Challenges Associated to High Power Hybrid Electric Propulsion in Aerospace

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ABSTRACT

With the increase of electrical power in the future aircraft, in particular for large electrified propulsion systems or high power military applications, the aerospace industry is striving to adapt and use the high power electrical systems existing in other industries. The adaptation of existing technologies to the aerospace constraints is nevertheless not an easy task due to various challenges linked to severe environments, safety and reliability constraints and the need for high performance.

This study presents some of the challenges and limitations that have been encountered in Airbus within the E-Aircraft System department, focused on developing and testing hybrid/electric propulsion systems for aircraft demonstrators.

Overall, it has been shown that, while no major showstopper has been identified to implement a large electrified propulsion system in an aircraft, the challenges that need to be overcome and the technology gaps that need to be addressed are significant in terms of constraints and as design drivers and need to be included in any future aircraft or military system development at a very early stage.

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1.0 INTRODUCTION

The level of electrification is continuously increasing in the industry and aerospace is not an exception with several research projects ranging from More Electrical Aircraft to full electric VTOLs and large electrified Propulsion Systems. The challenges of high power applications in aerospace is nevertheless more complex than in other industries such as automotive due to the severity of the aerospace environments, the stringent and necessary safety constraints and regulations and the need for high power densities, among others. Some well-known challenges are linked to Electromagnetic hazards, use of light high voltage components in pressurized and unpressurized areas or the development of safe and optimized energy storage concepts. The research currently ongoing at Airbus E-Aircraft Systems (EAS) on high power hybrid electric aero-propulsion systems is enabling those challenges to be more clearly identified and understood and therefore providing the first directions toward the solutions and future research needed to close those gaps.

By developing and testing on ground and in flight technologically advanced Electric and Hybrid Electric Propulsion Systems (EPS and HEPS respectively) of medium (hundreds of kW) to high (MW) power classes (Figure 1-1), EAS is confronted to the challenges of the integration of the demonstrators and can identify the gaps still required to successfully implementing the technologies into future commercial products.

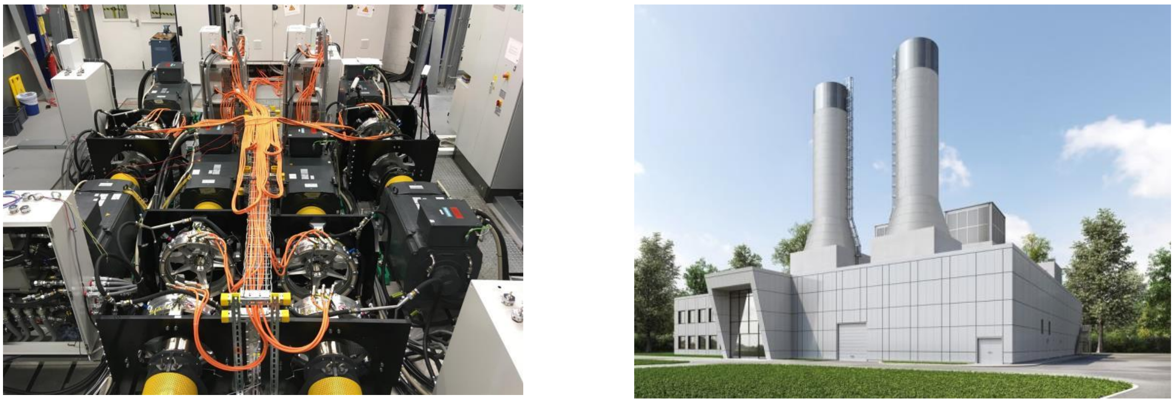

Figure 1-1 - EAS Functional Integrated Test medium and large power facilities (left and right respectively)

This testing includes both ground tests of fully integrated propulsion systems (with emulated thrust elements) and flight testing (see Figure 1-2).

