications where space is limited. In addition it is possible to stack multiple motors together to achieve the desired level of power or torque.

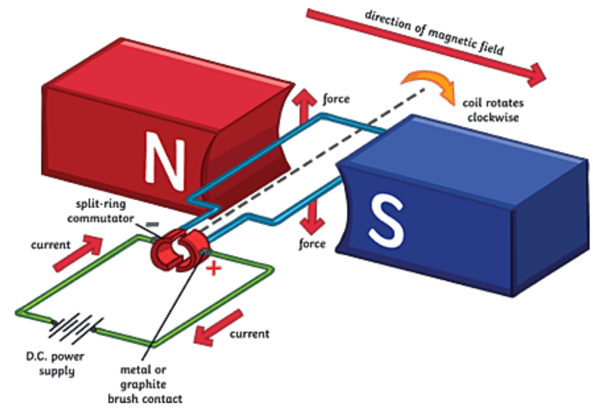


Figure 7 – Principle of operation of a simple electric motor.

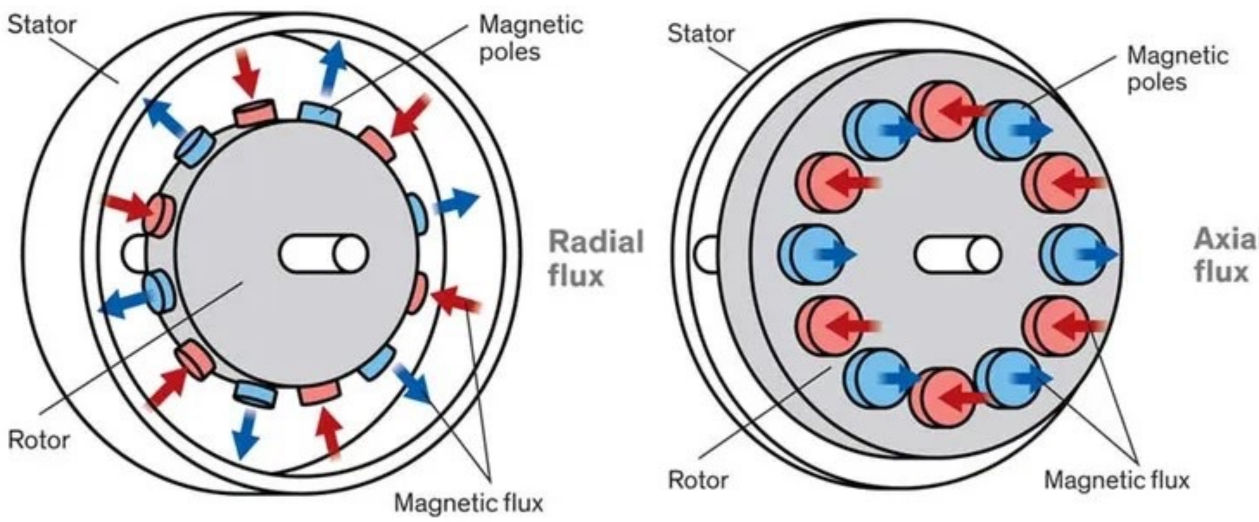


Figure 8 – Comparison of the radial-flux motor design (left) versus the axial-flux design (right) [11].

Examples of axial-flux motors currently available on the market include the EMRAX 348, and the YASA P400. As can be seen in Figure 9 the P400 has a very short axial length of only 80.4 mm.

Figure 9 – The EMRAX 348 (left) [12] and YASA P400 (right) [13].

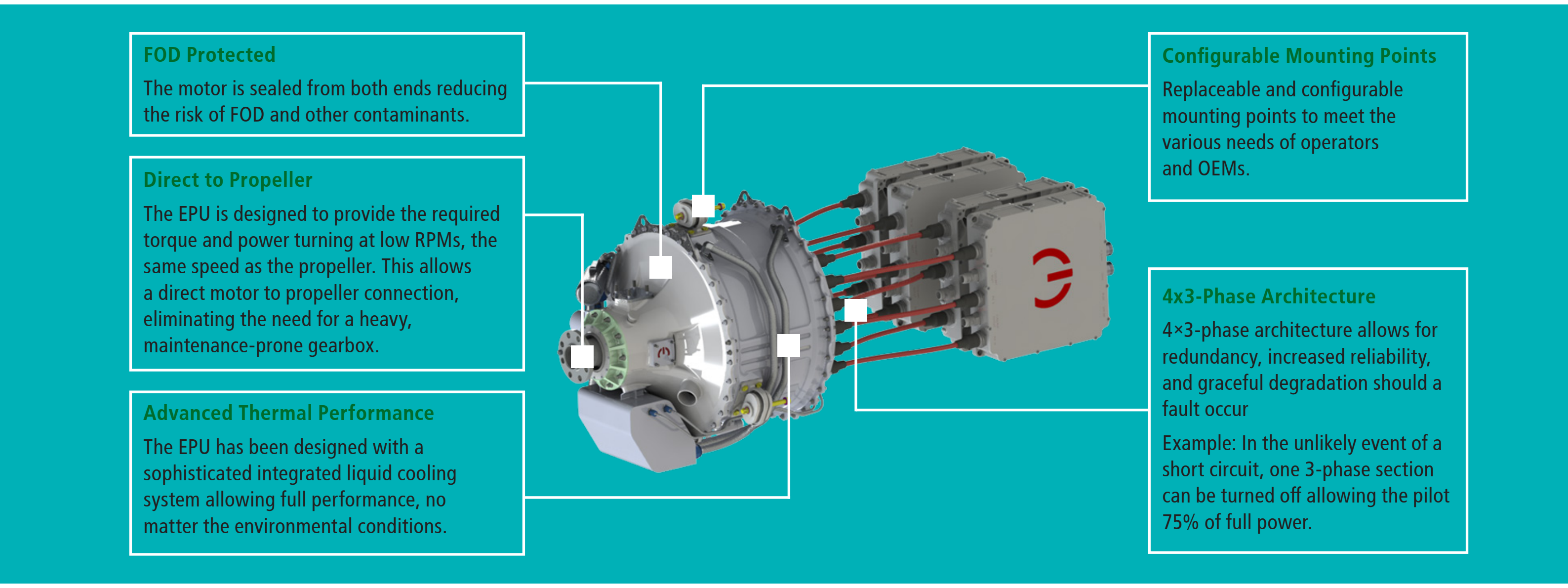


Figure 10 – magni650 EPU [14].

magniX is a leading developer of propulsion systems for electric aircraft including motors, inverters and motor controllers. The company manufactures a range of Electric Propulsion Units (EPU) including the *magni650 EPU* with a specification of 640 kW maximum and 560 kW continuous power. As shown in Figure 10 their propulsion units incorporate a number of features such as FOD (Foreign Object Debris) protection and redundancy that enable a simplified, reliable, and convenient adoption of all-electric power.

MagniX have been selected as the electric propulsion provider of choice by various experimental and commercial electric aircraft under development, including the *Eviation Alice* (recently redesigned around two magni650 EPU's [15]) and *Harbour Air eBeaver*. The company has also flown the *eCaravan*, a Cessna 208 Caravan modified to fly using a magniX EPU and lithium-ion battery. As of April 2022 this is the largest electric plane ever to fly [16].

I.3 Comparison to conventional propulsion systems

Electric propulsion offers many benefits over conventional fossil-fuel powered propulsion some of which are well known while others are less so. There are of course drawbacks too, some of which have already been touched on in this paper. Table 1 lists the main benefits and drawbacks as compared to conventional combustion engine propulsion (either reciprocating or turbine engines).

Electric Propulsion Benefits	Electric Propulsion Drawbacks (as of 2022)
▪ Several times the power-to-weight ratio of combustion engines. ▪ Electric motors are 3-4 times the efficiency of combustion engines. ▪ Scale-independent for power-to-weight and efficiency. ▪ Broad operating RPM (Revolutions Per Minute) that reduces the need for a gearbox. ▪ High efficiency across the power band. ▪ Highly reliable (fewer moving parts). ▪ Safety through redundancy (see Figure 10). ▪ Low cooling drag. ▪ Extremely quiet. ▪ No power lapse with altitude or hot day. ▪ 10x lower energy costs. ▪ Zero vehicle emissions (all-electric aircraft).	▪ Energy storage specific energy density is low compared to aviation fuels. ▪ Energy storage cost (initial outlay). ▪ Safety / certification uncertainty (see sections III and VI). ▪ Energy storage is more sensitive to environmental conditions (e.g. power loss in cold weather), and therefore vehicle range can be reduced.

Table 1 – Comparison of electric propulsion benefits and drawbacks [17].

Despite the major drawback regarding specific energy density that currently holds back the adoption of electric propulsion in larger long range aircraft, there are clearly many benefits that electric propulsion can offer to smaller aircraft. Not only does electric propulsion eliminate direct carbon emissions, it can also reduce fuel costs by up to 90%, maintenance by up to 50%, and noise by nearly 70% [5]. Specifically, electric motors have longer maintenance intervals than the combustion engines used in current aircraft, only needing an overhaul at 20,000 hours.

I.4 Distributed Electric Propulsion

One of the major new aircraft design architectures enabled by electrification is Distributed Electric Propulsion (DEP). Instead of having one, two, or three engines placed in conventional locations such as at the nose or under the wings of the aircraft; DEP aircraft have multiple (>3) motors distributed around the airframe, for example along the leading edge of the wing, wingtips, and on the tail (Figure 11). In this way the generation of thrust is spread around the aircraft as opposed to conventional designs where thrust is typically only generated in a few specific locations. DEP results in new degrees of design freedom that have not been available to aircraft designers until now.

Figure 11 – An example of DEP, the Joby Aviation S4 [19].

The ability to distribute the propulsion system across the airframe is penalty-free, or in many instances, offers substantial benefits [17]. For example DEP enables an increase in lift and stronger control forces at low speeds, meaning that the aircraft can operate more efficiently and maintain a high level of manoeuvrability allowing it to operate in confined spaces. Other benefits include reduced noise, and more degrees of redundancy thanks to the higher number of motors. The use of DEP is therefore very attractive to small eVTOL (electric Vertical Take Off and Landing) aircraft such as those that will be used for UAM, and indeed many aircraft being developed for this purpose are utilising DEP (see section IV.1).

I.5 Hybrids

It is important to note that electric aviation does not relate only to all-electric (also referred to as 'pure-electric') aircraft but also other aircraft design architectures that combine both combustion engines and electric propulsion known as hybrids. Hybrids can allow many of the benefits listed in Table 1 on the previous page to be realised while eliminating some of the drawbacks associated with electric propulsion, specifically low energy density. As such, hybrids may be seen as a good near-term solution before the introduction of all-electric aircraft is feasible, particularly in the mid to long range market. Hybrid design architectures reduce the certification risk of an electric aircraft since the acceptable safety targets and design criteria for combustion engine propulsion (reciprocating or turbine engines) are currently very well established [3].

The two main types of hybrid-electric propulsion are the 'Serial hybrid' and the 'Parallel hybrid' as shown in Figure 12. In the serial hybrid a combustion engine is used to generate electrical energy that charges a battery and/or runs the electric motor that spins the fan or propeller. In the parallel hybrid a combustion engine spins the fan or propeller directly however it is supported by an electric motor for peak performance (e.g. during take-off and climb).

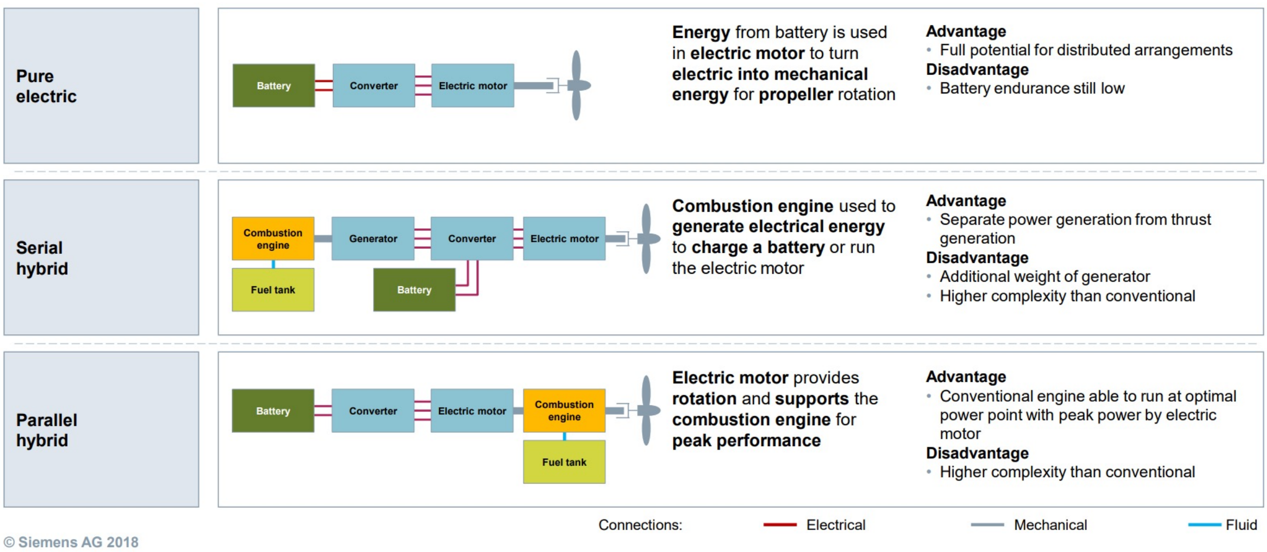


Figure 12 – Three different types of electric propulsion for aircraft [21].

Hybrid-electric aircraft are under consideration by various companies. In this section we give a short overview of several examples.

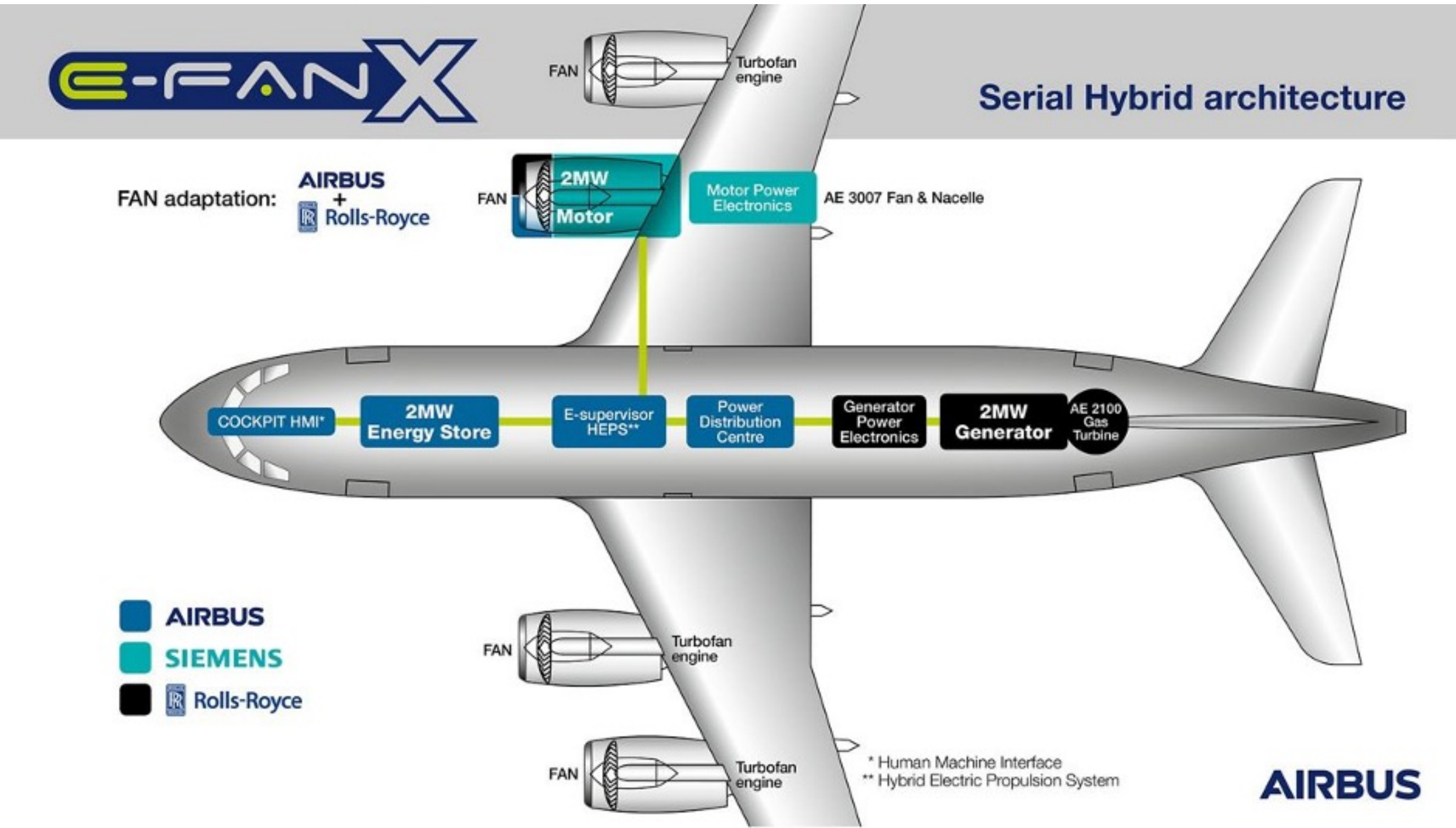
The American company *Ampaire* is pursuing a three-stage timeline of hybrid-electric development starting with its first test platform, *The Electric EEL*, that flew in 2019 (Figure 13). Based on a Cessna 337 Skymaster, the EEL is primarily a testbed for the development of high-powered electronics, inverters, motors, and related systems. The aircraft has a range of 200+ miles carrying 3 passengers, and delivers fuel savings of 50-70% and maintenance savings of 25-50% [22]. The second stage in the timeline is the *Eco Otter SX*, a 1 MW (Megawatt) low-emission variant of the DHC6 Twin Otter turboprop that is commonly used as a 19-seat commuter aircraft. Finally the third stage in Ampaire's hybrid development timeline is the *Tailwind*, a clean-sheet design concept for an all-electric ducted-fan passenger aircraft.

