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H_2Electra – a platform for comparative analysis of integration concepts for hydrogen-based electric propulsion in regional aircraft

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H_2Electra – a platform for comparative analysis of integration concepts for hydrogen-based electric propulsion in regional aircraft

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Abstract. Over the past decade numerous novel concepts for electric flight have been elaborated. Each unique in its own way and based on various assumptions and technological advances projected for the future. Within each concept design decisions have to be made on component level, propulsion system level and aircraft level. In order to be able to evaluate and analyse both, advanced components technologies and innovative propulsion system architectures, as well as to understand the effect of each design decision, a common baseline platform has been developed to allow for comparative analyses.

This work presents such a platform with the hydrogen-based electrified regional aircraft concept called $\texttt{H}_2\texttt{Electra}$. The iterative design process developed for this purpose is presented. It allows for a holistic approach to the development of an aircraft, its electrified propulsion system as well as the sizing of the components therein. Two propulsion system integration concepts are being considered in the evaluation: one partially fuselage-integrated and one nacelle-integrated. Challenges and trade-offs between the two concepts were analysed and evaluated, with safety and reliability being key design and decision-making metrics, alongside block-fuel efficiency and power density. In particular, the design decision on a suitable bus voltage and its effect on the powertrain sizing and integration were investigated.

1. Introduction

Besides the advances of electric flight in urban air mobility and general aviation, electrified aero engines are being investigated for commuter and regional as well as short- to medium-range aircraft classes to meet the ATAG Waypoint 2050 goals [1]. In particular, the reduction of greenhouse gas emissions, such as carbon dioxide, is a key driver for innovation is this field. The development of enabling technologies and the modification of existing technologies to comply with the stringent requirements of aviation have been challenging. It is necessary to maximise power density, to increase reliability and to tailor technologies towards the environmental conditions associated with the cruise altitude as well as hottest and coldest day requirements. Furthermore, an assessment on propulsion system and aircraft level is necessary to understand the full potential and limitations of these technologies.

By introducing electrification to aviation, the design space for an aircraft is being opened up, giving way to novel aircraft and propulsion system integration concepts, such as blended wing body and box-wing aircraft as well as boundary-layer ingestion. Jansen *et al.* [2] provide an overview of the state-of-the-art concepts explored by NASA in the field of electrified aircraft propulsion. The leading concept is the tube and wing, partially turbo-electric STARC-ABL aircraft concept [3], which utilises two turbofan engines to generate thrust as well as power for a third, boundary-layer ingesting fan integrated into the tail of the fuselage. The Boeing SUGAR Freeze concept [4] implements a similar propulsion system to the STARC-ABL with a solid oxide fuel cell (SOFC) powering the rear fan. Additionally, a truss-braced wing structure is utilised to improve the aerodynamic efficiency of the aircraft. The NASA N3-X turboelectric aircraft concept [2] achieves even greater aerodynamic benefits by applying a blended wing body structure, leading to fuel reductions of up to 70 % when compared to a Boeing 777 type aircraft. Finally, fully electric aircraft concepts are being explored. A distributed electric propulsion layout was being explored in the NASA X-57 Maxwell concept [5].

While these major advances in aircraft design bare the potential to significantly increase the viability of electric flight in terms of overall efficiency of the vehicle, comparability between the various concepts is very difficult. Therefore, the platform chosen for this work is a conventional tube-and-wing aircraft aiming to put the focus on the propulsion system and its components rather than the aircraft design. The goal is to evaluate the potential and challenges of electric propulsion systems in the medium term and with that employing more conventional aircraft designs. In the following sections the design and evaluation methodology of the $\texttt{H}_2\texttt{Electra}$ platform is being introduced. This includes an iterative design process that allows for consistent sizing of the aircraft, the propulsion system and the components therein. Two different integration concepts are being considered in the evaluation: the partially fuselage-integrated propulsion system (FIPS) concept and the nacelle-integrated propulsion system (NIPS) concept. Challenges and trade-offs between the two concepts are being analysed and discussed based on selected evaluation criteria.