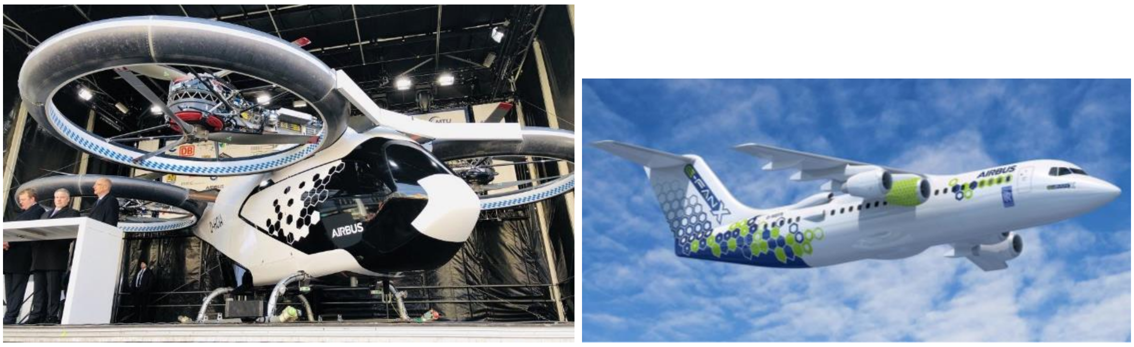

Figure 1-2 - CityAirbus (left) and E-Fan X (right) flying demonstrators

This paper focuses on some of the greatest challenges encountered by EAS within the projects as well as some of the future research that is deemed necessary to overcome them.

2.0 IDENTIFIED CHALLENGES

2.1 Performance

The first of these challenges is the performance of the new Propulsion Systems, which, regardless of the chosen architecture (serial, parallel or turboelectric), will require the increase of the power density of the components at the same time as the efficiency and reliability to successfully compete with conventional technologies. The developments of different components of the propulsive chain conducted at Airbus and its partners have successfully surpassed the state of the art benchmarks and provided a path to further develop them.

As mentioned, an enabler for a competitive electrified powertrain requires a significant improvement of the weight of the components as well as their efficiency (as single elements but more importantly when working as a whole chain from source to the consumer). The reason is evidently that both can have severe impacts on the range and/or payload via an increase of the “Zero Fuel Weight” and additional drag created by thermal management systems. This challenge is exacerbated by the fact that, generally, without changes to the topology and/or technology of the components, a reduction in weight implies a reduction in the efficiency and therefore an increase of losses.

As demonstrated by numerous aircraft studies, weight and volume of the platform have a large impact on the fuel consumption and overall efficiency and can therefore negate the benefits that electrical powertrains can theoretically provide. This effect is magnified by the integration of the powertrain into the aircraft and must be considered during the pre-concept studies as well as during the development of the project.

During the development of electrified propulsion systems in Airbus it was evident that not considering the magnitude of the accessories required to operate the electric powertrain can severely decrease the overall power density of the whole system.

Some examples of accessories that are typically not considered in the preliminary studies are the low voltage elements such as computers, sensors, power supplies and isolation elements. Other missing elements are the mounting systems, maintenance means and human safety concerns that typically require manual disconnection elements and FOD protections which are not taken into account in the figures of merit that focus on the active elements of the powertrain.

It is worth noting that these challenges, while considered in the automotive and ground transport industries, that guide today the technology, are more constraining in aerospace where weight and not volume of the systems is the critical parameter.

2.2 Safety

Undoubtedly, the aerospace industry has a focus on Safety as important as it has on Performance. Safety is ever present in the development and operation of aircraft and integrating high power electrical systems into an aircraft puts new and different risks to the platform that need to be tackled and contained,.

Most of the risks associated to the technology such as electrical arcs (Figure 2.2-1), novel energy source storage (Figure 2.2-2) or use of power electronics are not unknown to the aerospace community as they exist at a smaller scale or in other industries, but the criticality, violence and speed of the effects is greatly increased by the high voltage and high power combined with the stringent requirements and constraints of an aircraft. As a result, solutions have to be implemented, even at the expense of performance and cost to make the technology airworthy. To understand these risks and evaluate the current status and existing gaps, several solutions are being implemented in the designs to mitigate and control the risks while having a limited impact on the system performance.

It is worth noting that in the case of Medium Power applications, the levels of power are similar to the ones in the automotive industry, but the safety and platform constraints still remain and preclude in most cases a simple reuse of their hardware.

