NEWBORN - NExt generation high poWer fuel cells for airBORNe applications

WP9 – Subsystem mechanical modifications for integration into the full system

D9.1 Aircraft-level mechanical system integration analyses report

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Approval Table	Title	Name	Date and Signature
Prepared by	Responsible for preparation	Etienne Behar	19-Feb-2025 Signed by: Etienne Behar E974EAD174E14FD...
Approved by	Work Package Leader	Etienne Behar	19-Feb-2025 Signed by: Etienne Behar E974EAD174E14FD...
Approved by	Configuration Manager	Dorin Maxim	19-Feb-2025 DocuSigned by: Dorin Maxim F97C03BE7952428...
Approved by	Technical Leader	Ondrej Kotaba	19-Feb-2025 DocuSigned by: Ondrej Kotaba BFC376C9572A433...

Full list of contributors is presented in Table 3 of this document. Only the author responsible for preparation of the document signs the artefact, all other contributors are not required to sign.

REVISION HISTORY

Revision	Date	Revision summary
00	2025-02-19	Initial issue

Table 1 - Revision history

INTELLECTUAL PROPERTY

Section/Chapter/Item	Owning Entity	Nature of IP	Comments
Entire deliverable except for items below	Whole NEWBORN consortium	Shared Foreground	
CS-23 clean-sheet design airframe	PVS	Exclusive Foreground	
Reference CS-23 aircraft envelopes	PVS	Exclusive Background	
CS-25 clean-sheet 80 PAX aircraft	PVS, CIRA	Shared Foreground	
Section 2.2, FCPSS design	HON	Exclusive Foreground	
Section 2.3, Propulsion Subsystem design	PVS, HON, UON	Shared Foreground	
Section 3.2, NEWBORN integration concept within HERA airframe.	HON	Exclusive Foreground	
Section 3.4.1	PCS, PVS	Shared Foreground	
Section 4.1	PVS, TEF, PCS	Shared Foreground	
Sections 4.2, 4.3	PVS, HON, CIRA	Shared Foreground	
Fuel-cell stack design and stack safety concept	PCS	Exclusive Foreground	

Table 2 - Intellectual property

CONTRIBUTORS

Participating WP	Partner	Contributor Name
WP7	HON	David Klistinec
WP1	HON	Viktor Barus
WP1	HON	Tamas Nagy
WP1	HON	Ondrej Kotaba
WP7	HON	Tomas Damek
WP9	PVS	Emil Jebbawi
WP9	PVS	Gregory O'Sullivan
WP1	PVS	Riccardo Premuni
WP8	PVS	Luka Kambič
WP9	CIRA	Diego G. Romano
WP9	CIRA	Giovanni Fasulo
WP9	CIRA	Gianpiero Buzzo
WP2	TEF	Martin Boehm
WP4	PCS	Oskar Ekblad

Table 3 - List of contributors

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1 INTRODUCTION

1.1 Objective

The NEWBORN project develops a hydrogen fuel-cell-based powertrain for aeronautical applications, with propulsive power levels ranging from 1 to 8 MW. While one of the main focuses of the project is the ground demonstration of its fundamental 1 MW building block, a comprehensive analysis of the mechanical integration of the system into various aircraft remains a necessary undertaking to prove the feasibility and relevancy of the system for flying applications. Accordingly with the NEWBORN Grant Agreement, the following document summarises the feasible approaches to the fuel-cell propulsion system integration within the aircraft, both CS-23 and CS-25. The deliverable summarises primarily the effort performed in the project task T9.1, building on results from many other project tasks, such as the design tasks at various system decomposition levels, safety analyses, design on ducts and heat exchanger optimisation, and other.

The formal description of the deliverable objective per the Grant Agreement is “Document summarizing feasible approaches to the fuel cell propulsion system integration within the aircraft, both CS23 and CS25.”

1.2 Scope

This mechanical integration analyses report is split into three main aspects, reflected by the three main sections.

The first section provides the **definition of the envelopes used for the design of the ground demonstrator**, envelopes which were in the first place informed by an existing airframe.

The second aspect is the plain **mechanical integration of the system** into the clean-sheet design airframes, focusing on the Fuel-Cell Power Source Subsystem (FCPSS), the Propulsion Subsystem (PS), the Hydrogen Storage Subsystem (HSS), the Battery Subsystem (BS), and the Power Distribution Subsystem (PDS). In addition to these subsystems, a closer look at the various air inlets, their positioning on the airframe, is also provided when relevant.

The third aspect is the **safety considerations** surrounding these different integrations. The **ventilation, venting, and purging of hydrogen** through the relevant subsystems is first explored, preceding a discussion on the **failure modes and their effects on the aircraft**, a discussion rooted in the Ground Demonstrator Failure Mode & Effects Analysis (FMEA).

Figure 1 - NEWBORN CS-23 19-seater concept.

2 ENVELOPES DEFINITION & GROUND DEMOSNTRATOR SUBSYSTEMS' DESIGN

2.1 Envelopes definition

The NEWBORN system is, in essence, an aircraft powertrain. It is therefore a necessity for its first ground demonstrator to reflect volume constraints inherent to an aircraft. The first effort of this integration analysis activity was therefore to produce relevant design envelopes for the various subsystems of the ground demonstrator, envelopes informed by an existing, conventional CS-23 airframe, already certified, with power levels aligning well with the usage of two NEWBORN systems (composed of 3-stack fuel cell system). Such a configuration is described and reported in the report D1.1[1], as the *CS-23 conventional 2x3* configuration, and is in essence an ideal flying demonstrator, or flying laboratory aircraft. The philosophy behind this approach is to inform the design of most notably the FCPSS and the PS, by using the available volume in a contemporary CS-23 level 4 aircraft, rather than using a much less constrained clean-sheet design. In the latter case, we would iterate between the available volume for the FCPSS and the design of the airframe overall shape in a more time consuming and less efficient way.

This exercise presents the secondary added value of exploring the feasibility of a retrofit for the NEWBORN system.

In other words, the NEWBORN ground demonstrator mechanical arrangement is adapted for potential flying laboratory aircraft. The integration concepts for other aircraft classes are discussed in the subsequent sections of this report.

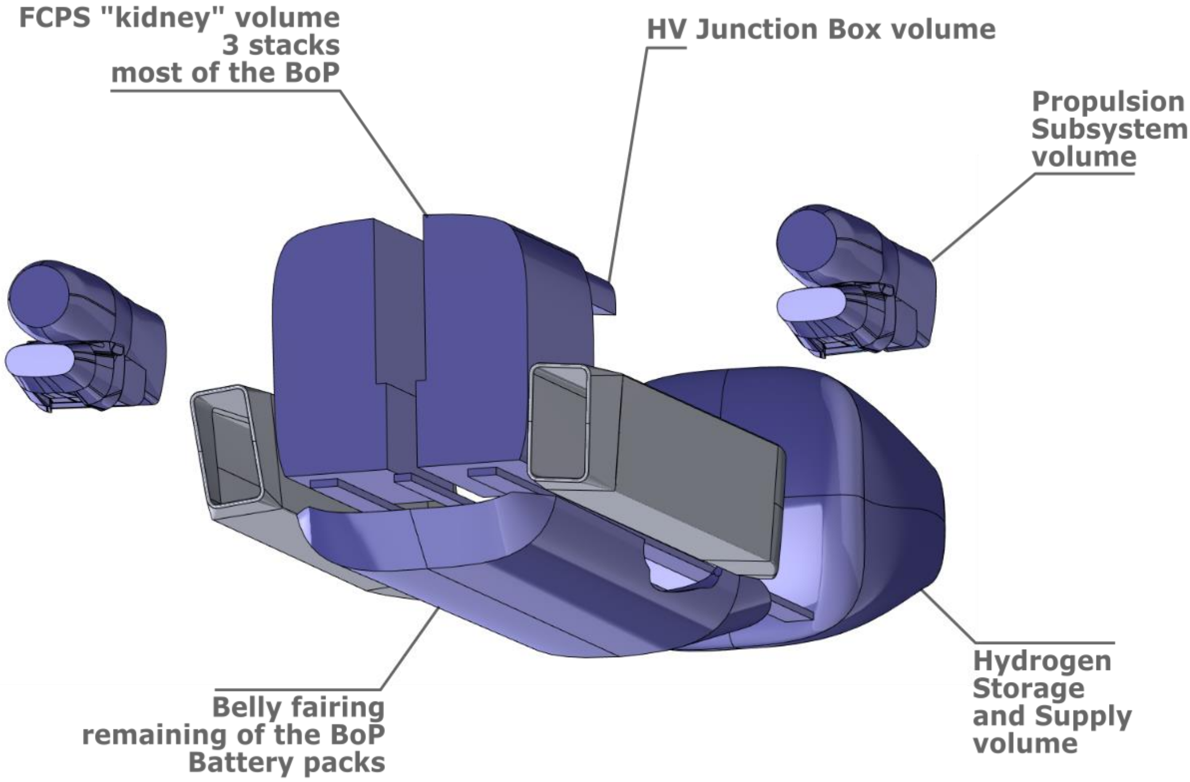


Figure 2 - Aircraft-informed design envelopes for the NEWBORN ground demonstrator.

The volume available in the airframe was analysed following a few rules: respecting the balance of the aircraft (no excessive displacement of the centre of gravity) while introducing the system and moving the seats and passengers, conserving the relevant certification aspects of it, such as the cabin aisle width and accessibility to the cockpit, making sure the original systems - such as the flight controls -

were not modified. Resulting from this exercise, after a few iterations alongside the early conceptual design of the demonstrator FCPSS, clear need for an additional use of belly fairing emerged, fairing which would also accommodate for the battery packs. (This holds for the TRL4 demonstration unit of NEWBORN, not for the final product-optimized system which is estimated to have much lower volume.) The original nacelle volume was plenty enough to host the electric propulsion unit, including the inverter, the controller, the gearbox, the governor and the overall thermal management system of these elements. The volume available in the empennage is also sufficient to host the LH2 storage (tank) for a meaningful mission, with sizing and mission described in D1.1[1].

The resulting envelopes are displayed in Figure 2. In order to respect the original centre of mass, the two FCPSS are integrated in the front of the cabin, behind the cockpit, balancing the weight of the hydrogen storage system, integrated in the tail. Moving the battery back along the longitudinal axis within the belly fairing allows to further act on the centre of mass. The two grey volumes represent the available space outside the airframe for the integration of the fuel-cell and balance of plant heat exchangers.

Important note: these envelopes were in no case meant to give a hard constraint for the design of the ground demonstrator subsystems. A first ground demonstrator is, in nature, a non-optimised realisation of a system, which includes margins generous enough to face the unknowns in a safe manner, and which also includes large amount of non-vital instrumentation, sensors and controls to maximise the output in terms of knowledge and parameter space exploration. The main intent of these design envelopes is a purely qualitative baseline, informing us on how compact the subsystem will need to be for future applications.

2.2 Ground demonstrator FCPSS design

The ground demonstrator will host a 3-stack fuel cell system, which on this reference aircraft would be contained in one of the two front volumes, dubbed “kidneys” in Figure 2. It also uses half of the forward part of the belly fairing, as displayed in Figure 3. Note that to limit the height of the ground demonstrator, the belly fairing volume was shifted upward, in contact with the kidney volume. A more detailed description of the FCPSS and its subsystems is given in the report D7.5[2].

It can be appreciated from these views that though many components are protruding from the envelope, the overall compacity of the FCPSS will certainly enable airborne applications. The three fuel cell stacks can be seen on the upper part of the volume, in red. These stacks are a first great illustration of an easy gain of volume (up to 35% in this precise case): as soon as the system will go through a first round of optimisations for its integration to an aircraft, the three stacks will be enclosed in a single, optimised housing, saving the dead volumes seen in-between the stacks on the lower row of Figure 3, an optimisation also directly reflecting in a decrease of the mass of the housing. Such a redesign may also start a virtuous cycle, driving additional mass and volume decreases: the three separate stack ventilation systems present on the ground demonstrator will then reduce to a single system. This is only one of the numerous easily implemented optimisations.

