Challenges & perspectives for future aviation e-powertrain concepts

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Introduction - Advanced Air Mobility Market

The aviation industry is facing transformative changes in the upcoming decades that are motivating multiple players to innovate & enter the Advanced Air Mobility (AAM) market. The Vertical Flight Society identifies more than 700 entrants in this new "playground". Two of the most impactful forces affecting the industry today are the push to renewable energy sources and the availability of high-power battery and powertrain technology.

AAM players strive to design sustainably powered passenger aircrafts for short range applications like inner city routes in heavily congested areas, connection of rural areas with the city center, or low distance regional flights.

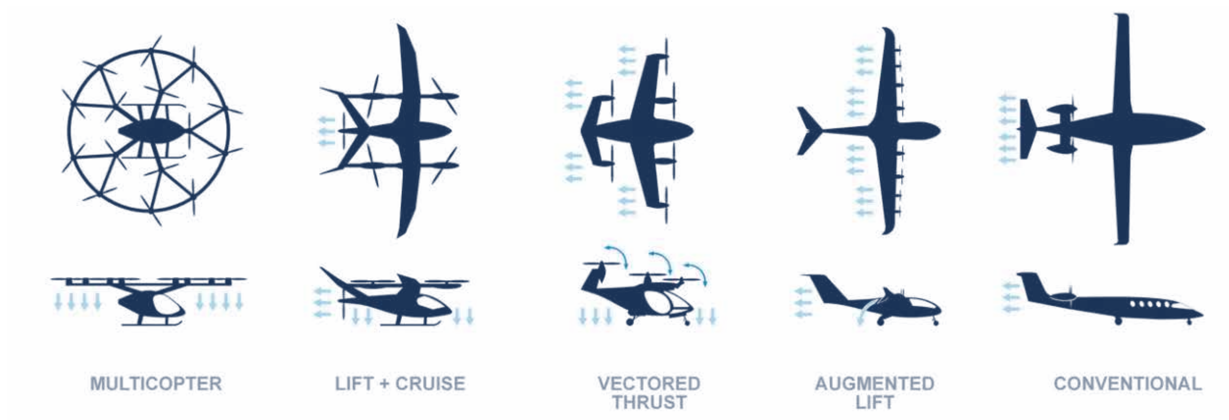

Figure 1: Basic AAM aircraft concepts (source: aamrealityindex.com)

Currently, there are five basic aircraft concepts with their own specific strengths and weaknesses. Any kind of wing improves the range of the aircraft due to generated lift, but reducing the area for thrust increases the power demand for vertical takeoff and landing.

While all current players have their own unique approach and are confident in addressing the needs of the changing landscape, the market is still wide open for any newcomers. Achieving certification from the appropriate regulatory bodies is complex and requires a lot of manpower & hours.

Given the current maturity of technology as shown by the five basic concepts, a second wave of evolution in aircraft design is bound to occur in the next few years. After certification for a new concept is achieved, the next challenge will be to create economically viable products. For that to occur, the e-powertrain is the make-or-break point for each player since it drives costs, performance and lifecycle of the aircraft.

Let's have a glance at the current state of the art aviation technology and the evolution we can expect for the next few generations.

2 /
Battery Technologies for eVTOL-Applications

On the roads all around the world, electrical vehicles are becoming the new normal. Conquering the sky is a completely different story, though.

Compared to the automotive sector, the aviation industry demands batteries with higher capabilities in terms of power density, energy density, and safety of the battery cell. As shown in Figure 2, the differences are significant. The diagram is normalized to the application-specific parameters for eVTOL applications.

