DOI: 10.13009/EUCASS2023-602
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Overall Parametric Design and Integration of On-Board Systems for a Hydrogen-Powered Concept Aircraft

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Abstract
During the aircraft conceptual design phase, overall on-board systems design is performed to estimate relevant systems design parameters such as mass, power consumption, and redundancies. In this paper, overall systems design is conducted for a hydrogen-powered regional concept aircraft with ten fuel cell-powered propulsion units. As a first step, the results of the applied in-house overall on-board systems design framework *GeneSys* are verified with available *ATR 72* data. Next, an electrified state-of-the-art systems architecture is defined to enable integration into the hydrogen aircraft. Moreover, concept studies for electric power supply are conducted, including the implementation of high voltage direct current and emergency power supply strategies. The results show an increase of the on-board and propulsion system mass for the hydrogen aircraft by about 61 % compared to a similar kerosene-powered aircraft. However, despite of a heavier systems architecture, in-flight carbon oxide emissions are eliminated.

1. Introduction

With the introduction of hydrogen-powered concept aircraft, in-flight carbon oxide emissions can be eliminated [13], complying with the targets defined by the European Union in the *Flightpath 2050* [11]. However, the feasibility of such hydrogen aircraft still needs to be evaluated. This also applies to the on-board systems (OBS) architecture, due to the storage of, for instance, liquid hydrogen in dedicated tanks or the integration of fuel cells and their peripheral systems (e. g. cooling and air supply) [16, 36]. In case the hydrogen aircraft is operated by fuel cells, the impact on OBS increases significantly due to the following aspects:

- Electrification of OBS due to the unavailability of bleed air
- Power for OBS is provided by (hybrid) fuel cell systems
- New concepts may be required for emergency power supply

As part of the aircraft conceptual design phase, overall systems design (OSD) is performed to identify and define an optimal systems architecture. To this end, rapid concept studies are conducted to estimate relevant system design parameters such as, among others, mass, power consumption, and compliance with architectural requirements (redundancy). For this purpose, the Institute of Aircraft Systems Engineering (FST) at Hamburg University of Technology (TUHH) has been developed the *GeneSys* software framework for OSD, providing high-fidelity and physics-based approaches for systems sizing [15, 26, 27, 30].

In this paper, the OSD framework is applied to present an approach for defining the systems architecture of a fuel cell-powered hydrogen aircraft. The approach consists of four relevant steps. First, the sizing results are verified by comparing them to an existing aircraft; in this case an *ATR 72*-like aircraft model. Second, the systems architecture is updated to a state-of-the-art (SOA) concept. Third, the updated systems architecture is electrified and technology functions for a future entry into service (EIS) are considered. Last, the electrified systems architecture is integrated into the hydrogen aircraft. In addition, further concept studies are performed on the defined systems architecture. Since hybrid fuel cell systems generate direct current (DC), it is proposed to integrate high voltage direct current (HVDC) as main voltage specification for the electric power supply system (EPSS). Furthermore, emergency power supply concepts are discussed. The final composed systems architecture provides an estimation on the impact of a fuel cell-powered regional hydrogen aircraft on the OBS design, using system mass and power consumption as evaluation criteria.