The rest of the subsystems are designated on the figure. The most voluminous one is the air supply subsystem, various filters, and particle separators feeding air to the fuel cell cathodes.

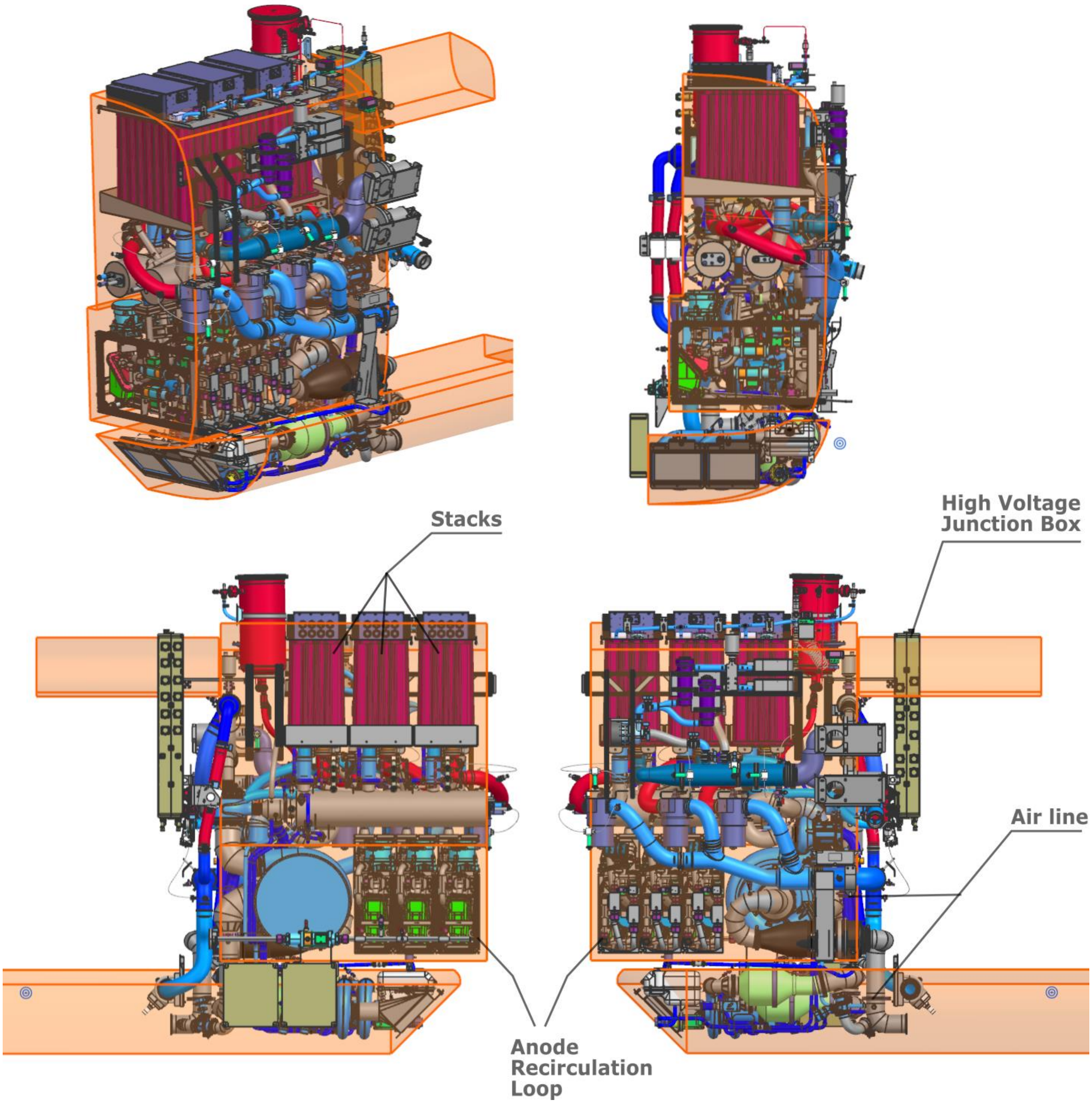


Figure 3 - FCPSS design compared to the CS-23 aircraft informed envelopes.

2.3 Propulsion unit integration

Figure 4 presents the second most complex assembly of the system, namely the propulsion subsystem, including the inverter, the motor controller, the electric motor with its gearbox, the propeller governor and the propeller itself, together with the overall propulsion thermal management system. The ground demonstrator propeller will have a diameter of 3.1 meters, while the motor will reach the 1 MW mark. As previously mentioned, this subsystem easily fits in the original nacelle, due to the fantastic power density of the motor. In terms of specific power, this component will demonstrate a staggering 15.4 kW/kg on the ground demonstrator: one million watts enclosed in about 50 litres, for just 68.67 kg, with even better figures estimated for its second iteration in development.

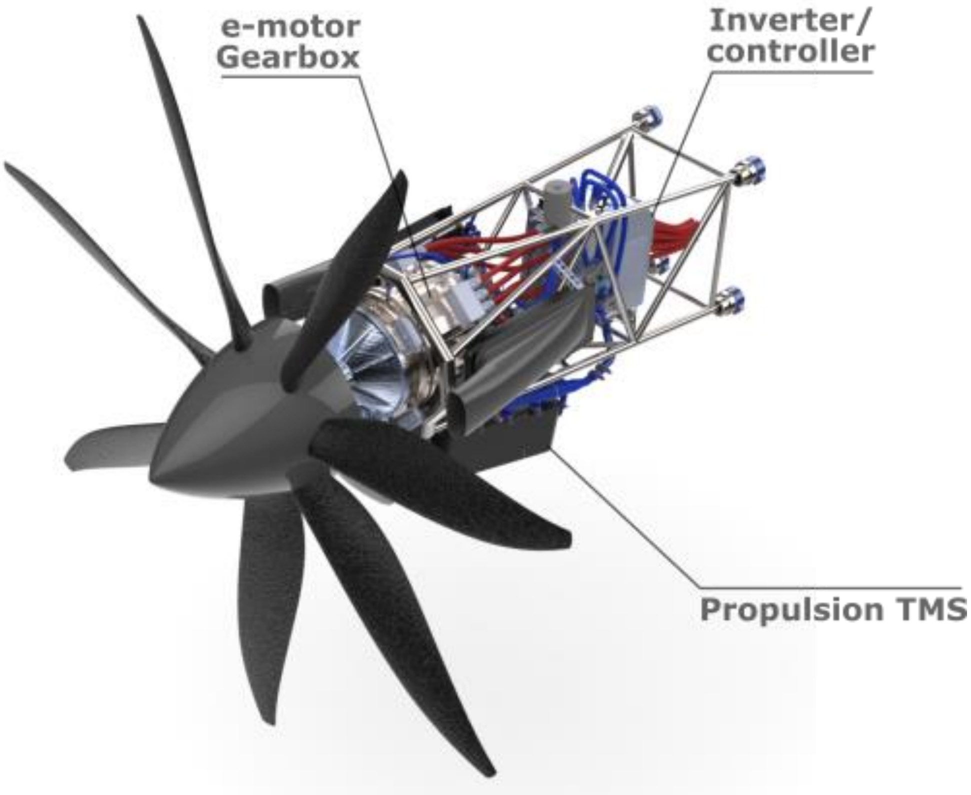


Figure 4 - The ground demonstrator propulsion unit assembly.

3 SYSTEM INTEGRATION

3.1 Specific powers and power densities of the FCPSS

The FCPSS is the core element of the NEWBORN system, and by far the most complex. Because of this shear complexity, it is also the subsystem that can be the most optimised. In the next section, the various integrations are demonstrating the specific powers and power densities summarised in Table 4. These values are the results of either simple calculations (see the example of the stack housing in the previous section) or engineering judgment based on the knowledge gathered throughout the design of the system. These calculations articulate plans for the product-related optimisations and further system improvements possible before the needed entry into service dates (platform dependent).

The CS-23 2x2 configuration, though shown in the table (greyed out), is not covered by the following integration analysis. It simply illustrates the mass penalty resulting from the additional parallelisation of the 4x1 configuration, for the benefit of higher level of redundancy desired for the initial product deployment of the break-through technology with early stage of maturity.

Table 4 - Specific powers and power densities for the various configurations.

	Reference CS-23	Clean-sheet CS-23 4x1	Clean-sheet CS-23 2x2	HERA	Pod	80pax
Specific power kW/kg	0.85 kW/kg*	0.9 kW/kg†	1.2 kW/kg	1.37 kW/kg‡	1.67 kW/kg§	1.37 kW/kg**
Power density kW/m³	254 kW/m³	261 kW/m³	348 kW/m³	460 kW/m³	526 kW/m³	460 kW/m³

* Overall significant reduction in the number of sensors and more tightly integrated subsystems. Piping and components made of optimal materials. Industrial and automotive COTS components switched to customized aerospace components. Rotating machines optimized for the specific use-case, optimized valves. Single Anode Recirculation Loop instead of three individual per stack. Fuel cell stacks electrically connected in series.
† All in previous + Independent balance of plant per stack to increase system reliability. Optimized subsystems, smaller components, simplification of subsystem architecture (removal of components currently includes as secondary solutions), removal of manifolds. Two-phase cooling introduced (developed in-kind separately). Optimization of low voltage power distribution.
‡ All in previous + Further improvement of fuel cell technology – slightly more efficient and higher temperature fuel cells. Due to better availability in comparison to CS-23, common subsystems, e.g., a single anode recirculation per 3 fuel cell stacks. Integration of anode recirculation into stack housings.
§ All in previous + Removal of main DC/DC conversion, shorter media connections positively impacting the rest of the system weights.
** Linearly scaled from HERA.

3.2 CS-23 19-passenger fuel-cell & battery aircraft

In the lineage of the UNIFIER19 concept[5], the NEWBORN 19-seater clean-sheet design will embody a new way to travel, in the philosophy of a fully electric regional commuter, nicknamed “Miniliner”. Just as important, such an aircraft will enable to amass the operational experience necessary for the development of larger platforms. This concept embarks four independent FCPSSs of one single stack each, an architecture allowing enough redundancy to enable the diversion to alternate airports in the event of a loss of half of the FPCSSs, while not relying on batteries, as detailed in D1.1[1]. Also found in this same report, the specifications of this aircraft are given in the following table. An initial mechanical integration, weight and balance analysis and static stability analysis for this aircraft is provided in the report D1.2[3].

Table 5 - CS-23 clean-sheet design aircraft specifications

Discretization of the FCPSS	4x1
Total number of propellers	2
Total net power FC (MSL)	960 kW
Total net power Batteries	1090 kW
Total shaft power	1370 kW
LH2 capacity	274 kg

Figure 5 - CS-23 NEWBORN clean-sheet design airframe.

Contrary to the reference aircraft for which the two FCPSSs were integrated in the front of the cabin, far away from the tank to conserve the centre of mass of the original aircraft, such a clean-sheet design adapts the airframe to the ideal layout of the powertrain. In Figure 6, the FCPSSs are enclosed in a bay in the aft section of the fuselage, behind a pressure and fire bulkhead. Behind another separation bulkhead is the tank bay, within the empennage. Because it is not withstanding any pressure difference, this separation air-tight bulkhead is following the shape of the tank forward dome, which is itself tucked into the FPCSS bay, its fuel conditioning components (enclosed in the so called cold and warm boxes) piercing through the separation wall and integrated at the heart of the FCPSSs, as best seen in the lower panel of Figure 7.

