

# Evaluation of One Engine Inoperative Scenarios for Electrified Multi Engine Aircraft from the Certification Perspective

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**Abstract:** One approach to make the aviation sector climate compatible is to minimize greenhouse gas emissions by employing electric and hybrid electric propulsion system concepts. The introduction of novel technologies introduces novel failure modes and consequently effects of failure conditions on the aircraft. This study examines the safety of distributed electrified aircraft propulsion systems and evaluates individual failure scenarios in the context of the relevant certification requirements. A comparison of the functional architectures of legacy and Electric Hybrid Propulsion Systems (EHPS) is conducted and the existing aircraft-level requirements that are based on experience with conventional propulsion systems, are assessed for their applicability to the certification of novel propulsion systems. Subsequently the relevant safety items from these requirements are identified in the context of a critical loss of thrust scenario. Analysis methods are assigned to these safety items in order to prove the compliance of the novel systems with the legacy certification documentation. This results in a validation concept for EHPS at aircraft level in the context of a critical loss of thrust. In particular, the distribution of individual subsystems and components throughout the aircraft leads to reduced isolation of the respective propulsion systems and thus potential safety-critical interactions with adjacent systems. The analysis demonstrate that the use of distributed propulsion systems increases the risk of multiple failures of redundant systems and cascading failure propagation, highlighting the need to develop targeted means of prevention and mitigation of failure conditions for these systems. .

**Keywords:** Aircraft Certification; Airworthiness; Distributed Propulsion; Electric Propulsion; One Engine Inoperative; Safety Analysis

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## 1. Introduction

To make the aviation sector climate compatible novel Electric Hybrid Propulsion System (EHPS) concepts are being developed. They represent a possibility to drastically reduce emissions and improve efficiency[1]. Their certification poses a considerable challenge and existing standards need to be rethought or novel standards need to be developed. The certification process in the aviation industry is a rigorous and closely regulated procedure that ensures the airworthiness of any aircraft, engine or component that is intended for the use in aircraft. For any aircraft to be certified in Europe, the process is governed by the European Union Aviation Safety Agency (EASA) [2]. The agency publishes Certification Specifications (CS) that define requirements and standards for initial and continued airworthiness. The primary function of the EHPS is to *provide propulsive power*, enabling the aircraft to generate thrust and maintain flight. This function is essential for continued

safe flight and landing. The detailed requirements for propulsion systems are provided in certification documents like CS 25 and CS 23 [3,4]. However, the novel propulsion architecture and interdependence of aerodynamic control and propulsion in DEP systems require clear guidance, which the established standards are unlikely to provide. Documents like Special Condition 19 (SC 19) [5] and Means of Compliance 80 (MOC 80) [6] begin to cover certification aspects of EHPS but do not consider DEP architectures on aircraft level. Advancements in the certification of electrified systems have been made in eVTOL and small single-engine aircraft, leading to the first type certificate for the LSA<sup>1</sup> the Pipistrel Velis Electro. Highly integrated Distributed Electrified Propulsion Systems (DEPS) have a significant influence on aircraft dynamics in flight. If a fraction of thrust generation is lost, engine, performance, and stability and control requirements need to be satisfied. Rajamani et al. assess unsolved issues in electrified aircraft certification in their research report [7]. They portray different perspectives on the certification process and highlight the relevant challenges in the certification of electrified aircraft. It is stated that the novel propulsion architecture and the interdependence of aerodynamic control and propulsion in DEPS, require clear guidance, which the established standards are unlikely to adequately provide. During the NASA project X-57, several safety issues, in particular in regard to the DEP concept have been identified [8]. Borer et al. [8] proposed a solution to manage the challenge to control a DEP aircraft like the X-57 in case of an inoperative engine. Measures herein proposed affect the certification of the operational flight manual of the respective aircraft and exceed the scope of an engine certification. Based on the state of the current research, this work assesses the applicability of legacy safety and certification requirements established in CS 25 to novel aircraft concepts that use DEPS for thrust generation. The *One Engine Inoperative (OEI)* scenario is used as a reference scenario for the applicability assessment. A coarse abstract functional system architecture of the aircraft and propulsion systems is used to evaluate the applicability of certification requirements. The system model is primarily based on previous project work [9] and on the input of corresponding system and subsystem specialists. It is assessed if the potential failure modes of the EHPS leading to an OEI case are comparable to the ones exhibited by LPS.