2. Methodology

2.1. Design Process in Aviation

The design of complex systems is usually supported by methodical design approaches, e.g. the Design for Six Sigma. Methodical design approaches reduce the complexity of a design task by breaking it down into simpler subtasks, while ensuring the recognition of complex dependencies. Furthermore, they support the identification and mitigation of weaknesses, as well as the management of requirements, interfaces and risks. For aviation applications, particular efforts are necessary to ensure safety and reliability of a product. Hence, following the safe design process in aviation based on ARP 4754A [6] reduces the potential for weaknesses and design errors in all design phases. The methods of this approach are described in ARP 4761 [7] and are applied to validate the system requirements as well as ensure its functions. Therefore, an approach based on ARP 4754A and ARP 4761 is applied during the design of each concept emerging for the $\texttt{H}_2\texttt{Electra}$ platform.

2.2. Iterative Design Process

As part of the design process for the $\texttt{H}_2\texttt{Electra}$ platform, an iterative process for the aircraft and the propulsion system sizing had to be developed to consider:

(i) the effect of the component placement within the aircraft on the balancing as well as the sizing of various sections of the aircraft itself, and

(ii) the dependencies between battery capacity and total energy and the mission requirements.

The individual steps of the design process developed for the $\texttt{H}_2\texttt{Electra}$ aircraft concepts were derived and are displayed in Fig. 1.

The first steps of the design loop involve the specification of the top-level aircraft requirements (TLARs) and the selection of a reference aircraft. Subsequently, the mission is defined and an initial aircraft design is generated. The sizing of the aircraft is performed

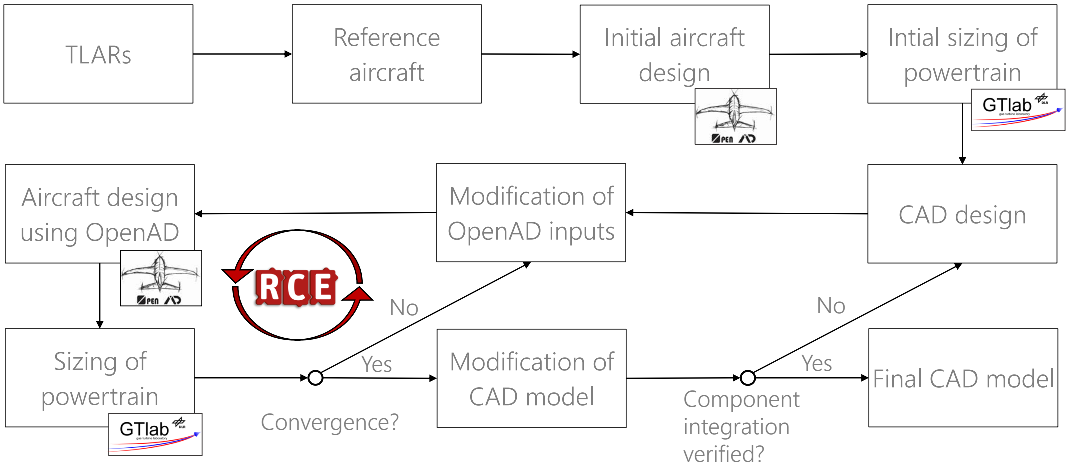


Figure 1: Iterative design process for sizing of aircraft, propulsion system and its components.

using the preliminary aircraft design tool `OpenAD` [8] developed by DLR-Institute of System Architectures in Aeronautics, which is mostly based on common handbook methods, such as those from Raymer [9], Torenbeek [10], and Roskam [11]. `OpenAD` requires the TLARs and design parameters related to the configuration of the aircraft such as the wing and tail positioning, engine location, and landing gear configuration. It can be integrated into an `RCE` [12] workflow together with other tools using the XML-based data exchange format Common Parametric Aircraft Configuration Schema (CPACS).

Given the initial aircraft parameters and mission requirements, the individual mission phases are defined and the thrust required for each phase is derived. Based on the design point, the initial sizing regarding mass and dimensions of the individual powertrain components is performed.

Subsequently, a parametric CAD model of the aircraft is designed using output parameters of `OpenAD` that determine the dimensions of the aircraft. In addition to the aircraft CAD model, simplified CAD models of the respective propulsion system components are designed. An integration concept for the propulsion system can be derived. Thereby, the design space for each component can be specified in the desired aircraft zone, which can be in the nacelles, wingbox or the fuselage – under the cabin or in a separate zone behind the cabin. Next, geometric parameters of the aircraft may need to be adjusted to ensure that all the components fit inside the aircraft. Based on the individual component masses and their position in the aircraft, the weight distribution within the aircraft may change. However, by adjusting the respective centres of gravity by means of the integration concept, an inner fully-automated iterative design loop is created using RCE.