Both bays are ventilated to disable the accumulation of gaseous hydrogen, as discussed in the dedicated Section 4.2. The proximity of the two bays allows for the shortest hydrogen supply line, linking the tank to the FCPSSs, and therefore minimising mass. The same applies to the propulsion high-voltage (HV) wires, running from the high voltage junction box to the propulsion unit along the shortest path possible. The four radiators, commonly used within each FCPSS by the fuel-cell TMS and the Balance of Plant TMS, are integrated tightly along the FCPSSs bay and along the tank bay.

The ground demonstrator propulsion unit assembly, shown in Section 2.3, is directly used for the sake of visuals, in the following figures. However, further simplifications of the system (mainly, the use of a single coolant loop for the whole unit) are planned to increase the availability of the propulsion system.

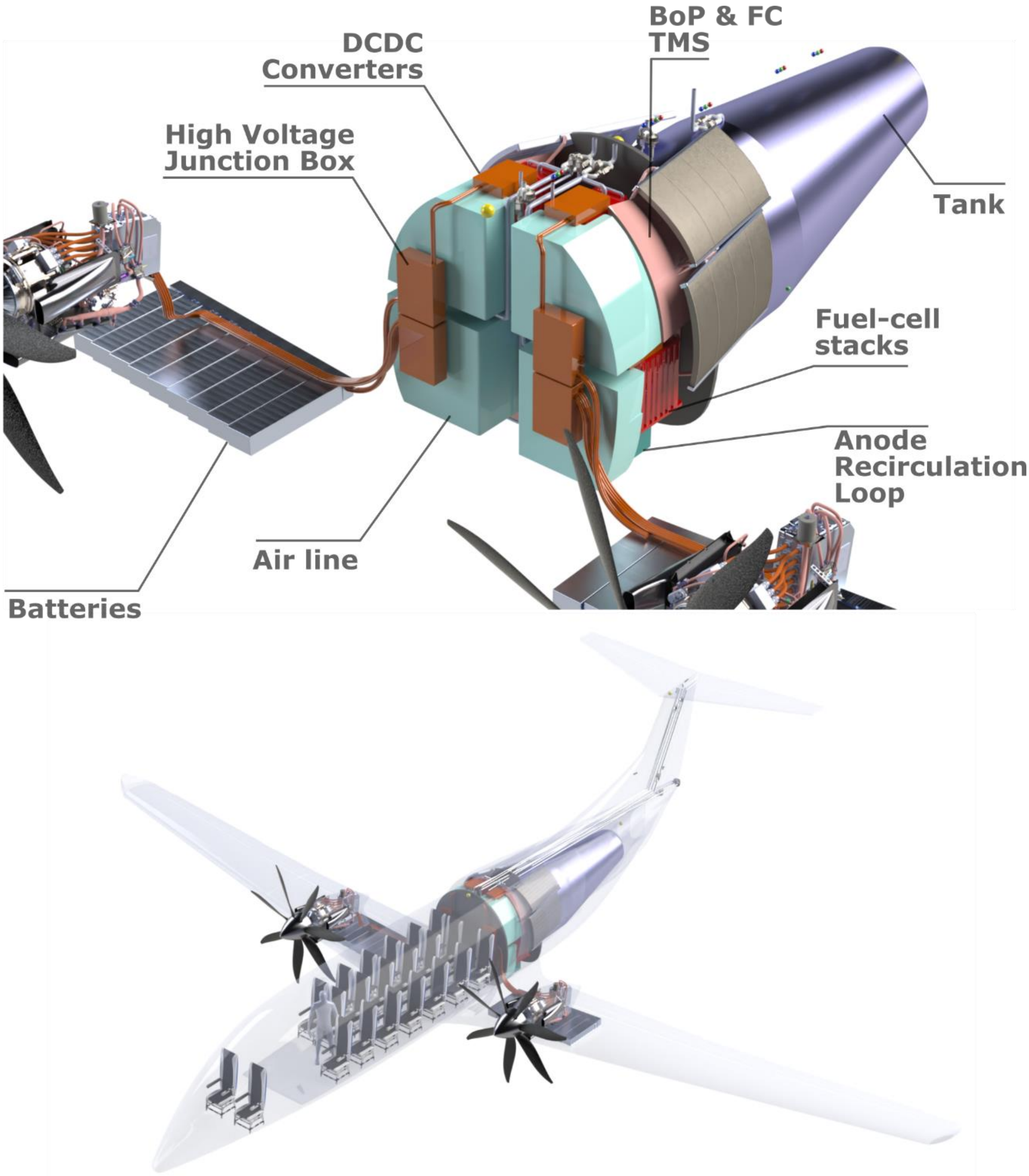


Figure 6 - CS-23 NEWBORN integration.

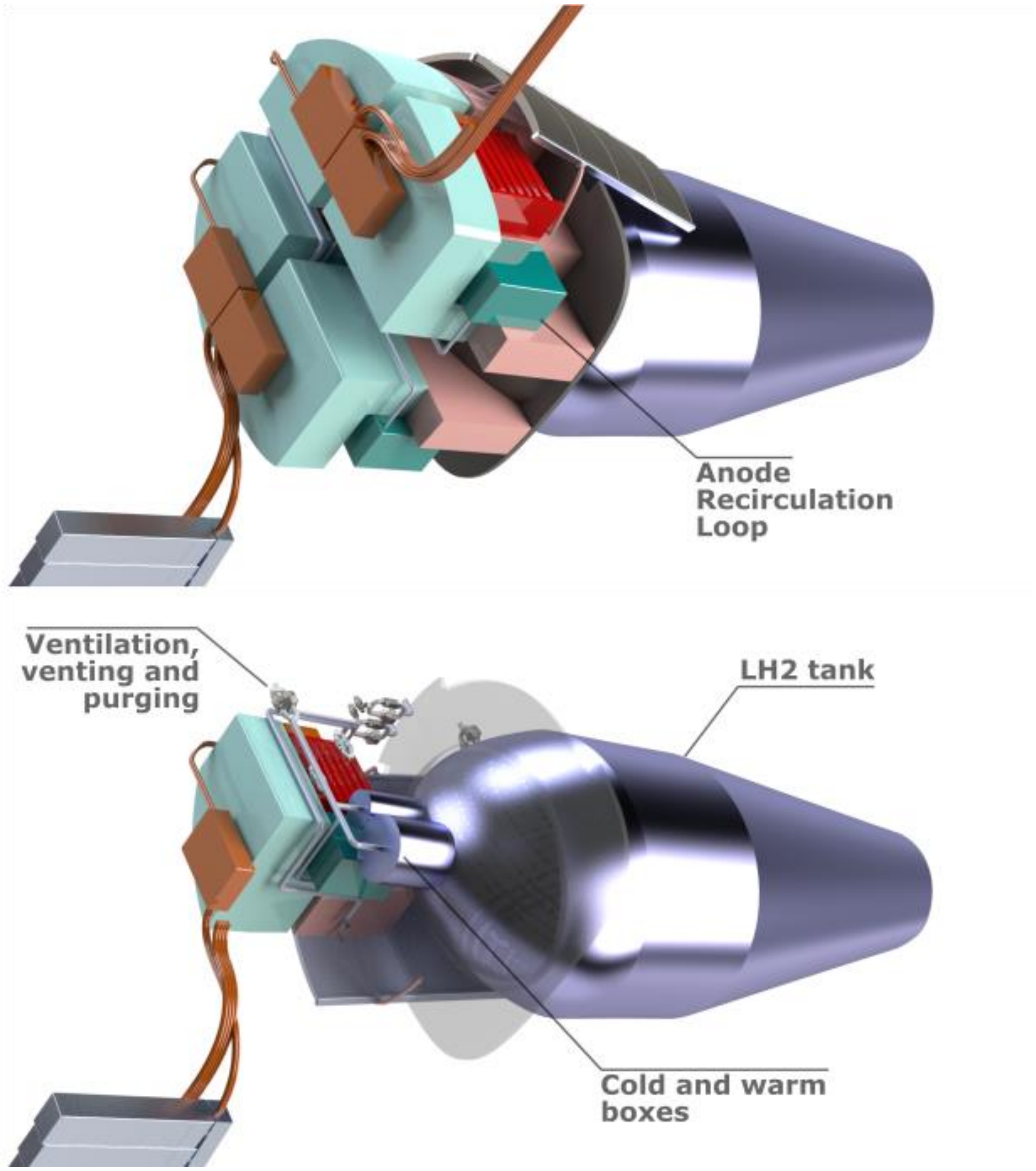


Figure 7 - Up: additional view; Down: isolated single FCPSS, and details of the HSSS.

The NEWBORN system needs to breath air, a substantial amount of it, and for various functions. The largest need is for the cooling of the FCPSSs, reflected by the four main inlets wrapped along the fuselage, seen in Figure 8. The battery thermal management together with the propulsion thermal management are rejecting their heat within the nacelle, with the ground demonstrator design using three different inlets. The battery thermal management system radiator is placed behind the lower central inlet, increasing its size compared to the ground demonstrator version. Finally, the oxygen fed to the fuel cell cathode is taken from the atmosphere through each inlet on the wing root fairing left and right, connected through a duct to the air line subsystem. All these intakes recuperate some amount of the upstream dynamic pressure, limited by the influence of either the fuselage boundary layer or the propeller downwash. De-icing and water & particle rejection systems are not represented.

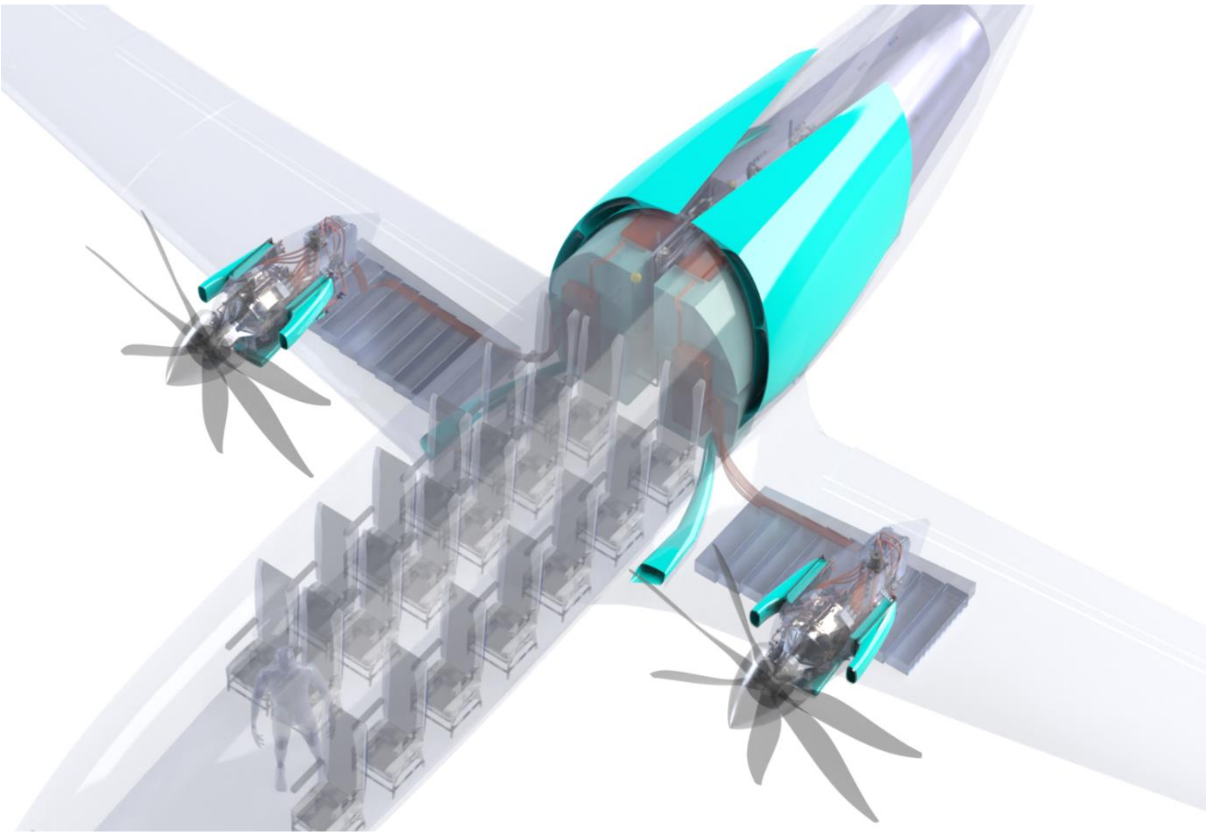


Figure 8 - CS-23 NEWBORN air intakes.