## 2. Methodology

### 2.1. Functional System Architecture

To conduct a preliminary safety assessment, a coarse functional system architecture is defined. A Functional Block Diagram (FBD) is used to describe the system architecture and its behavior. The FBD depicts the major subsystems and interfaces, with each subsystem assigned a basic function from which failure conditions and malfunctions are subsequently derived. The FBD shown in figure 1 depicts the relevant subsystems and functions of an EHPS. It serves to establish the system boundaries, which are crucial for implementing specific safety analyses [10].

### 2.2. Elaboration of a Certification Approach

The relevant and valid certification specifications and according requirements are identified, based on the context of this work and the previously defined system architectures. The differences in the certification of novel EHPS and LPS was already explained in [11] by the EASA. Two ways of EHPS certification approaches are described in the document. On one hand the aircraft approach, where "[...] the EHPS is certified as part of an aircraft." and on the other hand the engine approach where "[...] the EHPS is certified as an engine product -by determining those components and equipment (of the EHPS) necessary for the functioning and

<sup>1</sup> LSA - Light Sport Aircraft

*control[...]”* [11, p.4] of the respective engine. As the level of safety must remain stable regardless of the certification approach used, the requirements for the certification of the EHPS remain the same. The novelty is introduced in the phase of validation and the demonstration of compliance with the certification requirements in the development process as well as in the responsibilities of the continued airworthiness. A way of validation and compliance demonstration of the certification requirements of a DEPS<sup>2</sup> is described in the following sections of this document, followed by a recommendation of a certification approach. When implementing the certification approach, it is necessary to identify what requirements are valid for the concerned system and to check their feasibility and validity for the developed product. When evaluating the system’s compliance with the certification requirements two perspectives need to be considered - the proper functional performance of the system and the integration of the system into the aircraft. Settele et al. [12] describe the challenges that arise with the certification of an EHPS as well as the test and verification steps to demonstrate the compliance of subsystems and components. However verification prerequisites safety and reliability targets based on a hazard assessment and a validation towards the proper certification requirements on aircraft and system level.

### 2.3. Compliance Validation

The validation of the system regarding the compliance with the safety standards of the respective certification specification is based on the methodologies for safety analysis according ARP 4761A [13]. Based on these methodologies, a strategy is developed to define means of hazard prevention and mitigation of the severity of failure effects. As a baseline for any following safety considerations, the FHA is crucial to define the severity of functional hazard and consequently the required reliability and failure tolerance. This is the reason, why the function *provide propulsive power* was initially assessed on aircraft level, based on the safety standards of the CS 25 [3]. Therefore every CS provides a risk classification for the respective product and the inherent functions it has to fulfil. For CS 25 categorized aeroplanes the severity of the effect of a failure condition is defined in AMC 25.1309 [3]. Depending on the respective classification, safety requirements are provided. The safety strategy of certification is based on two different kinds of safety requirements. The ones that aim on preventing the occurrence of failures and errors and the ones that aim to mitigate the severity of effects of failure conditions.