RCE can concatenate multiple tools and contains built-in convergers and optimisers, which are used for the various studies and analyses performed on the $\texttt{H}_2\texttt{Electra}$ platform. The inner loop is repeated until the operational empty weight (OEW) of the aircraft, the components and the maximum take-off mass (MTOM) converge. Specifically, the sizing of all components, such as the battery packs, fuel cells and TMS is highly dependent on the power requirement throughout the mission and, therefore, dependent on the aircraft as well. When convergence is achieved, the CAD models are adjusted to match the `OpenAD` and powertrain sizing results and verified the compatibility and integration concept. If the component volume and available design space are not congruent, the component position or the aircraft fuselage dimensions are adjusted accordingly and an outer loop is triggered. Once compatibility is verified, the design loop ends and a final CAD model is obtained.

2.3. Propulsion System Sizing
Based on the TLARs a suitable propulsion system topology has to be chosen for the aircraft and its mission. The sizing process is conducted in two directions. Firstly, given the power requirement of the different flight phases, the front-end components of the propulsion system are sized, taking into account the efficiencies of individual components. In an all-electric propulsion system architecture these would include, for instance, propeller, gearbox (if required), electric motor and power electronics. Secondly, the power flow through the powertrain is analysed and the energy required is calculated based on the mission profile. As a result, the total amount of hydrogen required for the fuel cell operation and the electrical energy required to be stored in battery packs, is identified.

The propulsion system components are sized for mass, volume and efficiency based on analytical and empirical models, described by Bahrs *et al.* [13, 14] and Ludowicy *et al.* [15]. An active thermal management system (TMS) is used to remove the waste heat from the components. The dependency of the overall TMS sizing on the various design parameters as well as the scaling behaviour are described by Link *et al.* [16]. Due to the large amount of waste heat generated by the fuel cell system (FCS) it requires a separate TMS from the remaining electrical components. Furthermore, cables, circuit breakers and the battery are assumed to be passively air cooled. The balance of plant components of the TMSs and the FCSs, such as compressors or pumps, also require power. This parasitic power is being accounted for in the sizing procedure.

The drag induced by the propulsion system presents an additional important parameter required for the aircraft design. It depends strongly on the integration concept, in general, and the detailed design of the TMS and the air supply system of the FCS, in particular. The drag penalty assumed in this work as an initial estimate is a factor of 1.25. More accurate values require detailed analyses or high-fidelity simulations.

2.4. Evaluation Method
Decision-making within design processes is mostly assisted by evaluation methods that provide objective means to assess different solution options or to carry out trade-off studies. In this work, a method that enables the consideration of qualitative metrics is particularly useful, as not all criteria can be assessed based on numerical results during the early preliminary design phase. Hence, the weighted point method is selected to assess both aspects, the two integration concepts and the trade-off between different levels of bus voltage, by means of their fulfilment of different evaluation criteria. Here, the individual criteria are weighted against each other in a pairwise comparison with respect to their importance. The process of this method is outlined in Fig. 2. A more detailed description and the application can be found in Kazula *et al.* [17].

Figure 2: Individual steps in the evaluation process.

3. Selected Results
3.1. H2Electra Platform
The TLARs defined for the H_2Electra platform are listed in Table 1. The reference aircraft selected is the ATR72 in terms of aircraft overall dimensions. With regards to the number of passengers (PAX), however, the reference aircraft is closer to the ATR42.

Table 1: H_2`Electra` top-level aircraft requirements.

Range	PAX	Cruise Speed	Cruise Altitude	Payload
1000 NM	50	170 m/s	5000 m	6 t (50 PAX + 1 t cargo)

Both turboprop-powered aircrafts utilise a high wing configuration with a T-tail type empennage and a fuselage attached landing gear. A similar conventional aircraft design has been chosen for the H_2`Electra` platform as the focus is not on the aircraft design, but on the possible propulsion system architecture types and their integration. The two integration concepts investigated in this work, FIPS and NIPS, fulfil the same TLARs. However, the number of propulsors is different as well as the placement of the components. Important characteristics of all the powertrain components are summarised in Table 2.