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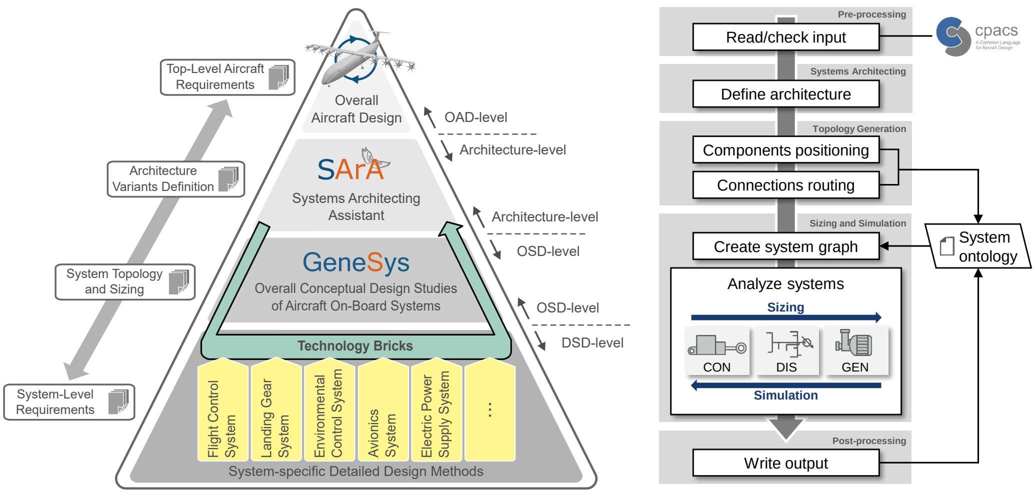
2. Overall systems design framework

To create and analyze OBS architectures by performing technology concept studies during aircraft conceptual design phase, different levels of abstractions and disciplines need to be considered to enable a seamless process chain [30]. These levels are overall aircraft design (OAD), systems architecting, OSD, and detailed systems design (DSD) as shown in fig. 1(a).

First, aircraft characteristics, geometry, and top-level aircraft requirements (TLAR) are defined at OAD-level [30]. On this level, OBS are typically considered based on regression functions and statistical methods [15]. Second, at architecture level, OBS architecture variants are created and down-selected for which the in-house *Systems Architecting Assistant* (*SArA*) methodology is used [30]. Third, a geometrical 3D topology is created for the down-selected architectures and OBS are preliminarily sized at OSD-level based on the high-fidelity, physics-based *GeneSys* software framework [15, 26, 27]. Finally, the most promising architecture variants are analyzed in further detail at DSD-level based on high-fidelity models and transient simulation, which require high development times and efforts [15].



(a) Different levels and disciplines of the conceptual aircraft design phase (b) Process diagram for OSD

Figure 1: Overall systems design framework

This paper focuses on the OSD framework consisting of *SArA* and *GeneSys* for performing concept studies based on the underlying process as shown in fig. 1(b) [15]. The process starts with a pre-processing step during which inputs are checked. The inputs include TLARs and aircraft geometries provided by the standardized Common Parametric Aircraft Configuration Schema (CPACS), which is being developed by the German Aerospace Center (DLR) [14]. As second step, *SArA* is used for exploring the vast design space during conceptual design, resulting in generated logical OBS architecture variants [30]. This also includes architecture validation and evaluation, reducing the design space to only promising architecture variants [30]. The selected variants are then provided to *GeneSys*. Next, the geometric 3D topology of these architecture variants is created. This includes defining the positioning of components and the routing of connections between components, which is based on generic, knowledge-based design templates [15, 27]. To verify geometric positions, systems topology is visualized (cf. fig. 11) [15]. Last, architectural information about OBS as well as geometric positions are used as input for preliminary systems sizing, taking into account interdependencies on system level. Based on the geometrical parameters, the *GeneSys* software framework is used to assess the remaining OBS architecture variants based on, among others, mass and power consumption [15, 27].

3. Overall aircraft design results of the hydrogen concept aircraft *ESBEF-CP1*

By applying the OSD framework, a suitable OBS architecture is defined and preliminarily sized for the hydrogen-powered regional concept aircraft *ESBEF* (german acronym for *Development of Systems and Components for Electrified Flight*) *Concept Plane 1* (*CP1*) [30]. The *ESBEF-CP1* has been derived from an *ATR 72*-like aircraft model and is shown in fig. 2. In the scope of OAD, the geometry and the TLARs (cf. table 1) are provided by the German Aerospace Center (DLR).

