

Proceeding Paper

# Overall Design and Technology Integration for a Nine-Seater Hydrogen-Electric Commuter Aircraft Concept <sup>†</sup>

Sören Kolb-Geßmann <sup>1,\*</sup>, Jonas Ludowicy <sup>2</sup> , Ivo Zell <sup>1</sup> and Thomas Zill <sup>1</sup>

<sup>1</sup> Institute of System Architectures in Aeronautics, German Aerospace Center (DLR), Hein-Saß-Weg 22, 21129 Hamburg, Germany; ivo.zell@dlr.de (I.Z.); thomas.zill@dlr.de (T.Z.)

<sup>2</sup> Institute of Electrified Aero Engines, German Aerospace Center (DLR), Lieberoser Straße 13a, 03046 Cottbus, Germany; jonas.ludowicy@dlr.de

\* Correspondence: soeren.kolb-gessmann@dlr.de

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## Abstract

New propulsion technologies not only allow reducing the climate effect of aircraft, but also enable new architectures and integration options. To make use of this increased design space variety, new design methods need to be developed. In this work, an existing design process for CS-23 hydrogen-electric aircraft is expanded with the capability to design various powertrain options. These methods are used to evaluate the designs of two different concepts for small commuter aircraft with centralized and distributed fuel cell (FC) systems, respectively. The results show that the overall mass and performance of both concepts are very similar. However, the concept with distributed FC systems has a lower energy consumption, better FC cooling, and improved maintainability. Thus, the distributed concept is chosen. The final design has the powertrain components distributed among 10 engine pods. To transport nine passengers over 600 km without exceeding the targeted Maximum Take-off Mass (MTOM) of 5700 kg, the propulsion system's power-to-weight ratio needs to be improved by 1.2% from the current technology level.

**Keywords:** aircraft design; hydrogen propulsion; fuel cell; small air transport

## 1. Introduction

One of the biggest challenges of the global aviation industry is the reduction in the climate effect of air traffic. Due to the continuously growing demand for flexible and fast mobility, it is necessary to drastically reduce the negative effects on airplane level [1]. New propulsion technologies, such as hydrogen-electric propulsion, could enable significant improvements in efficiency and emissions. However, the financial and technological risks for introducing such technologies in large CS-25 aircraft are considerable, as shown by the delay of the Airbus ZEROe program [2]. In contrast, smaller aircraft in the CS-23 category are more suitable for implementing novel technologies, because of the less strict certification requirements [3,4] and the smaller scale, both of which reduce costs and complexity.

To evaluate a possible application of a hydrogen-electric powertrain, a nine-seater commuter aircraft is designed and analyzed. Based on an existing design [5], the concept is refined and additional disciplines are taken into account in greater detail. The focus lies on the integration of the powertrain components and the hydrogen tanks, primarily considering the aspects of performance and safety.



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## 2. Overall Design

As a starting point, the “D-Light” aircraft design is used [5]. Changes to the propulsion system are made, specifically the fuel cell type and tank integration.

### 2.1. Requirements

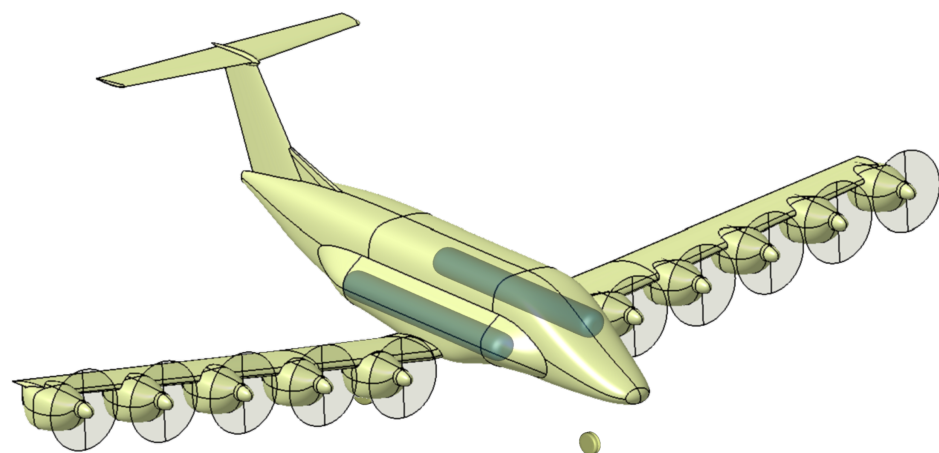
The design is aimed at a typical commuter role, i.e., flights between small regional airports or from smaller to larger airports. The Top-Level Aircraft Requirements (TLARs), such as Take-off Field Length (TOFL), reflect the intended use case and are mostly identical to the initial concept [5]. The selected values are shown in Table 1.