Another American company *Electra* is developing a hybrid-electric ultra-short takeoff and landing aircraft that aims to deliver more than twice the payload and an order of magnitude longer range than vertical takeoff UAM alternatives. Electra's design utilises a small turbogenerator to power eight electric motors and charge the batteries during flight. The aircraft will also utilise 'blown lift' technologies whereby

Figure 13 – The Ampaire Electric EEL [22].

Figure 14 – The Electra hybrid-electric blown lift concept [23].

Figure 15 – The E-fan X hybrid-electric architecture [21].



the electric motor-driven propellers blow air over the entire span of the wing and its flaps (see Figure 14), allowing energy-efficient takeoff and landings at speeds below 30 mph and in distances under 150 feet [23]. Flight testing of a demonstrator is expected in 2022 with the first commercial product planning to achieve FAA (Federal Aviation Administration) certification in 2026. The aircraft will be able to carry seven passengers up to 500 miles.

Possibly the most ambitious hybrid-electric project to-date has been the E-fan X demonstrator that was launched in 2017. The project aimed to convert an Avro RJ100 aircraft (a 100 seat regional airliner) with one of the four jet engines set to be replaced by a hybrid-electric propulsion system consisting of a Siemens 2 MW electric motor powered by a Rolls Royce gas turbine-driven generator and an Airbus power distribution and battery system (Figure 15). Despite significant progress being made the consortium made the decision to bring the project to an end in 2020 while the knowledge gained will be leveraged in future hybrid development.

Following the conclusion of the E-fan X project, both Airbus and Rolls-Royce have started development of other hybrid-electric demonstrators including the Airbus EcoPulse (see section V.1) and the Rolls-Royce APUS i-5 (see section V.2).

Hybrid regional airliners are also being considered by other groups such as British company, Electric Aviation Group (EAG). EAG's concept is for the world's first 90-seat hydrogen hybrid-electric regional aircraft, targeting a 100% reduction in CO_2 and NOx emissions and 50% improvement in profitability over equivalent sized turboprop aircraft. Such ambitions however are not expected to be realised before 2030.

I.6 Autonomy

The development of autonomous flight (i.e. flight ultimately without a human pilot) is a trend that is running in parallel with propulsion system electrification, and one that could be a key building block for certain use cases such as UAM and eVTOL [7]. Autonomous air taxis will result in improved safety of operations, just as self-driving cars have the potential to reduce the number of automobile accidents. Autonomy is likely to be implemented over time, as users and regulators become more comfortable with the technology and see statistical proof that autonomy provides greater levels of safety than human pilots [26]. In the near-term, autonomy may only provide limited functions such as obstacle detection, health monitoring of components such as battery systems, active vehicle stabilisation, and management of distributed propulsion systems. The automation of such functions will be beneficial in reducing pilot workload, particularly since in many Urban Air Taxis (UAT) there is only expected to be a single pilot.

In the longer term fully autonomous systems will allow the removal of a human pilot altogether, although some ground-based monitoring of the autonomous aircraft will remain. Although currently in the minority, some companies are already testing fully autonomous air taxis that are hoped to gain certification in the mid 2020's (e.g. the *EHang* 216 in China). The evolution of autonomous capabilities in aircraft will follow a number

<table>
<tr><th>SAE level</th><th>Name</th><th colspan="2">Definition</th></tr>
<tr><td colspan="4">Human driver monitors the driving environment</td></tr>
<tr><td>0</td><td>No Automation</td><td colspan="2">Full-time performance by the human driver of all aspects of the dynamic driving task.</td></tr>
<tr><td>1</td><td>Driver Assistance</td><td colspan="2">Driving mode-specific execution by a driver assistance system of either steering or acceleration / deceleration.</td></tr>
<tr><td>2</td><td>Partial Automation</td><td colspan="2">Driving mode-specific execution by one or more driver assistance systems of both steering and acceleration / deceleration.</td></tr>
<tr><td colspan="4">Automated driving system monitors the driving environment</td></tr>
<tr><td>3</td><td>Conditional Automation</td><td rowspan="2">Driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task.</td><td>Expectation that the human driver will respond appropriately to a request to intervene.</td></tr>
<tr><td>4</td><td>High Automation</td><td>No expectation that the human driver will respond appropriately to a request to intervene.</td></tr>
<tr><td>5</td><td>Full Automation</td><td colspan="2">Full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.</td></tr>
</table>

Figure 16 – Levels of on road autonomy (SAE International).

of stages in a similar manner to that of automobiles (Figure 16). In addition, the technologies on-board autonomous aircraft will have a strong commonalty with those used in other autonomous vehicles (for example cameras, radar, ultrasonic sensors, LIDAR etc.).

Significant progress is currently required to enable a future in which autonomous aircraft can fly in an unsegregated airspace alongside other air traffic, safely navigating around the built environment at low altitude. To handle this environment, aircraft will rely on advanced on-board autonomous piloting and 'sense and avoid' technologies. Advanced sensors, increased processing power and decision-making processes relying on machine learning / artificial intelligence may constitute some of the key aspects of these technologies [7]. Aside from these technological challenges, a current barrier to the adoption of full autonomy is that no regulatory structure exists that would allow for the certification of an autonomous, passenger carrying aircraft [9].

Several backup alternatives will exist for autonomous air taxis to ensure safe operation e.g. remote ground-based pilots and automated ground-based vehicle flight verification. These vehicles therefore have the potential to progress at a rapid pace, perhaps even more rapidly than cars or aircraft that aren't operating on a highly structured and standardised UAM infrastructure [26] (see section II.3). Nevertheless due to regulatory constraints it is not expected that full vehicle autonomy will be the norm in passenger aircraft until the 2030's.

I.7 Technology development timeline

As explained previously in section I.1, the greatest hurdle to be overcome in the long-term development of electric aviation is battery specific energy density. This is true for both all-electric as well as hybrid-electric aircraft. Alongside this are significant challenges in achieving a level of certification for revolutionary electric propulsion systems and new aircraft architectures equivalent to that seen in conventionally powered aviation.

On the one hand, various startup companies forecast entry into service of their aircraft based on an optimistic view of the progress of battery technology. More conservative views (Figure 17) see an entry into service of small hybrid-electric aircraft in the 15-20 seat category by 2030, and regional hybrid-electric aircraft of 50-100 passengers by 2035. This view is mainly influenced by an expected longer time needed for battery technology development.

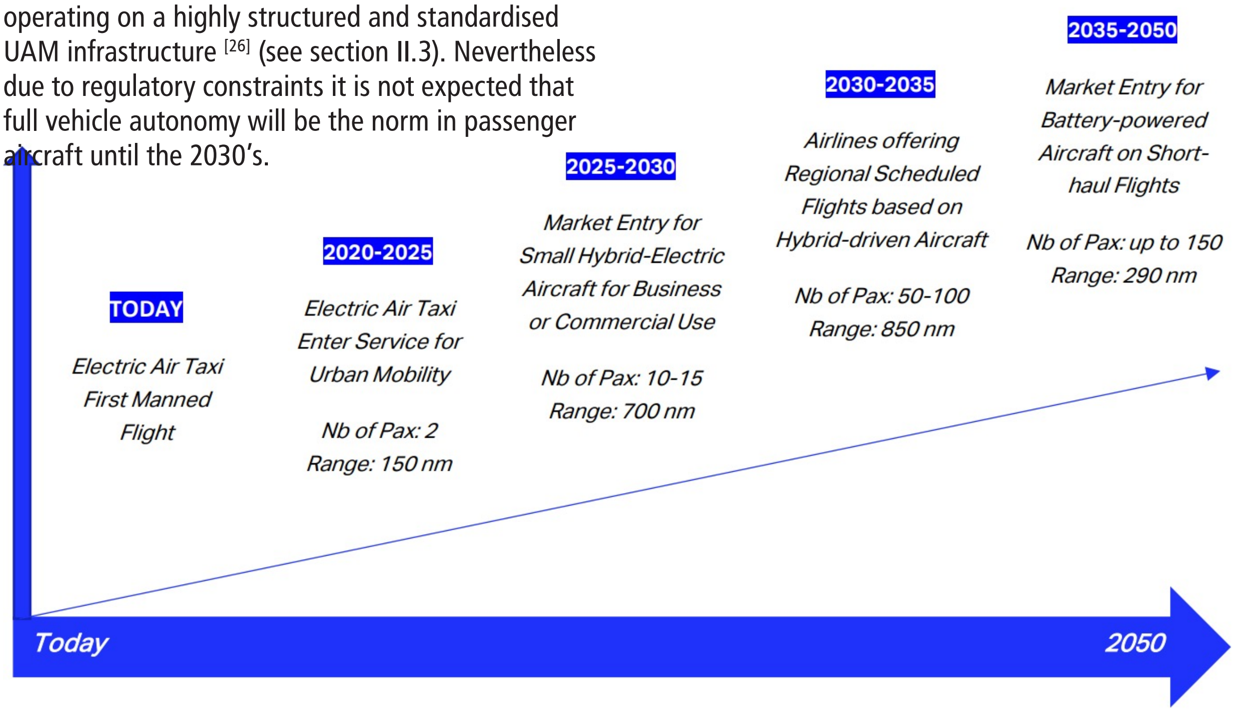


Figure 17 – Outlook for the electric-propulsion aviation market (conservative view) [28].

A timeline for entry into service of various forms of electric aviation *with reference to increasing battery energy density and available electrical power / voltage* is given in Figure 18. Recently, public funding bodies have focused more strongly on electric aviation as part of future sustainable transport (e.g. in the UK and the EU). This may contribute to the acceleration of the development and maturation of electric aircraft propulsion. The bolstering of efforts to fund electric aircraft technology development are not only motivated by the expected climate impact, but also by the benefits for noise and air quality [28].

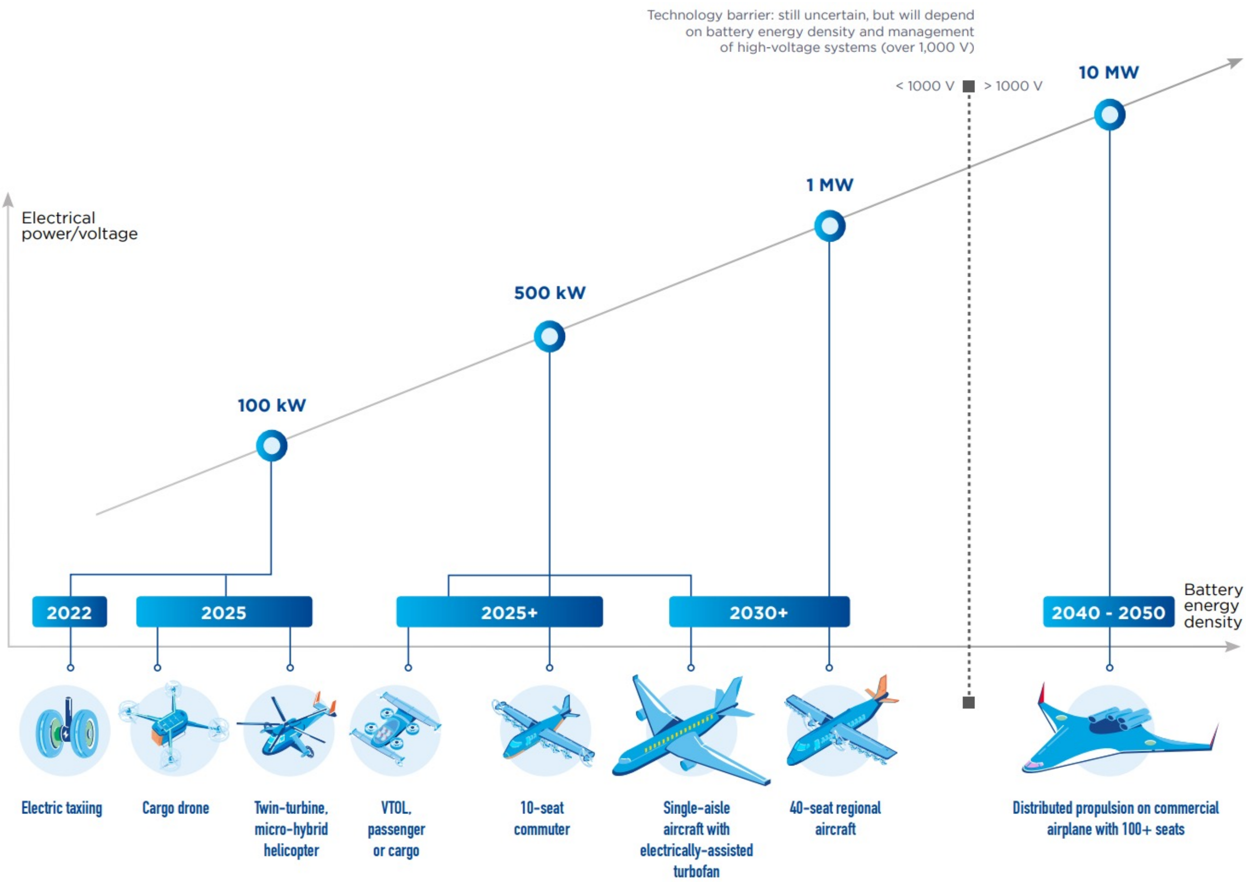


Figure 18 – Timeline for entry into service of various forms of electric aviation based on increasing battery energy density and available electrical power / voltage [29].

More conservative views see an entry into service of small hybrid-electric aircraft in the 15-20 seat category by 2030, and regional hybrid-electric aircraft of 50-100 passengers by 2035.

II. Design Architecture, Applications, and Concept of Operations

Electric propulsion technologies will ultimately lend themselves to all areas of aviation from small and short range cargo delivery drones to large and long range commercial airliners. As shown in Figure 18, in the near and medium-term (into the 2030's) electric aviation is expected to permeate each of these areas with the exception of large commercial airliners.

In the insurance sector, aircraft have traditionally been classed according to whether they are 'Fixed Wing' or 'Rotorwing'. However within the near and medium-term there are several emerging electric aircraft design architectures, only some of which are comparable to these conventional designs. As shown in Figure 19, at the technical level electric aircraft can be categorised into eight classes based on how they generate lift (wings, rotors, or a combination of the two) and whether or not the aircraft utilise some form of distributed propulsion (defined as having more than three independent motors) [3]. The eight classes can be simplified into four groups shown by the coloured boxes:

- Fixed Wing,
- Distributed Electric Propulsion (DEP) Powered Lift,
- Multirotor,
- Rotorcraft.

In this section the four electric aircraft design architecture groups are defined before descriptions are given of applications (e.g. UAM), the associated infrastructure, and concepts of operation.

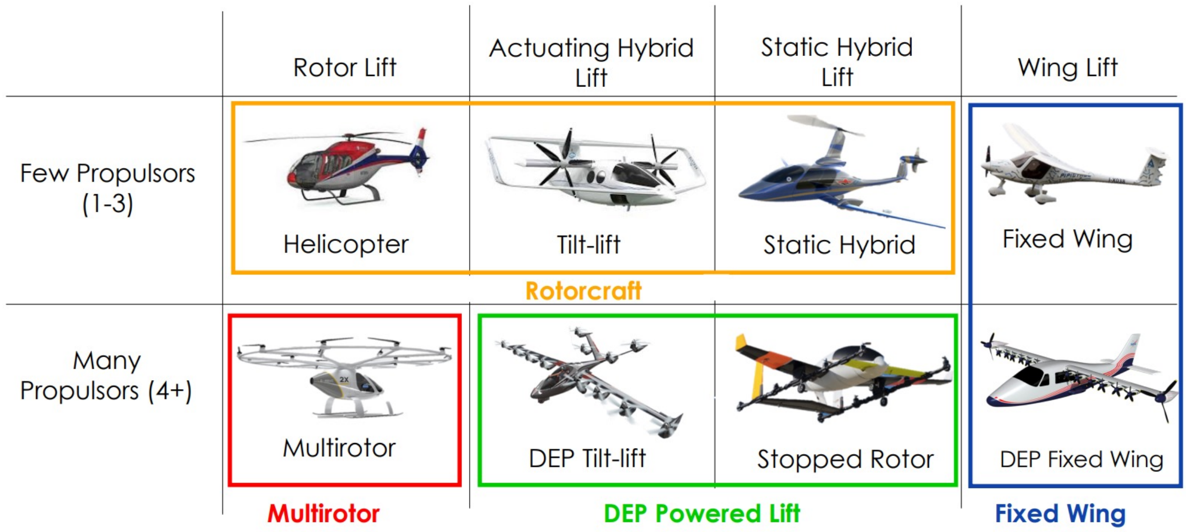


Figure 19 – Categorisation of emerging electric aircraft design architectures [3].

II.1 Design architecture groups

II.1.1 Fixed Wing

Fixed Wing aircraft are supported by lift generated by the wing through all phases of flight. Benefits of the Fixed Wing configuration include range, speed, payload capability, smaller required propulsion systems, and the ability to glide.

Various electric aircraft are being developed within the Fixed Wing group for a number of applications including light sport and training (Pipistrel Velis and Alpha Electro, Bye Aerospace eFlyer2), and intercity or regional passenger flights (Eviation Alice, Harbour Air eBeaver, Ampaire Electric EEL, Bye Aerospace eFlyer 800, Heart Aerospace ES-19, Wright Electric Wright 1, Electra hybrid-electric blown lift). Electric aircraft in the Fixed Wing group are also being developed for air racing purposes e.g. Rolls-Royce ACCEL "Spirit of Innovation" / 'E-NXT', Air Race E etc.