3.3 CS-25 HERA

The CS-25 HERA (Figure 9) is equipped with two parallel hybrid power plants located in two underwing nacelles. The parallel hybrid electric propulsion (one per side) consists in one thermal and one electric engine assuming target technology for EIS 2035. CS-25 HERA 80 passengers at 30'' seat pitch in a 5-abreast cabin configuration, with underfloor baggage compartment. The aircraft configuration has a higher aspect ratio wing with respect to the ATR72, structurally supported by the struts but the wingspan is limited less than 36 m to allow operation within airport gate size C.

Table 6 - CS-25 HERA specifications

Discretisation of the FCPSS	2x6
Total number of propellers	2
Total net power FC (MSL)	2880 kW
Total net power Batteries	1500 kW
Total shaft power (MSL)	2200 kW
LH2 capacity	600 kg

Figure 9 - CS-25 HERA airframe.

An integration effort has been conducted in collaboration with HERA. Specifically, the current assumption for the fuel cell installation on the CS-25 HERA includes two modules, with each module occupying an approximate volume of 3.13 m³. Considering the volume reductions achieved in the NEWBORN project, as summarised in Section 3.1, the FCPSS reaches a power density of 459.5 kW/m³.

The design assumes that the two modules are installed on independent lines, one on each side of the aircraft, providing a total power output of 2.88 MW. This configuration includes 6x2 FC stacks, organised in 2 superstacks (1x3 stack) per side (Figure 10). The FCPSS is enclosed beneath the floor in the mid-section of the fuselage.

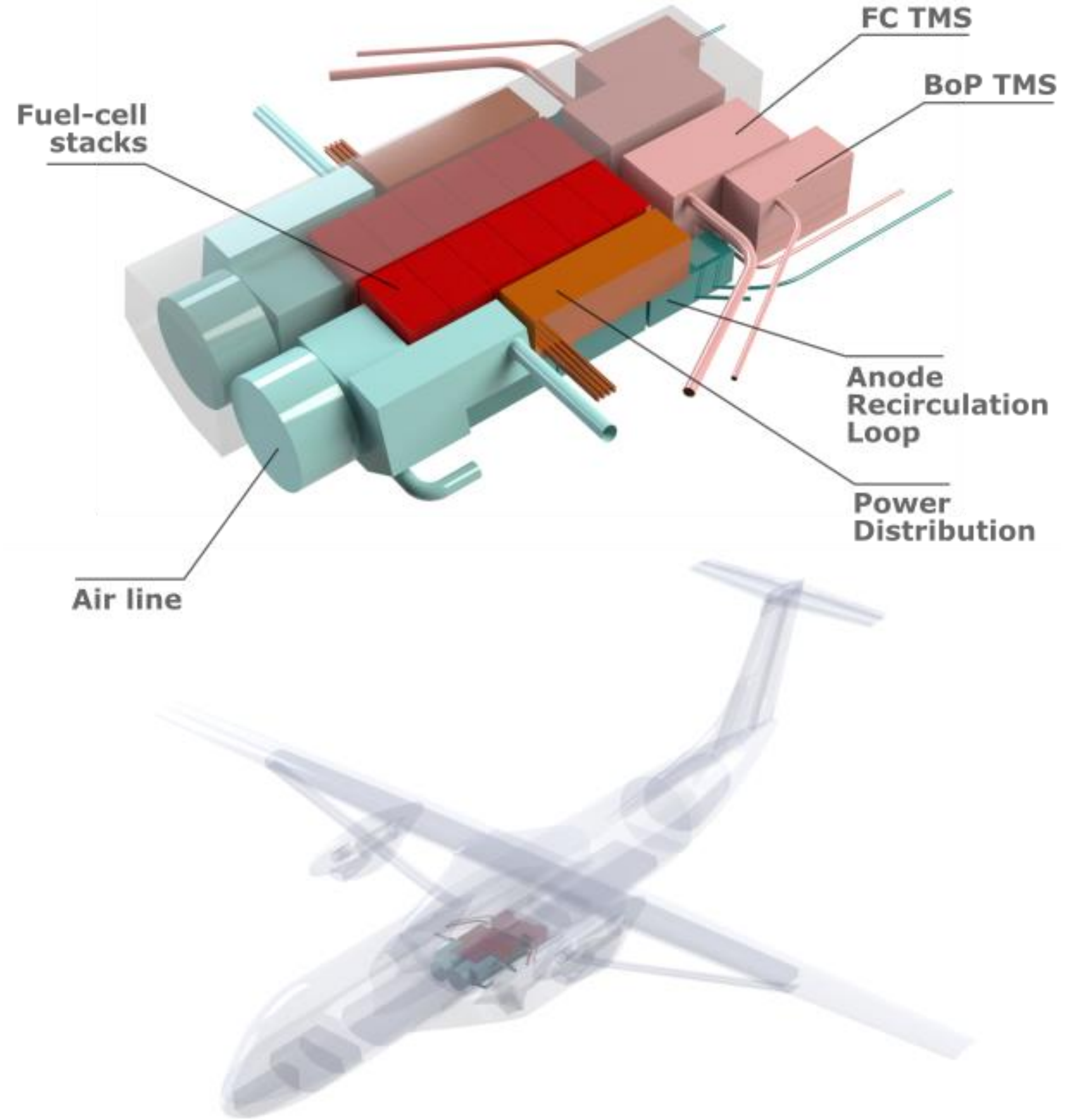


Figure 10 - FCPSS break-out in the belly fairing volume. CS-25 HERA.

3.4 CS-25 80-passenger Fuel-cell & battery aircraft

This section focuses on a CS-25 80-passenger aircraft configuration developed withing NEWBORN Project and derived from an existing aircraft (ATR72-600 aircraft configuration). Its fuselage is widened and extended with respect to current aircraft available on the market to allow for the 5 abreast seating to accommodate 80 seats and to fit all the necessary FC and battery system components.

Table 7 - NEWBORN clean-sheet CS-25 80-passenger aircraft specifications.

Discretisation of the FCPS	10x3
Total number of propellers	4
Total net power FC (MSL)	7200 kW
Total net power Batteries	1976 kW
Total shaft power (MSL)	7969 kW
LH2 capacity	845 kg

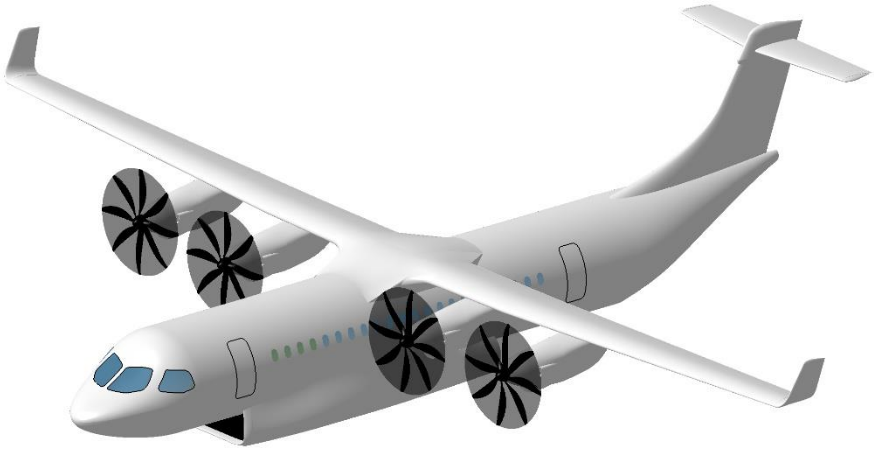


Figure 11 - CS-25 80 PAX airframe.

3.4.1 FCPSS

The current design for the fuel cell installation in the CS-25 80 PAX aircraft assumes a configuration consisting of 10x3 FC stacks, with 5 super-stacks (1x3 stack) per side. These modules collectively provide a total power output of 7200 MW. It is further assumed that the same technologies employed in the HERA configuration (refer to Section 3.1) are applicable to the CS-25 80 PAX aircraft. Therefore, based on a power density of 460 kW/m³, the required volume to accommodate the FCPSS is estimated at 15.65 m³. Further simplifying the integration, this volume is comprised of two main elements:

1. Stacks: accounting for the volume occupied by the FC stacks (2.95 m³).
2. BoP: which includes additional components necessary for system operation (12.7 m³). Specifically, it includes the air line, anode recirculation loop (ARL), DCDC converter, control systems, high-voltage junction box (HVJB), and thermal management system (TMS) without the heat exchanger (HX).

Figure 12 illustrates the design of the FCPSS, detailing the volume allocated for both the stacks and the BoP.

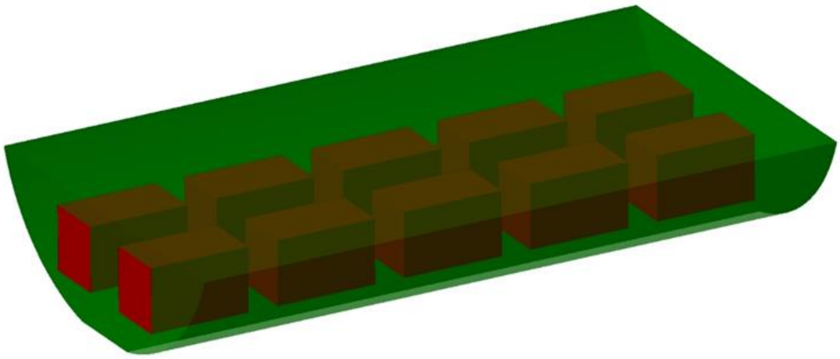


Figure 12 - FCPSS volume for CS-25 80 PAX (superstacks in red, BoP in dark green).

The FCPSS was positioned within the fuselage, located beneath the passenger seats. The volume of each superstack (1x3 stack) is 0.295 cubic meters, resulting in a total of 2.95 cubic meters for ten superstacks, as reported earlier. Figure 13 demonstrates the integration of the FCPSS within the fuselage of a CS-25 80 PAX.

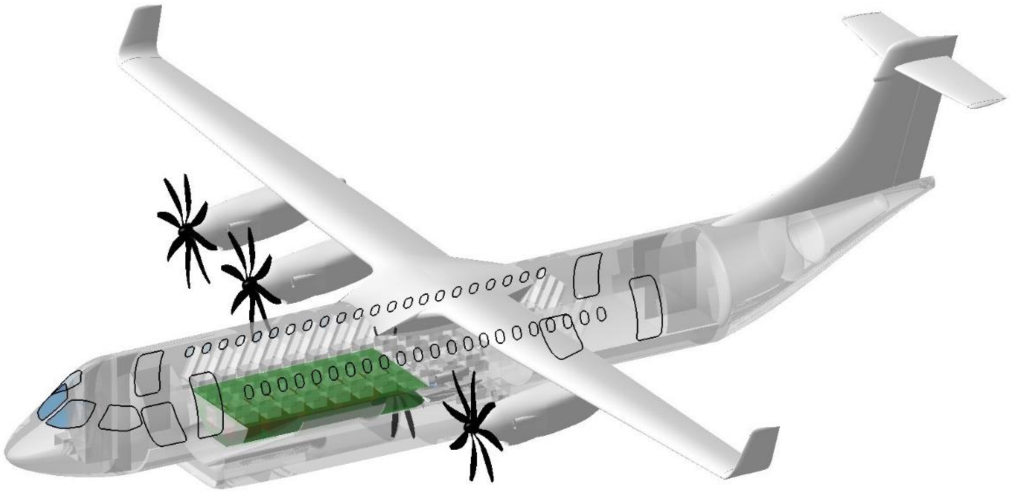


Figure 13 - Integrated representation of FCPSS within CS-25 80 PAX.