**Table 1.** TLARs and criteria.

| TLAR   | Value     | Comment                                  |
|--|-----------|--|
| Passengers                                       | 9         | Project requirement                      |
| Design payload                                   | 855 kg    | 95 kg per pax                            |
| Design range                                     | 600 km    | Market analysis, demand model [6]        |
| Cruise altitude                                  | 10,000 ft | FC performance, cabin pressure           |
| Cruise speed, True Airspeed (TAS)                | 300 km/h  | Analysis of flight data of similar A/C   |
| TOFL, 0 ft, standard atmosphere conditions (ISA) | ≤800 m    | Analysis of airfield data (Germany) [7]  |
| TOFL (6600 ft, ISA+15)                           | ≤1200 m   | Assumption                               |
| Landing Field Length (LFL), 0 ft, ISA            | ≤800 m    | Analysis of airfield data (Germany) [7]  |
| MTOM   | ≤5700 kg  | Runway limit of many small airfields [7] |
| Wing span  | ≤24 m     | ICAO Aerodrome Classification [8]        |
| Entry into Service (EIS)                         | 2035      | Project-defined requirement              |

### 2.2. Configuration

The overall aircraft configuration is generally unchanged from the initial concept [5]. A conventional tube-and-wing configuration is used with a low-mounted wing. A Distributed Electric Propulsion (DEP) system is used, which consists of 10 engine pods mounted under the wing. The overall configuration is illustrated in Figure 1.



**Figure 1.** Visualization of the overall aircraft configuration and the tank integration concept.

### 2.3. Propulsion System

In the initial concept, an air-cooled Proton Exchange Membrane (PEM) fuel cell system was used. The reason for that design choice was to reduce complexity, thus reducing cost and improving maintainability [5]. However, the air-cooled fuel cell technology is currently not sufficiently mature to be entered into service. To be operated in transport aircraft, the technology needs to be significantly upscaled and undergo expansive demonstration and certification processes.

Therefore, a liquid-cooled PEM fuel cell system will be used instead. This technology is already demonstrated as a propulsion system in-flight [9]. The liquid cooling system enables separating the fuel cell stack and the cooling system. Thus, new propulsion architectures and integration options are possible. The design methods and decision process for the propulsion architecture and integration are further described in Sections 3 and 4.

#### 2.4. Hydrogen Tank Integration

For hydrogen storage, a pressure tank with 700 bar is used. While the structural efficiency of a pressure tank is lower compared to cryogenic tanks, the complexity of the on-board systems and of the ground infrastructure is much lower. Due to the operation from smaller airports with limited ground infrastructure, reducing complexity is given a higher priority.

In the previous concept, the tanks were placed above the cabin [5]. However, further investigations regarding crash safety showed that heavy tanks above the cabin can compromise its structural integrity in case of a crash with vertical loads and pose a significant danger to the passengers. Thus, a new integration concept is selected.

Following an evaluation of different concepts, two tanks located to the side of the fuselage directly above the wing root are chosen. As they are outside of the cabin, the tanks offer good safety and are favorable in terms of structural integration and Center of Gravity (COG). The tank integration is also shown in Figure 1.

#### 2.5. Technology Factors

The tools used in the aircraft design process, described in more detail later in Section 3.1, are based on existing technology and aircraft. Technology factors are utilized to include expected improvements for some disciplines and to enable the design to meet the TLARs.