II.1.2 DEP Powered Lift

As discussed in section I.4, Distributed Electric Propulsion (DEP) concerns the utilisation of many (>3) motors distributed around the airframe. DEP as a form of propulsion can be applied to the Fixed Wing, Multirotor, and DEP Powered Lift groups as shown in Figure 19. In the DEP Powered Lift group the motors are located in various locations and power the aircraft in both horizontal and vertical flight. Benefits of this configuration include improved cruise speed and range relative to a Multirotor, while maintaining VTOL and noise-related design freedoms.

Aircraft being developed within the DEP Powered Lift group are primarily for the UAM application and include the Lilium Jet, Joby Aviation S4, Archer Maker, Vertical Aerospace VA-X4, Volocopter VoloConnect, and Wisk Cora. Several of these aircraft are described in more detail in section IV.1.

II.1.3 Multirotor

Multirotor aircraft are supported by rotor lift alone through all phases of flight utilising a DEP system. Attitude control is accomplished using differential thrust between the motors, either by changing motor speed or via a variable pitch mechanism on each rotor. The primary benefits of Multirotor configurations are low cost due to mechanical simplicity and possible noise benefits relative to helicopters.

Examples of aircraft being developed in this group include the Volocopter VoloCity and the EHang 216. In addition, most drones (including those for cargo delivery, see below) utilise a Multirotor design architecture, as well as upcoming 'Personal Electric Aerial Vehicles' such as the Jetson ONE.

II.1.4 Rotorcraft

Rotorcraft are aircraft that use rotors at least for the takeoff and landing portion of flight and possibly for the entire flight, but do not utilise DEP. This architecture is used on helicopters and conventionally powered aircraft such as the Bell Boeing V-22 Osprey and the Augusta Westland AW609. Benefits of the Rotorcraft configuration include VTOL capability and the ability to autorotate in the event of power loss.

Examples of electric aircraft that have been developed in this group include the Aquinea Volta light helicopter and a retrofitted Robinson R44 helicopter.

II.2 Applications

II.2.1 Cargo drones

One application in which electric aviation is already being utilised is cargo drones or Unmanned Aerial Vehicles (UAVs). Although yet to become a common service as has been proposed by Amazon [30], drones have been used in trials to deliver items to remote locations [31]. Looking to the future, electric cargo drones could help delivery companies solve the logistics problem of the 'last 10 miles' which at present is particularly inefficient due to growing road congestion and increasingly restrictive CO2 and particle emissions standards in urban areas [29]. The market potential for air logistics mobility is valued at €100 billion for 2035, equating to half of the total predicted UAM market size [32].

One example of a heavy-lift cargo drone under development is the *Volocopter VoloDrone* (Figure 20). This all-electric unmanned aircraft has a payload carrying capacity of 200 kg and a range of up to 40 km in either remotely piloted or autonomous modes. A demonstrator performed its first flight in 2019 and today it is in active tests with logistics solutions partner DB Schenker.

II.2.2 Urban Air Mobility

UAM represents a significant departure from the current paradigm of commercial aircraft design, certification, and operations; enabled by the development of electric aviation and specifically DEP. It will allow a dramatic increase in the mobility of people living in major urban areas by decreasing travel times and avoiding surface congestion. Not only this, electric propulsion and eventually autonomous flight operations aim to slash running costs by an order of magnitude, meaning that UAM will steadily become available to the public at costs higher than taxis but much less than today's helicopter services.

Operation within urban areas necessitates the ability to land and take-off vertically, hence many of the aircraft being developed for UAM application are termed as *eVTOL* (electric Vertical Take-Off and Landing). Over 60 examples of this type of electric aircraft are currently under development [34].

The three major use cases for UAM are as follows:

1. **On-demand air taxis**
   - A point-to-point non-stop service from one destination to another within a defined area for several passengers.
   - Landing sites spread around the city to service key points of interest, with charging facilities ideally in place at each station.
   - Short distances between landing sites (<50 km).
   - Multirotor aircraft are ideally suited to this particular use case [35].
2. **Scheduled airport shuttles**
   - Fixed flight plans and pre-booked flights for several passengers with additional payload allowance for luggage.
   - Landing sites located at strategic locations around the city and at the airport.
   - Up to medium distances between landing sites (<100 km).
   - DEP Powered Lift aircraft are ideally suited to this particular use case [35].
3. **Intercity flights**
   - Scheduled services between specified cities that are too close to be viable for regular aviation links.
   - Capacity for several passengers with additional payload allowance for luggage.
   - Long distances between landing sites (<250 km).
   - DEP Powered Lift and Fixed Wing aircraft ideally suited to this particular use case [35].

Figure 20 – The Volocopter VoloDrone [33].

Over the coming decade various UAM projects are scheduled to go live in cities such as Dubai, Singapore, Los Angeles, and Dallas. As of 2022 many eVTOL aircraft are under development with some such as those by Volocopter and Lilium in advanced certification stages [36]. Success of any particular project will depend on choosing the right aircraft architecture from the wide array of options (Figure 19); development of suitable infrastructure for takeoff and landing, maintenance, energy supply and communication (5G networks); robustness of the commercial and operating models; and a regulatory framework to control and govern safety, liability, emissions and a host of other issues [35]. Autonomous flight operations are expected to start being implemented from the 2030's. Many of these factors making up the 'UAM ecosystem framework' are shown in Figure 21.

Market research suggests that close to 100,000 UAM aircraft could be in the air worldwide by 2050. By this time around 100 cities worldwide are expected to have implemented UAM services, however the number of aircraft per city is expected to range from 60 for a small metropolitan area to 6,000 in the largest ones [35]. Based on this scenario, UAM aircraft will become an integral part of electric aviation over the next three decades.

II.3 Infrastructure

The infrastructure demands for electric aircraft will be markedly different to those of combustion engine powered aircraft due to the nature of their propulsion systems. For example, electric aviation will demand high voltage electric power supplies and rapid chargers in place of the aviation fuel (kerosene) storage and refuelling systems that are commonplace at today's airfields. However beyond the familiar forms of commercial aviation an entirely new infrastructure is required for UAM, and this must be implemented in densely populated urban areas.

Infrastructure is a key enabler of the UAM business model: eVTOL landing sites otherwise referred to as 'vertiports' or 'vertistops', battery charging capacity, and maintenance facilities. Another element of infrastructure required for UAM is a low-latency cellular network (e.g. 5G) to enable communication between eVTOL aircraft, other flying objects, and control centres. Especially for on-demand services, predictive air traffic management will be key to ensure smooth and efficient operation of the entire eVTOL system, while control centres will take care of both routing and contingency management [35].

Figure 21 – The 'UAM ecosystem' [32].

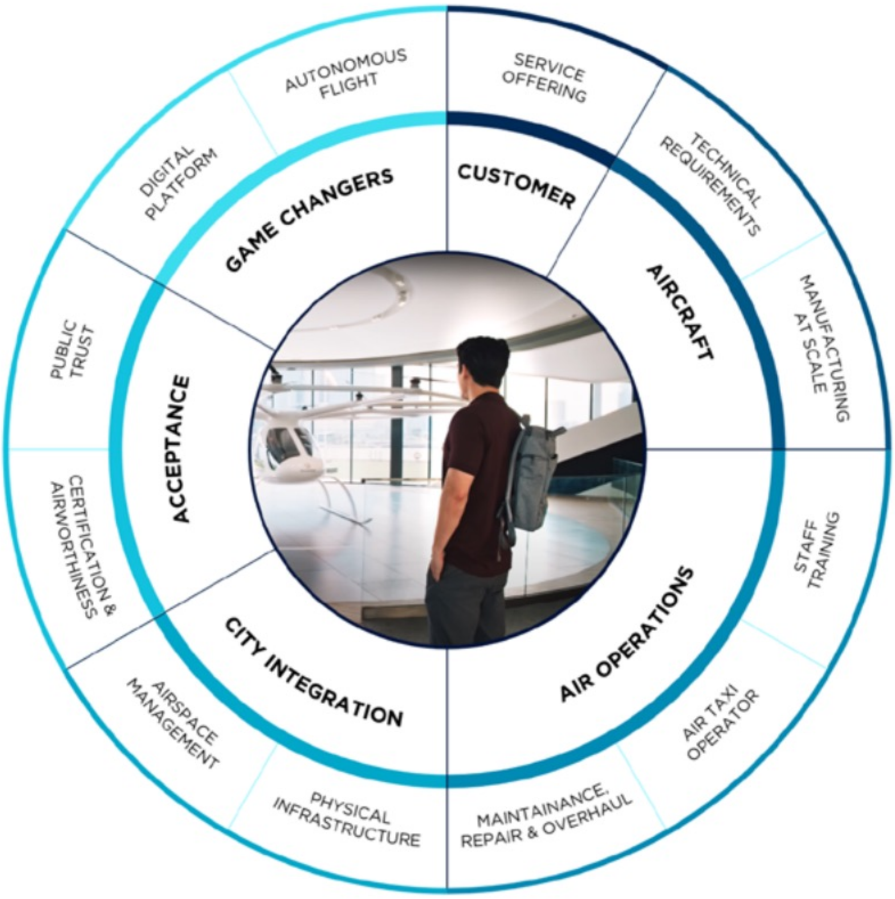


Figure 22 – Artist's rendering of the top level of a multi-storey car park utilised as a vertiport [26].

An eVTOL fleet will likely be supported in a city through a mixture of both 'vertiports' and 'vertistops'. *Vertiports* will be large multi-landing locations that have support facilities (e.g. battery chargers, support personnel etc.) for multiple vehicles and passengers, limited to approximately 12 vehicles at any given time [26]. *Vertistops* on the other hand will be single vehicle landing locations akin to helipads – without support facilities but where passengers can be quickly picked-up and dropped-off. Both types of landing site need to be unobstructed by buildings, trees, or other obstacles, although they may be in close proximity to all of these. Examples of potential sites that could easily be converted to vertiports include floating barges in cities with rivers, lakes, or harbours; and the top level of multi-storey car parks as depicted in Figure 22. The former offers advantages in that aircraft approach and departure can occur over the water and therefore limit community annoyance (i.e. noise) and risk. The latter provides the opportunity to repurpose existing infrastructure while offering operational advantages such as unobstructed glide slopes, space for multiple aircraft landing pads, and pre-existing automobile and pedestrian access.

As shown in Figure 22, parked aircraft are kept away from the touchdown pads until needed. Each parking spot provides charging facilities, while the touchdown pads may also provide recessed rapid chargers that enable an aircraft that only intends to land and then reload passengers to recharge for a short time. The active flight operations area is restricted by a building that provides the security, screening, waiting area, and other functions; with access to the touchdown pads only through the building [26]. A separate section of the rooftop allows customers to be dropped-off and access automobile or pedestrian egress points.

A novel location for vertistops that has been proposed is within the 'cloverleaves' of major roads, as depicted in Figure 23. In this scenario a raised helipad-like structure could be built within the cloverleaf with space underneath to be used for additional functionality such as a passenger pickup and waiting area [26]. This UAM infrastructure approach has a number of operational advantages including:

- re-use of existing (and otherwise unused) land,
- aircraft approach and departure trajectories could be performed over major roads with no flights over neighbouring private property,
- eVTOL generated noise would be masked by the existing road noise, limiting community annoyance,
- the eVTOL infrastructure would immediately couple into the existing road network to minimise travel time and provide a good fit with existing ride-sharing business models to avoid the need for parking facilities.

Figure 23 – Proposed cloverleaf vertistop [26].

Entirely new vertiport infrastructure as opposed to the conversion and reuse of existing infrastructure is also under development by a number of companies. *Urban-Air Port* [37], a company specialising in the development of zero emission infrastructure for future air mobility, have partnered with the Urban Air Mobility Division of Hyundai Motor Group and Coventry City Council to open the world's first fully-operational hub for eVTOL aircraft, *Air-One*, in Coventry in 2022 (Figure 24). This pop-up vertiport is being built as a proof of concept, however over 200 examples of this design are expected to be installed worldwide over the next five years. Using innovative construction, the sites can be installed in a matter of days, emit net zero carbon emissions and can be operated completely off-grid, meaning they do not always have to rely on a suitable grid connection [38].

The company *Volocopter* in partnership with *Skyports* developed and built the world's first full-scale passenger air taxi vertiport prototype, the *VoloPort*, in Singapore in 2019. This prototype enabled real-life testing of the full customer journey including pre-flight checks, passenger lounges, and boarding procedures [39].

Figure 24 – The Urban Air Port Air-One [38].

As has been seen in the automobile world, electric transportation for many is not a viable option until the charging infrastructure is in place to support it. Vertiports therefore will need industrial-grade connections to the power network and/or methods of power generation and storage (e.g. solar arrays and permanently installed battery packs), in a manner similar to that demonstrated in emerging electric automobile charging hubs (e.g. the *Gridserve* Electric Forecourt [40]). Each vertiport will need multiple high voltage rapid chargers as well as slower low voltage chargers for overnight charging. Provision for battery swapping may also be needed as some vehicles may utilise this functionality to improve productivity. This method however does introduce logistical and certification challenges that may preclude its wider adoption.

Vertiports will need industrial-grade connections to the power network and/or methods of power generation and storage (e.g. solar arrays and permanently installed battery packs).

II.4 Operations

To operate electric aircraft commercially the staff involved at all stages will need specific training.

- **Flight:** Pilots must know how to operate the aircraft safely, therefore aircraft-specific flight training (e.g. conversion training) will be required, especially in the case of UAM. Currently there is no pilot license for eVTOLs, however the European Union Aviation Safety Agency (EASA) is working on new regulations to address this. Pilots will need to be trained to operate in an urban environment, at low altitude, over congested areas, and with other passenger and cargo drones flying in the same area.
- **Maintenance:** Maintenance staff will need training that addresses new aircraft types and especially the electric propulsion systems before any maintenance can be legally conducted and approved. Particular attention will need to be given to aircraft battery maintenance, battery replacement, working with high-voltage systems, and battery storage and handling [41].
- **Ground:** Ground personnel are responsible for handling the aircraft while it is on the ground and will need training in new procedures applicable to electric aircraft such as recharging and battery swaps. These personnel will also need to become familiar with new working environments such as vertiports.

Air Traffic Management (ATM) is essential to separate and deconflict all flight activities, and crucial to ensure aviation remains the safest means of transport. The development of UAM will necessitate a higher frequency and airspace density of vehicles operating over urban areas, and to meet this demand the complexity of ATM will increase exponentially beyond today's operational activities [26]. It is therefore critical that operators, regulators, and other stakeholders develop solutions to enable safe, efficient, and high-capacity urban environments to accommodate this dramatic increase in aerial traffic density. Integrating these environments within existing airspace is recognised by ATM organisations such as NATS (National Air Traffic Services) as the key to unlocking the next era of aviation while maintaining the same safety standards [42].

Current ATM technologies such as ADS-B (Automatic Dependent Surveillance–Broadcast) that provide aircraft with situational awareness and allow self-separation are a great starting point for initial low density UAM operations. However more comprehensive low altitude airspace solutions will be required to meet long-term higher density operations. Emerging concepts such as the Unmanned Aircraft System Traffic Management (UTM) initiative are a start towards an airspace system that will enable low altitude flight above urban areas [26]. Some reports highlight that traditional ATC (Air Traffic Control) is not expected to provide separation services to aircraft in UTM airspace (<500 feet) as it does for airline and General Aviation (GA) traffic in controlled airspace. Therefore it must be possible for UAM aircraft to navigate independently of ATC while they are in this low altitude airspace. Meanwhile UAM aircraft may need to be capable of transitioning between airspace types, as shown in Figure 25.

Another operating consideration particularly applicable to electric aviation is sensitivity to weather conditions since each new aircraft design architecture discussed earlier will respond in a different way compared to conventional aircraft. Batteries have a narrow operating temperature range, outside of which they can degrade or lose performance. In the UAM scenario, aircraft operating at low altitude will be susceptible to conditions not experienced by aircraft at higher altitudes e.g. wind shear and gusts, precipitation, and low visibility. For this reason, meteorological services providing high accuracy for localised geography will be important to permit short flights in non-optimal weather conditions.

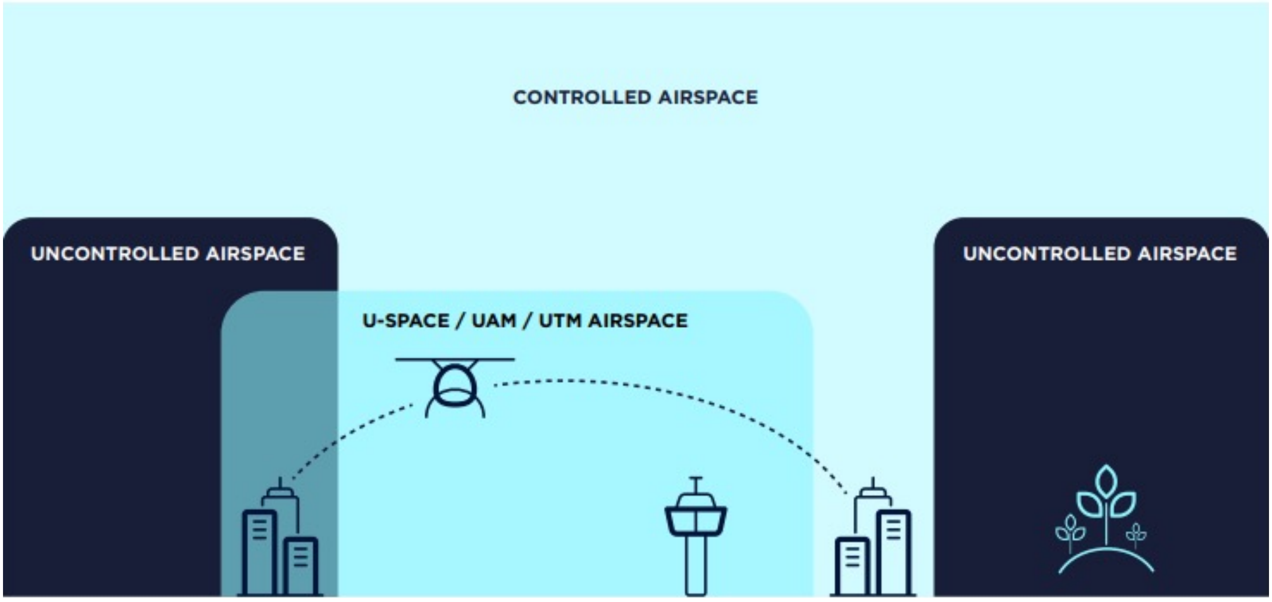


Figure 25 – Airspace types that may be encountered by UAM aircraft [32].