The *ESBEF-CP1* is characterized by ten disruptive, stand-alone propulsion units (Pods) which each include hybrid fuel cell systems and necessary peripheral systems [30]. In this context, peripheral systems consist of the

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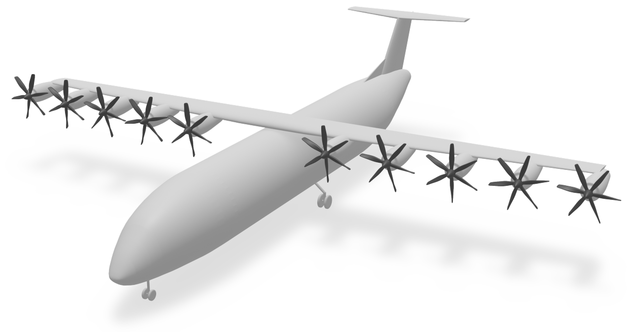

Figure 2: Hydrogen-powered concept aircraft *ESBEF-CP1* [30]

cooling system, the hydrogen supply system, the air supply system, and the electric power management and distribution unit (PMAD), which supplies electric power to the power train (primary power) and to on-board consumer systems (secondary power) [15]. It is assumed that the fuel cells in each Pod can provide up to 400 kW of electric power.

The hydrogen for the fuel cells is stored as liquid hydrogen (LH2) in two cryogenic tanks located in the aft fuselage (cf. fig. 11). However, to transport a similar payload as an *ATR 72*, the fuselage is widened, resulting in a 5-abreast seating configuration [30]. Since the *ATR 72* has a 4-abreast configuration, the cabin itself is shortened, maintaining a seating capacity for 70 passengers (cf. table 1). The cabin layout of the *ESBEF-CP1* includes a galley and a lavatory in the aft section of the cabin. Furthermore, two separate cargo compartments are positioned below the aircraft cabin: one between the nose landing gear (NLG) and the main landing gear (MLG), and the second, smaller one between the MLG and the LH2 tanks. An avionics compartment is located below the cockpit at the front of the aircraft, whereas the compartment for electrical distribution components is positioned in the cowling in front of the center wing box above the aircraft cabin (cf. fig. 11).

Table 1: TLARs of the *ESBEF-CP1*

Characteristic	**Value**
Year of entry into service	2040
Design range	1 000 nm
Cruise speed (Ma)	0.55
Cruise altitude	27 000 ft
Number of PAX seats	70

The *ESBEF-CP1* is developed for an EIS in 2040. Assuming a development time for the aircraft of at least five years [41], technologies, which are assumed to be available in 2030-35, and include a sufficient technology readiness level (TRL), are considered for OBS systems architecture definition.

4. Approach for systems architecture definition for a hydrogen concept aircraft

As described above, several relevant steps are performed to define the systems architecture for the *ESBEF-CP1*. The considered approach is visualized in fig. 3. First, a verification of the OSD framework is performed for this aircraft category. Hence, relevant systems of an *ATR 72* are sized with the OSD framework on the basis of an *ATR 72*-like aircraft model provided by OAD. The results are compared to internal available data for verification. Second, the systems architecture of the *ATR 72*-like aircraft model is adapted to a SOA systems architecture. The more modern architecture is integrated into the *ESBEF-SOA2025*, which is also provided by OAD for an EIS in 2025. Third, the defined systems architecture is electrified to be compatible for integration into a hydrogen fuel cell-powered aircraft, requiring an electric ice protection system (IPS) and an electric environmental control system (ECS). Furthermore, the systems architecture is projected to an EIS in 2040, considering relevant technology functions for system improvements. The electrified systems architecture is integrated into the *Research Baseline ESBEF-RB2040*. Last, the electrified systems architecture of the *ESBEF-RB2040* is integrated into the *ESBEF-CP1*.

In the following, the verification of the OSD framework and the definition of the systems architecture of the *ESBEF-SOA2025* and *ESBEF-RB2040* is further described. All TLARs of the *ESBEF* aircraft models are equal to the

DOI: 10.13009/EUCASS2023-602

ones listed in table 1. However, the *ESBEF-SOA2025* and *ESBEF-RB2040* have a 4-abreast seating configuration like the *ATR 72* (cf. section 3).