The following assumptions are therefore applied:

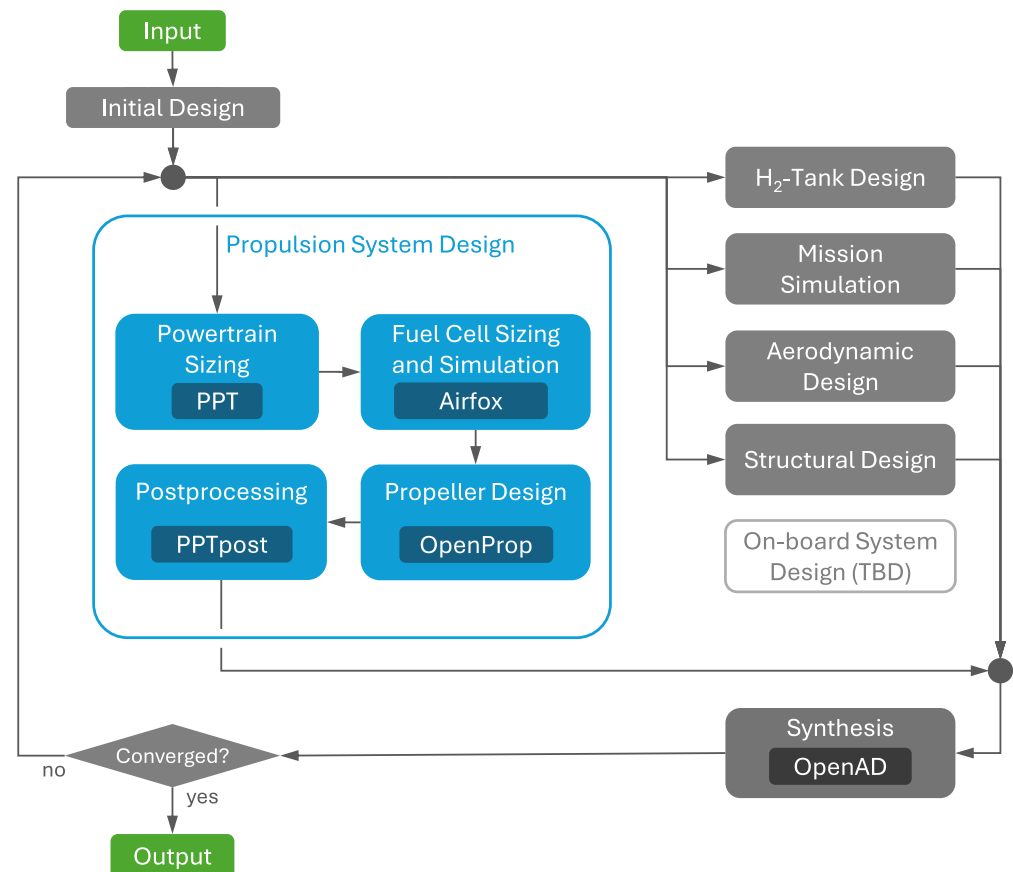
- The hydrogen tank mass is reduced by 10%. This is justified by available carbon fibers with an 18% higher tensile strength compared to the fibers used in the tank sizing tool [10].
- The masses of the airframe components—fuselage, wing and tail—are reduced by 20%. This is due to the fact that most existing commuter aircraft designs date back to the 1960s and 70s, and further improvements can be expected with better calculation methods and the use of Carbon Fiber-Reinforced Polymer (CFRP).
- The drag increase due to the cooling drag of the fuel cell system is estimated based on the Computational Fluid Dynamics (CFD) results of comparable configurations [11]. The drag forces are scaled with respect to heat flow, cruise speed, and reference area. For the centralized fuel cell system, a drag increase of 90 drag counts is assumed. For the distributed fuel cell system, an increase of 10% of the viscous drag component is used.
- The fulfillment of the 5700 kg MTOM limit is critical and largely depends on the powertrain mass. Therefore, the mass of the fuel cell system and electric motor are adjusted such that the MTOM limit is met. The required powertrain mass reduction factor is a result of the design process and is used as an evaluation metric.

### 3. Powertrain Integration

The hydrogen-electric powertrain is the most important innovation of this aircraft concept. Due to its significance in both propulsion efficiency and mass contribution, it has a high impact on aircraft performance. Therefore, it is necessary to consider its integration into the overall aircraft with a high level of detail.

### 3.1. Design Methods

Based on the methods introduced in the D-Light project [5], existing tools are refined and new tools are included. The design process is fully automated, which allows the flexibility to quickly design and evaluate different configurations. An overview of the design workflow is shown in Figure 2.