Table 2: H_2`Electra` powertrain component characteristics.

Component	Main characteristics
Propeller	Rotational speed of 2240 rpm at take-off
Gearbox	Planetary gear box with a ratio of 1:5 for propeller to electric motor speed
Electric motor	Permanent magnet synchronous machine (PMSM); three phase; six pole; design speed of 11 200 rpm
Inverter	Three phase, three level neutral-point-clamped (3L-NPC) inverter with passive output filters (inductor and capacitor)
Cable	Aluminium conductors with high voltage insulation and shielding
Circuit-breaker	Parallel and series connection of IGBT switches
Converter	Boost- and buck-converters comprising switches, capacitors and inductors
FCS	HT-PEMFC with a power density of 6 kW/kg
TMS	Active TMS comprising a compressor, heat-exchanger, liquid pump and water-glycol-mixture as cooling fluid
Battery	Lithium-Ion battery with an energy density of 300 Wh/kg and minimal state of charge of 20 %
Hydrogen tank	LH_2 aluminium tank with polyurethan insulation, piping and valves

In both cases, FIPS and NIPS, a hybrid of battery system and hydrogen-based FCS is implemented as electrochemical power source. A peak-power-shaving concept is used as energy management strategy to achieve an optimal power-to-weight ratio of the overall system. An electric machine is powering the propeller via an interfacing gearbox. Due to the gearbox the rotational speed of the motor can be increased, which results in a lighter and smaller electric machine. Three-phase alternating current is supplied to the electric machine by an inverter, which is connected to the distribution grid in the FIPS concept or directly connected via a short cable in the NIPS concept. The converters are needed for setting the voltage to a constant input voltage at the inverter or the bus, taking the voltage drop of the cables and circuit breakers into account. Depending on the aircraft topology and the powertrain integration, the length of the cable from power source to sink varies. A high-temperature polymer electrolyte membrane fuel cell (HT-PEMFC) was chosen as fuel cell technology to be evaluated here. This choice was driven by previous studies on several fuel cell types and their suitability for aviation application [17, 18]. Two redundant liquid hydrogen (LH2) tanks are implemented – each provides the hydrogen for half of the FCSs. In low power demand flight phases, such as descent, the battery can be recharged with surplus power from the FCS until fully charged.

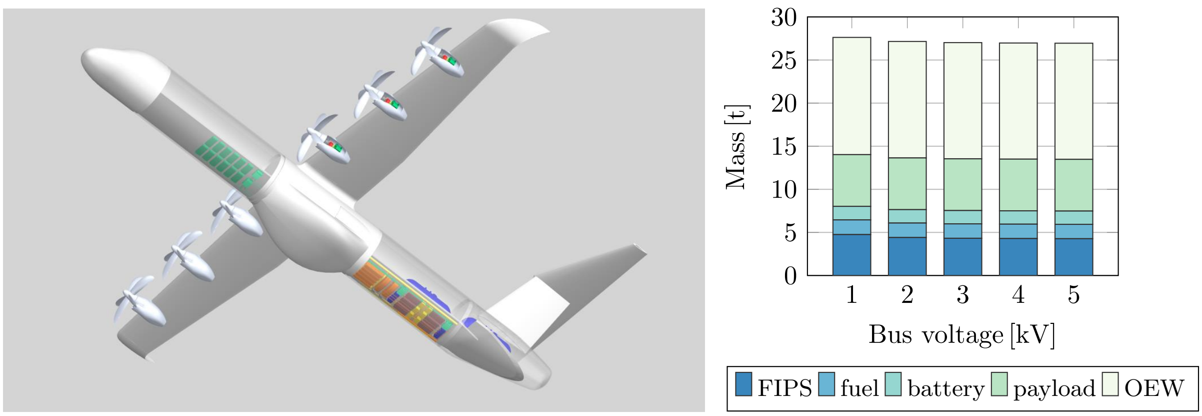
In the FIPS concept, all source-side components are located in the fuselage and the electric power is distributed equally to the three propulsion units on each wing. In contrast, the NIPS concept constitutes of only one propulsion unit on each wing and all components of the propulsion system are integrated into the nacelle directly or the wingbox close by. While the placement of the front-end components is defined by the location of the nacelles and the wing itself, the electrochemical power sources can be located anywhere in the aircraft for the FIPS concept. Their placement is performed based on the following guidelines:

- Components are placed symmetrically about the centerline of the aircraft,
- additional pitch moments about the aircraft centre of gravity are minimised by distributing the weight equally in the front and the rear of the aeroplane and
- the stability of the aircraft can be ensured as the hydrogen is being consumed throughout the mission, causing a transition of the centre of gravity of the aircraft.