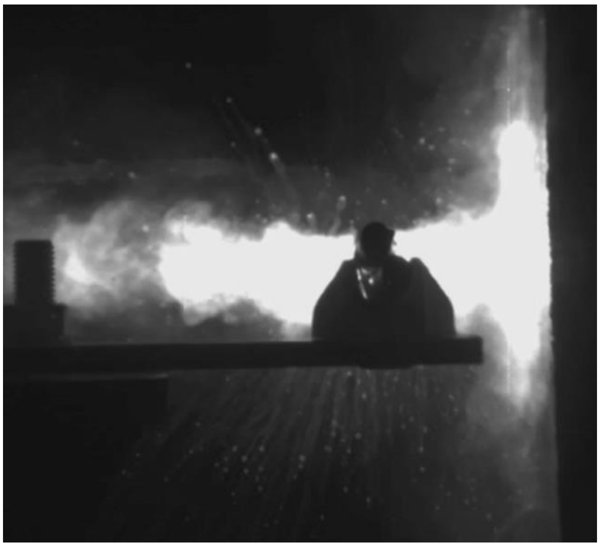

Figure 2.2-1 – 3 kV DC electrical arc impacting structure

Figure 2.2-2 – Li-ion cell

thermal runaway

2.3 High Voltage Electrical installation

The first risk that comes to mind when developing high power electrical powertrains is the electrical risks linked to the combination of high voltages and high currents in a constrained environment. The rise in power necessary for the propulsion leads to a rise in voltage to comply with the current limits intrinsic to copper or aluminium thermal integration. As a result of this voltage increase, more stringent requirements in terms of insulation are needed and the short-circuit current is increased, and thus the energy liberated (linked to the square of the voltage) is multiplied.

Many risks and issues have been identified and are being tackled within the Ground and Flight Demonstrators and technology brick projects and are already providing valuable lessons learnt for future design rules, technologies to be matured and system integration drivers. These include insulation issues and failure effects.

The most obvious insulation requirement is linked to the clearances, i.e. the shortest distance in the air between two conductive non-insulated parts. In practice, the clearance requirements drive the choice of materials for the live electrical elements, but also for the segregation distance and materials between live elements and with adjacent structures. It should be noted that these requirements are a function of the electrical characteristics of the network including during faults.

Other challenges are linked to the partial discharge effect, i.e. the degradation of wiring insulation due to internal discharges. This effect, already existing in newer generation of aircraft due to the increase of voltages in combination with the high altitudes where large transport aircraft are operated, can, if not treated properly severely affect the insulation materials of the components and therefore invalidate the insulation requirements. This needs to be taken into account as part of the life definition of electrical components and wires.

The partial discharge phenomenon can also be linked to the power electronics that need to be designed to allow operation in unpressurized conditions where the low density of the air together with the high frequency switching of the power converters may allow internal partial discharges and therefore rapid degradation of the electrical components and subsequent system failures.

These phenomena, when not treated properly can drive and increase the severity of the electrical faults which can lead to a faster degradation of the life of the electrical components to a level where failures can lead to ignition sources, structural damages, human safety hazards and other effects.

These electrical faults, namely short-circuits leading to parallel or serial arcs and large magnetic forces see their effects greatly increased. To characterize the new threats, testing has been conducted.

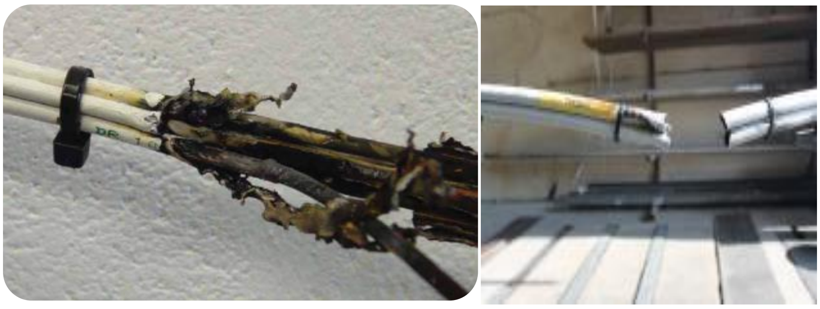

Figure 2.3-1 - Arc tracking and different power levels: 270 V (left) vs 3000 V (right)

Figure 2.3-1 shows the results of an arc tracking test at 270 V and 3000 V. It should be noted that the high voltage test was stopped after a couple of hundreds of milliseconds but still resulted in a rapid vaporization of a significant length of cabling. That vaporization and related plasma creation, in addition to damaging the electrical system, can be an ignition source for flammable gases and may also damage neighboring structures and systems.