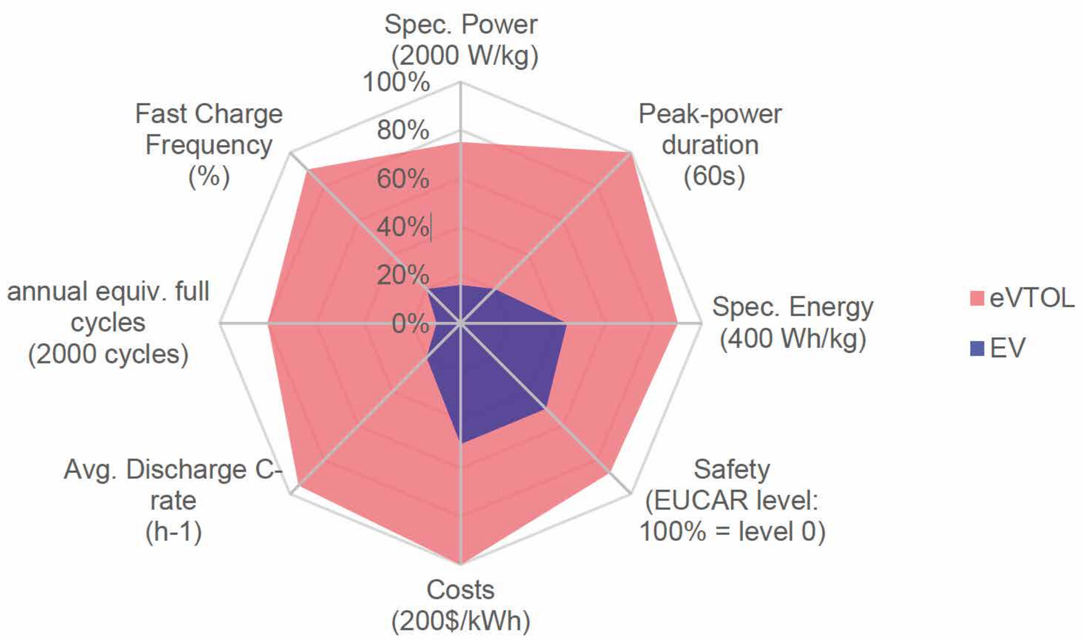

Figure 2: Battery requirements for eVTOLs versus for EVs (source: Yang et al. and P3 research)

EASA and FAA have introduced a special category for this new mode of transportation. The small category VTOL (SC-VTOL) aircraft sets the limit for failures of critical systems to 10-9. Fulfilling these high safety standards while providing high power and energy densities for critical maneuvers and long-range flying current battery technologies is the core challenge.

But as soon as costs are added to the equation, the search for more efficient technologies in the future to achieve a viable business case for scalable operations also becomes a challenge. Current research is focused on developing battery technologies with more suitable characteristics, such as solid-state, lithium-air, and lithium-sulfur batteries. Additionally, new manufacturing techniques and materials are being developed to improve the durability and longevity of aviation batteries.

2.1 / State of the art battery technologies

For eVTOL applications, the main drivers are performance, weight, and safety. Unfortunately, each variable is negatively correlated to the other two.The production of conventional lithium-ion batteries has reached a high level of industrialization. The resulting economic efficiency makes these cells interesting for high-volume products such as consumer electronics or EVs. However, the poor performance values, especially the too-low gravimetric energy density, prevent a viable mainstream application in aviation.

In the automotive industry, there is an increasing trend towards lithium-iron-phosphate (LFP) or, due to recent breakthroughs, sodium batteries. Unfortunately, these costly chemical compositions are not suitable for aviation applications, so electrified aviation will have to pioneer other types of batteries.

Batteries with high-silicon anodes have the best chance of success in the near future. This technology essentially resembles a conventional lithium-ion battery but relies on a silicon-enriched anode and cathodes with high nickel content. In combination with further optimization measures such as the reduction of inactive cell materials (separator, electrolyte, ...), these advanced lithium-ion batteries offer high energy and power densities. Disadvantages that have not yet been solved are the significantly reduced cycle stability and the high reactivity of the active materials.

From 2030, batteries with liquid electrolytes will gradually be pushed out of the market with all-solid-state batteries on the rise. In these lithium metal batteries, no liquid electrolyte is used, and the anode contains lithium in metallic form. In combination with a ceramic-based separator, very high energy densities can be achieved. The technology is still in the development stage and large-scale production is not expected before 2030.