## 3. Results

### 3.1. System Definition

The definition of system boundaries, the subsystems and components is crucial for the propulsion system safety assessments as well as for the development of a proper certification strategy. The propulsion system is defined by the EASA as “*an engine used or intended to be used for aircraft propulsion.*” in [14, p.9]. The S1000D categorizes air vehicle, engines and equipment into chapters [15, 8.2.4]. Chapter 72-“Engine Electric” lists all systems and subsystems concerned with the energy transformation from alternating current into torque at the shaft. Considering the different functionalities, necessary for thrust generation, this work identifies a definition that is valid for EHPS as well as LPS:

*The smallest isolated, self sufficient thrust producing arrangement of subsystems.*

Figure 1 shows the basic main functions of an exemplary all electric EHPS architecture, the corresponding subsystems and the system boundaries (dashed lines) proposed by the EUROCAE WG 13 [17]. Compared to LPS, the EHPS subsystems are not necessarily

<sup>2</sup> Concept consist of several EHPS subsystems and components distributed alongside the wingspan of the aircraft and other EHPS subsystems and components located in the fuselage of the aircraft.

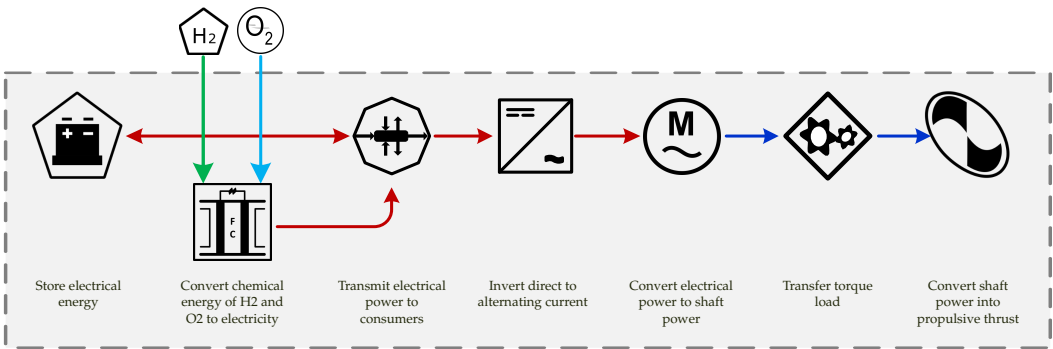


Figure 1. Functional Block Diagram (FBD) of the EHPS according to [16]

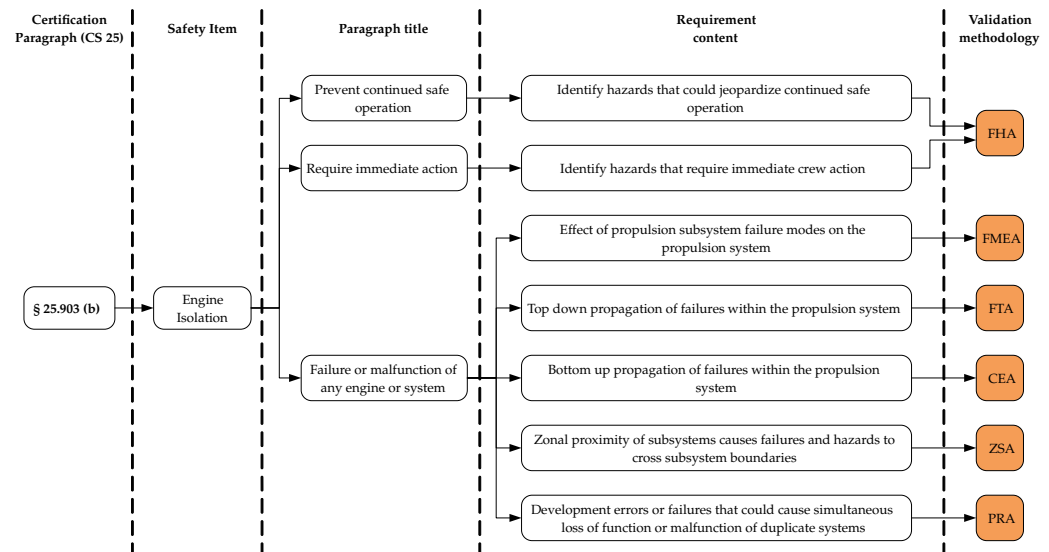
| Powerplant                                                                                                             | Performance                                                                                                                         | Stability & Control                                                                                                                                                   |
|------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Installation</b><br>25.901 Engine Installation                                                                      | <b>Take Off</b><br>25.107 Take-off speeds<br>25.109 Accelerate- stop distance<br>25.111-25.115 Take-off path, Distance, Flight path | <b>Stall</b><br>25.103 Stall Speed<br>25.203-207 Stall Characteristics                                                                                                |
| <b>Engines</b><br>25.903 (a) Engine type certification<br>25.903 (b) Engine Isolation<br>25.903 (e) Restart capability | <b>Climb &amp; En route</b><br>25.121 Climb; OEI<br>25.123 En-route flight path (two engine inoperative net flight path)<br>c)      | <b>Controllability &amp; Manoeuvrability</b><br>25.143 General<br>25.145 Longitudinal Control<br>25.147 Directional & Lateral Control<br>25.149 Minimum Control Speed |
|                                                                                                                        | <b>Landing</b><br>25.125g Landing distance OEI                                                                                      | <b>Stability &amp; Trim</b><br>25.161 Trim<br>25.173-175 Static & Longitudinal Stability<br>25.177 Static directional & lateral stability<br>25.181 Dynamic stability |