III. Electric Aviation Specific Hazards

Electric aviation is set to revolutionise air transportation, however as with any technological revolution there are new risks to be mitigated and hazards that must be considered early in the development cycle. Much of the electric aircraft design architecture is new, from the batteries to electric motors, high voltage wiring, and power electronics. The testing of aircraft that are fully dependent on all these technologies operating together has only recently begun, and it is likely that some hazards may only be realised once many hours of flight testing have been conducted.

In this section an overview is given of the key hazards specific to electric aviation with reference made to the electric aircraft design architectures described in section II.1.

III.1 Battery thermal runaway

Despite improvements over the last three decades in Li-ion battery performance, safety related issues remain a concern. The majority of reported incidents have been due to one or more faulty cells reaching operating conditions beyond their safety limits, leading to *thermal runaway*. Thermal runaway is where an exothermic reaction and ignition (i.e. fire) in one cell cascades into similar reactions in neighbouring cells and eventually a critical portion of the battery pack itself [43]. This reaction results in a rapid and uncontrolled increase in battery temperature, off-gassing, fire, and/or a battery explosion [3]. Given the potentially catastrophic nature of this hazard especially on an aircraft, thermal runaway is one of the primary concerns in the development of electric aviation.

There are three stages to thermal runaway as shown in Figure 26. In stage 1 the batteries change from a normal to an abnormal state, and the internal temperature starts to increase. In stage 2 the internal temperature quickly rises, and the battery undergoes exothermal reactions. Finally in stage 3 the flammable electrolyte combusts, leading to fires and even explosions.

The initial overheating in stage 1 can occur for a number of reasons:

- Internal short circuits – can be caused by separator issues, dendrites (metallic microstructures that form on the negative electrode during the charging process), mechanical damage (e.g. puncture or deformation), or manufacturing defects.
- External short circuits – due to faulty wiring etc.
- Overcharging – the battery is charged beyond the designed voltage for example due to a malfunction of the charging unit.
- Exposure to excessive temperatures.

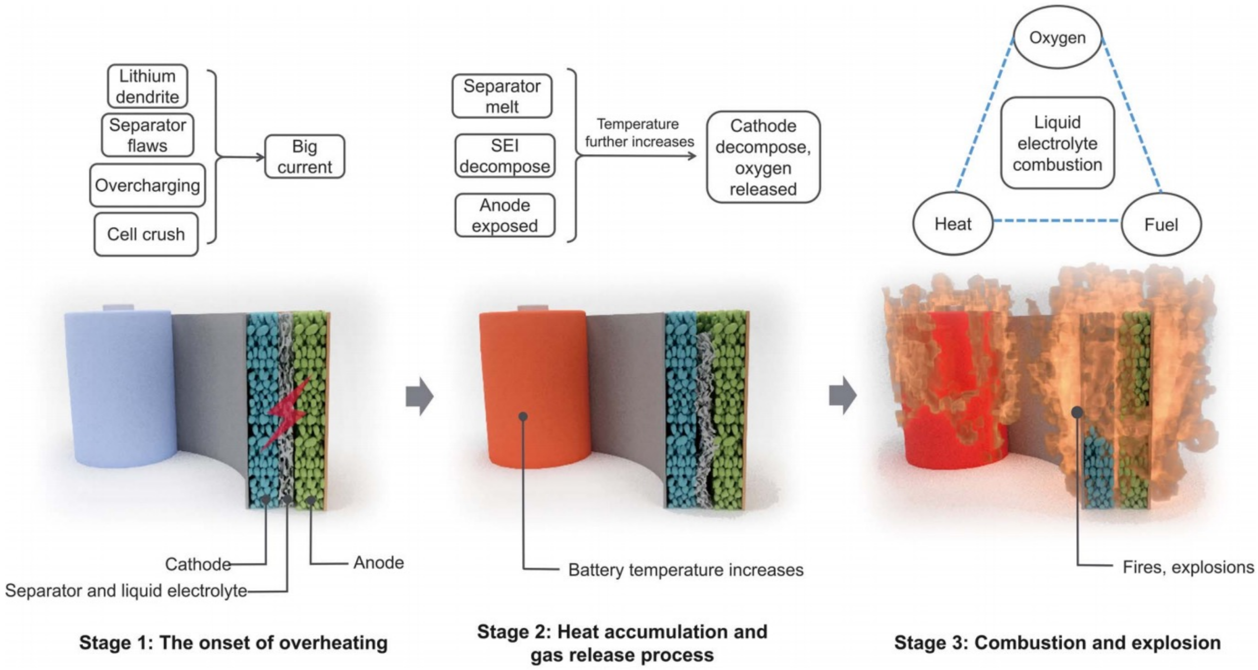


Figure 26 – The three stages of the thermal runaway process [44].

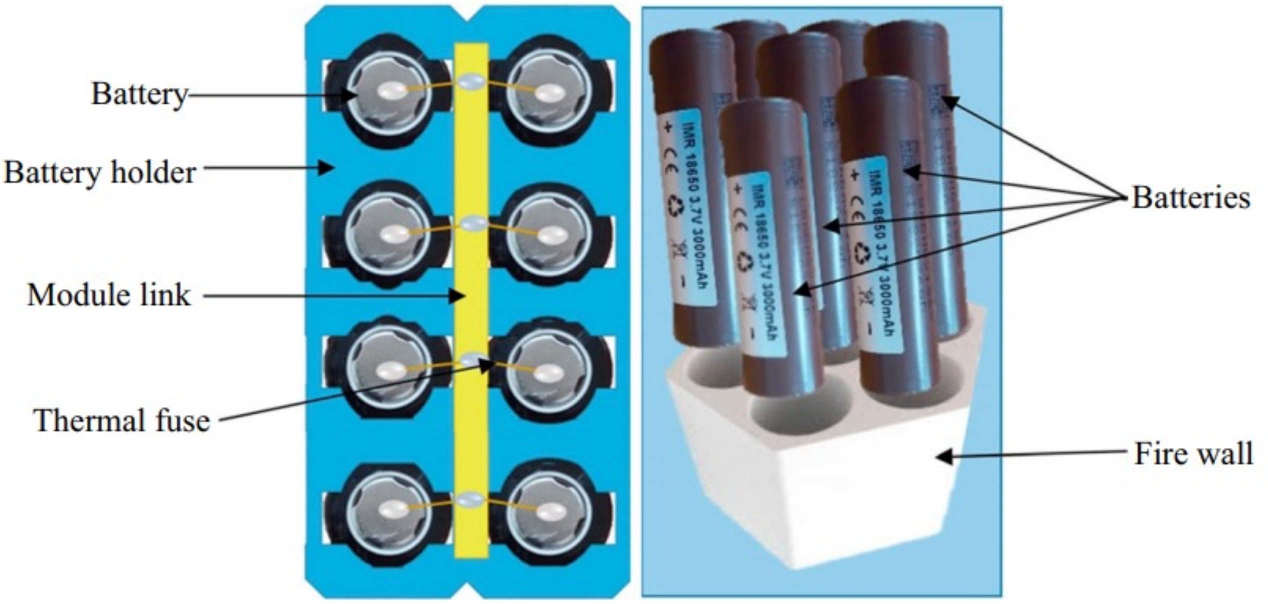


Figure 27 – Battery pack architecture showing mechanisms to protect against thermal runaway with a thermal fuse and heat dissipating material between cells [45].

If the overheating is mitigated in stage 1 then thermal runaway can be avoided. However an important point to note for electric aircraft is that once stage 1 occurs then functional safety (see section III.2) cannot be guaranteed since the battery has transitioned from normal to abnormal behaviour [43]. Mitigation strategies for stage 1 include requiring much higher quality control standards compared to batteries manufactured for other applications, thereby minimising the incidence of manufacturing defects. Cell design decisions are also instrumental in mitigating stage 1, for example in the choice of anode material, usage of multifunctional liquid electrolytes and separators, and the inclusion of overcharge protection additives [44]. For electric aircraft, mandating compliance with a set of minimum cell design metrics such as minimum separator thickness, electrode porosity, and heat capacity of the cell stack could avoid the use of cells that have been designed primarily with performance rather than safety in mind [43]. This is a prime example of how regulations (see section VI) will need to be applied in the certification of electric aircraft.

The onset of stage 2 effectively implies cell failure, and the mitigation measures must then focus on containing the hazard. A popular fail-safe is the use of cell-venting mechanisms. The vent once activated releases all the gaseous products in a controlled manner into the surrounding environment [43]. The release of gases simultaneously balances the heat accumulated within the cell, and so this fail-safe can help to prevent transition to stage 3. Cell design decisions are also effective in mitigating stage 2, for example choosing materials with higher thermal stability, incorporating methods of shutting down the conduction pathway, and designing batteries with integrated cooling systems [44].

If stage 2 is not controlled, the cell inevitably goes to stage 3 where the electrolyte forms the primary fuel for combustion aided by accumulated heat, gaseous decomposition products and oxygen from the cathode. The priority at Stage 3 is to prevent propagation of the fire, thermal runaway and system-failure [43]. High safety battery packs designed specifically to prevent stage 3 from cascading have been developed previously for NASA's manned missions. Such design approaches, an example of which is shown in Figure 27 could be adapted to the needs of electric aviation.

In summary, mitigation strategies for battery thermal runaway can be classified according to whether they reduce the consequence or the probability of thermal runaway as shown in Table 2.

Mitigation Description	Mitigation Reduces
Battery containment and physical separation	Consequence
Advanced fire suppression	Consequence
Improved manufacturing, testing, and inspection	Probability
Improved electrical protection and monitoring	Probability

Table 2 – Summary of mitigation strategies for battery thermal runaway [3].

While good design practice and operational controls have proven effective in mitigating most causes, thermal runaways due to manufacturing defects have proven very difficult to reliably prevent. Manufacturing defects in the batteries were the cause of highly publicised thermal runaway events in the lithium batteries of a commercial airliner in 2013 [46] and 2017 [47]. This led to the development and installation of battery containment systems on all aircraft of this type; these are solid structures than can contain the effects of a thermal runaway, but which add considerable weight to the battery system. Clearly any measures taken to mitigate the effects of thermal runaway on all-electric aircraft will need to be effective while keeping additional weight to a minimum.

III.2 Battery energy uncertainty

Battery failure modes other than thermal runaway could arise due to accelerated degradation, change in discharge performance, or faulty state of charge or state of health monitoring systems. In electric cars the safety risks from these modes are not high, but the risk is critical for aircraft [43]. These aspects may be referred to as functional battery safety, however here they will be grouped under the heading *battery energy uncertainty*.

The amount of useful energy in a Lithium battery depends not only on its state of charge but also strongly on its age, past charge / discharge cycles and handling, as well as the ambient temperature [48].

For example Tesla recently reported average age-related battery degradation of 10% after 200,000 miles of driving in their vehicles [49]. While it is important to note that this is clearly acceptable for automobiles (at this mileage the vehicle is typically at end-of-life), the impact on aircraft of even minor age-related battery degradation will be more significant given the safety factors involved. As another example of how the amount of useful energy in a Lithium battery can vary based on certain factors, those who drive electric cars will be familiar with the loss of range attributable to cold weather.

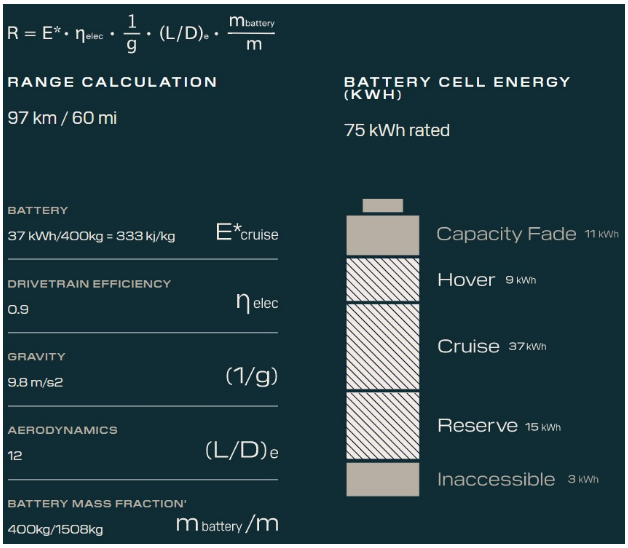


Figure 28 – Example of the calculation of aircraft range based on battery capacity and other factors [50].

This combination of factors means an accurate estimation of the battery energy cannot be done from a single measurement as it requires knowledge of the battery's past history and operating conditions. This in turn makes it difficult to verify that reserve mission requirements will be met (see Figure 28). Battery energy uncertainty is considered a greater hazard for those aircraft design architectures that rely on vertical thrust in the landing phase (e.g. DEP Powered Lift, Multirotor, and Rotorcraft), since for these designs the highest-power demand conditions come at the end of the mission when the available power reserves are lowest. For purely Fixed Wing aircraft the hazard is less since they typically only demand high power at take-off and have the ability to glide in the event of power loss.

There are several ways battery energy uncertainty can be mitigated as shown in Table 3. The most efficient way to do this would be improved battery monitoring or state-of-charge technologies. This may need to include entire life cycle monitoring of the batteries used, which would then require the development of the regulatory framework to certify those processes [3]. Redundant battery systems could be used with stringent requirements on battery replacement, for example a single-use emergency battery could be installed as a reserve system which is replaced after every use [3]. However a drawback of such a system would be increased vehicle cost and weight. The vehicle could be overdesigned for the worst-case battery state at the worst allowable temperature, however again this could significantly increase vehicle weight. Finally a Ballistic Recovery System (BRS) could be utilised as a last resort to mitigate this hazard.

Mitigation Description	Mitigation Reduces
Improved battery monitoring and state estimation	Probability
Redundant systems	Consequence
Overdesigned batteries	Probability
BRS (aircraft parachute)	Consequence

Table 3 – Summary of mitigation strategies for battery energy uncertainty [3]

III.3 Common mode power failure

Common mode power failures are where multiple power systems fail in the same way for the same reason. Such failures may be caused by maintenance errors, systematic manufacturing defects, environmental factors, unforeseen operating conditions, or unexpected software states. While this hazard is not specific to electric aviation it is considered here as one of the key hazards given the untested nature of many of the electric aircraft design architectures being developed (section II.1), their reliance on electrical power, and the potentially catastrophic nature of total power failure.

Mitigation Description	Mitigation Reduces
System redundancy and design practise	Probability
BRS (aircraft parachute)	Consequence

Table 4 – Summary of mitigation strategies for common mode power system failure [3].

While redundancy in the powertrain is often cited as a reason that DEP vehicles will be safer than most aircraft, they are still susceptible to common mode power system failures [3]. For both DEP and Fixed Wing design architectures such a failure is of higher consequence at low altitude than high altitude since at lower altitudes the ability to manoeuvre for a safe landing is restricted. The consequence for Rotorcraft is generally less than other design architectures since they can enter autorotation at any altitude. Common mode power failure for a Multirotor design architecture is typically of a higher consequence than for other architectures since they neither have the ability to glide nor to autorotate. Two possible mitigations for common mode power failure are given in Table 4.

Good systems redundancy and design practise enables the development of highly redundant systems that can drastically reduce the probability of a common mode failure occurring in the first place. The challenge in the context of UAM will be meeting the required levels of safety (close to commercial air travel) within the tight cost and weight targets of these vehicles [3]. BRS systems may be particularly attractive to Multirotor and DEP aircraft as a way to mitigate this hazard, however they are not effective in all situations and should not replace a highly reliable vehicle design.

III.4 Fly-by-wire system failure

Fly-by-wire (FBW) is a system that replaces the conventional manual flight controls of an aircraft with an electronic interface. In a conventional system the flight controls such as those for controlling attitude (roll, pitch, yaw) are mechanically linked to the flight control surfaces (ailerons, rudders, flaps etc.) whereas in an FBW system digital flight controls send electrical signals transmitted by wires via a flight control computer to actuators at each control surface.

While FBW systems have become commonplace on modern airliners, electric aircraft will have an elevated level of dependency on them given the nature of the design architectures being considered. For example Multirotor and DEP Powered Lift design architectures require active stabilisation to convert pilot stick inputs into the correct motor differential thrust, and to stabilise the vehicles in vertical flight and transitional phases [3]. For any electric aircraft design architecture, failure of the FBW system is likely to result in loss of attitude control unless there is a conventional backup. FBW system failure therefore presents a significant source of risk for any all-electric aircraft design architecture with the severity considered equivalent to a power system failure. Potential mitigation strategies are the same as those for common mode power failure in Table 4.

III.5 High-level autonomy failure

Most proposals for UAM systems identify the need for pilotless operations as critical to the long-term viability and scalability of the UAM concept [3]. A high-level autonomy failure therefore is considered a key hazard to electric aircraft given that many of them are being developed with an autonomous future in mind. To replace a pilot sophisticated systems are required that must among other things be capable of sensing the surrounding environment, adapting to any degraded vehicle modes, and replanning the vehicle path [3]. It is clear that the failure of such a system in-flight would be equivalent to the loss of the pilot, and so this is a high-severity risk regardless of vehicle design architecture.