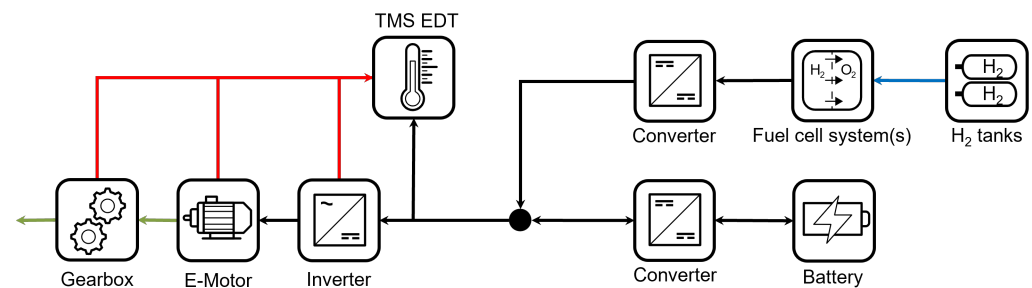
**Figure 2.** Overall structure of the design workflow. The propulsion system design subprocess is highlighted.

For the design of the propulsion system, the following tools are used:

- The Python Powertrain Tool is based on the method and models described in [12–14] and is used for the components responsible for producing propeller shaft power from electric DC power. It takes the whole mission shaft power requirements as well as environmental conditions into account, sizes the components, and handles the operating strategy by calculating the electric power demand for the fuel cell system or batteries in each step. Furthermore, it includes a thermal management system for its components as well as the battery sizing. Version 0.6 was used.
- Airfox [15] is used to design and size the FC system and to simulate its performance over the entire envelope. Its capability includes the design of air-cooled open-cathode, air-cooled closed-cathode, and liquid-cooled FC systems. The underlying models are obtained from experimental testing of commercially available fuel cell stacks. The additional FC system components, such as the heat exchanger, compressor, humidifier, and cooling system, are sized from balance of plant requirements. Version 0.2 was used.
- OpenProp [16] is used to simulate the propeller. The tool reads the propeller geometry from the overall design and simulates the propeller performance using blade-element momentum theory in the design point and for off-design phases. Version 2.0 was used.

### 3.2. Powertrain Architecture

The basic powertrain architecture that is modeled by these tools is shown in Figure 3. A single-stage gearbox with a fixed transmission ratio of 1:5 is used to increase the shaft rotational speed of 2250 rpm at the propeller and decrease the required torque from the motor to allow for a more lightweight motor design. The gearbox, motor, and inverter are liquid-cooled via a shared thermal management system (TMS). Electric direct-current power at system voltage level is provided from the fuel cell system(s) or batteries, depending on the degree of hybridization.



**Figure 3.** Powertrain architecture overview. Blue lines: hydrogen; Black lines: electrical energy; Red lines: thermal energy; Green lines: mechanical energy.

### 3.3. Integration Concepts

Keeping in line with the overall configuration and TLARs, two main integration concepts are analyzed. The gearbox, inverter, and propeller are in each nacelle for both concepts. The main difference is the number and location of the FC systems:

- Ten smaller FC systems distributed among all nacelles.
- Two large FC systems integrated within the rear fuselage (for redundancy, at least two independent FC systems are necessary).

These concepts are implemented in the design process, taking into account the impact on disciplines, such as mass and mass distribution, systems architecture, aerodynamics, and structure. However, not all effects can currently be represented with the design methods. For example, the aerodynamic interactions between the propeller slipstream and the cooling system are too complex to be modeled with a sufficient level of detail at the preliminary design stage. Therefore, assumptions have to be made for several aspects.

## 4. Results

To find the most suitable powertrain architecture and integration concept, the results of the design process, as well as the qualitative aspects of both integration concepts, are evaluated.

### 4.1. Powertrain Architecture Selection

An overview of the design results is given in Table 2.

The results show that the overall results are very similar for both concepts. The difference of the powertrain mass reduction factor is 1.2 percentage points, which certainly lies within the accuracy of the design methods. A notable difference is that the distributed concept has a higher FC system mass, which is attributed to the negative scaling effects of using 10 individual FC systems. On the other hand, the centralized concept has a higher mission fuel mass, thus increasing energy consumption and consequently requiring heavier H<sub>2</sub> tanks. This is due to the increased drag of the FC cooling system.