3.4.2 Radiators

A radiator design similar to that of the CS-23 aircraft is introduced along the belly of the airframe. The total radiator surface area was estimated based on the NEWBORN requirement per FC stack and heat exchanger core characteristics used in the project so far. Considering the total number of 30 FC stacks installed in the CS-25 80-passenger aircraft, the final area of heat exchangers is estimated to be slightly above 20 m². This total area was split and distributed on both sides of the aircraft, ensuring balanced thermal management and structural integration (Figure 15).

The air intakes were positioned below the aircraft, integrated into the belly fairing. This placement should ensure reduced aerodynamic interference while effectively serving the cooling requirements. Each intake and outlet pair were positioned on opposite sides of the aircraft, with each side dedicated to its respective radiator.

Figure 14 - Radiators volume for CS-25 80-passenger aircraft.

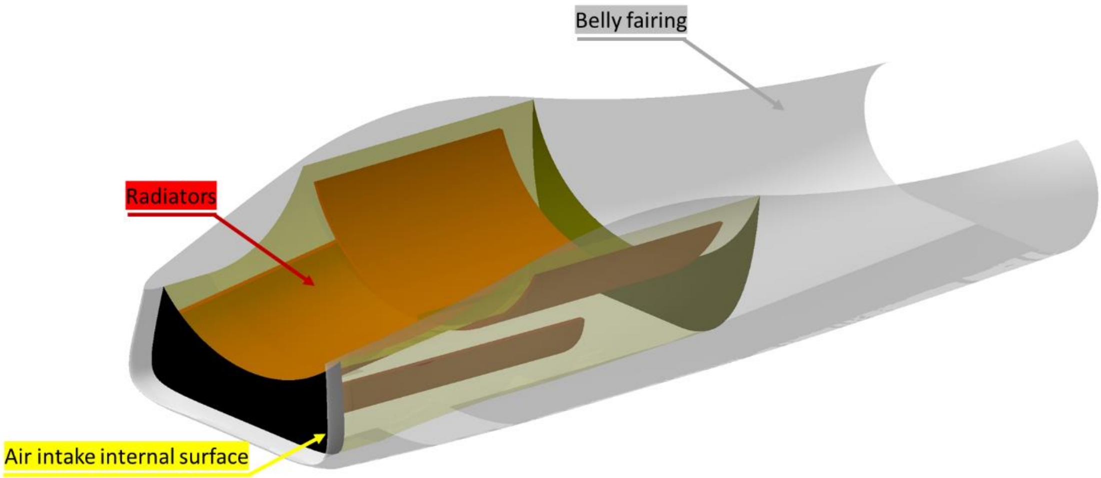


Figure 15 - Integrated representation of radiators within CS-25 80-passenger aircraft.

3.4.3 Tank, Venting and Purging Lines

Two independent conical tanks were designed, with capacities of 18.4 cubic meters and 3.7 cubic meters, respectively, for a total capacity of 22.1 cubic meters (Figure 16). The venting system was designed following the same sizing approach as described in the previous sub-section.

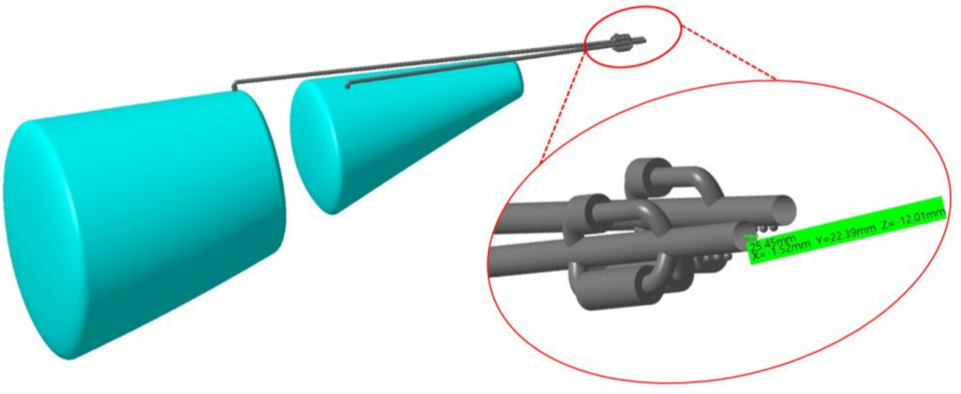


Figure 16 - CS-25 80 PAX hydrogen fuel tank and venting system design.

Figure 17 illustrates the integration of the tanks and the venting system within the CS-25 80-passenger aircraft configuration.

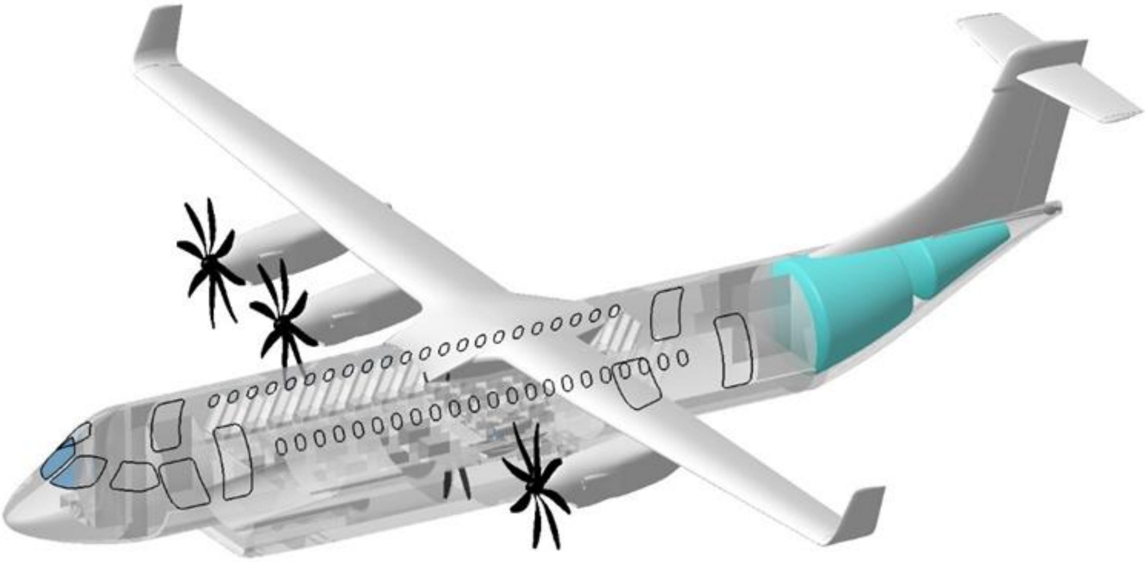


Figure 17 - Integrated representation of fuel tank within CS-25 80-passenger aircraft.

3.4.4 Battery System

Using the same battery characteristics as in D1.1[1], i.e. a power density of 1.5 kW/kg and an energy density of 0.25 kWh/kg, and the battery performance also described in that same document, the final volume of batteries is derived and integrated in the airframe as shown in Figure 18.

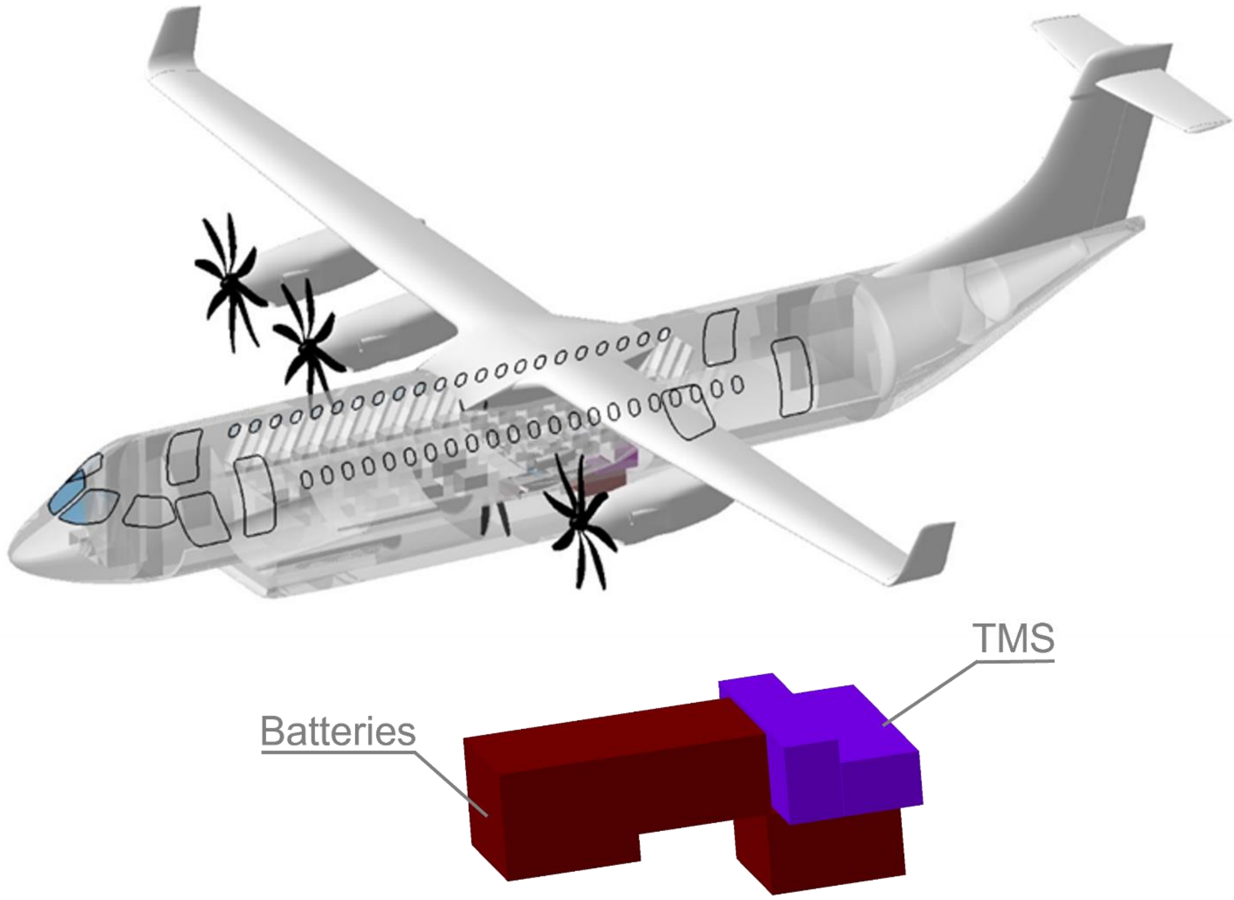


Figure 18 - Battery System integration, CS-25 80-passenger aircraft.

3.4.5 Propulsion System

The 1 MW electric motor envelope from the CS-23 platform was adapted to meet power requirements of CS-25 80-passenger aircraft using scaling defined by the following relationship:

$$P = C_m \omega_r d_r^2 l_r$$

where P is the motor's power, C_m is the utilization factor, ω_r is the rotational speed, is the rotor d_r diameter, and l_r is the rotor length. In this document, it was assumed that the motor technology of the baseline motor and of the one installed in the 80-passenger platform does not vary. Similarly, the rotational speed of the motor is kept constant. Thus, both C_m and ω are constant.
With the aim to maximise power density, the increase in rotor diameter was prioritised over increasing the rotor length, with weights of 80% and 20%, respectively (Figure 19).