Similarly, Figure 2.3-2 shows that the short-circuit damage can be substantial if not correctly protected. The main difference shown in the course of the tests performed for the different power levels is that the segregation distances and isolation protection trip curves need to be greatly increased and reduced respectively.

As mentioned before, the significantly higher damages in the tests are linked to the current and energy increases during the short-circuit events.

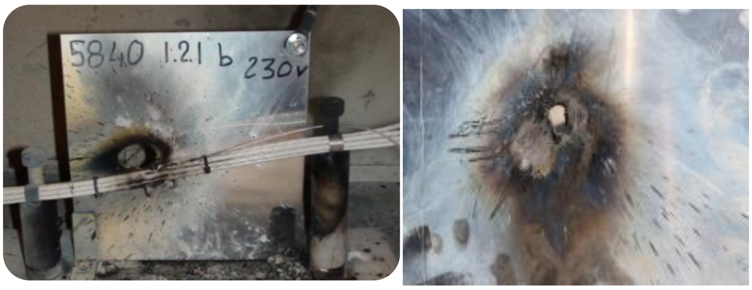

Figure 2.3-2 - Short circuit damage to structure: 230 V no tripping (left) vs 3000 V tripping in tens of milliseconds (right)

Finally, the high levels of current and voltage present during the faults in the new electrified propulsion systems, both in the medium and high power classes, also create significant magnetic forces on the cables and neighboring elements, which can further reduce the effective segregation distances and therefore potentially invalidate the design rules if not taken into consideration. In addition to these new rules, new specific requirements need to be defined for harness fixation and electrical connections (e.g. connectors or lugs), in some cases in detriment of the weight.

When developing high voltage components it has been noted that great care needs to be taken to prevent the leakage from the high voltage network into the low voltage network that enables the communication and power supply of the control elements of the system, and in an integrated system, of the aircraft. Such a leakage, when not stopped, could be a common cause leading to the loss of critical systems of the aircraft.

2.4 Energy sources

Similarly, the electrical energy storages and generation needs for electrified propulsion of small and large aircraft are orders of magnitude above what is used and known in the aerospace industry.

The search for that energy source performance leads to the use of highly energetic technologies that have different characteristics and risks.

When focusing on battery technologies, it is agreed that the current state of the art technologies that could be considered for short term electric transportation relies on the Lithium Ion battery chemistry which is well known for the possibility of thermal runaway, a rapid and uncontrolled exothermic reaction within the cell leading to fire (Figure 2.2-2). Note that this phenomenon, very present with Lithium Ion batteries is not exclusive to it, but can be present in any high power or energy density technology based on electrochemical reaction. The thermal runaway phenomenon is well known both in aerospace (e.g. Li-ion low voltage batteries used in B787 and other aircraft) and ground transportation, in particular in the automotive industry but the weight, operation and installation constraints of the larger aircraft applications requires more novel systems and protections to ensure the safety of the platform. These protections shall include, but may not be limited to, detection of events, avoidance of the propagation and mitigation of its effects by integration, reduction of the effect (e.g. inerting or extinguishing) and a correct understanding of the energy release path.

In addition, new battery chemistries and technologies developments will drive batteries to higher energy and power densities but also to potential different failure characteristics that will need to be mastered and designed to when introducing them into future designs.

Similarly, other energy sources such as alternative fuels (hydrogen, methane or other hydrocarbons) have different storage and flammability characteristics that may invalidate the typical safety measures put in place in the current kerosene-based aviation.

2.5 Human Safety & Operation

In addition to the safety risks identified in the above paragraphs, the integration of the high power electrical systems and their associated sources brings a change to the Human Safety considerations that need to be taken into account to secure the manufacturing, operation and maintenance of the aircraft.

The manipulation and safety precautions of electricity are already known and mastered in aerospace, but only in Low Voltage applications. High Voltage and near-High Voltage brings new or magnified threats to human operators and while some industrial HV regulations and precautions may be adapted, the well-known constraints of aerospace will require specific and novel procedures and tools which could ultimately impact the design of the aircraft electrical components. Examples of potential design functions to be added are interlock functions to prevent access to high voltage compartments under charge and disconnection means. It should be noted that this challenge is made more complex by a lack of harmonization of the industrial regulations between different countries, which require various levels of training and methods to the operators.