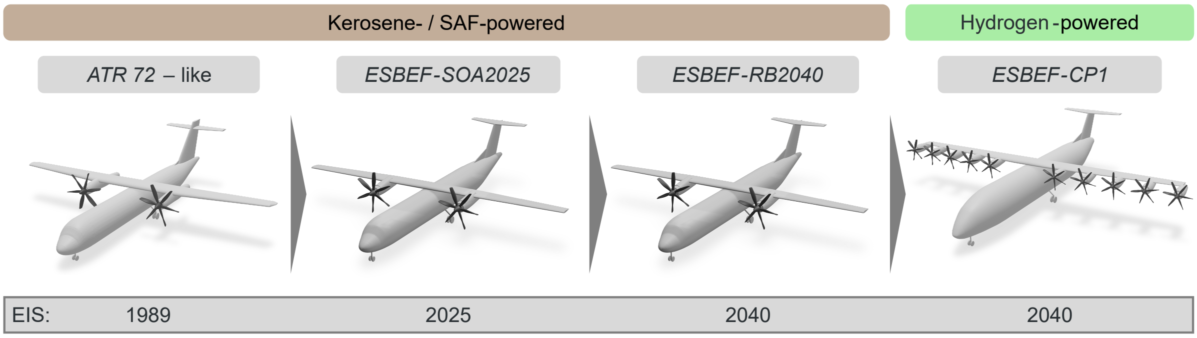

Figure 3: Aircraft models used for systems architecture definition

4.1 Verification of OSD framework based on *ATR 72* on-board systems architecture

Relevant OBS of the *ATR 72* are sized with the OSD framework and the results are compared to internal available data of the *ATR 72* for verification. The considered systems for verification are the ECS, the fuel system, the landing gear (LDG), the cabin equipment & furnishing (CAB), the hydraulic power supply system (HPSS), and the EPSS (cf. fig. 4) [1, 2].

However, due to the limited availability of reference data, mass estimations based on NASA [46] or Thorenbeek [20] are used to calculate the system mass of the CAB, the fuel system, and the LDG (highlighted with an asterisk (∗)) for comparison with the results of the OSD framework. In conclusion, the relative deviation of the system mass results lies within a range from $-10\,\%$ to $+10\,\%$, which is acceptable for OSD [29]. Thus, it is assumed that the system and component sizing laws of the OSD framework are valid for a regional aircraft.

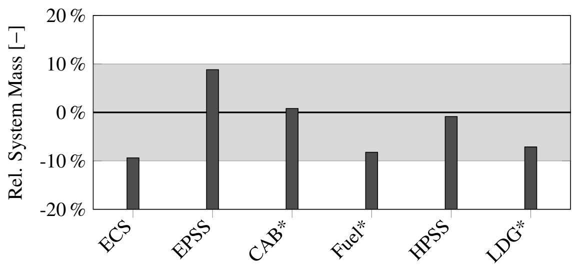

Figure 4: Results of mass estimation of relevant systems in relation to real reference data

Furthermore, system sizing is also performed for the propulsion units of the *ESBEF-CP1*. To this end, the masses of relevant *ATR 72* engine components are listed in table 2. However, the structure of the nacelle is not considered for this analysis due to limited availability of parameters.

Table 2: Mass of the *ATR 72* engine (*PW127*)

System	Mass in kg	Source
Gas turbine	480	[6]
Propeller	165	[9]
Oil and operating fluids	20	[6, 9]
Total mass	**665**	

4.2 State-of-the-art systems architecture for the *ESBEF-SOA2025*

After verification of the OSD framework, the systems architecture of the *ATR 72* is updated to a state-of-the-art systems architecture, which is derived from more modern aircraft such as the *Airbus A350* [15, 26, 27]. The definition of the

DOI: 10.13009/EUCASS2023-602

systems architecture as part of the OSD framework is described in the following. Table 3 lists the calculated systems mass results.