Lithium-sulfur batteries are a technology of the future that is so far only available inside laboratories. The technology combines high energy densities and a non-flammable material (safety!). The expected market price is comparatively lower due to the inexpensive materials, however,a significant disadvantage is the low peak power, which makes the technology unsuitable as a stand-alone energy storage solution for aviation.

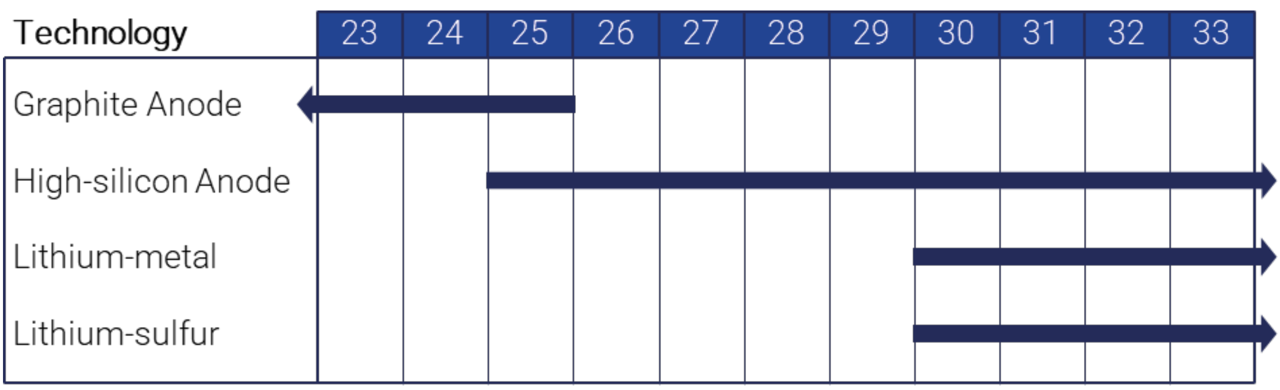

Figure 3: Battery technologies and their estimated large scale market entry (Source: P3 research)

2.2 /
Hedging technology weaknesses by optimized design: Cell to pack / Cell to x design

The future development of battery packs for aviation is largely dependent on the type of deployed battery cells. Even by 2030, battery packs will still be based on cells featuring high-silicon anodes and liquid electrolytes. These cells have a high safety risk connected with the high reactivity of the materials and can suffer from thermal runaway during flight. This means that advanced thermal management systems must dispose of the heat generated by the cells and contain propagation in case of a runaway event.

In the automotive industry, active solutions based on air or liquid cooling are standard. However, this makes the overall system bulky, heavy and expensive.

A more suitable solution for aviation is passive cooling systems, which rely on phase change materials (PCM) or heat pipes to absorb the heat generated by the cells. Both operate on the same principle: the ability of certain materials to absorb and release heat during phase change. PCMs can easily be embedded in the structure of the battery, resulting in minimal waste of space. The main disadvantage is the low heat extraction capacity, meaning that large amounts of material are required to absorb the heat. Luckily, new, highly performant materials with a heat capacity above 80 kWh/m^3 are likely going to be available in the coming years.

The introduction of solid-state cells after 2030 will reduce the need for thermal management. These batteries have solid electrolytes and have minimal risk of thermal runaway. Passive cooling materials will only be employed to maintain low cell temperatures and increase the lifetime of the cells.

The adoption of solid-state cells will also open the door to new battery architectures. An example is cell-to-body design, which can already be observed in the automotive industry. The cells are integrated into the chassis to avoid compartmentalization, which reduces the overhead weight and results in increased energy density of the overall system.

2.3 /
End of Life strategy

As soon as the battery does not meet the requirements of first life applications, there are three potential end-of-life paths. To identify the most suitable path, a testing process is required to decide whether a battery is to be remanufactured, used for another application or recycled.