3.2. Comparative Analysis of Bus Voltage Levels

The choice of bus voltage V_{bus} majorly effects the sizing of the cables, power electronics components and the battery pack. An ideal bus voltage can therefore only be found in combination with the integration concept as the cable length plays a major role here.

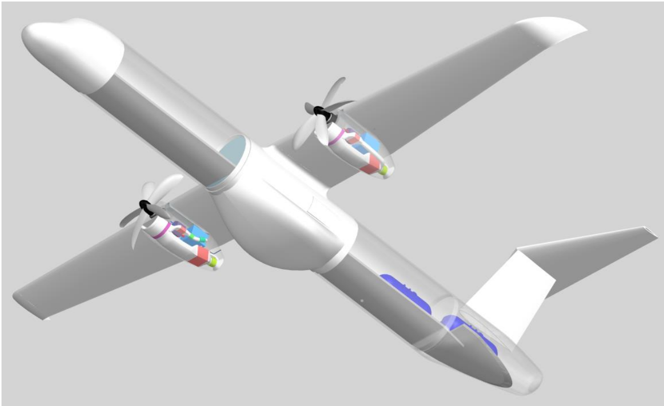
Fig. 3a shows the FIPS on a conceptual level, while Fig. 3b details the mass breakdown for propulsion system, fuel, battery, payload and the empty mass of the aircraft for different voltage levels from 1 kV to 5 kV. While the propulsion system mass is reduced by 9.04 % with an increase V_{bus} from 1 kV to 3 kV, the MTOM reduces only by 2.17 %. Furthermore, it can be observed that the additional reduction in weight for all system components is marginal, when increasing V_{bus} further to 5 kV.



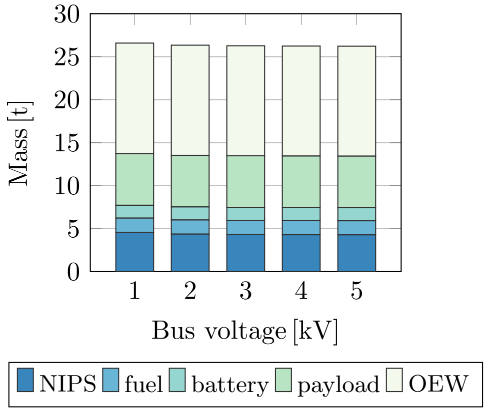
(a) Component placement FIPS (b) Mass breakdown FIPS

Figure 3: Results for partially fuselage-integrated propulsion system concept.

A similar trend can be observed for the NIPS, except that the reduction in mass is not as significant as for the FIPS. With an increase in V_{bus} from 1 kV to 3 kV a reduction by 5.63 % and 0.91 % is calculated, for propulsion system and MTOM respectively. This has to do with the cable length naturally, but also with the battery mass, which, in fact, increased with increasing bus voltage. The boost converter for the battery system can only realise a certain difference in voltage. Therefore, the battery packs are sized for capacitance with additional parallel packs. This leads to additional energy being brought onboard, which does not get utilised during the mission. Consequently, this is additional dead weight.



(a) Component placement NIPS

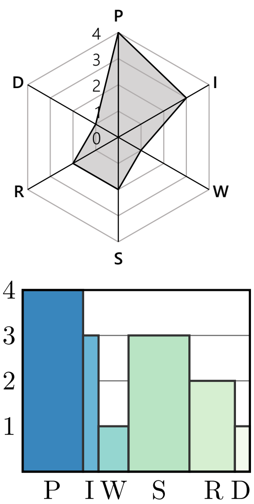


(b) Mass breakdown NIPS

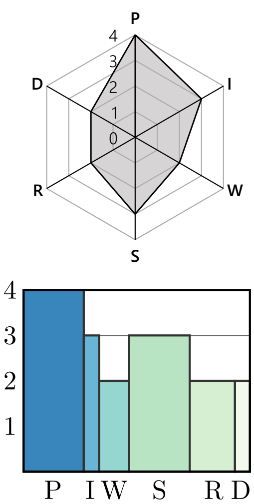
Figure 4: Results for nacelle-integrated propulsion system concept.