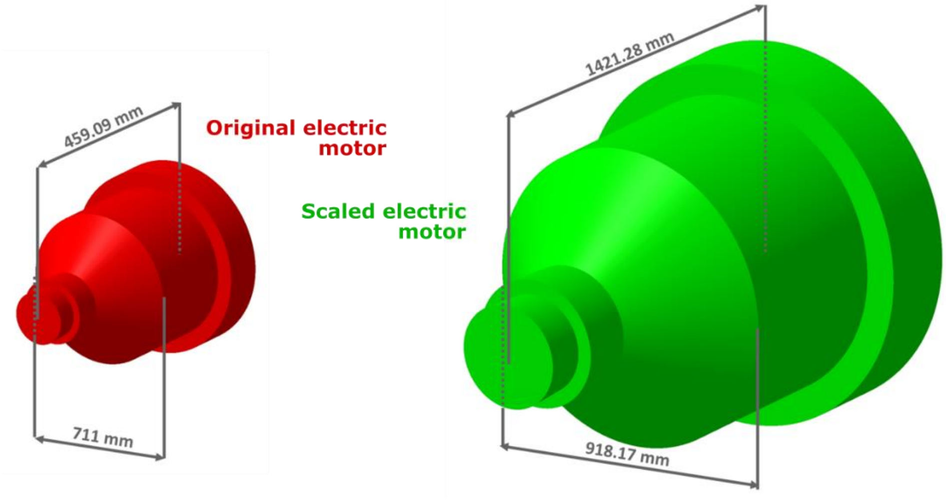


Figure 19 - 1 MW electric motor (left), version scaled for CS-25 80-passenger (right).

The TMS for the propulsion system (represented by light and dark blue volumes in Figure 20) and the inverter (violet volume in Figure 20) were scaled appropriately. Specifically, the scaling process assumed that the ratio of volume is proportional to the ratio of power. Using this relationship, the components were resized and integrated within the nacelle envelope designed for the CS-25 80-passenger configuration. For the structural aspects (i.e. the frame to which the motor and the other components are fixated), a preliminary design based on prior knowledge and established methodologies was finalised.
Figure 20 provides a detailed view of the relative positions of the components within the nacelle.

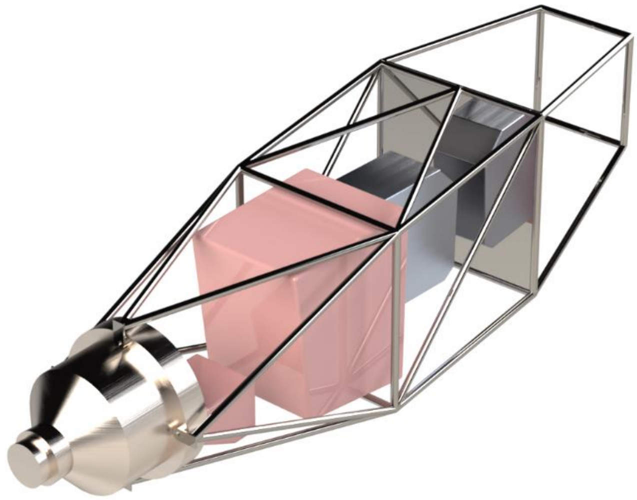


Figure 20 - Propulsion system components within the CS-25 80-passenger aircraft nacelle.

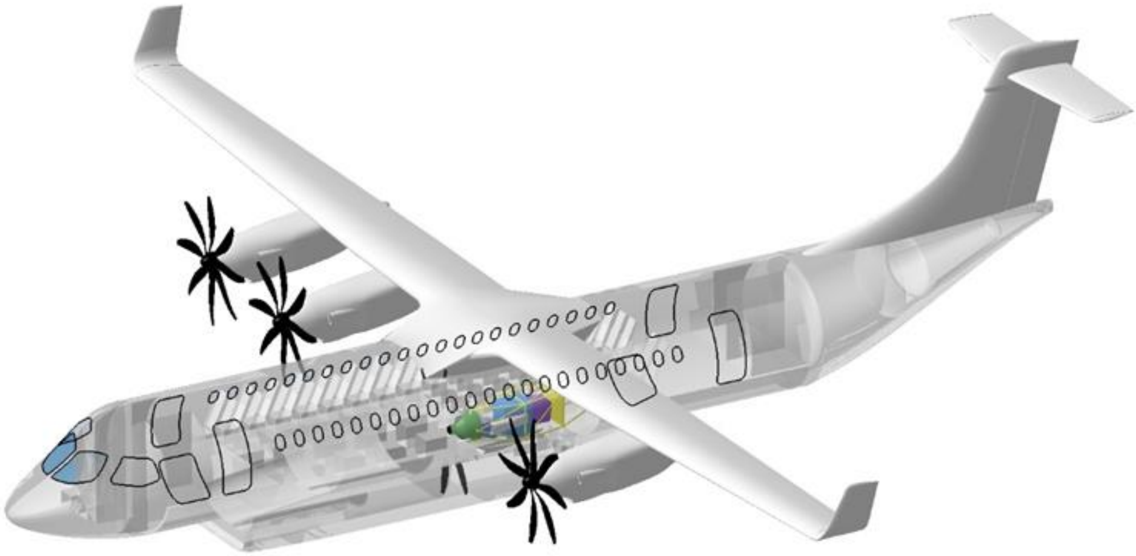


Figure 21 - Propulsion unit, CS-25 80-passenger aircraft.

3.5 CS-25 Pod configuration

An additional configuration was deemed worthy to explore for the NEWBORN system, namely a pod configuration, in which the FCPSSs and the propulsion unit are stacked together, allowing profound simplifications and optimisations, both in terms of mass and volume. In other words, this configuration could possibly present the most compact and light-weight version of the NEWBORN system, though detailed analyses were not conducted as the project primarily focuses on system integration in the aircraft fuselage. We give here a first exploration of the concept, based on engineering projections which can be achieved as of today.

Table 8 - Pod integration

Discretisation of the FCPS	2x5
Total net power FC (MSL)	2400 kW

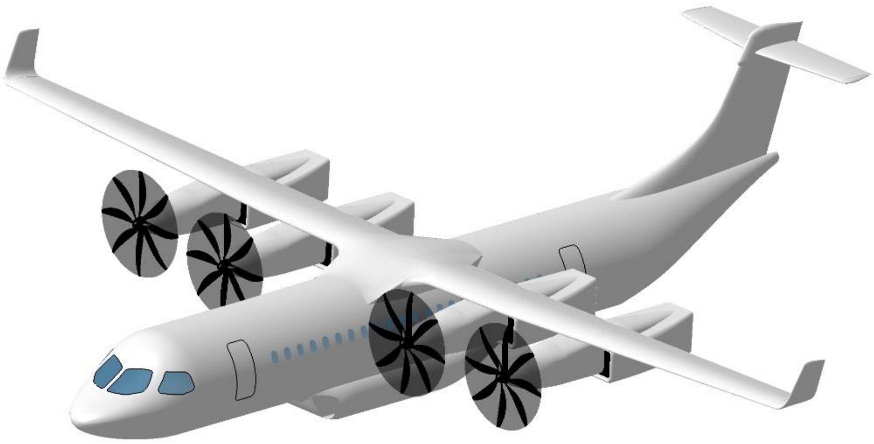


Figure 22 - CS-25 pod configuration.

Figure 23 - Pod concept.

The current design for the fuel cell installation in the pod assumes a configuration of 2x5 FC stacks per pod, arranged in two adapted superstacks (1x5 stacks instead of 1x3). These modules collectively provide a net power output of 2400 kW. The stack and BoP volumes were derived from section 3.1, resulting in two 0.4 m^3 superstacks and BoPs of 1.67 m^3, for a total volume of FCPSSs per single pod of 4.14 m^3, and displayed on Figure 24.

The rectangular radiators for the pod (Figure 24) were positioned as close as possible to the components requiring cooling, specifically the fuel cells. Their placement aims at reducing the aerodynamic impact by situating the radiators at the rear of the pod, tapering them towards the pod structure.
The total radiator surface area was estimated to be around 7 m^2 for dissipating the heat generated by the system, scaled from the knowledge developed around the CS-23 concept, and without performing dedicated aerodynamic co-optimisation. It is assumed that internal fans within the ducting are counteracting the pressure drop through the heat exchanger cores, thus decreasing their effective area. This is done at the cost of a power consumption from the total net 2400 kW. The total radiator area was then divided and distributed on both sides of the pod (Figure 24). The single air intake was designed with the aim to minimise the aerodynamical impact on the wing, resulting in the u-shaped geometry, slightly downward the central axis of the pod.

The propulsion unit was sized and integrated in the same manner as for the clean-sheet 80-passenger aircraft and can be seen integrated in the pod in the Figure 24.

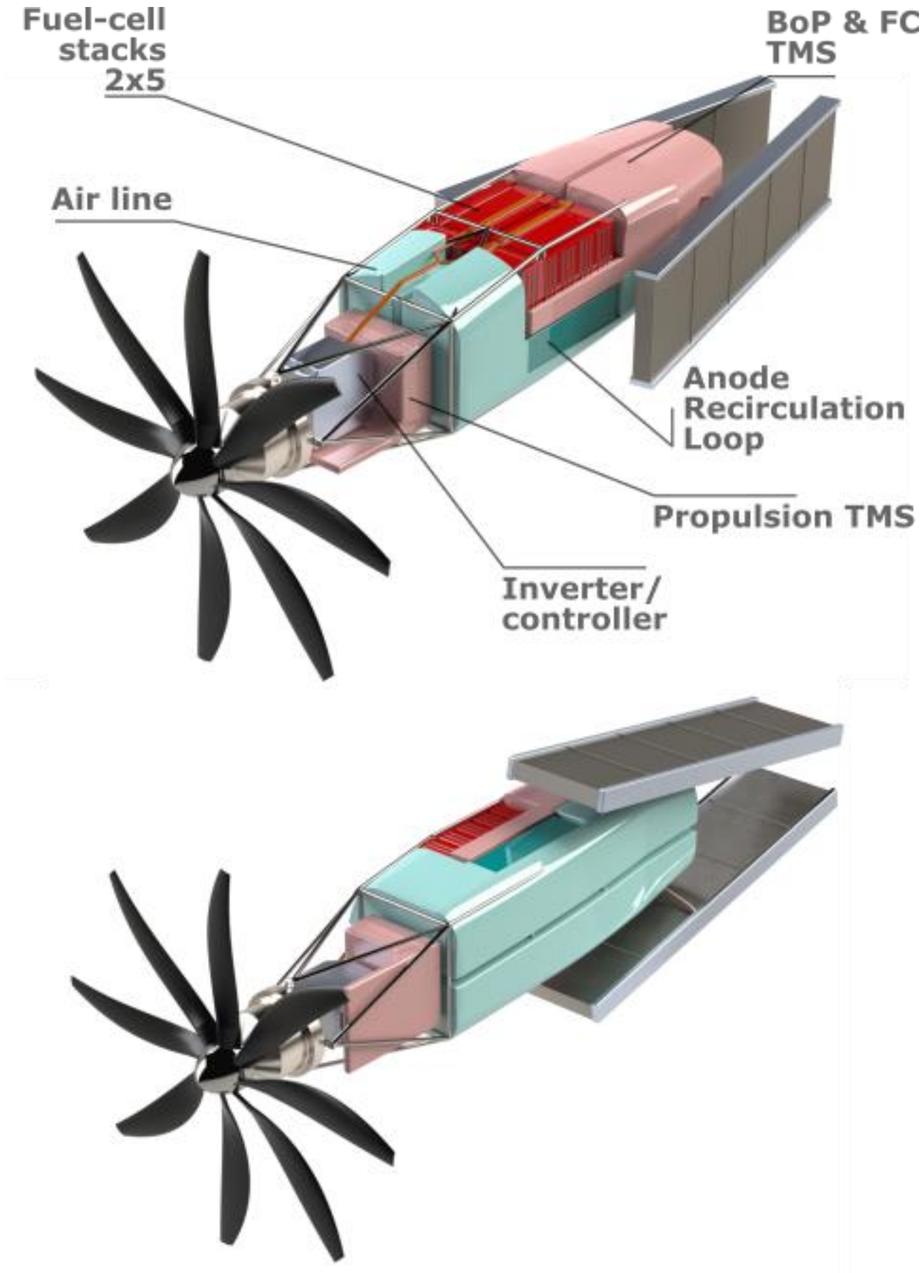


Figure 24 - Pod integration.