Figure 2. CS 25 paragraphs defining design and integration requirements for OEI case mitigation [3]

located within the physical system boundaries of the engine nacelle, but they are distributed throughout the whole aircraft. This aspect is crucial for the compliance check, that is also discussed later in this chapter. The hydrogen storage subsystem is not considered part of EHPS in hydrogen-powered aircraft, consistent with legacy propulsion architectures [17].

3.2. Certification Approach

As mentioned in section 2.2, there are different ways to certify an EHPS. A significant decision criterion is the composition of the design organisations involved for the certification of the respective subsystems on the one hand, but also the integration specifications resulting from the aircraft design. According to the definition for engines by the EASA [14, p.9] fuel cells, propulsion batteries or the power management subsystem must be certified within the context of an entire power train. Whereas the electric propulsion motor, can be certified as a separate entity as per SC E 19 with many of the certification requirements referring to the CS E [5,18]. In the case of a distributed EHPS architecture, issues arising due to the EHPS integration exceed the scope of the engine certification. This results in the need to consider an aircraft-based certification of the entire propulsion system with the SC E 19 referring to aircraft certification documents as well. Redundant compliance demonstration with certification requirements from different CS shall be prevented; however, safety issues that originate due to the systems complexity must be addressed when assessing a safety and certification strategy. In the case of safety considerations regarding the function *provide propulsive power*, the CS 25 and CS 23 specify requirements for the prevention and mitigation of failures and their effects occurring in the propulsion system of an aircraft. Figure 2 depicts the central CS 25 paragraphs that define the design and integration requirements mitigating the OEI failure case. The Requirements are generally divided into the three categories system level power plant, aircraft level performance and aircraft level stability and control. As the engine is an aircraft system, the engine requirements (SC 19 und CS E) are cascading down from the aircraft requirements (CS 23 and CS 25). Therefore the DEHPS must also be validated against the applicable aircraft level requirements. Conversely, the



**Figure 3.** Exemplary flow chart for a compliance assessment

existing requirements may not longer be directly applicable and alternative requirements or means of compliance must be established. The requirement 25.903(b) *Engine Isolation* is used to portray and explain the way of elaboration. This requirement is the basis for all further considerations that take the operational status *OEI* into account. The main intention of this requirement is the isolation of the respective engines and contain the effect of a failure to the single engine. Another important aspect is the fault tolerance of the whole aircraft. It has to be able to continue a safe flight and landing in case of a faulty or inoperative engine. This failure case shall also "[...]not require immediate actions by any crew member" to limit the crew workload as mentioned in [3, CS 25.903(b)(2)]. When the requirement is applied to the EHPS architecture, it becomes clear that the term engine is ambiguous. The reason for this is, that requirement 25.903(b) refers to the entire propulsion architecture due to the sequential functional dependencies, as shown in Figure 1. The term engine however, could for example refer to the electric motor only. To account for that ambiguity, the requirement in this context is adjusted to *propulsion system isolation* referring to the definition elaborated in subsection 3.1.