3.3. Overall Evaluation

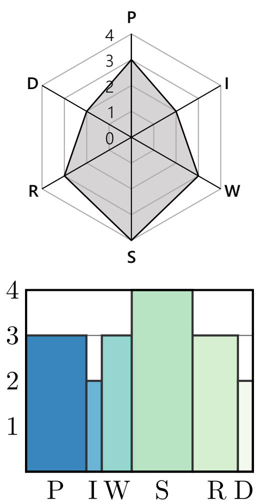
For the overall evaluation only two voltage level categories were selected: 1 kV and 3 kV. Beyond the mass and volume of the propulsion system, other aspects can play a significant role in the decision making process. The criteria chosen for the overall evaluation of the concepts and their relative weighting factors r are: (P) *Performance and Efficiency* [$r_{\mathrm{P}} = 0.27$], (I) *Ease of Integration* [$r_{\mathrm{I}} = 0.07$], (W) *Weight* [$r_{\mathrm{W}} = 0.13$], (S) *Safety* [$r_{\mathrm{S}} = 0.27$], (R) *Reliability and Maintainability* [$r_{\mathrm{R}} = 0.20$], (D) *Development and Manufacturing Costs* [$r_{\mathrm{D}} = 0.07$]. These are the same criteria as had previously been used by Kazula *et al.* [17] in evaluating different fuel cell types for aviation applications. Fig. 5 shows the scoring of each concept with regards to each criterion in a spider plot and directly below the corresponding value profile. In the latter, the relative weighting factor is represented by the width of each bar, while the height represents the score in this criterion. The area under each graph is the overall score of the respective concept. Thereby, the best overall score is achieved by the low voltage NIPS with 0.78, closely followed by the high voltage FIPS with 0.72.



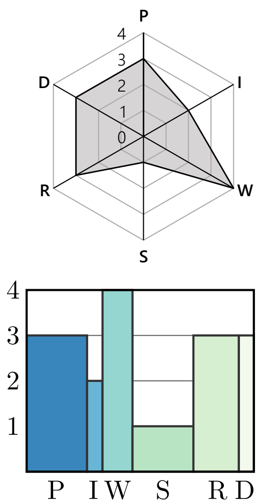
(a) FIPS (1 kV)



(b) FIPS (3 kV)



(c) NIPS (1 kV)



(d) NIPS (3 kV)

Figure 5: Overall score of the four concepts under evaluation.

4. Conclusions and Outlook

A holistic design and evaluation process has been developed in accordance with aviation specific requirements. This approach has been applied to derive the $\texttt{H}_2\texttt{Electra}$ platform for comparative analyses. The platform allows for the evaluation of pivotal design decisions. A first trade-off study has been performed regarding a suitable bus voltage level for two integration concepts of a battery-fuel cell hybrid propulsion system. The results highlight that the nacelle-integrated concept is ideally realised with 1 kV, while the increased voltage of 3 kV bus was overall beneficial for the partially-fuselage integrated concept. The integration into a single nacelle is advantageous with regards to maintainability due to a lower number of components, but safety measures associated with the leakage of hydrogen become necessary in various zones of the aircraft. Furthermore, the flexibility with regards to operating strategies is reduced. In the FIPS concepts challenges associated with electromagnetic interference, fire hazards as well as with trimming and accessibility for maintenance are more prominent. Due to an increased number in components the mass is higher and the reliability lower than in a NIPS concept.

More investigations have to be carried out to evaluate the critical aspects of the design with a higher degree of detail. Currently, a trade-off study is being carried out on the design of the hydrogen system in terms of extraction method and distribution architecture. Similarly investigations of a safe source-side electrical architecture are ongoing. In the future, a higher degree of accuracy can be achieved with improved component models as well as more estimations of the incurring drag penalties. In parallel, an aircraft zoning concept is to be developed to include fire, electromagnetic compatibility and overpressure hazard considerations.

The $\texttt{H}_2\texttt{Electra}$ platform provides a basis for comparison of various architectures and key enabling technologies against the state-of-the-art and thereby assists the design of future aero engines.

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