**Table 2.** Comparison of design results.

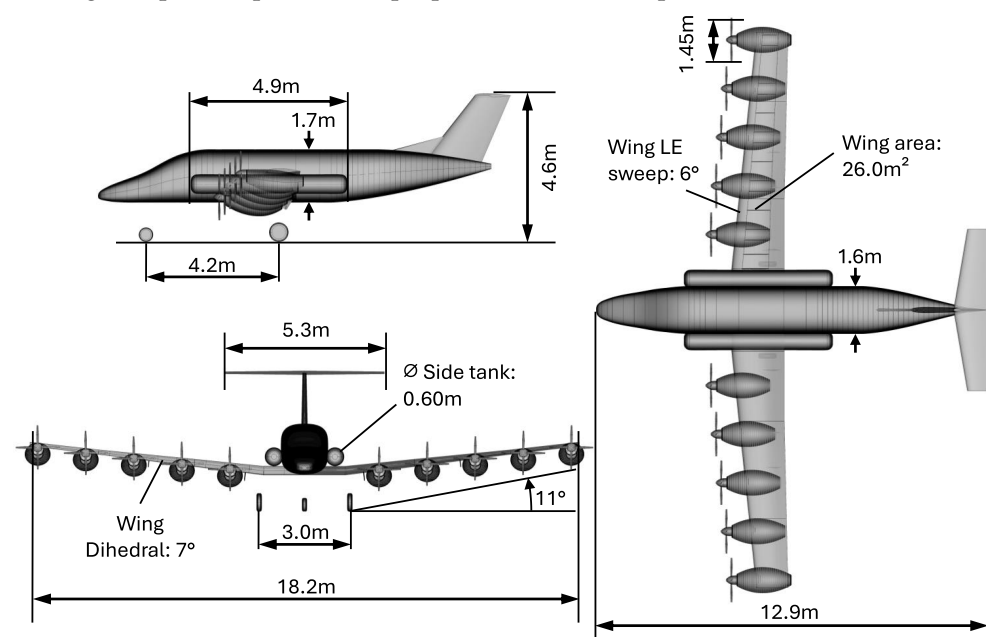
|                                     | Distributed | Centralized |
|-------------------------------------|-------------|-------------|
| MTOM, kg                            | 5692        | 5696        |
| Operating Empty Mass (OEM), kg      | 4753        | 4741        |
| Powertrain mass, kg                 | 1100        | 920         |
| incl. fuel cell system mass, kg     | 958         | 742         |
| Hydrogen tank mass, kg              | 801         | 930         |
| Hydrogen tank diameter, m           | 0.6         | 0.62        |
| Fuselage length, m                  | 12.3        | 13.6        |
| Mission fuel mass, kg               | 84.6        | 100.0       |
| Powertrain mass reduction factor, % | 1.2         | 2.4         |

In addition to the design results, a qualitative analysis of the two concepts was done. The integration of the centralized concept is facilitated by the large amount of space available in the rear fuselage and results in much smaller pods. On the other hand, the distributed concept has several advantages, mainly improved cooling performance due to the propeller slipstream. The accessibility and maintainability are improved due to pod integration (the distributed concept allows the exchange of the entire pod for maintenance, similar to the procedure for turbofan engines). Furthermore, on a broader scope, the propulsion system is more modular. By varying the number of pods, it can be flexibly applied to larger or smaller aircraft without the need to redesign the engine pods.

Overall, the quantitative and qualitative results indicate that the distributed concept is favorable on the overall aircraft level for this type of aircraft.

#### 4.2. Final Design

Using the design process, the final design with the selected propulsion architecture is generated. Figure 4 shows the overall geometry and important dimensions. Notably, the powertrain integration in the nacelles results in large engine pods. To store the required fuel, voluminous H<sub>2</sub> tanks are required. The H<sub>2</sub> tank integration on the side of the fuselage limits the space available for windows and exits. As a consequence, the exit door and emergency exit have the minimum required size and are located in the very back of the fuselage. Important powertrain properties and overall performance are listed in Table 3.