### 3.3. Compliance Validation

The certification requirements lead to direct safety items - like the engine isolation, compliance with which is in turn directly influenced by the design and architecture of the EHPS. The assessments as described in ARP 4761A [13] can be assigned to the safety items and the interpretation from the perspective of the individual analysis. This relationship is visualized in Figure 3 for the example requirement 25.903(b) *Engine isolation*. Assuming that the failure behaviour of an EHPS will differ from that of an LPS, it is necessary to carry out an FHA at aircraft level with a focus on propulsion system-specific failure cases. Due to the failure behaviour of EHPS, in addition to the total failure of one engine (*OEI*), there is also the possibility of partial failure of one or more engines. This results in a "Partial loss of thrust" failure scenario. The classification of the failure condition *partial loss of thrust* is complex and has an eminent impact on subsequent design decisions at subsystem and component level. Classification in the context *partial loss of thrust* has already been discussed for electrified single engine CS 23 Category 1 and 2 general aviation aircraft. This discussion was held by a Working Group of EASA, FAA and other aviation authorities [19] as well as in the proposal of the MOC to the EHPS 80 by the EASA [6], but no safety objects have been defined yet. With regard to crew workload and decision-making options

in cases of failures, a fundamental investigation into the severity for the respective hazards is necessary in this context. Experience from the use of twin-engine piston aircraft already shows that a *partial loss of thrust* may have an as *major* or even *hazardous* classified effect on the crew and an as *major* classified effect on the aircraft [20]. Failure modes relating to subsystems and components have to be analysed with regard to their effect on the next higher level system, in this case the EHPS. Findings in the failure modes and Effects Analysis (FMEA) emphasise the need for additional redundancies to mitigate the failure mode effects or preventing means to lower the probability of the occurrence of a failure event. A failure mode within a system or component can lead to several failure conditions with different effects. A thermal runaway occurring in a propulsion battery can cause both fire and toxic fume propagation, as well as a reduction or loss of thrust in depending motor and propeller units [21]. The severity of the respective failure condition effect can be completely different. Consequently the severity of the failure mode thermal runaway in the battery compartment can be classified as *catastrophic* considering the effect of fire or explosion on the occupants or on the aircraft, following the argumentation of Rempe et al. [22]. Whereas the effect on the aircraft as result of the reduction or loss of thrust can be classified as *major* under certain conditions if it only affects one motor and propeller unit according to [3, AMC 25.903(b)]. For aircraft that use hydrogen as the primary energy source, distributed electric propulsion concepts compliant with [3, CS 25.903(b)] pose a challenge in distributing propulsion-related energy to electric motors. To be compliant with said paragraph, each propulsion system according to the definition from subsection 3.1 needs its own fuel cell, a concept that is already discussed as potential solution for nacelle integrated EHPS by Sain et al. [23]. On one hand these nacelle integrated thrust units would fulfill all the functions of the EHPS that are listed in figure 1 in an isolated physical space, and meet the requirements of CS 25.903(b). On the other hand such concepts presuppose a hydrogen fuel system that meets the requirement of [3, CS 25.953] to allow "*the supply of fuel to each engine through a system independent of each part of the system supplying fuel to any other engine*" or "*any other acceptable method.*". This in turn raises additional certification challenges related to the hydrogen fuel system, which is outside the scope of this paper but is discussed in more detail in [22]. The FMEA is complemented by a Fault Tree Analysis (FTA) conducted as a Design Assurance Level (DAL) FTA, as described by Kritzinger [10]. This FTA aims to support the FMEA by identifying system design improvements that can reduce the probability of a top-level failure event such as a one engine inoperative scenario on one hand. On the other, means to mitigate the effect of a failure mode can be implemented to lower the severity of the respective failure condition. Both FMEA and FTA rely on reliability data, including failure rates and failure probabilities. This data of the novel electrified systems is crucial for assessing the compliance of an EHPS with the engine reliability requirements. As the current OEI failure condition is classified as a *minor* failure case on aircraft Level, an engine has to show a failure rate of at least  $1 \times 10^{-3}$  occurrences per flight hour [3, AMC 25.1309]. The accident of a DC 10-10 in July 1989 caused by an uncontained failure of an engine fan disk, demonstrates the potential effect component failures can have on adjacent systems [24]. The investigation of the FAA [25] concludes from this the need to comprehensively analyse both zonal hazards and common causes that lead to multiple system failures. In order to validate EHPS compliance with [3, §25.903(b)] which requires that "*failure or malfunction of any engine, or of any system that can affect the engine, will not [...] prevent the continued safe operation of the remaining engines.*" Common Cause Assessments (CCA), consisting of Zonal Safety, Particular Risk and the Common Mode Analysis can be conducted to identify failures and hazards whose effects cross subsystem boundaries. The results of the CCAs are particularly affected by the design and the architecture in relation to the position of the respective subsystems. That is why