Mitigation Description	Mitigation Reduces
Windscreen / Rotor design criteria	Consequence
Redundancy	Consequence
BRS (aircraft parachute)	Consequence

Table 5 – Summary of mitigation strategies for bird strike [3].

III.6 Bird strike

While bird strike is not a unique hazard to electric aviation it is considered here as a key hazard for two reasons. Firstly many electric aircraft particularly those operating in a UAM capacity will be flying at low altitude where the probability of bird strike is higher. Secondly it is possible that with many of the aircraft design architectures being developed utilising smaller than normal propellers or fans, impacts due to bird strike could cause more damage. In some design architectures debris from one failed propeller could impact adjacent ones, potentially leading to cascading failures, vibratory issues, and degraded flight control [3]. The severity of a bird strike depends strongly on the number of birds impacted, flight speed, and vehicle design among other factors. Several mitigations for bird strike are given in Table 5.

Windscreens on current aircraft must meet stringent requirements on the ability to withstand bird strike and it is expected that similar standards would be applied to UAM aircraft. The placement of rotors can be carefully considered to avoid cascading failures. Redundancy inherent in the design of many DEP architectures should be effective in mitigating the consequences of a bird strike. As with other key hazards BRS systems may be utilised as a mitigation however they should not replace redundancy in the vehicle design.

Risk Severity= Probability x Consequence
High, Medium, Low

Hazard Description	Multirotor	DEP Powered Lift	Powered Lift	Fixed Wing
Battery Thermal Runaway	High	High	High	High
Battery Energy Uncertainty	High	High	Medium	Medium
Common Mode Power Failure (Low-/High-Altitude)	High/High	High/Medium	Medium/Medium	Medium/ Medium
Fly-By-Wire System Failure	High	High*	Low**	Low
High-Level Autonomy Failure	High	High	High	High
Bird Strike	Medium	Medium	Medium	Medium

*Including Tilt-Lift vehicles **Except Tilt-Lift vehicles

Figure 29 – Key hazards for each electric aircraft configuration group, with a baseline risk severity assessment for each [3].

III.7 Estimates of baseline risk severity

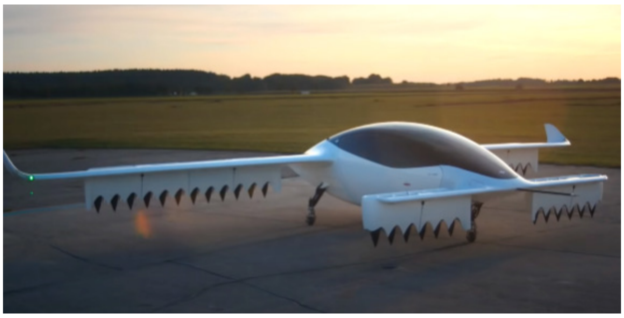
Estimates of the baseline risk severity for each of the key hazards applied to the four major vehicle design architecture groups identified in section II.1 are given in Figure 29.

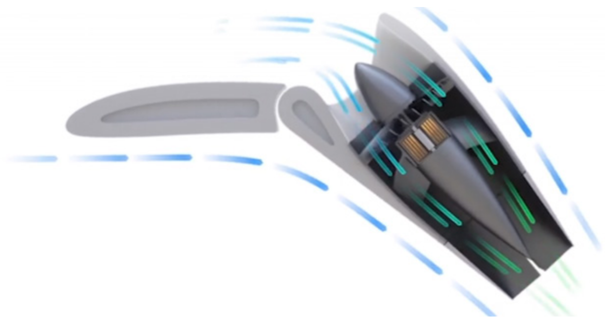
It should be reiterated that the assessment given here has focused primarily on hazards specific to electric aviation and is not intended to comprehensively encompass all possible hazards. Nevertheless it can be seen in Figure 29 that the Multirotor and DEP Powered Lift design architectures are generally considered to be at higher risk than the more conventional powered lift and Fixed Wing architectures. The main reasons for this are firstly the ability of both powered lift and Fixed Wing to descend (relatively) safely without power, either via autorotation or gliding; and secondly that both of these design architectures are inherently stable, meaning that they may be controlled by conventional means in the event of a fly-by-wire failure.

IV. New Players in the Electric Aviation Market

As of 2022 there are over 200 different electric aircraft under development worldwide. Many of the companies developing these aircraft have been in existence for less than 10 years. In this section the aircraft designs from several of these new players are presented, some of whom are expected to operate commercial services in the near future.

Figure 30 – From top: Lilium Jet with propulsors in vertical takeoff position, DEVT during transition to/from horizontal position, key specifications [51], prototype with propulsors in horizontal flight position.





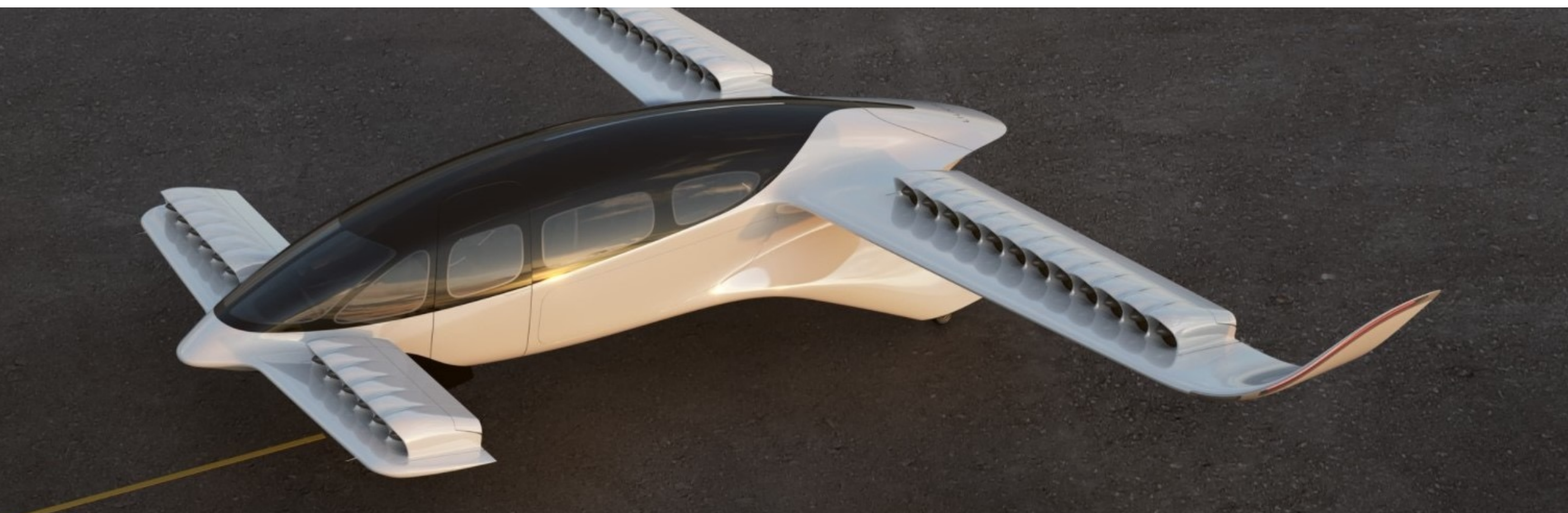
Passengers	6
Pilot	1
Wingspan	13.9 m / 45.6 ft
Length	8.5 m / 27.9 ft
Ducted fans	36
Cruise altitude	3,000 m / 10,000 ft
Cruise speed	280 km/h / 175 mph
Maximum physical range	250+ km / 155+ miles (service range + reserves)

IV.1 Air taxis

IV.1.1 Lilium

The German company Lilium was founded in 2015 and is developing the *Lilium Jet*, a DEP tilt-lift eVTOL. The production version of the aircraft will be a 7-seater (one pilot + passengers) and is planned to launch commercial operations in 2024 [51]. A unique aspect of the design is its use of Ducted Electric Vectored Thrust (DEVT) that has been refined through successive generations of technology demonstrators. A total of 36 electric propulsors are integrated into the forward and main wing flaps, thus providing advantages in payload, aerodynamic efficiency, and a low noise profile (below 60 dBA at 100 m). The DEVT provides thrust vector control to manoeuvre the jet through every phase of flight (Figure 30) and the combination of fixed wings, integrated propulsion, and no tail means the jet is highly efficient in cruise flight. Type certification is currently in progress with both EASA and the FAA.

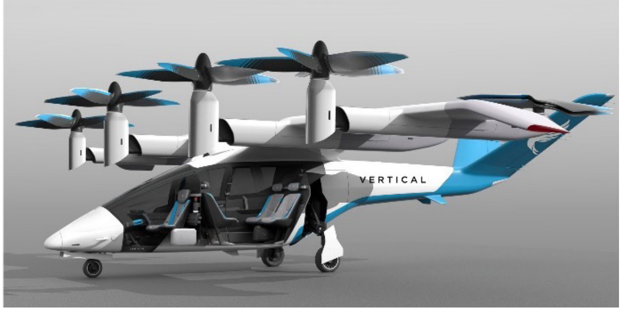
The largest domestic airline in Brazil, *Azul*, entered into negotiations with Lilium in August 2021 to sign a $1 billion commercial deal for 220 of the aircraft. Azul would expect to operate and maintain the Lilium Jet fleet, while Lilium would provide an aircraft health monitoring platform, replacement batteries and other custom spare parts. Azul also expects to support Lilium with the necessary regulatory approval processes in Brazil for certification of the Lilium Jet and any other required regulatory approvals [52]. Should the two companies come to an agreement deliveries are expected to start in 2025.



IV.1.2 Vertical Aerospace

The British company Vertical Aerospace was founded in 2016 and is developing the *VA-X4*, a DEP tilt-lift eVTOL. The aircraft will be a 5-seater (one pilot + passengers) and is targeting a first flight in 2022 and type certification with both the CAA (Civil Aviation Authority) and EASA in 2024 [53]. Notable design features include a high-aspect ratio wing with 4 tilting rotors at the front and 4 stowable rotors at the rear enabling high efficiency in all phases of flight (Figure 31); a powertrain being co-developed with Rolls Royce; Honeywell avionics; and a lightweight carbon fibre composite airframe. The company claims a perceived noise signature that is 100x quieter than a comparable helicopter both in cruise and hover.

In June 2021 the company teamed up with American Airlines, aircraft lessor Avolon, Rolls-Royce, Honeywell, and Microsoft's M12 as partners and investors. The partners and investors enable an expected path to certification in 2024, de-risk execution, and production at scale. Pre-order contracts of reportedly $4 billion have been agreed with American Airlines (up to 350 units), Virgin Atlantic (150 units), and Avolon (up to 500 units) for a total of up to 1,000 aircraft. Avolon expects to place its aircraft with other airlines and possibly new operators, and will use its network to help Vertical gain more orders. American will also help Vertical work on passenger operations and infrastructure development in the U.S., while Virgin will explore a joint venture with Vertical to develop a short-haul network in the U.K. [55].



Passengers	4
Pilot	1
Noise	100x quieter than a helicopter
Powertrain	8 propulsors (4 tilting, 4 stowable), >1 MW total power
Cruise speed	320 km/h / 200 mph
Range	160+ km / 100+ miles
Safety	EASA / CAA certification

Figure 31 – From top: VA-X4 with propulsors in horizontal flight position, birds-eye view with forward propulsors in vertical flight position, close-up of forward propulsors in vertical position, key specifications [54].

Passengers	2
Pilot	Autonomous (self-flying)
Altitude	~1500-5000 ft
Dimensions	21 feet long with a 36 foot wingspan
Vertical lift	12 independent lift fans
Range	Initially 25 miles plus reserves / 40 km plus reserves
Speed	160 km/h / 100 mph

Figure 32 – From top: Wisk Cora, birds-eye view showing the 12 lift fans for vertical flight, key specifications [57].

IV.1.3 Wisk Aero

The American company Wisk Aero, a joint venture between Boeing and the Kitty Hawk Corporation, was established in 2019 to continue the development and commercialisation of the *Cora*, a DEP 'stopped rotor' eVTOL (refer to Figure 19 for categorisation). Launched in 2017 and with its first flight a year later, the Cora has established a basis for the certification of the world's first passenger carrying, *autonomous* air taxi [56]. The aircraft is a 2-seater (both passengers) with 12 independent lift fans (6 per wing) for vertical lift and a single propeller at the rear for horizontal flight (Figure 32). From a safety perspective the aircraft is designed and built with multiple redundant systems meaning there is no single point of failure, and an aircraft parachute is provided as an additional safety measure [57].

As of 2022 the Cora is classed as an experimental aircraft and the development programme is ongoing. Wisk has not published a timeline for the anticipated type certification of the aircraft, however in March 2021 the company announced that it would be moving forward with its "Transport Trial" in the second half of the year to advance autonomous flight in New Zealand. The purpose of these flight trials is to test and demonstrate the integration of unmanned aircraft into existing airspace [58]. To date, Wisk has made around 1,500 test flights with the Cora, and a sixth version of the aircraft is expected to be announced soon.

IV.1.4 Volocopter

The German company Volocopter was founded in 2011 and is developing several electric aircraft including the *VoloDrone* (see section II.2.1), *VoloConnect* DEP Powered Lift passenger aircraft, and the *VoloCity* Multirotor air taxi. The latter will be a 2-seater (initially one pilot + passenger, future autonomous mode will allow two passengers) with 18 motors providing all flight control (Figure 33). The aircraft has been designed to be very quiet in operation, utilises a highly redundant and simple to operate fly-by-wire system, and incorporates a battery swapping system that enables short flight stops with minimum time on the ground [59]. VoloCity has already received permits to fly in manned or unmanned configurations for test flight purposes in Germany, Dubai, Helsinki, and Singapore.

Volocopter will be manufacturing the aircraft, building 'Voloports', allow passengers to request a flight through a dedicated app, and aims to run the air taxi service at competitive prices. However the company is not currently planning to sell their aircraft to consumers [60].

Volocopter is expected to launch the first commercial flights in Singapore and Paris by 2023, based on the expectation that VoloCity will receive a type certification from EASA [60]. In addition the company announced in January 2021 that it is seeking to bring air taxi services to the USA and an application has been accepted to start the process of certification with the FAA which may take two to three years. EASA is currently finalising the new Special Condition VTOL (SC-VTOL) certification to which the VoloCity aspires [62].

Passengers	1 (2 when autonomous)
Pilot	1 (until autonomous mode certified)
Battery system	Exchangeable rechargeable battery packs
Dimensions	2.5m height, 11.3m diameter including rotors
Powertrain	18 independent brushless DC electric motors
Range	35 km
Speed	110 km/h

Figure 33 – From top: VoloCity, the aircraft on takeoff, close-up showing the exchangeable battery packs at the rear, key specifications [61].

Figure 34 – Harbour Air DHC-2 'eBeaver'.

IV.2 Regional / short-haul

IV.2.1 Harbour Air

The Canadian company Harbour Air is North America's largest seaplane airline, with major hubs at Vancouver Harbour and Victoria Harbour airport. In 2019 the airline partnered up with *magniX*, a company that designs and builds electric motors for commercial aviation with the aim of ultimately converting the entire Harbour Air seaplane fleet to electric propulsion. The airline currently operates a fleet of ~40 Fixed Wing seaplanes consisting primarily of the de Havilland Canada 6-seater DHC-2 Beaver and 14-seater DHC-3-T Turbo Otter. Following their partnership with magniX, the first successful flight of an electrified DHC-2 Beaver equipped with a magni500 propulsion system (Figure 34) took place in December 2019, making it the world's first all-electric commercial aircraft [63].

As of April 2021 a new partnership between the airline, magniX, and H55 – a company producing highly efficient certified battery packs, has been announced with the intention of certifying the electric Beaver (*eBeaver*) commuter aircraft through a Supplemental Type Certificate (STC) program. The companies will collaborate together with Transport Canada to certify the installation of the magniX electric propulsion unit and the H55 enhanced battery system, transforming Harbour Air's seaplanes into an all-electric commercial fleet [64]. In addition the propulsion, battery storage, and related aircraft systems will continue to be optimised based on ongoing flight testing.

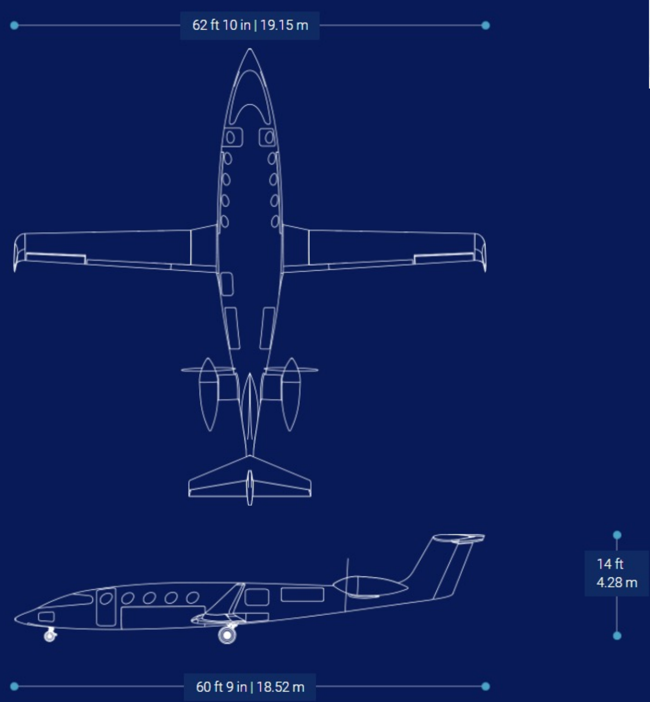
IV.2.2 Eviation

The Israeli company Eviation was founded in 2015 and is developing the *Eviation Alice*, a Fixed Wing all-electric aircraft designed for short-haul passenger and freight transportation (Figure 35). The production version of the aircraft is an 11-seater (two pilots + passengers) with its first flight planned for 2022 before certification and introduction to service in 2024 [65]. Notable features include a construction incorporating 95% composite material, two magni650 power plants (Figure 10) provided by magniX to be mounted one on each side of the aft fuselage, a range of 440 nautical miles, and power provided by a 820 kWh lithium-ion battery [66]. Full technical specifications are given in Figure 36.