4 INTEGRATION OF THE SAFETY FEATURES

The present section introduces the safety features notionally for both CS-23 and CS-25, while their high-level mechanical integration is illustrated on the CS-23 platform.

4.1 Venting & purging lines integration

Venting and purging are vital functions of both the Fuel-Cell Power Source System (FCPSS) and the Hydrogen Storage and Supply System (HSSS) systems.

For the first system, the FCPS, and in normal operation, two lines are needed. The purging of the Anode Recirculation Loop (ARL) needs to happen periodically whenever the nitrogen or water concentration is too high, with a dedicated line ending with two check valves in parallel. The Fuel-Cell stack housing needs to be continuously ventilated to remove any permeated or leaked hydrogen. This second line ends with a single check valve. Additionally, and in case of emergency, the burst disk of each stack (a secondary measure to prevent housing explosion in case of multiple failures in the stack) is vented out through a third line, ending by another burst disk and a check valve in parallel.

For the HSS, two safety lines ending with a burst disk and a check valve in parallel, are implemented.

The tank has three pressure relief components. A pressure relief valve for venting the boil-off in nominal operation; a safety relief valve in case the boil-off venting is not sufficient, leading to a rising pressure in the tank (e.g. due to physical damage to the tank or damage of the insulation); a burst disk, that serves as a last safety resort. For redundancy the safety valve and the burst disk are connected to separate vent lines. Safety line 1 is used for the nominal boil-off gases, the tank's burst disk and the cold and warm boxes vent. Safety line 2 is connected to the tank's safety valve which is set to open at a lower pressure then the tank's burst disk.

The exhaust positions of all the lines are divided into two outlet areas, indicated in the schematics of Figure 25. The first area is at the top aft of the vertical tail, where all lines that are used in normal operation of the aircraft are routed, making use of the buoyancy and diffusivity of hydrogen to exhaust as far aft and as high as possible. The second area is located at the aft tail of the fuselage, hosting all the emergency lines.

These lines and components are illustrated on the CS-23 integration, both in the simplified schematics of Figure 25 and shown in the mechanical integration of Figure 26.

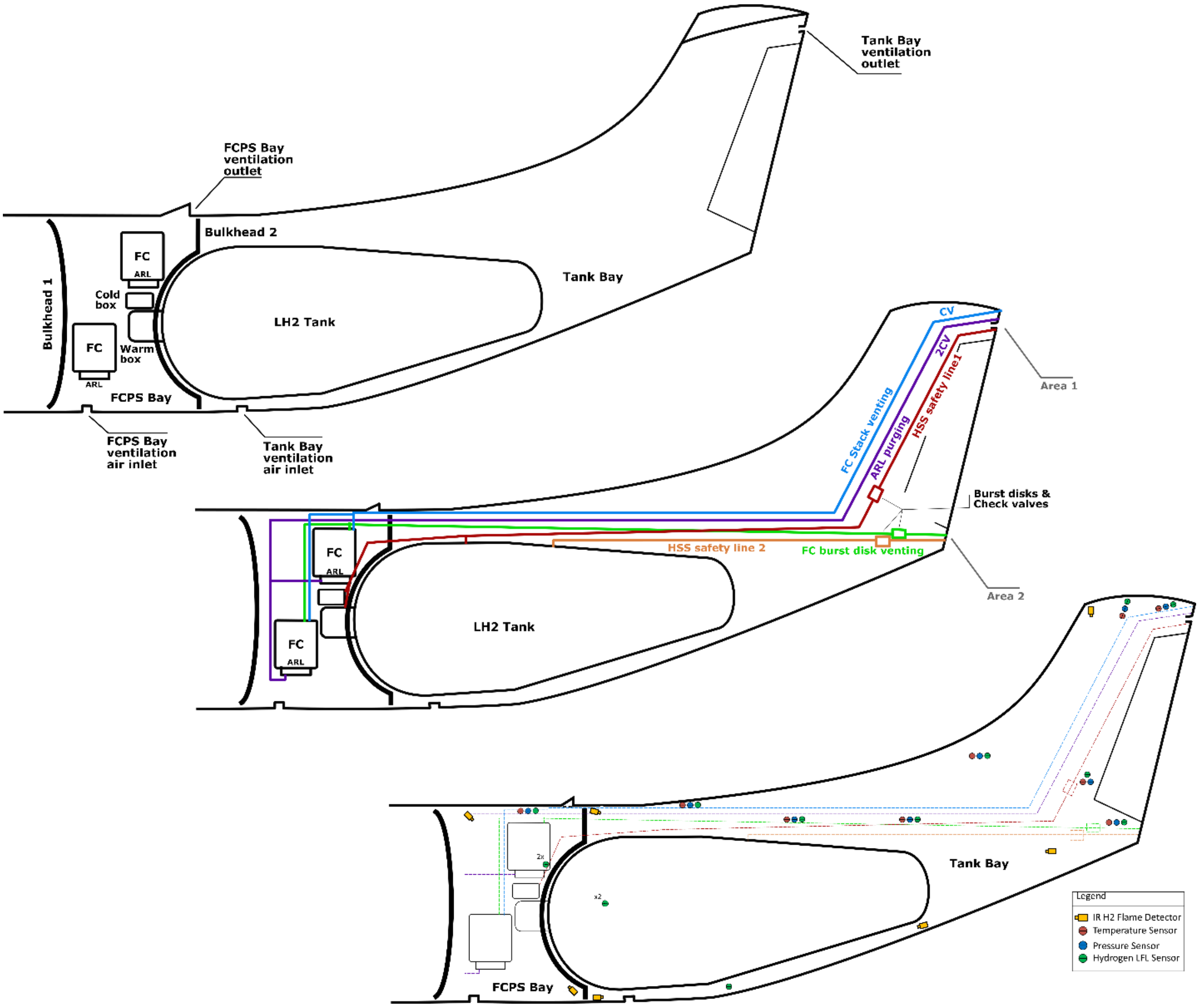
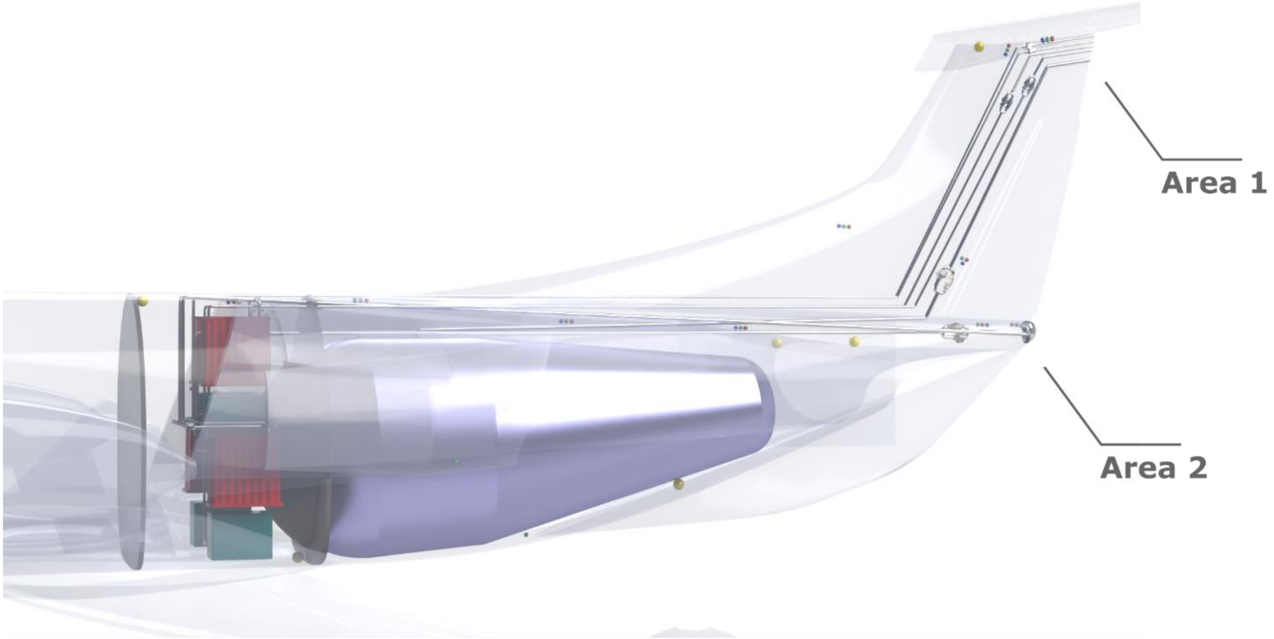


Figure 25 - Diagram of venting, ventilation, and sensing.



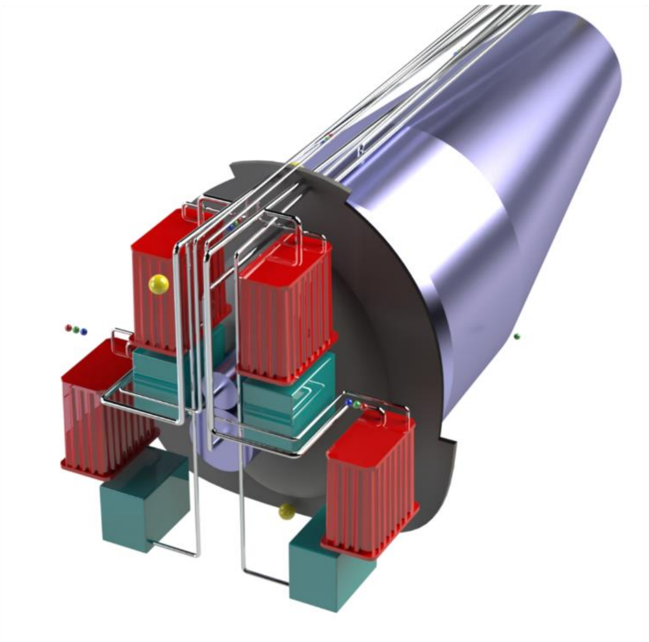


Figure 26 - Mechanical integration of the venting and purging lines, and sensors.

4.2 System ventilation

The FCPSS and HSSS are enclosed in bays which must be separated hermetically from the rest of the aircraft. These bays must be continuously ventilated to keep the hydrogen concentration well below 4% in air (the lower flammability limit) to prevent fire or explosion. This ventilation is active, i.e. consuming a small fraction of the system total power. This is especially true during ground operations, as during flight the dynamic pressure is recuperated. NACA inlets at the *bottom* of the fuselage are feeding the bays, while outlets on the *topside* of the fuselage allow the air to exit the bay. Figure 26 illustrates the simplified ventilation inlets and outlets of both bays on the CS-23 platform. Note that the high-voltage junction box, potential source of sparks, is kept outside the FCPSS bay (see the lower panel of Figure 6), connected through the pressure bulkhead to the hermetic DCDC converters, using hermetic sleeves.

4.3 Sensors and their placement

Sensing and Monitoring will be required throughout every aircraft system, both for functionality and safety. In the scope of this integration analysis report and specifically for the CS-23 aircraft, a set of various sensors have been placed within the FCPSS and the HSSS bays, fulfilling two fundamental functions. The first is to ensure safe flight and ground operations (during nominal, off-nominal and emergency conditions) by providing the pilots, ATM, and other involved parties with the right information to make the correct decisions. The second function is automation, aiming at reducing the amount of data the pilots must interpret to make safety-critical decisions in-flight.