Table 3: Estimation of the OBS masses of the *ESBEF-SOA2025*

System	Mass in kg
Environmental control	330
Electric power supply	555
Cabin equipment & furnishing	2 400
Flight control	285
Fuel	250
Hydraulic power supply	155
Ice protection	30
Landing gear	865
Lights	95
Auxiliary power[a]	115
Ram air turbine[b]	40
Other systems	570
Total systems mass	**5 690**

[a]Accounting for the gas turbine and housing
[b]Accounting for the propeller and housing

As with the *ATR 72*, consumer systems of the *ESBEF-SOA2025* are supplied by both hydraulic and electric power. However, both of these supply systems are significantly adapted compared to the systems of the *ATR 72* [2]. Two electrical networks (E1 and E2) are defined for the EPSS, each powered by one variable frequency generator (VFG) (cf. fig. 5). To comply with the electric power demands of the consumer systems and the required redundancies [15, 35], a single VFG needs to be able to provide a constant electric power of up to 40 kVA. The main voltage specification is assumed to be 200/115 V three-phase alternating current (AC). Three transformer rectifier units (TRU) (including one TRU for emergency power supply) are installed to supply power to the 28 V DC network. One inverter is integrated to provide three-phase AC in case of an emergency (e.g. failure of AC power supply). Furthermore, to comply with extended twin operations regulations (ETOPS), an auxiliary power unit (APU) is installed in the aft fuselage [10]. The APU is able to provide bleed air and powers one 40 kVA generator, providing 200/115 V three-phase AC at a constant frequency of 400 Hz, being able to replace one VFG. The flight control system (FCS) of the *ATR 72* is a partly mechanical system [2]. Hence, the operation of the ailerons, elevators, and rudder requires no significant electric power [31]. However, the defined FCS of the *ESBEF-SOA2025* is partly electrified (cf. fig. 5), creating the urge to integrate a ram air turbine (RAT). The RAT is connected to a 30 kVA generator that can provide emergency power at a voltage level of 200/115 V three-phase AC. Furthermore, two lithium-ion batteries [3] are integrated into the system architecture of the EPSS, supporting the RAT with providing emergency power, for example, during the approach when the incoming air velocity is reduced. It is assumed that the batteries need to be capable of producing 30 kW of electric power for 15 minutes. For the *ESBEF-SOA2025*, the energy density of the batteries is assumed to be 150 Wh/kg (cf. table 5) [12].

The HPSS is adapted to a single hydraulic system, powered by a central hydraulic power package (HPP), which is located in the center of the aircraft near the main landing gear [26, 42]. Both of the electric networks E1 and E2 are connected to the HPP for redundancy (cf. fig. 5). The HPP provides hydraulic power for the electro-hydraulic servo actuators (EHSA) of the FCS (cf. fig. 5), for extending and retracting the LDG, for the nose wheel steering, and for the braking system.

As shown in fig. 5, the FCS is defined as a partly electrified fly-by-wire system. The ailerons and the rudder are each controlled by one EHSA, which are powered by the central hydraulic network, and one electro-hydrostatic actuator (EHA). The EHA includes a dedicated hydraulic system and is powered electrically [26, 31]. Furthermore, the elevators are controlled by one EHSA and two EHAs. The increased redundancy is necessary because the horizontal stabilizer is not trimmable like the one of the *ATR 72* [2]. In contrast to the *ATR 72*, two spoilers are defined per wing side by OAD. Each spoiler is powered by an electro-mechanical actuator. The secondary FCS has not been adapted compared to the *ATR 72*. It is a single drive system with four flaps in total. Each of the flaps is driven by one EHSA [2].

A thermal anti-ice system is integrated for wing ice protection, using the bleed air provided by the engines. Other components that are relevant for the ice protection system, for example, the windshields and the measuring instruments, such as the pitot-static system, are heated electrically.