Similarly, the use of new technologies brings the risk of the existence of new dangerous materials that will require dedicated mitigation means to ensure the safety of the operators.

2.6 Electromagnetic Hazards

Electromagnetic compatibility and resistance to phenomena such as lightning strikes, High Intensity Radiative Fields (HIRF) or Electromagnetic Interference between different elements of the aircraft need to be taken into consideration in the design of the components by incorporating classical protections such as shielding, bonding points and/or filters.

However, the emissions from the Electric Propulsion System must be controlled to allow its operation within the constrained environment of an aircraft as high power, high frequency, switching leads to high energy radiations due to the high voltage changes (dV/dt).

Tests performed in the demonstrators under development and operation have proven that the conducted emissions, ground voltage fluctuation, crosstalk and broad band threats of the high power systems and rapid switching power electronics in both AC and DC lines are well above the CE standards in several frequency bands. Further tests have shown that the HV filtering and shielding does not always provide sufficient protection against the emissions caused by the capacitive and inductive coupling of the new systems and therefore need to be combined with other mitigation means such as victim cable shielding, increased segregation rules and even requalification of equipment to higher levels. This potential standard review may not be limited for the levels to be tested but also for the methods used to validate the qualification. For example, current qualification is done by sweeping from one frequency to another but our tests have shown that the broadband footprint of the hybrid electric propulsion systems is higher than the ones created by the radars or aircraft communication systems.

As a result, the incorporation of shields and filters and the creation of effective segregation and bonding rules is a complex trade with the performance requirements discussed above.

2.7 Human Machine Interface

Finally, the implementation of novel technologies such as electrification, especially when combined with higher autonomy and digitalization and their capability to open the design space of the aircraft require significant changes to the Human Machine Interfaces and to the aircraft operation and maintenance that need to be tackled to better integrate the system with the aircraft.

The Airbus demonstrators allow us to create operating concepts and interfaces with the flying and maintenance crews and better understand the constraints and needs that a future product may have.

In particular, the increasing complexity of the propulsive system and its interactions with the aircraft is growing and will likely make it more difficult for the operator to control or even monitor the system as in legacy and current aircraft. This is very evident in the Urban Air Mobility landscape with multi-rotor configurations where systems serve as thrust and flight control and their control will need to also incorporate power management and mission computation.

Similarly, the new threats require novel procedures and precautions to ensure the safety of flight and the maintainability of the aircraft airworthiness.

2.8 Integrated architectures

All of the above clearly shows that electrification, while being an enabler for future aircraft concepts creates more interdependencies between all parts of the system. In particular, failures can rapidly propagate all along the system from the propulsion element (e.g. fan) to the energy source (e.g. battery) or any other part of the system. These failures and their associated hazards, such as in the case of short-circuit, require immediate reactions that potentially cannot rely on the pilot due to extremely fast reaction time needs. Other events to be considered and designed around are sudden step load changes, due to fast protection tripping for instance, leading to overvoltage in the system.

The systems shall therefore be designed to effectively protect the aircraft from the effects of the fast dynamic faults without endangering the reliability of the systems or creating secondary hazards. Reconfiguration of the electrical network can for instance provide a redundancy benefit to the system by allowing the circumvention of a fault but can create common mode failures if not properly understood and addressed. Detailed simulations and tests are required to master and understand the transient and fault behavior of these new complex systems.

As a result, the safety cases and Common Modes created by the new elements but also by the integrated system architecture shall be reassessed and carefully studied.

This interdependency goes further than the system itself as the different aircraft systems will share increasing amounts of information with the propulsion system and the rest of the aircraft and therefore create further complexity in the failure propagation scenarios.

2.9 Certification gaps

In line with that increased interdependency, the new architectures blur the borders between CS-25, CS-E, CS-P and CS-APU for the large aircraft applications and in a similar manner for the other applications.

In addition, the new risks and architectures dealing with them, while following the intent of the rules are not always in line with some of the texts. This requires new rules and standards guiding the industry towards acceptable means of compliance to ensure the safety and airworthiness of the new technologies and concepts. The work performed on DO-311A for the battery safety is a clear example of new regulations and standards that are being developed to support this gap. Note that if new rules are not properly adapted, such as too conservative or stringent, they can impair the system feasibility and performance.