Several orders have already been placed with Eviation for the aircraft including from regional airline Cape Air and international courier DHL. DHL announced in August 2021 that it had placed orders for 12 aircraft to transport air freight, and would be setting up an electric Express network to make a first step towards a sustainable aviation future [68]. These aircraft are expected to be delivered in 2024 by which point they are expected to have FAA certification.

Figure 35 – From top: Eviation Alice in flight, on ground, interior, freight version (DHL) [67].

Figure 36 – Eviation Alice technical specifications (as of April 2022) [67].



PERFORMANCE	
Typical Cruise Speed	250 kts
Max Range	440 NM
Landing Distance	2,040 ft
Take-off Distance	2,600 ft
Climb Rate	2,000 ft/min
WEIGHTS	
MTOW	16,500 lbs
Payload (Commuter)	2,500 lbs
POWER PLANT	
Model	magni650
Max Power	2 x 640 kW

IV.2.3 Heart Aerospace

The Swedish company Heart Aerospace was founded in 2018 with the goal of developing an all-electric short-haul aircraft. The company's planned 19-passenger, ES-19 (Figure 37), will have a range of 400 km (250 miles) and be able to operate from runways just 750m long. With a targeted first flight by the end of 2024 and certification by summer 2026, Heart is developing its design while progressing steadily through testing and certification.

The Fixed Wing aircraft features a modular electric propulsion system consisting of four nacelles (two on each wing), an aerodynamically optimised design, and a lightweight aluminium frame. In terms of safety and redundancy, each of the four nacelles is a completely self-isolated unit containing an electric motor, batteries, and power electronics [69]. The battery system is being developed by British company *Electroflight* and will make use of their significant expertise gained from several aerospace electrification programs [70].

The aircraft will be certified to existing EASA CS-23 certification standards, the same as used by all conventional aircraft [71]. These standards have recently been rewritten to allow the commercial aviation industry to introduce new technology that would have been more difficult under past regulations. EASA Special Condition (SC) E-19 (see section VI.1) will apply to the certification of the ES-19 propulsion system.

From an economics perspective, the ES-19 is expected to have a similar acquisition price to competing fossil fuel powered aircraft, while offering direct operating costs (i.e. energy and maintenance) that are 50-70% lower [71]. As the result of a successful funding round in July 2021, Heart Aerospace announced that both United Airlines and Mesa Airlines had placed purchase orders for a total of 200 aircraft with options for an additional 100 [72].

Passengers	19
Pilot	2
Battery system	*Electroflight* lithium-ion battery packs with integrated BMS (Battery Management System)
Powertrain	4 self-isolated nacelles each with a 400 kW motor
Range	400 km / 250 miles

Figure 37 – From top: ES-19 in flight, interior, key specifications, ES-19 in the hanger.

IV.2.4 Wright Electric

The American company Wright Electric was founded in 2016 and is developing the *Wright 1*, currently the only single-aisle, zero-emissions aircraft being designed for airlines that fly short to medium routes of 800 miles or less [73]. Utilising a distributed motor design architecture and designed for up to 186 passengers, the Wright 1 is targeting an entry to service in 2030. The company is currently focusing its efforts on developing a 2 MW electric motor, high frequency inverter, and full propulsion system that incorporates the motor, inverter, and thermal management system [74]. This system is aiming to be 75% lower weight and 50% smaller in size than equivalent products today, and will be compatible with any energy source, from batteries to fuel cells to hybrid-electric systems.

The company has partnerships with various organisations including the airline EasyJet, NASA, the U.S. Department of Energy, and BAE Systems. A 10-year development vision for the aircraft sees completion of ground and flight tests of the motor by 2023, achieving flight certification by 2027, and finally entry to service by 2030.

Passengers	186
Energy storage	Battery, fuel cell, or hybrid-electric
Powertrain	Distributed megawatt-class motors
Range	800 miles
Other features	High aspect ratio wings, 20% quieter and 20% lower fuel costs than conventional short-haul airliners

Figure 38 – Wright 1 and its key specifications [73].

As of 2022 there are over 200 different electric aircraft under development worldwide. Many of the companies developing these aircraft have been in existence for less than 10 years.

V. Established Aerospace Organisations

In addition to the plethora of new players in the electric aviation market, established companies and aerospace organisations are also developing electric aircraft. In this section a few examples of these are presented.

V.1 Airbus

Airbus has been engaged in the development of electric aviation since it first participated in a project to electrify the *CriCri* ultralight aircraft in 2010. Since then the company has made significant progress through various projects including (Figure 39):

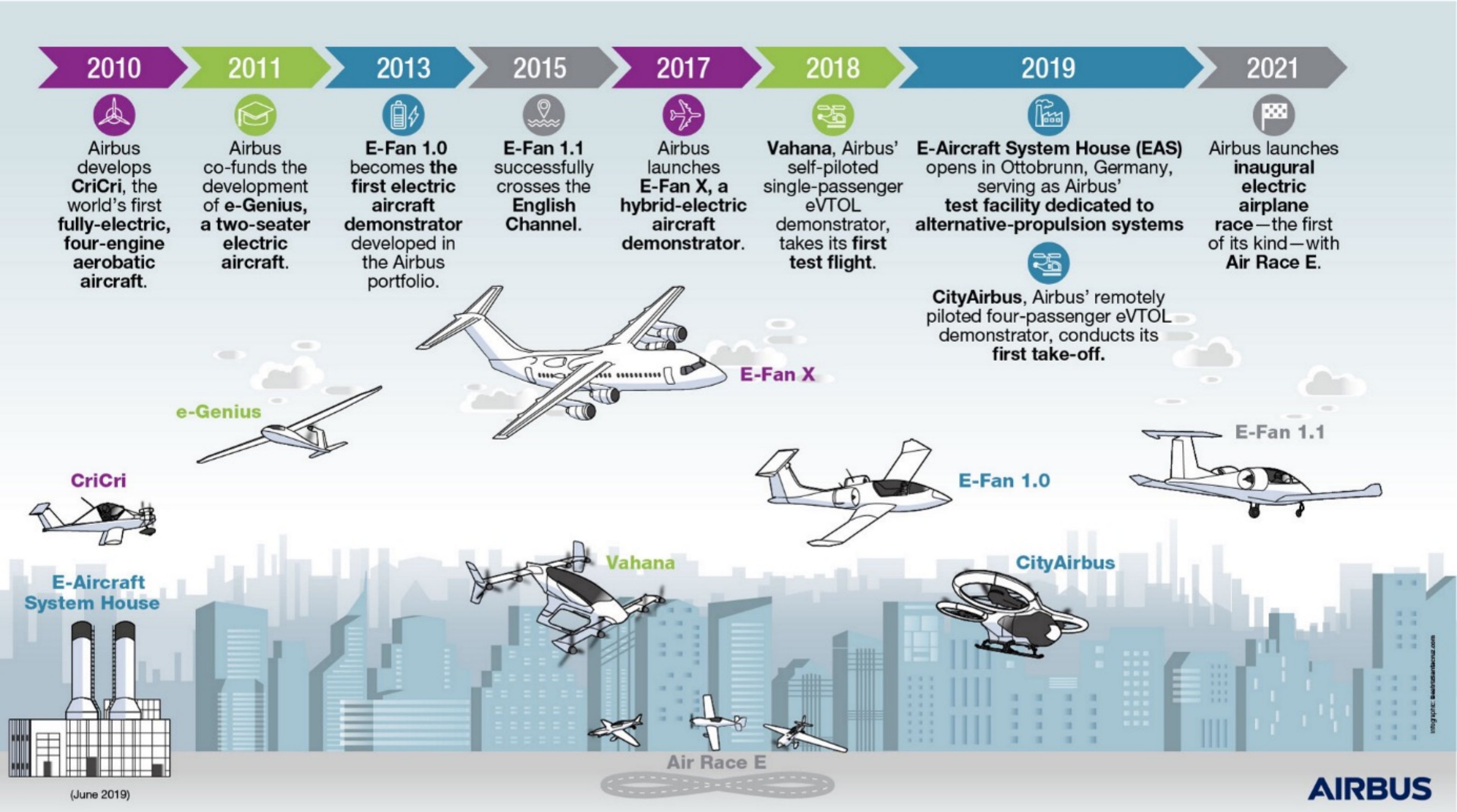
- *E-fan*, an all-electric twin-propeller aircraft that successfully crossed the English Channel in 2015;
- *E-Fan X*, a hybrid-electric demonstrator project that was launched in 2017 and has provided invaluable insights on serial hybrid-electric propulsion (see section I.5);
- *Vahana*, an autonomous, single passenger eVTOL demonstrator that flew test flights through 2018-19;
- *CityAirbus*, an autonomous all-electric four-seat multicopter eVTOL demonstrator that conducted its first take-off in 2019.

Current ongoing activities include development of the *EcoPulse* distributed hybrid-propulsion demonstrator and backing of the electric aircraft race series *Air Race E*.

EcoPulse is being developed in partnership with several other aerospace organisations and focuses on evaluating the benefits of distributed propulsion and its possible integration on future aircraft. Based on a modified Daher TBM turboprop aircraft, the standard engine and propeller systems are augmented by six wing-mounted propellers, each of which is driven by 50-kW ENGINeUS™ electric motors powered by batteries or an auxiliary power unit [76]. Airbus is contributing several aspects to the project including development of a high-energy-density battery, aerodynamic and acoustic integration of the distributed propulsion system, and development of a flight control computer system. As of June 2021 wind tunnel testing of the distributed propulsion system has been completed and the consortium are working towards the start of production, ahead of ground testing and a first test flight in 2022 [77].

Air Race E will become the world's first all-electric airplane race when it launches its inaugural series of international races in 2022 (postponed from 2021 due to the Covid-19 pandemic). The competition aims to drive the development and adoption of cleaner, faster and more technologically advanced electric engines that can be applied to UAM vehicles and, eventually, commercial aircraft [78]. Airbus's primary role will be to work with both Air Race E and other Air Race E partners to help shape the exact format and technical regulations for the inaugural season.

Figure 39 – Timeline of Airbus achievements in electric propulsion [75].



V.2 Rolls-Royce

Rolls-Royce (RR) has an electric propulsion portfolio stretching from electric motors and generators to power electronics, control systems and battery systems. The company acquired the Siemens electric propulsion branch (Siemens eAircraft) in 2019 and is engaged in a number of high-profile projects spanning several aircraft categories:

- Light sport and training aircraft – these small aircraft are currently used as either technology demonstrators or 'flying testbeds' to test RR electric propulsion systems, and are essential for bringing the experience of electric flight to the pilots of today and tomorrow.
  - *ACCEL "Spirit of Innovation"* – a project in collaboration with the British companies YASA and Electroflight to build the world's fastest all-electric aircraft (see Figure 40). Designed to reach a speed of over 300 mph, the project's overarching mission is to develop the requisite technology and supply chain knowledge to spur development of future aircraft concepts, and establish the UK as a global leader in electric aviation. The aircraft completed its maiden flight in September 2021 and set a new all-electric world speed record of 345 mph in November the same year.
  - *Magnus eFusion* – a 2-seat training aircraft serving as a flying testbed for the sub-100 kW electric propulsion systems developed by Rolls-Royce Hungary. The aircraft had its maiden flight in 2016 and subsequent test flights resulted in the RRP70D motor and inverter being the first electric power unit in the RR Electrical portfolio registered for certification [79].
  - *Extra 330LE* – a 2-seat aerobatic aircraft serving as a flying testbed for motors in the class of 0.25 to 0.5 MW.

Figure 40 – The ACCEL "Spirit of Innovation" [79].

- Air taxis
  - *Vertical Aerospace VA-X4* (see section IV.1.2) – RR will design the system architecture of the whole electrical propulsion system, the electric power system that includes the latest 100kW-class lift and push electrical propulsion units, the power distribution and the monitoring system that will support operations [80].
  - *CityAirbus* – RR developed the RRP200D electric motor to meet the challenge of very high torque at low rotational speed for this Airbus demonstrator.
- Commuter aircraft – RR are developing electric powertrains in the power class of half a megawatt that will help hybrid- and all-electric commuter aircraft operate commercially in the second half of this decade.
  - *P-Volt* – RR are working with aircraft manufacturer *Tecnam* and Scandinavia's largest regional airline *Widerøe* to deliver an all-electric passenger aircraft for the commuter market that will be operational by 2026 [81].
- Hybrid aircraft – RR are embracing the challenge of hybrid-electric propulsion in regional aircraft and the future of commercial flight through the development of up to MW-class power and propulsion systems.
  - *E-Fan X* – RR participated alongside Airbus in the hybrid-electric demonstrator project (section I.5). The project has been mutually concluded and will not fly as originally planned but ground testing of the RR system will continue.
  - *APUS i-5* – a project to demonstrate the practical application of hybrid electric technology for a 4000 kg conventional take-off and landing flight test vehicle. The aircraft will integrate a M250 gas turbine engine (over 33,000 examples of which have been delivered to the helicopter and fixed-wing markets) with a high energy density battery system, electric generators, power converters and an advanced power management and control system [25].

V.3 NASA

NASA Aeronautics has committed resources to electric aviation in a bid to develop aircraft propulsion technologies that could benefit the environment, aircraft efficiency, and the flying public. NASA's Glenn Research Center is conducting research into Electrified Aircraft Propulsion (EAP), primarily focused on hybrid and turboelectric systems that could operate on large commercial aircraft [82], and hosts the NASA Electric Aircraft Testbed (NEAT, see Figure 41). Meanwhile, work at NASA's Armstrong Flight Research Center is focused on the development of advanced experimental aircraft ('X-planes') and one project, the *X-57 Maxwell*, aims to be the first manned X-plane to feature a distributed electric propulsion system (DEP).

NEAT is a reconfigurable testbed used to design, develop, assemble, and test electric aircraft power systems, from a small one or two person aircraft up to 20 MW airliners [83]. Designed to enable end-to-end development and testing of full-scale electric aircraft powertrains, the facility is available to industry, academia, and government to further mature electric aircraft technologies.

The X-57 Maxwell is an experimental aircraft being developed to demonstrate technology to reduce fuel use, emission, and noise. The project involves replacing the wings on a twin-engined Tecnam P2006T (a conventional four-seater light aircraft) with DEP wings that are 42% of the original size to reduce drag [84]. Twelve small electric motors along the wing's leading edge will be used to nearly double lift during takeoff and landing, while two larger electric motors on the wingtips will be used during cruise (see Figure 42). When not in use the twelve smaller propellers fold back to avoid additional drag. As of August 2021 the aircraft has completed high-voltage functional ground testing and will now undergo verification and validation testing before taxi tests begin [85].

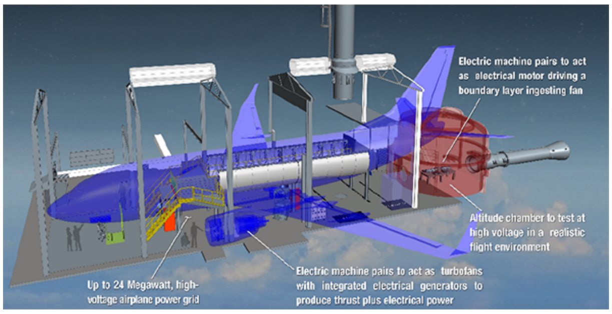


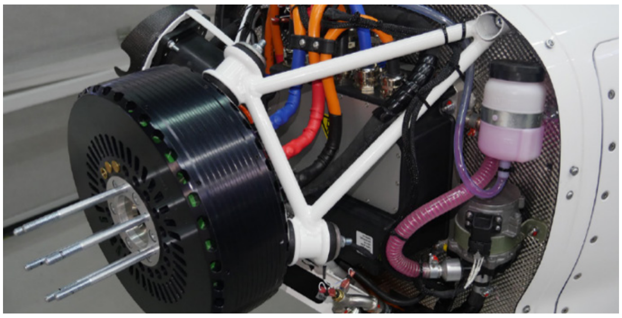
Figure 41 – NEAT configured to test a lightly distributed turboelectric aircraft [83].

Figure 42 – The NASA X-57 Maxwell [84].

V.4 Pipistrel

The Slovenian company Pipistrel has been designing and manufacturing light aircraft since 1989, and has produced over 2000 aircraft. The company manufactures several light electric aircraft, its own electric propulsion system, battery packs and BMS (Battery Management System), and battery charging infrastructure.

The *Velis Electro* is the first and as of 2022 still the only type-certified electric aircraft in the world [86]. The two-seater aircraft is intended primarily for pilot training and was EASA type certified in June 2020 (see section VI.1), giving it full approval for pilot training as well as other commercial operations. Velis Electro is considerably quieter than other aircraft, produces zero emissions, features reduced maintenance costs, and the risk of malfunction is minimised thanks to a built-in continuous health-monitoring system. The powertrain incorporates a liquid-cooled Pipistrel *E-811* propulsion system and two Pipistrel *PB345V124E-L* batteries with a total nominal capacity of 24.8 kWh. The batteries are installed in a redundant 2-unit arrangement with one battery pack located in the nose and the second behind the cabin (Figure 43). In the event of a battery failure, the malfunctioning battery would get automatically disconnected from the system. A single battery is capable of standalone operations and has enough power to support climbing and continuation of flight [86]. As part of the certification process the powertrain has demonstrated the ability to withstand faults, battery thermal runaway events, and crash loads.