In the present integration, a variety of four different sensor types have been chosen, in the logic of covering in a comprehensive manner all the pathways towards a future, redundant, certifiable Flight Safety System. These four sensors are hydrogen concentration sensors, pressure sensors, temperature sensors and flame detectors. They are placed in a way to be closest to the highest risk and hazard components, and areas likely to have localised stagnation, as illustrated in the schematics of Figure 25, and using the same colour scheme, represented in the 3-dimensional mechanical assembly of Figure 26.

4.4 Additional considerations

With regard to crash safety, considerations are made in relation to the impact area and in particular to the safety of the hydrogen tank. Since a crash resistant tank might require significant design protections which might reduce the aircraft's energy efficiency, it is advised that the airframe should include a deformation zone, similar to modern automotive applications, which would absorb the majority of the energy from a possible impact. The design is to be calibrated based on the expected aircraft gliding performance.

In case a crash landing is foreseen (e.g. failure of landing gear to extend, or high-speed landing), appropriate procedures would be in place to perform a safe shutdown of the fuel cell system, which includes purging of the inert gas from the hydrogen lines.

Batteries are less affected by a crash landing as they do not involve explosive material, and since their position is already segregated from the rest of the powertrain system. However structural damage might ignite a fire. For this reason, the batteries should be appropriately enclosed as to prevent the distribution of a potential fire to the cabin environment.

Note that as per current certification specifications, the fire zones are defined as the area in which the powerplant, usually constituted by a combustion engine, is located. Due to the nature of the NEWBORN powertrain, fire zones definition would have to follow different criteria based on the possibility of a fire to ignite and be sustained in any location of the aircraft. This is true for the hydrogen storage and distribution bay, as well as for the fuel cell system area (whether these are in the same space or separate). It is arguable that the batteries might involve individual casings which would prevent the spread of a fire, so that the battery area might not need to be a fire zone. Each fire zone would have to comply to the relevant certification requirements including, but not limited to, the presence of a firewall to separate from adjacent zones.

5 SAFETY: HYDROGEN LEAKAGE, VENTILATION, AND VENTING

This section describes the preliminary analyses of the aircraft and system safety from the point of view of the hydrogen leakage, permeation, and location of the venting exhausts. It introduces the ventilation concept used for the aircraft sections holding the hydrogen related equipment. An FMEA has been performed to evaluate the failure modes and effects of the aforementioned ventilation and purging lines, as well as the subsystems connected to these lines. This section will look into the possible failures of the systems carrying hydrogen and the mitigations in place or necessary mitigation measures to account for in the CS-23 miniliner concept.

As a baseline, both for the CS-23 clean-sheet design aircraft and the Reference CS-23 aircraft, it is safe to assume that the zones of the aircraft containing hydrogen will be isolated and sealed from the zones of the aircraft containing passengers, such that no hydrogen leakage could enter the cabin and represent a hazard for the occupants.

The subsystems assessed are:

a) Fuel cell stack
b) Fuel cell balance of plant
c) Hydrogen distribution
d) Hydrogen storage

5.1.1 Fuel cell stack

The hazard derived from the minor hydrogen leakage alone does not represent a significant reduction of safety margins since proper ventilation should be in place for the zones of the aircraft containing hydrogen. The leak can become a fire hazard in the presence of an ignition source. Hydrogen monitoring is present in the affected zones and the hydrogen provision can be immediately stopped (normally closed) if the concentration goes above safe levels.

Redundancy is in place in the number of fuel cells, and the number of distribution lines. A failure of a single component of the fuel cell stack subsystem leading to a leakage, cannot affect both sides at the same time as the sides have fully independent components.

Monitoring and independent mitigations are in place when assessing subsystem failure conditions, however mechanical rupture of pressure-loaded components can still occur. For this reason, it is fundamental that the material has the proper qualification based on the aircraft operational environment and sufficient safety margins are used in the design. Note that as soon as a significant leakage would be reported from the monitoring system, emergency procedures, possibly including the stack shutdown, would be in place to prevent the accumulation of hydrogen in the rear part of the aircraft. The remaining fuel cell stacks can still provide electric power.

Overall, the redundancy in fuel cells stacks and distribution lines allows for availability of electric power generation in case of a failure. Hydrogen risks are reduced with proper detection and ventilation of the bay. Fire risk is reduced for the components that are deemed as possible sources of ignition.

5.1.2 Fuel cell balance of plant

Differently from the other subsystems, the balance of plant includes rotating machines which could represent a hazard when a failure was to occur. Failures in the balance of plant mainly lead to overheating of the affected subsystem with consequent loss of function.

In particular the rupture of the hydrogen recirculation pump, in addition to degrading the operation of the powerplant system could pose a significant hazard in terms of fire since it could cause hydrogen leakage coupled with sparks. For this reason, proper reliability and maintenance procedures are required for these components.

Damage to the coolant pumps, or valves could lead to an overheating of the subsystem with subsequent stoppage of operation. Redundancy is in place in the design to ensure that the failure would not affect the entire powerplant of the aircraft, and maintenance procedures so check the components during service.

Failure of sensors could trigger a balance of plant failure but there is sufficient redundancy in the monitoring system to detect possible BoP malfunctions, allowing for appropriate action to be taken by the crew or the maintenance personnel.

Leakage, in particular of the cooling liquid, would affect the operation of the BoP and related fuel cells. However, this does not represent a direct safety hazard.

5.1.3 Hydrogen distribution

Hydrogen distribution failures can result in either leakage in the aircraft hull, or loss of hydrogen provision to the fuel cells. Valves failures, in particular the water valves, can lead to freezing of pipes and components.

In general, unmitigated hydrogen system failures would lead to accumulation of hydrogen in the hull which could create a fire hazard, that could lead to a catastrophic event. In this section, the mitigations and safety measures to prevent hydrogen accumulation in case of failure are presented.

Leakage can occur due to the failure of a valve. Leakage can be both external and internal (when the valve is supposed to be closed but hydrogen is still penetrating). Leakage outside the distribution system will cause gaseous hydrogen to accumulate in the aircraft bay. Proper monitoring and ventilation are in place to prevent unsafe levels of hydrogen to accumulate. To mitigate the risk of the hydrogen distribution piping rupture, associated with rapid increase of hydrogen concentration, dual-walled vacuum insulated pipes are assumed. The small hydrogen leakage itself does not represent a hazard in absence of a fire ignition source if it occurs in minor quantities. A reasonable ventilation of the hydrogen zones is not effective against significant hydrogen leakage. For this reason, fire protection measures will be in place (grounding of components, fire sleeves, insulators) to limit the possible ignition sources. The monitoring system is in place to detect when unsafe levels of hydrogen are reached in the aircraft hull.

Note that as soon as a significant leakage would be reported from the monitoring system, emergency procedures, possibly including the stack shutdown, would be in place to prevent the accumulation of hydrogen in the rear part of the aircraft. A burst disk is present to quickly purge all the hydrogen in case of need.

Valves stuck open could lead to a waste of hydrogen since the excess would be vented. Valves stuck close would simply prevent the proper functioning of the hydrogen distribution system, hence turning off the fuel cells. Note that each side of the aircraft has an independent set of valves, such that no single valve failure would lead to a total loss of fuel cell electric power provision.

Hydrogen pressure is measured in the distribution system such that a failure in the pressure regulation valves can be detected and mitigated. This might include purging/venting if the pressure is too high, or increasing the hydrogen pressure in the opposite case.

Overall, the hydrogen distribution system has high integrity when it comes to pressure regulation of the system. Multiple venting and safety lines are present to deplete the excess pressure buildup which could potentially create an unsafe concentration of hydrogen (if there is a leakage). Fire ignition sources such as electrical components would also be protected with proper insulation and grounding to prevent sparks. The bay is properly ventilated.

5.1.4 Hydrogen storage

Failures of the pressure vessel would lead to a significant amount of hydrogen being introduced in the aircraft. For this reason, the design is made to prevent such an occurrence to happen. The following section will describe the measures in place to reduce the risk of a hydrogen fire due to hydrogen storage failures.

The primary safety mitigation of major leak relies on dual containment of hydrogen, easily achieved by dewar tanks, and possible with the foam-insulated tanks by adding additional hydrogen barrier (not holding pressure) with proper ventilation.

Cracks and tear are caused in time by thermal cycles. These faults would be detected during periodic checks to the hydrogen system. Where these are non-detectable, the parts should be replaced at regular intervals. Hydrogen pressure and concentration monitoring are in place to detect early cracks and leakage from the hydrogen storage and conditioning subsystems. Temperature sensors are also present to detect possible leakage, contributing to the fast response of the emergency procedures.

Failure of the inner tank electrical evaporators could lead to an erroneous pressure being fed in the system. The failure would be easily detected by the pressure sensors and the excess pressure depleted from the venting valves through overpressure safety valves. Lower pressure in the system could reduce the available hydrogen in the fuel cells, reducing the electric power provision. Note that the electric and passive evaporator can offer some redundancy in case one of the two fails. Maintenance procedures would be used to detect and correct potential evaporator failures.

Erroneous or no signal from sensors in the hydrogen storage subsystem would trigger safety measures from the monitoring system, possibly leading to the system purging all hydrogen. Depending on the sensor that malfunctions, different safety procedures are in place to either reduce the hydrogen pressure or completely empty the tank (in extreme cases). Pressure and temperature sensors offer redundancy in the detection of potential malfunctions of the system or structural failures such that data can be compared.

Damage to the supporting structure of the tank could lead to improper hydrogen conditioning and pressure regulation. This failure could also affect the measure of the hydrogen level in the tank and change the balance of the subsystem. Multiple attachment points are used to mount the pressure vessel and conditioning system in the aircraft such that no single failure can affect the vessel's position.

Welding failures that would affect inner and outer tanks would be detected by pressure and temperature sensors, which would trigger the emergency response. The tank would be depressurized in a safe manner to prevent the creation of an explosive environment.

Assuming proper fuelling procedures are in place, failure to the refuelling lines would only limit the ability to fill the tank, hence does not represent a hazard.

All in all, although the hydrogen storage subsystem is a high-pressure vessel, multiple provisions are in place to prevent the tank from explosion or large hydrogen leakage. Redundant monitoring is present, meaning any failure would be detected by pressure, temperature, or hydrogen concentration sensors. Multiple purging lines, including a burst disk are in place to reduce a sudden buildup of hydrogen pressure in the system.

6 REFERENCES

ID	Reference	Title	Revision
[1]	NS-WP01-SE-NO-DEL-100001	D1.1 Aircraft-level requirements summary	02
[2]	NG-WP07-SE-NO-DEL-000002	D7.5 Stack mechanical integration design description	00
[3]	NS-WP01-SE-NO-DEL-100002	D1.2 Regional and Commuter aircraft integration concepts description	00
[4]	NG-WP01-SE-NO-DEL-100001	D1.15 Preliminary safety analyses report	03
[5]	D1.2, UNIFIER19	The design framework for an NZE 19-seater	

7 GLOSSARY

ARL	Anode Recirculation Loop
BS	Battery Subsystem
COTS	Component of-the-shelf
CS	Certification Specification
DEL	Deliverable
FCPSS	Fuel Cell Power Source System
FMEA	Failure Mode and Effect Analysis
GH2	Gaseous Hydrogen
HEA	Hybrid Electric Aircraft
HERA	Hybrid-Electric Regional Architecture
HVJB	High Voltage Junction Box
HPA	Hydrogen Powered Aircraft
HSSS	Hydrogen Storage and Supply System
HV	High Voltage
HX	Heat Exchanger
ID	Identifier
LH2	Liquid Hydrogen
LRU	Line-Replaceable Module
MSL	Mean See Level
NEWBORN	NExt generation high poWer fuel cells for airBORNe applications
PC	Project Coordinator
PDS	Power Distribution Subsystem
PS	Propulsion Subsystem
TL	Technical Leader
TMS	Thermal Management System
WP	Work Package