**Figure 4.** Dimensions of the overall aircraft, not showing the H<sub>2</sub> tank fairings and wing fairing.

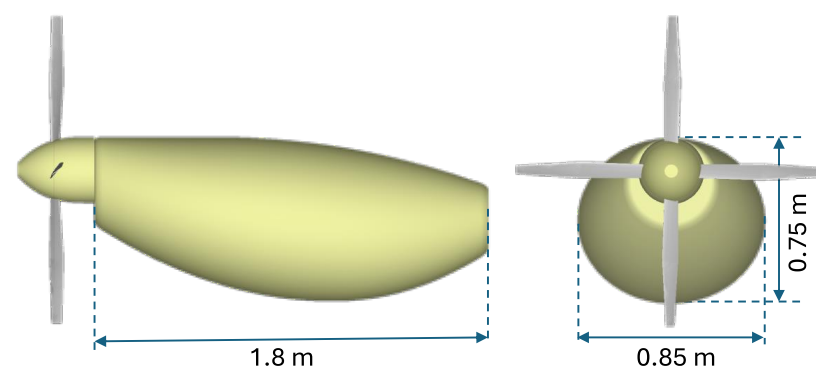
Because almost all powertrain components are distributed among the engine pods, the component masses and integration into the pod are critical design results. The FC system including TMS has the largest impact, contributing almost 2/3 of the total mass; see Table 4. The packaging of the components within the pod is not performed in the current state of the design process. Therefore, the pod is sized preliminarily by estimating internal geometry and the component arrangement. The resulting pod dimensions are shown in Figure 5.

**Table 3.** Key aircraft parameters.

| Parameter                                  | Value | Unit              |
|--|-------|-------------------|
| H <sub>2</sub> tank gravimetric efficiency | 9.5   | %                 |
| Fuel cell efficiency (cruise)              | 54.6  | %                 |
| Required specific power of FC system       | 0.81  | kW/kg             |
| L/D max.                                   | 15.4  |                   |
| Wing loading                               | 219   | kg/m <sup>2</sup> |
| Power loading                              | 0.11  | kW/kg             |
| Installed power                            | 680   | kW                |
| Cruise power                               | 396   | kW                |
| Block energy consumption                   | 1.29  | MJ/Pkm            |
| Block fuel mass                            | 58.1  | kg                |

**Table 4.** Masses of engine pod.

|                   | Mass per Pod, kg |
|-------------------|------------------|
| FC + TMS          | 94               |
| E-motor           | 5.2              |
| Inverter          | 5.1              |
| Powertrain TMS    | 1.9              |
| Gearbox           | 2.9              |
| Nacelle structure | 29               |
| Propeller         | 13               |
| Total             | 155              |



**Figure 5.** Dimensions of engine pod (pod shape is not representative).

## 5. Discussion

The presented results suggest that a hydrogen-powered nine-seater commuter aircraft is generally feasible. At the considered detail level and with the assumed technology factors, the targeted mission performance can be achieved. The heavy powertrain and H<sub>2</sub> tank significantly contribute to the overall mass. To keep the MTOM below the imposed limit of 5700 kg, minor mass reductions are still necessary. Improving the power-to-weight ratio of the propulsion system by 1–2% is sufficient, which is considered to be feasible until the EIS.

The evaluation of different powertrain architectures shows that the overall mass of both distributed and centralized FC system integration concepts is similar. The major difference is in fuel consumption, with the distributed concept requiring a 15% lower mission fuel mass. In terms of qualitative considerations, the distributed concept shows further advantages, such as cooling performance, maintenance, or transferability to other aircraft configurations. Consequently, the distributed concept is selected.

Although many dependencies and interactions are represented in the design methods, some gaps with potentially significant impacts on the overall results were identified. Most importantly, to understand the effect of the propeller slipstream on aerodynamics and cooling performance, more detailed investigations are required. This also includes the effect of the engine pods on the overall lift distribution. The cooling system performance is particularly relevant in high temperatures and flight phases with high power demand, such as a go-around. These aspects will be focused on in the further course of this work, improving the accuracy and certainty of the design methods and enabling a more dependable conceptual design.

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## Abbreviations

The following abbreviations are used in this manuscript:

|      |                                 |       |   |
|------|---------------------------------|-------|---|
| A/C  | Aircraft                        | ICAO  | International Civil Aviation Organization |
| CFD  | Computational Fluid Dynamics    | ISA   | Standard Atmosphere Conditions            |
| CFRP | Carbon Fiber-Reinforced Polymer | LFL   | Landing Field Length                      |
| CoG  | Center of Gravity               | MTOM  | Maximum Take-Off Mass                     |
| CS   | Certification Specification     | OEM   | Operating Empty Mass                      |
| DEP  | Distributed Electric Propulsion | PEM   | Proton Exchange Membrane                  |
| DLR  | German Aerospace Center         | TAS   | True Airspeed                             |
| EASA | European Aviation Safety Agency | TLARs | Top-Level Aircraft Requirements           |
| EIS  | Entry into Service              | TMS   | Thermal Management System                 |
| FC   | Fuel Cell                       | TOFL  | Take-off Field Length                     |

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