Seats	2
Propulsion	Pipistrel E-811 EASA Type-Certified, 49.2 kW (continuous power) liquid-cooled axial flux motor
Battery system	2x PB345V124E-L liquid-cooled Li-Ion (NMC), 345 VDC, total 24.8 kWh
Payload	172 kg
Service ceiling	3,660 m (12,000 ft)
Endurance	Up to 50 minutes (plus VFR reserve)
Wingspan	10.71 m

Figure 43 – From top: Pipistrel Velis Electro in flight, E-811 motor and power controller installed on the airframe, redundant 2-unit battery arrangement (one in the nose, one behind cabin), key specifications [86].

The E-811 propulsion system consists of a liquid-cooled electric motor and power controller and is the first electric propulsion system certified by EASA for use on GA aircraft. The system may also be installed on Part-23 Level 1 aircraft and other distributed propulsion applications by applying the corresponding special conditions (see section VI.1) [87]. The motor is an axial flux (refer to Figure 8) synchronous permanent magnet electric motor that allows the propeller to be mounted directly on the rotor. The associated controller converts direct current (DC) from the batteries to alternating current (AC) for the motor.

The PB345V124E-L battery pack is liquid-cooled and has been designed for powering electric vehicles. The pack is constructed of cylindrical Li-Ion cells that use a NMC (Nickel Manganese Cobalt) chemistry. From a safety perspective the battery is equipped with a venting channel and exhaust to controllably release gasses in the event of a thermal runaway. Safety features of the BMS include cell over-voltage and under-voltage protection, and over temperature protection. The BMS also calculates SOC (State of Charge) and SOH (State of Health) of the battery pack [88].

VI. Regulatory Environment and Electric Aviation Certification

Aviation is one of the world's most stringently regulated industries, and as a result it has developed an unprecedented level of safety over more than a century. Regulations enforced by air-worthiness authorities control standards for vehicle design, production, pilot licensing, and maintenance and operating requirements [26]. In order for many of the electric aviation developments discussed in this paper to succeed they will need to satisfy this complex regulatory environment while at the same time delivering revolutionary aircraft advancements. Innovative technologies and components in electric aircraft will pose challenges to the existing certification standards in place for conventional aircraft. Therefore, the adaption or even creation of new regulations by authorities such as EASA and the FAA is necessary to enable these new aircraft to take flight.

The FAA and EASA function as regulators for the majority of the world's aviation activity. This means electric aviation developers will ultimately need to secure their approval to achieve mass-scale adoption. Cooperation between the FAA and EASA has resulted in reciprocal arrangements so an aircraft approved in one jurisdiction can be flown in another e.g. the *Bilateral Aviation Safety Agreement* (BASA). Pilot training and commercial operator certification varies by country, but the requirements are similar [26].

In many respects the certification process for electric aircraft will not be very different to that for conventional aircraft. It will use the same approach and demand supporting data that is equivalent to that currently used. The main challenges lie in the ability to design the aircraft to meet the regulations and the ability to show compliance. This may involve the creation of new verification test procedures / regimes, e.g. how to verify battery health, temperature management & crash safety; how to ensure high voltage cabling is appropriately protected and packaged, etc. These technical challenges do not have a direct parallel in present commercial aviation, however there may be partial parallels within the wider aviation system that can be drawn upon [89].

On the other hand, new certification pathways are also being developed, commonly referred to as *industry consensus standards*, whereby the commercial aviation industry is allowed to introduce new technology that would have been more difficult under past regulations [71]. This approach offers the potential to radically accelerate the development of new standards because the community takes responsibility for developing the certification basis and then presents it for adoption by the regulator [26].

In this section an overview is given of the current regulatory environment and electric aviation certification. A separate subsection is devoted to UAM given the unique challenges that certification of this new operating environment will bring.

VI.1 EASA

The European Union Aviation Safety Agency (EASA) is one of the world's two leading regulatory authorities in aviation. It carries out certification, regulation and standardisation, and also performs investigation and monitoring. It collects and analyses safety data, drafts and advises on safety legislation and co-ordinates with similar organisations in other parts of the world.

Steps have been made by EASA to adapt their regulations for small General Aviation (GA) aircraft, paving the way for easier certification of electric aircraft. For example the CS-23 rules (Certification Specifications for Normal, Utility, Aerobatic, and Commuter Aeroplanes) have been revamped and specific technical design requirements have been replaced with safety-focused objectives [7].

EASA provided the world's first type certification to a fully electric aircraft, the *Pipistrel Velis Electro* (section V.4), in June 2020 marking an important milestone in the development of electric aviation. The certification, completed in less than three years, was only possible in that time-frame due to close cooperation between the aircraft manufacturer and EASA [90]. During the course of the certification process EASA gained first-hand experience in electric flight, and learnt about batteries, their management systems, and electrical engine power units.

Following this first certification of an electric aircraft, EASA published in 2021 the 'Special Condition' for Electric / Hybrid Propulsion Systems (EHPS), *SC E-19* (see [91]). This document provides the certification requirements for an EHPS in CS-23 aircraft. Notably, SC E-19 is only applicable when the intended aircraft application is identified. An EHPS for which no intended aircraft application has been identified is outside of the scope of this Special Condition.

VI.2 FAA

The Federal Aviation Administration (FAA) is the second leading regulatory authority in aviation alongside EASA. Its major functions include regulating civil aviation in the United States, encouraging and developing new aviation technology, issuing pilot licenses, operating a system of air traffic control, regulating airport design and flight inspections, and regulating U.S. commercial space transportation.

In a similar manner to EASA, the FAA has made steps to adapt their existing regulations for GA aircraft to the specifics of electric aviation. For example the Federal Aviation Regulations (FAR) Part 23 (Airworthiness Standards for Normal, Utility, Acrobatic, and Commuter Category Airplanes) has been rewritten with more flexible performance-based standards (i.e. *industry consensus standards*) [7]. Part 23 certifies aircraft for commercial use up to a maximum size of 19,000lbs or 19 passengers. Following the rewrite, certification is now allowed under any set of standards acceptable to the FAA. One such set of standards is ASTM F3264 (Standard Specification for Normal Category Aeroplanes Certification), which has been accepted by the FAA as a means of compliance with Part 23 [3]. In recent years ASTM F3264 has been updated to allow the certification of electric aircraft, and other relevant standards such as ASTM F3239 (Specification for Aircraft Electric Propulsion Systems) and ASTM F3316 (Specification for Electrical Systems for Aircraft with Electric or Hybrid-Electric Propulsion) have been published.

In 2018, the FAA publicly approved testing for the eVTOL *Workhorse Surefly* by providing an Experimental Airworthiness Certificate. This form of limited certification has also been applied to fixed-wing aircraft such as the Pipistrel *Alpha Electro* [92]. It is believed that from 2021 onwards electric aircraft capable of wing-borne flight during any phase of the mission will be FAA certifiable under the new Part 23 [3], with Special Conditions *in addition* to Part 23 being used to define the certification basis for eVTOL aircraft [93]. This certification basis will then be formalised under an FAA Issue Paper (IP) G-1.

In addition to regulations such as Part 23, the FAA also publishes 'Advisory Circulars' (AC) that provide guidance for compliance with airworthiness regulations. One such example is AC 20-184 'Guidance on Testing and Installation of Rechargeable Li Battery systems on aircraft'. This provides manufacturers and installers with an acceptable means of compliance to meet the installation, operation, maintenance and airworthiness requirements for installation of lithium batteries on aircraft, including those covered by Part 23.

AC 20-184 is currently being revised to invoke *RTCA D0-311A* – the current industry standard and accepted means of compliance for certifying liquid electrolyte lithium-ion batteries. The test involves forcing 2 adjacent cells into thermal runaway, and showing it does not lead to a chain reaction thermal runaway, no release of fragments outside the battery system and no escape of gases outside the battery system except through designated venting [71].

VI.3 SAE International

An organisation currently very active in the development of electric aircraft standards is SAE International. As an international global standards organisation, SAE are active in the aerospace, automotive, and commercial vehicle industries; with one of their core competencies being voluntary industry consensus standards development [94].

To facilitate the development of new commercial electric aircraft, SAE International created the Electric Aircraft Steering Group (EASG) in 2015. The group meets online every month and twice a year face to face and includes representatives from major aerospace companies and organisations, including Airbus, Boeing, Bombardier, Embraer, EASA, FAA, GE, Honeywell, Lockheed Martin and Rolls-Royce. The aim of the Group is to: 'strategically identify, landscape and coordinate the various standardisation activities necessary to support full-electric and more electric aircraft applications at the top level system, subsystem and component levels' [95].

As of 2017 the EASG was working on defining the 'standardisation landscape' needed to support the power and infrastructure 'backbone' for electric aircraft and system functions, to develop a matrix of existing or in-progress standards which will highlight where work is still needed and to liaise with existing standard developing committees. The EASG considers such subjects as types of vehicle, energy and power storage, hybrid/electrical propulsion, more electric engines, safety, power generation, maintenance, operations, testing, controls, power electronics and modular open architecture [95].

In addition to the EASG, the E-40 Electrified Propulsion Committee was created in 2018 with the responsibility to develop and maintain technical reports (Aerospace Standards, Aerospace Recommended Practices and Information Reports) covering electrified propulsion for aircraft. The E-40 committee provides recommendations to and collaborates with the EASG and other relevant standards committees to develop necessary standards, recommended practices and information reports [96].

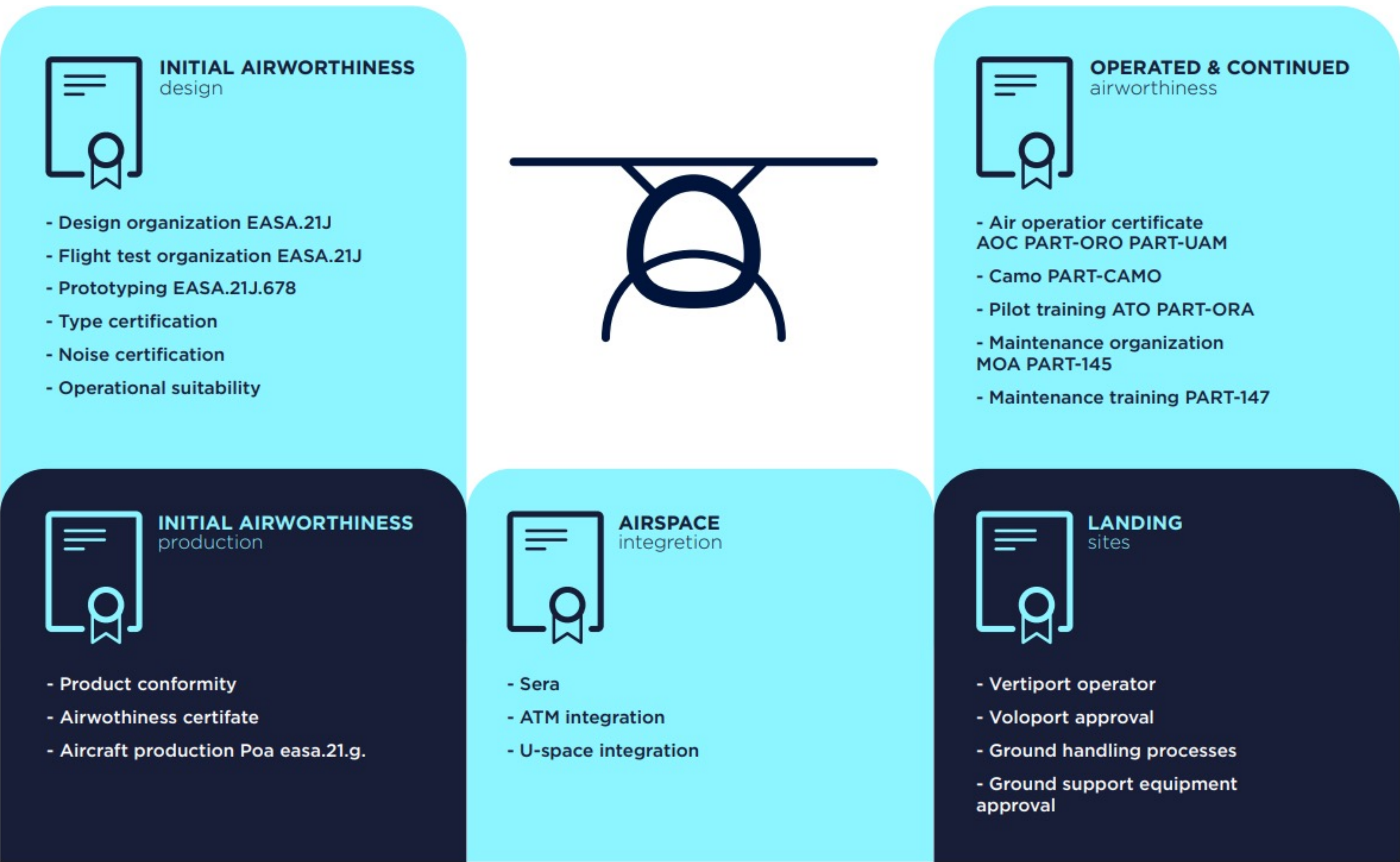
VI.4 Urban Air Mobility

In the case of UAM and eVTOLs the certification challenges are more significant than for other electric aircraft. Merely translating old regulations will not work since there is a multitude of new considerations including new types of vehicles, unprecedented ways of operation, unique environmental situations within an urban environment, and new operators [32]. The following is quoted from Paul Hutton, CEO at Cranfield Aerospace Solutions:

> *"Due to the nature of their usage (generally urban, low altitude and not via the traditional airport system), the certification of these vehicles must be done in conjunction with the development of new airspace management and infrastructure. This has already been recognised by a number of countries across the globe, including the UK. There is the potential to need to consider the entire operational environment as a whole to ensure safety rather than rely on essentially separate, certification regulations and processes for the air vehicle, the operator, the traffic management system, etc., as we do for the majority of civil aviation at present."* [89]

As such, in the case of UAM a new and comprehensive regulatory framework will be essential to guarantee the safety of people, infrastructure, and third party property. It is only once this framework is established that commercial UAM services at scale will become possible. An illustration of the holistic landscape of European certification requirements for UAM aircraft is given in Figure 44.

Figure 44 – Holistic landscape of European certification requirements for UAM aircraft [32].



EASA has already started creating a regulatory framework, building notably on the results of a 2021 study on societal acceptance (reference [36]). The following building blocks have already been achieved [97]:

- Airworthiness – EASA was the first aviation authority to publish in July 2019 a new set of airworthiness requirements for small VTOL aircraft via Special Condition *SC-VTOL-01* (see [98]). These requirements draw from existing regulations used for the certification of airplanes and Rotorcraft. They have been developed in consultation with the industry over many years to provide clarity on the standards that the new wave of small VTOL aircraft must comply with [93].
- Operations and pilot licencing – the launch in early 2019 of preparatory activities that will lead to rules for the pilots / remote pilots, their operators, and for the infrastructure.
- Airspace integration – preparation of a world-first U-Space / UTM regulatory package to become applicable by 2023, enabling the safe integration of UAM operations in urban environments.
- R&D – engagement in a large number of projects and signing a manifesto of UAM initiatives by European cities.

EASA was the first aviation authority to publish in July 2019 a new set of airworthiness requirements for small VTOL aircraft via Special Condition SC-VTOL-01.

In addition to the above mentioned *SC-VTOL-01*, EASA has also published a 'Means of Compliance' (MOC) with the Special Condition VTOL, *MOC SC-VTOL* (see [99]), which provides acceptable means for complying with these airworthiness requirements.

The FAA in consultation with NASA has developed a *Concept of Operations for Urban Air Mobility (UAM) (ConOps v1.0)* which it shared with both internal and external stakeholders in 2020. This describes the envisioned operational environment that supports the expected growth of flight operations in and around urban areas (see [100]). Mature state UAM operations are envisaged to be achieved at scale through a step-by-step approach, wherein:

1. Initial UAM operations are conducted using new vehicle types that have been certified to fly within the current regulatory and operational environment.
2. Higher tempo UAM operations are supported through regulatory evolution and UAM Corridors that leverage collaborative separation methodologies.
3. New operational rules and infrastructure facilitate highly automated traffic management enabling remotely piloted and autonomous vehicles to safely operate at increased operational tempos.

Traditionally, the end-to-end certification process (type and production) for a simple case, like a new model of conventional general aviation aircraft, takes about two to three years for a type certificate, plus another year for a new production certificate. The introduction of a new class of aircraft, however, requires a new certification basis, developed in parallel with the type certificate, and this could extend the end-to-end certification process (Figure 45) to 4 to 8 years [26]. Fortunately, in 1995 the U.S. Congress passed a law to favour industry consensus standards rather than the government's own prescriptive standards. As explained previously, this approach offers the potential to radically accelerate the development of new standards (which is required for the certification of new eVTOLs) because the community takes responsibility for developing the certification basis and then presents it for adoption by the regulator [26].