Remanufacturing

For batteries in good condition (SOH >90%) the preferred way is remanufacturing. This is partly being conducted by automotive OEMs during the warranty period. In this process, the batteries are disassembled (usually to module level) and reassembled with similarly aged modules to build a remanufactured battery for further use. Higher repair depth – driven by smaller modules and easy access – could be worth investigating for the aviation industry but surely is limited by intensive thermal propagation and safety measures.

2nd-Life

If remanufacturing is not appropriate due to advanced aging (70-90% SOH) , a battery can be used for secondary applications with lower requirement profiles. These so called “2nd life” use cases may be emergency power supply or compensation of voltage peaks in electricity networks (peak shaving). Specialized 2nd life companies are currently in the early phases of the market cycle, but there are approaches for intelligent use of battery modules from different sources and varying SOH conditions in a single battery storage system. Due to lower requirement profiles of 2nd life applications and a limited willingness to pay for high performance aviation batteries compared to batteries developed for the applications, niche applications as energy trading (requiring high c-rates) are seen as viable options.

Recycling

Batteries that do not meet the requirements for remanufacturing and 2nd life (Automotive <70% SOH, limit for aviation will probably be higher) are to be recycled. Today, recycling companies charge a fee for the recycling of batteries, primarily due to the low industrialization and volume levels of the processes. Batteries are mostly recycled in a pyrometallurgical process by incinerating the batteries to achieve around 25% of the materials. In the coming years, the industry will move towards mechanical-hydrometallurgical processes, which will increase the recovery rates of battery recycling to >95%, lower the carbon footprint, and create the possibility of a closed material cycle.

There is no perfect answer yet, and aviation players will have to include end of life strategies into their battery system design right from the start. Additionally, regulations such as the implementation of recycling quotes in cell production and the requirement of a closed-loop economy for battery materials also may apply.

3 / E-Motor

3.1 / Introduction

The current approach of most of eVTOL manufacturers with many individual e-motors due to safety and other reasons is a huge challenge for a cost-efficient e-motor concept. Multiple instead of one or few e-motors typically decreases the power density of the system and on the other hand a high power density is one of the major requirements.

3.2 / Promising e-motor technologies for eVTOLs

General Overview

E-motors have been available for various applications for many years. The most used technology in industrial applications is the induction motor (IM). Since magnets are not required, this has been established as the most cost-efficient solution. But in terms of efficiency and power density, better solutions are available. The permanent magnet synchronous motor (PMSM) has been established as the leading technology where efficiency and power density are the major criteria, like in electric vehicles. On the downside, permanent magnets are expensive, and the most commonly-used neodymium magnets contain rare earth minerals that are volatile in availability and prices. Therefore, the electrically excited synchronous machine (EESM) has been established in the automotive industry with great efficiency, but slightly lower power density.

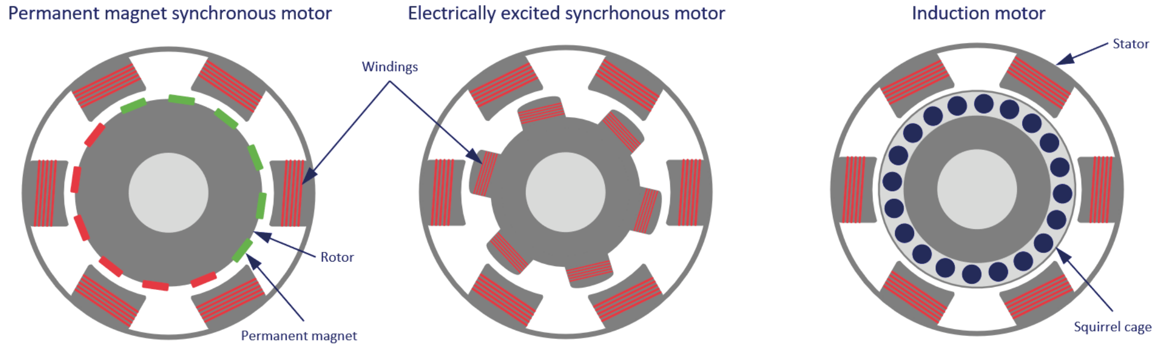

Figure 4: overview of leading e-motor types

E-Motor Types in eVTOLs

For eVTOLs, only PMSM concepts are known due to their superior power density. PMSM is likely to remain the leading technology, as the cost of lower power density is high and increases the required battery capacity and cost. Additionally, in low volume production, the relevance of the material price is lower than in high-volume production. Whereas the magnet price share of a high-volume automotive e-motor can be up to 40%, it is only half of that at production quantities of ~1,000-5,000 units/year.