2.10 Qualification for flight envelope

As mentioned several times, the use of high voltage, highly energetic electrical components for transportation is not novel, but it does provide new challenges when combined it with the very stringent and extreme environment faced by the aerospace industry that most equipment developed for terrestrial transport have not tackled.

Environmental qualification in aerospace is a complex topic that combines high altitudes, extreme temperatures and maneuver loads with high reliability and long life requirements.

Altitude is seen as a major challenge for the adaptation of industrial or automotive components as it has a significant effect on the partial discharge phenomenon, the isolation and the radiations to the power electronics. Indeed, as mentioned before, the lower density of the air decreases the inception voltage at which the phenomenon can occur on wires or between electronic components (partial discharge). Similarly, flying at high altitude in some areas of the world drives the aircraft components to be submitted to atmospheric radiation (neutrons and protons) effects. The atmospheric radiation responsible for the radiation exposure of the crew and passengers is also responsible for causing the single event effects in the electronic equipment. This effects are well known in the aerospace industry, but the effect on high power electronics is magnified by stronger possibility of gate ruptures and burns due to the impact of the particles on the electronic components. As a result, the elements need to be balanced between oversizing versus reliability (i.e. in most cases oversized) to take into account this ageing and failure phenomena.

Furthermore, the range of operational temperatures of aircraft, especially in unpressurized areas at high altitude, can have a detrimental effect on power electronics and the energy storage elements.

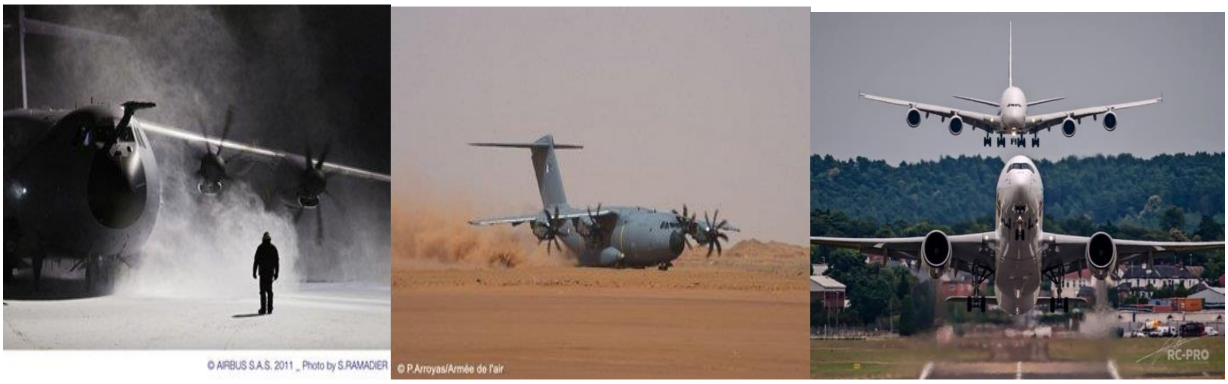
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Figure 2.10-1 - Illustration of the high range of operational conditions faced by large aircraft

Similarly, as opposed to the ground transport industry where the mean life of a vehicle is 1000 to 10 000 hours of operation, the life of an aircraft and its components varies between 10 000 for the components replaced at major overhauls to 100 000 hours of operation for the ones following the full life of the aircraft.

3.0 CONCLUSION AND RECOMMENDATIONS

Military applications of Hybrid/Electric Propulsion or Mission Systems will feature the same constraints as the ones identified during the EAS developments and tests and will benefit from the knowledge and solutions gained within.

As shown in this paper, the development and successful integration of a Hybrid/Electric Propulsion or Mission System in an aircraft requires a complex trade between Performance, Safety and Reliability / Availability. These trades, while also existing in the automotive and general transport industry, are not directly transposable to aerospace where the risks and overall constraints are different. This is particularly true in the high power applications where power levels and therefore voltage and current levels are greater than the current transportation industry standards.

In conclusion, the learnings that have already been identified not only show the need to tackle several potentially hazardous risks but also that any study on the feasibility and potential development of a new hybrid electric propulsion aircraft must consider and account for the various integration constraints that will shape the system and impact its performance.