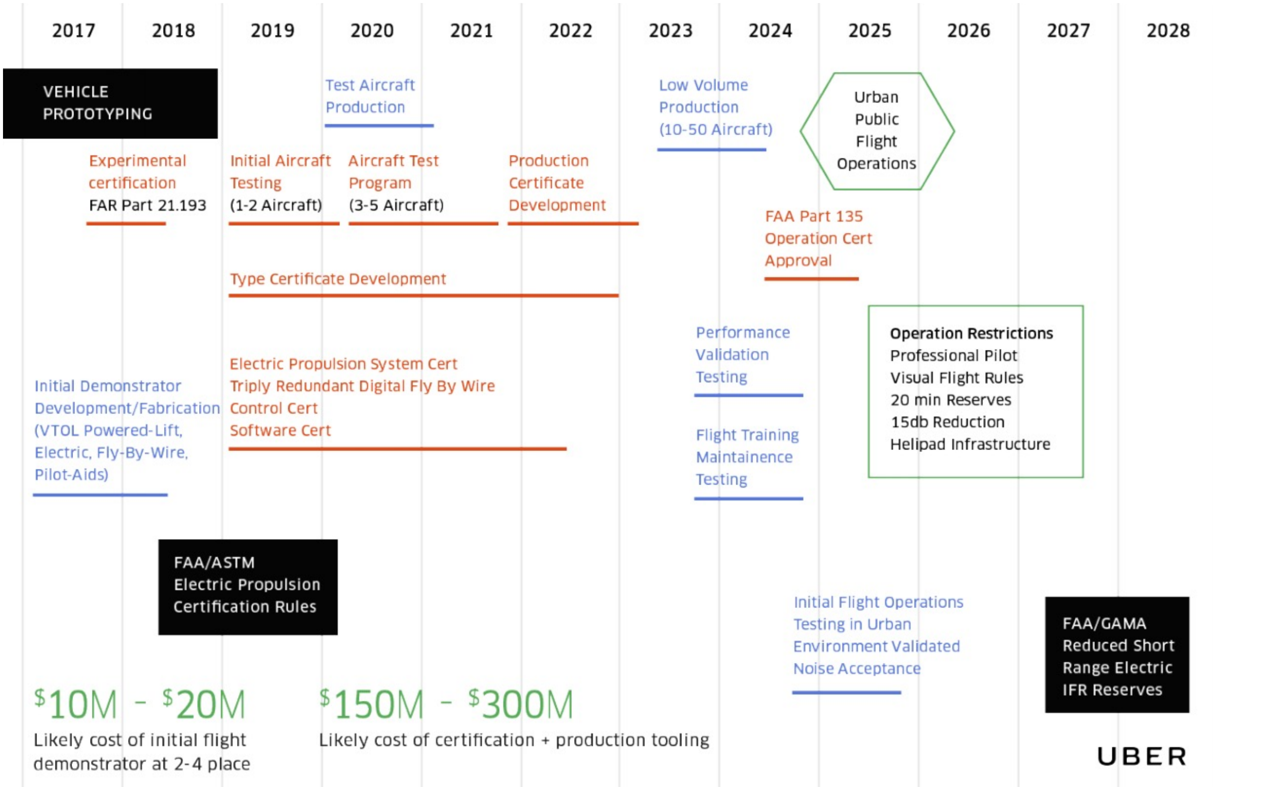


Figure 45 – Prospective certification pathway for UAM vehicles [26].

The earliest estimated certification year amongst the numerous UAM vehicles under development is 2023 for Volocopter, followed by others in 2023 including Airbus and Joby. The bulk of players (e.g. Lilium, EHang, Wisk etc.) have announced that they expect certification in 2024 or later [36]. An illustration of Lilium's path to certification for the 7-seater Lilium Jet is given in Figure 46. The most ambitious timelines are four years from the start of the design phase to planned certification e.g. Vertical Aerospace.

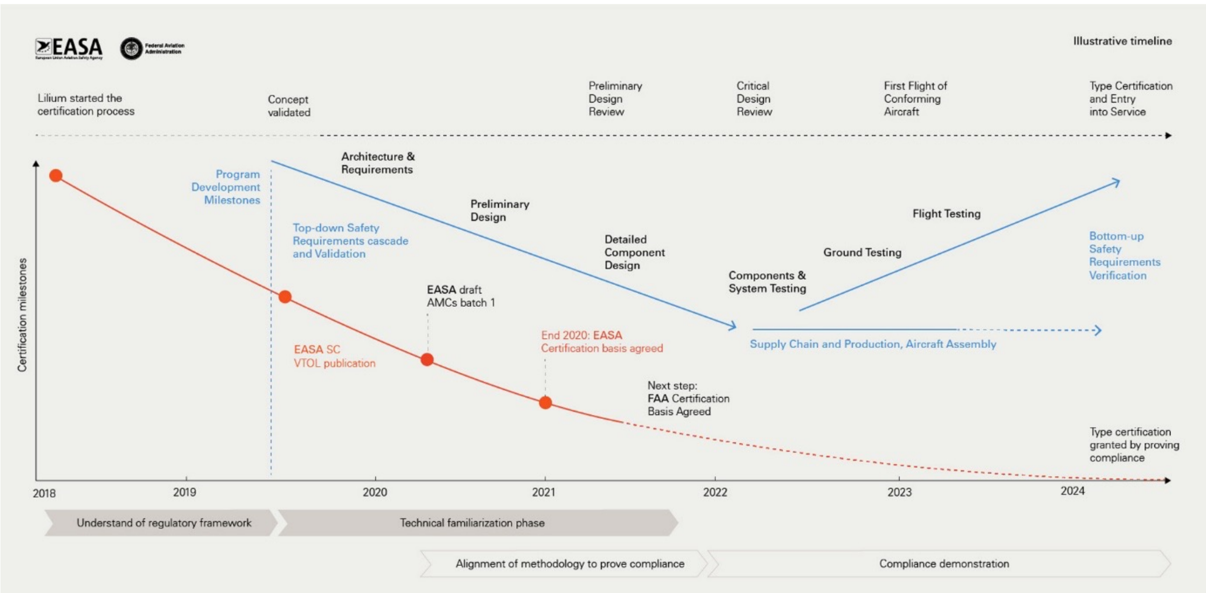


Figure 46 – Illustration of Lilium's Validation and Verification process closely aligned with publications on the development of complex aircraft and systems to satisfy EASA and the FAA means of compliance [93].

VII. Present Insurance Standpoint

As with electric aircraft certification, electric aircraft insurance in some respects may not differ greatly from that provided for conventional aircraft. For electric aircraft with conventional design architectures and conventional flight profiles (e.g. the Pipistrel Velis Electro), similar liability and hull coverage will be required as you would expect with any aircraft, albeit with some modification to account for the electric propulsion system. In this case it may simply be a matter of the cost to repair or replace an electric aircraft that dictates the premium [101]. On the other hand, UAM eVTOL aircraft may disrupt current insurance models for individuals, aircraft manufacturers, and insurance companies; requiring a new approach to underwriting and potentially even creating an entirely new submarket for aviation insurance firms.

VII.1 Coverage availability and development

Coverage specifically for electric aircraft is currently only advertised by a few niche insurers. One such insurer has established a wide range of policies covering commercial drone operation, however they have also started offering specialist cover for eVTOLs / air taxis and cargo delivery. Other insurers currently provide cover for electric aircraft via their existing General Aviation policies.

Insurance coverage for eVTOLs will be a new product with unique risk exposures that will need to be assessed by insurers.

Despite liability and insurance considerations being a frequently overlooked topic in UAM services, some developers such as Volocopter (see section IV.1.4) are taking a proactive approach. Thanks to a strategic partnership with experts in aviation insurance, Volocopter is working to ensure appropriate risk-management at all levels [32].

While none of the established insurers have yet announced they will be providing UAM coverage, it is not unreasonable to expect that work behind the scenes is currently ongoing. The rapid progress being made in the development of these aircraft and their certification suggests that there are large insurance policy contracts to be won by insurers competing for widespread commercial flying taxi operations.

It is recognised that as the prevalence of electric aircraft increases, more specifically tailored wordings and coverages may be required than the lightly adapted General Aviation policies currently used. Some insight may be obtained from looking at electric car insurance policies and how they differ compared to conventionally powered cars e.g. extra coverage for batteries and charging cables etc. One of the biggest issues foreseen is the susceptibility of batteries to theft since these may be targeted by criminals for their value. Despite the correctly held perception that electric aircraft are in their infancy, many insurers have stated that their long-term commitment to the GA market extends to supporting innovation in electric flight.

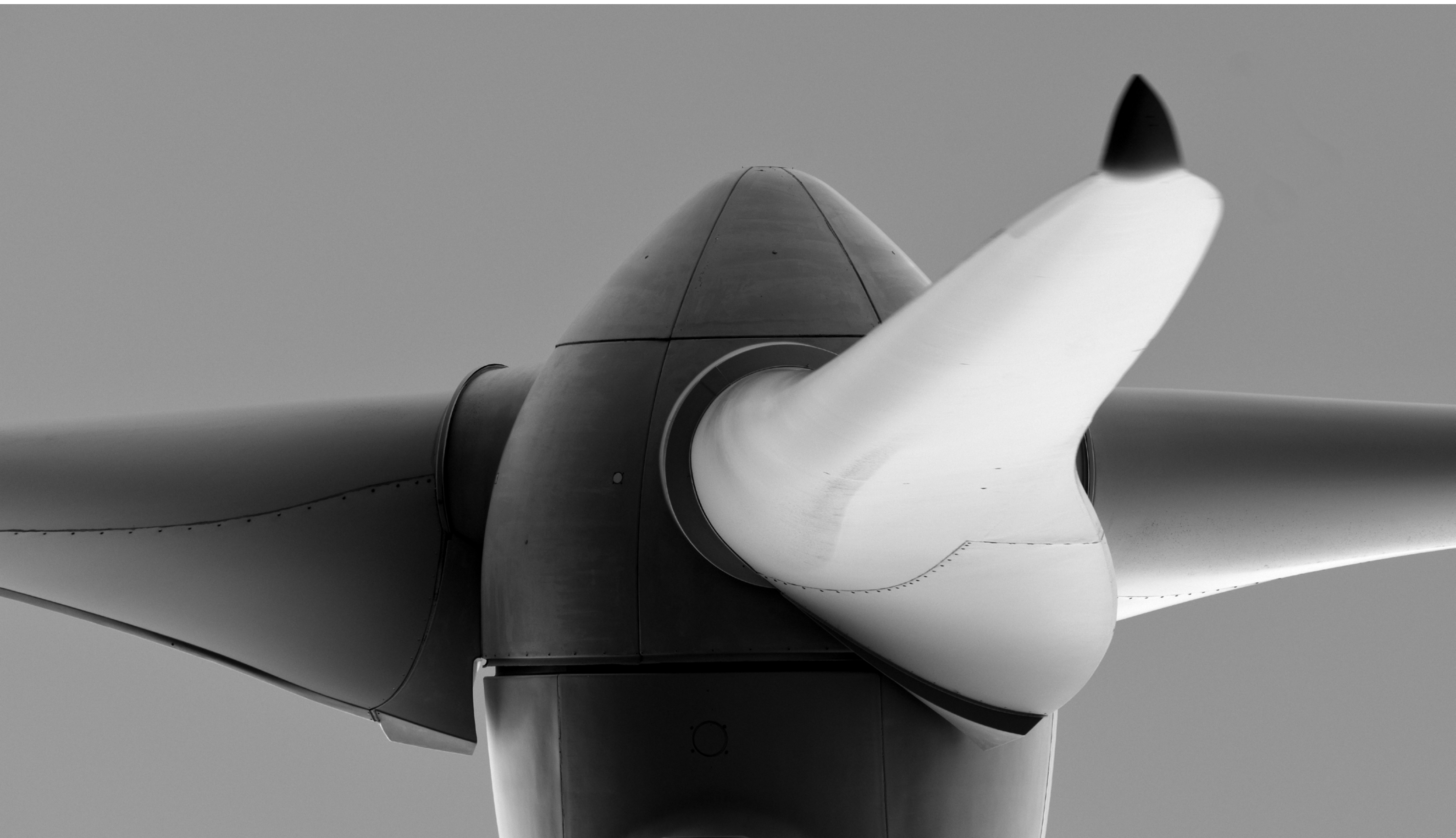
VII.2 Urban Air Mobility

The current insurance policy that most closely resembles the commercial flying taxi business structure is that of a standard commercial aircraft operator, however the format of such existing policies has remained relatively unchanged for the past 30 years [102]. The new design architecture of UAM aircraft combined with the use of electric propulsion systems, new flight profiles, and increasing levels of autonomy will likely demand significantly updated or redesigned existing policies, or even entirely new insurance solutions. Like any new product, UAM risk exposures will need to be assessed by insurers, but adequate historical data doesn't yet exist. It will therefore be important to generate sufficient data and make it available to all stakeholders. Once authorities have cleared the technology, the public may embrace it and insurers will step-up their commitment to offer solutions. Hull and physical damage coverages will be similar to aviation coverages that already exist, while liability scenarios will likely change [103].

On the subject of historical data, one electric taxi manufacturer *Horizon Aircraft* believes that most eVTOL aircraft seeking to become commercially operational will fail to secure insurance at an affordable price as they will be unable to meet the requirements of insurers, which includes providing enough data for their underwriters to assess the risks [104]. Brandon Robinson, CEO and co-founder of the company has stated:

> *"Insurance coverage for eVTOLs will be a new product with unique risk exposures that will need to be assessed by insurers. This will require huge amounts of data for them to review, covering a wide range of issues such as safety, operational cost, vehicle performance and reliability, to the level of pilot training required. Only the safest eVTOL companies with sufficient data and evidence to support their product claims in this area will be able to secure affordable insurance."*

One unique aspect of general aviation insurance is the duality of coverage – not only must an aircraft be insured in the air, it must also be insured for any possible damage to third parties and bodily injury that occurs on the ground. The risk to third parties posed by UAM must be highlighted since the aircraft will operate over densely populated areas with much greater frequency than other aircraft. As a result, aviation insurance firms that plan to provide UAM insurance policies will need to take this into account.



Conclusion

The aim of this study has been to provide an overview of the state of knowledge in April 2022 surrounding electric aviation. It is recognised that developments in this field are accelerating (refer to Figure 1) and therefore the information that has been presented here will only remain current for a short period of time.

Electrification represents the next major revolution in aviation; enabling new non-conventional aircraft design architectures, improved efficiency, decreased operation costs, and the introduction of futuristic Urban Air Mobility services. One of the major driving forces behind the development of electric aircraft is decarbonisation. While other solutions to this problem exist such as the introduction of Sustainable Aviation Fuels and liquid hydrogen, electrification is expected to play a major part across various classes of aircraft over the coming decades. Small all-electric and more-electric (i.e. hybrid) aircraft are set to become increasingly common from the mid 2020's onwards. Hybrid-electric airliners seating >50 passengers may start to be introduced from 2030, however all-electric aircraft of this size and above are not expected in the near-term due to the limitations imposed by battery specific energy density.

- In section I the key technologies both required and enabled by electric aviation were described. These include the batteries and electric motors common to all electric aircraft, plus technologies particularly relevant to UAM such as Distributed Electric Propulsion. Hybrid-electric and autonomous technologies were discussed and timelines for the development of different classes of electric aircraft were presented.
- Major electric aircraft design architectures, applications, and concepts of operation were discussed in section II. Many electric aircraft being developed today fit into one of three design architectures: Fixed Wing, DEP Powered Lift, or Multirotor. The majority of these aircraft are being designed for UAM – a new aviation segment that brings with it entirely new infrastructure demands. Specific training will be required to operate electric aircraft, and new forms of air traffic management are required for UAM.
- Section III outlined the key hazards applicable to electric aircraft. Battery technology concerns include thermal runaway and energy uncertainty. Other relevant hazards include failures of the secondary systems on which electric aircraft will depend. A baseline risk severity analysis shows that Multirotor and DEP Powered Lift design architectures are considered to be at higher risk than Fixed Wing aircraft.
- A selection of new players in the electric aviation market were presented in section IV. These include various companies developing electric UAM aircraft ('eVTOLs') intended to operate within and between urban areas, and others who are developing regional or short-haul aircraft intended to operate with larger numbers of passengers over longer distances. Several aircraft developed by these companies are expected to be commercially operational by the mid 2020's.
- In section V the development of electric aviation by established aerospace organisations was discussed. Both Airbus and Rolls Royce are engaged in multiple projects while NASA is working on maturing electric aircraft technologies for larger commercial aircraft. The company Pipistrel produces the Velis Electro, the first and as of 2022 the only type-certified electric aircraft in the world.
- An overview of the regulatory environment and electric aircraft certification was given in section VI. For electric aircraft to provide commercial services they will need to satisfy a complex regulatory environment largely dictated by EASA and the FAA, both of whom have only recently started adapting their regulations to allow the certification of electric aircraft. Industry consensus standards are widely recognised as the best way forwards, particularly given the new technology and airspace use necessary for UAM services, and the short time-frame in which a regulatory framework needs to be established.
- Finally in section VII the present insurance standpoint on electric aviation has been discussed. While some electric aircraft with conventional design architectures are already insured via existing GA policies with minor adaptions, the future UAM ecosystem will demand significantly redesigned policies, or even entirely new insurance products. A few niche products are currently available, however many established insurers will likely wait until vehicle reliability data is available.

Conclusion *continued*

In conclusion, it is clear from this study that the field of electric aviation is rapidly expanding and that a wide array of small electric passenger aircraft are expected to begin commercial operations within this decade. The largest application of these aircraft is also the most revolutionary – Urban Air Mobility is set to introduce completely new aircraft design architectures and change the way large numbers of people travel in urban areas. Several UAM services are expected to gain certification and begin operations as soon as 2024. With the introduction of these aircraft rapidly approaching it is imperative that insurers gain a clear understanding of the technology, concepts of operation, and regulations to which the aircraft will be subject.

Certain risks will need to be considered when evaluating such aircraft for insurance policies, for example the resilience of aircraft to battery thermal runaway events, the effectiveness of battery management systems in prolonging battery life, and the redundancy inherent in the aircraft design. Many aircraft in the UAM class are both of non-conventional design and under development by new companies as opposed to the established aerospace organisations. Only those companies with sufficient data and evidence to support their product claims are likely to succeed in gaining certification and thereafter secure affordable insurance.

While many insurers understandably will wait for the aircraft and regulatory environment to mature before developing insurance products, those who develop their understanding early will be in a better position particularly when it comes to addressing the new UAM market. One of the key challenges to be faced is the current lack of historical, performance and reliability data. Steps towards meeting this challenge could be taken by meeting with some of the companies discussed in this paper in order to gain greater technical insight into the systems being developed.

The field of electric aviation is rapidly expanding and a wide array of small electric passenger aircraft are expected to begin commercial operations within this decade.

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