The ECS, the fuel system, and the LDG are adapted with minor changes. As described in section 3, an avionics compartment is defined in which the flight control computers, required for the integration of a fly-by-wire FCS, are

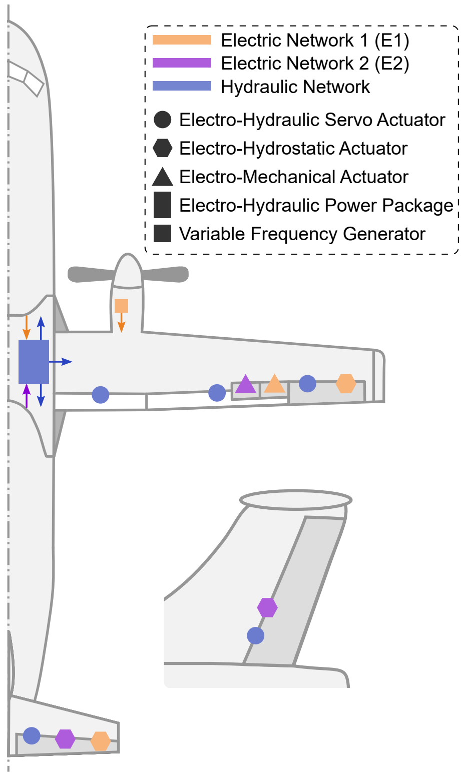

Figure 5: Architecture of the flight control system and its power supply of the *ESBEF-SOA2025*

positioned. Furthermore, an electrical compartment is integrated, containing the primary and secondary power distribution centers for the EPSS [15]. The ECS is enhanced by a ventilation and extraction system for venting these compartments. The fuel system of the *ESBEF-SOA2025* is enhanced by a third electrically powered booster pump to provide fuel for the APU. Since the HPSS is reduced to one central system, it is necessary to implement a further redundancy for the brakes of the LDG. Hence, the brakes are both hydraulically and electrically actuated [26].

The value for the entry *other systems* in table 3 accounts for systems that are not considered during OSD such as, among others, fire protection, oxygen, navigation, communication, and water/waste. System masses for the ECS, FCS, LDG, HPSS, EPSS, and equipment and furnishing account for 80 % to 85 % of the total OBS mass [29]. Since further systems such as the IPS, fuel system, lights, APU, and RAT are listed in table 3, the system masses calculated with the OSD framework account for about 90 % of the total OBS mass and is calculated to 5 120 kg. Hence, the value calculated for *other systems* is 570 kg. This value is assumed to remain constant for all *ESBEF* aircraft models since the above described estimation may not be valid for heavier systems such as the hydrogen storage and supply system.

4.3 Electrification of the systems architecture for the *ESBEF-RB2040*

As the next step, the previously defined SOA systems architecture is electrified and projected to an EIS in 2040. Hence, relevant technology functions are projected to the years 2030-35 (cf. section 3). The system masses of the *ESBEF-RB2040* calculated with the OSD framework and the considered technology functions (TF) are listed in table 4.

Due to the electrification of the OBS, bleed air is removed from the aircraft. This has a significant impact on the ECS and IPS. For the definition of the systems architecture, both of these electrified systems are derived from systems architectures of more electric aircraft, such as the *Boeing 787* [31]. The electrified ECS leads to an increase of the system mass because cabin air compressors (CAC) and additional ram air channels need to be integrated to provide fresh air [31]. However, the electric ECS can be improved by adding a turbocharger to the air extraction network. In this case, the energy that is contained in the extraction air is used to compress the fresh air [48], reducing the mass and power requirements of the CACs significantly. The latter is reduced by up to 66.2 % [48]. It is assumed that two turbochargers are added to the system for redundancy. Each of them has a mass of about 10 kg (Holset HX35W [48]). In addition, ducts of the extraction networks have to be added to the network. In total, these changes lead to a predicted reduction of the ECS mass by about 5 kg (cf. table 4).