As PMSM are seen as mandatory for eVTOL applications, the question is which PMSM technologies will be the best compromise between cost, efficiency, safety and power density. A closer look at the e-motor types shows the differentiation between radial and axial flux and the differentiation of quantity and arrangement of rotors and stators.

Radial vs. Axial Flux

Radial flux motors are the most common e-motor type where either the stator or the rotor is on the inside and the other part on the outside. For axial flux topologies, the rotors and stators are arranged at different axial positions.

Especially in automotive, axial flux machines gained much recognition during the past few years due to their superior power density which can potentially be more than twice as high as for radial flux machines (Source: Nishanth et. Al (2023)). However, the current axial flux market focuses on larger e-motors above 100 kW, which is less suitable for most of the current eVTOL concepts. Most of today's eVTOL concepts rely on radial flux motors as they also achieved high power densities which are not far off the maximum axial flux values.

Outer vs. Inner Rotors (Radial Flux)

The rotor of a radial flux e-motor can be positioned inside or outside. Whereas the inner rotor is most common for industrial and automotive applications, the outer rotor enables a better torque density which is important for direct drive propellers at eVTOLs as their rotational speed is relatively low. Another very rare concept is a dual-rotor configuration with an inner and outer rotor. This concept recently received recognition in the automotive industry when BMW invested into startup DeepDrive. Dual-rotor motors combine advantages of both single-rotor approaches and enable high torque and power densities, it could also become relevant for eVTOLs as well.

2 Rotors vs. 2 Stators (Axial Flux)

For axial flux machines, either a 2-rotor-1-stator or 2-stator-1-rotor configuration is typical. Both concepts are in the market and there is no clear trend towards one technology today. The advantage of the first solution is a better potential efficiency due to the yokeless stator design. However, it is challenging to design a robust stator without a yoke and thermal management is more challenging as well. (Source: Habib et. al 2022)

Today, not many axial flux motor suppliers have eVTOL applications. One of the most recognized companies, Yasa, and their eVTOL propulsion spin-off, Evolito, use the yokeless 2-rotor-1-stator design which is seen as the more promising axial flux technology in the future due to the higher efficiency.

3.3 /
Outlook

High power densities and high efficiencies are already possible today with PMSM concepts either with radial or axial flux technology. The major challenge for the future will be to develop a cost-efficient and robust series product. Especially since axial flux motors are very expensive today, major achievements in industrialization and cost-reduction are expected within the next few years. Unlike the automotive sector which currently switches from permanent magnets to magnet-free e-motors at times, eVTOLs will have to rely on permanent magnets since the performance of the substitutes does not meet the requirements.

4 /
Conclusion

Good news is that the challenges are the same for all players and that sophisticated engineering will enable viable products. Due to the specific needs of aviation applications, a “copy and paste” approach from other industries will not work. There is no plug-and-play solution as of today.
In order to get the most out of performance and efficiency for specific use cases and mission parameters, many good decisions need to be added up.

- Choose a progressive but mature technology
- Find the right partners and suppliers
- Build, test and incorporate the learnings in adequate iterations
- Carefully balance the tradeoffs of design variants
- Effectively manage your schedule, resources and processes

For this, long-term data, best practices and even failures from other industries can be valuable input. P3 is one of the leading consultancies with a strong record in the field of e-mobility and has proven to be a valued partner for these challenges. P3 provides technology and industry insights, best practices, implementation support and access to an extensive network of experts.

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Contacts

Contact us for additional details, or if you are looking for expertise, or for specific project support.

We are happy to connect!

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