the assessments are crucial for the safety of the entire propulsion system. For instance placing subsystems like the fuel cell or the propulsion battery in the fuselage is in contrast to the spatial separation which is inherent to the nacelle integrated systems. The objective is the evaluation of the independence of the subsystem functionalities and their respective monitoring units. Development errors or failures that could cause simultaneous loss of function or malfunction of duplicate systems as well as environmental influence or external events that could violate the independence of the subsystem are identified.

#### 4. Conclusions

The development of novel electric propulsion systems for aircraft requires a profound understanding of the impact of failures on the system. To analyze the safety of an EHPS, a system description based on functional abstraction was established. Based on this description, a certification approach for EHPS was discussed, taking into account the current regulatory framework and industry best practices. It became clear that a more detailed conceptual delimitation and allocation of subsystems is required for the certification of an EHPS. To integrate the certification of the propulsion system into the certification process of the respective aircraft, the relevant existing requirements defined in the CS 25 [3] were identified and assessed for their applicability to a DEPS. The basic intents of the requirements remain applicable, but the means of compliance, including hazard mitigation and failure mode prevention, require redevelopment. An approach has been developed to incorporate the experience gained from the use of LPS into the design of novel safe EHPS, by applying the analysis methods recommended by the ARP 4761A [13]. Future research should focus on the development of novel integrated flight and engine control technologies to meet performance, stability, and control requirements. Furthermore the work done by several aviation authorities regarding novel propulsion system safety in small commuter aircraft [6,19], is to be further developed to also apply to larger, multi engine DEPS aircraft.

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#### Abbreviations

|      |                                           |      |                                 |
|------|-------------------------------------------|------|---------------------------------|
| OEI  | One Engine Inoperative                    | AMC  | Acceptable Means of Compliance  |
| CS   | Certification Specification               | LSA  | Light Sport Aircraft            |
| AD   | Airworthiness Directive                   | FBD  | Functional Block Diagram        |
| LPS  | Legacy Propulsion Systems                 | ARP  | Aerospace Recommended Practice  |
| EHPS | Electric Hybrid Propulsion Systems        | FHA  | Functional Hazard Analysis      |
| DEPS | Distributed Electrified Propulsion System | DAL  | Design Assurance Level          |
| DEP  | Distributed Electrified Propulsion        | FMEA | failure mode Effects Analysis   |
| EASA | European Union Aviation Safety Agency     | FAA  | Federal Aviation Administration |
| SC   | Special Condition                         | FTA  | Fault Tree Analysis             |
| MOC  | Means of Compliance                       | CCA  | Common Cause Assessment         |

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