With respect to IPS electrification, it is assumed that the area of the stagnation point at the leading edge of the

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Table 4: Estimation of the OBS masses of the *ESBEF-RB2040*

System	Mass in kg (2025)	Relevant TF[a]	Mass in kg (2040)
Environmental control	420	33.8 % · $P_{\mathrm{CAC,el}}$ [48][b]	415
Electric power supply	960	cf. table 5 and fig. 7	720
Cabin equipment & furnishing	2 400	-	2 400
Flight control	285	-	285
Fuel	250	-	250
Hydraulic power supply	155	-	155
Ice protection	10	9 % · $P_{\mathrm{WIPS,el}}$ [39][c]	10
Landing gear	855	-	855
Lights	95	-	95
Auxiliary power	115	-	115
Ram air turbine	40	-	40
Other systems	570	-	570
Total system mass	**6 155**		**5 910**

[a]The focus lies on decreasing the electric power demand
[b]Integration of a turbo charger
[c]Integration of a hybrid wing IPS

wing is heated constantly while the surfaces of the wing are heated cyclically, reducing the required electric power compared to constantly heating the wing surfaces. However, the impact on the EPSS is significant since the power requirement of this system is about 45 kW for this aircraft. As shown in table 4, a hybrid IPS is introduced. The stagnation point at the leading edge of the wing is still constantly heated electrically with the hybrid IPS. However, the ice on the surfaces of the wing is removed electromechanically by using piezoelectric actuators [39]. With the hybrid IPS, the required electric power can be reduced by up to 91 % [39] while the mass of the system does not significantly change compared to the electric IPS [5].

Compared to table 3, the mass of the LDG decreases by about 10 kg for the *ESBEF-RB2040*. The LDG is sized according to the maximum landing weight (MLM), which is provided by OAD with a lower value for the *ESBEF-RB2040*. The MLM of the *ESBEF-RB2040* is 21.3 t while the MLM of the *ESBEF-SOA2025* is 22.4 t. Apart from the LDG, the other consumer systems of the *ESBEF-RB2040* are not further adapted.

Table 5: Relevant technology functions for the EPSS

Component	State-of-the-art		Projected values for 2030-35	
Generator	3.3 kVA/kg	[44]	8.0 kVA/kg	[44]
Lithium-based battery	150 Wh/kg	[12]	500 Wh/kg	[37]
Static inverter (up to 5 kW)	167 W/kg	[17]	500 W/kg	[4]
Inverter (50 kW)	1.05 kW/kg	[17]	6.49 kW/kg	[32]
TRU	1.0 kW/kg	[43]	1.6 kW/kg	[22]
SSPC[a]	15 kW/kg	[23]	30 kW/kg	[21]
DC/DC converter[b]	5.88 kW/kg	[17]	25 kW/kg	[37]

[a]Solid-state power controller
[b]Relevant for *ESBEF-CP1*

The mass of the EPSS increases significantly compared to the *ESBEF-SOA2025*. This is due to the electrification of the ECS and the IPS. Concerning the voltage specifications and number of voltage transformers, the EPSS architecture is not changed compared to the *ESBEF-SOA2025*. However, two engine generators, each capable of providing a constant electric power of up to 70 kVA, are installed at each engine. Hence, the maximum available electric power is increased by a factor 3.5. The generators are also used to electrically start the engine, since bleed air systems are removed from the aircraft. This also has an effect on the APU. As part of the electrified OBS architecture, the APU has to power two generators, each capable of providing a constant electric power of 70 kVA. Furthermore, several technology functions are added for the generators and voltage transformers of the EPSS. These assumptions are listed in table 5.

Figure 6 shows the electric power demand of the *ESBEF-RB2040* with and without considering the technology functions for ECS and IPS. As it can be seen, the electric power demand is reduced by about 120 kW by integrating

DOI: 10.13009/EUCASS2023-602

the proposed technologies. In this case, the power requirements of the VFGs and APU generators are reduced as well. Hence, each of the generators needs to provide a maximum electric power of 25 kVA.

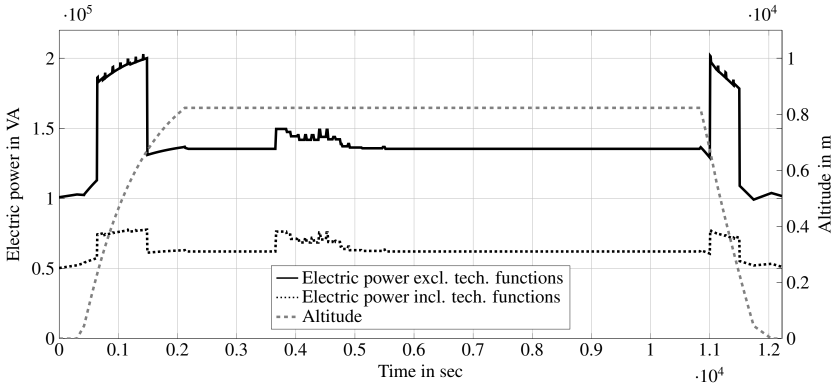

Figure 6: Total load profiles of secondary electric power

Figure 7 shows the impact on the EPSS mass due to the technology functions listed in table 4. First, the mass is reduced by applying the technology functions of the components of the EPSS, such as the generators, batteries, and voltage transformers as shown in table 5. Second, the mass of the EPSS is further decreased by integrating the turbocharger into the ECS. As shown in fig. 6, the required power is significantly reduced. This has an effect on the power that needs to be provided by the generators, the size of the voltage transformers, and the size of affected cables, decreasing the mass of these components. Last, the mass of the EPSS is further reduced by integrating the hybrid IPS, implying the same effects on the EPSS as described above for the ECS improvements. In total, the mass of the EPSS is decreased by 25 %. However, this value has high uncertainties due to dependencies on the assumed technology functions. Since the focus of the introduced technology functions presented in table 4 lies on reducing the electric power demand, further potential mass improvements of other OBS due to, for instance, lighter materials are neglected in the scope of this paper.

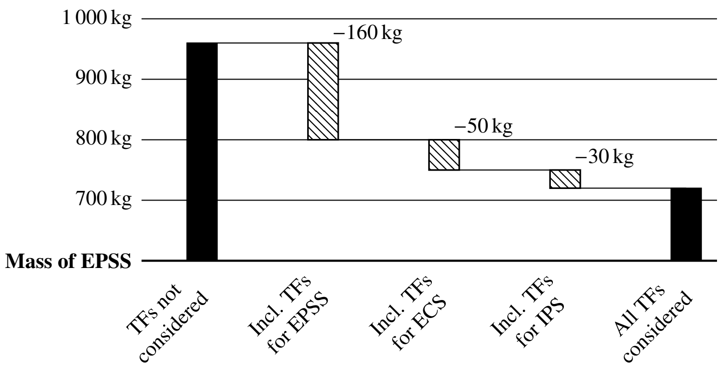

Figure 7: Impact of technology functions on the mass of the EPSS (cf. table 4)

5. Systems architecture definition of the *ESBEF-CP1*

In the following, the definition of the OBS architecture for the *ESBEF-CP1* and its integration is described. Because the hybrid fuel cell systems serve as sources for primary and secondary power, concepts for the EPSS architecture and for emergency power supply are also discussed.

5.1 Integration of the systems architecture based on the *ESBEF-RB2040*

As a first step, the OBS architecture of the *ESBEF-RB2040* is integrated into the *ESBEF-CP1*. The OBS masses calculated with the OSD framework are listed in table 6. The masses are calculated for SOA (2025) and for EIS in 2040, applying the technology functions from section 4.3.

DOI: 10.13009/EUCASS2023-602

Table 6: Estimation of the OBS masses of the *ESBEF-CP1*

System	Mass in kg (2025)	Mass in kg (2040)
Environmental control	420	415
Electric power supply	530	490
Cabin equipment & furnishing	2 575	2 575
Flight control	285	285
Hydrogen supply	1 670	780[a]
Hydraulic power supply	160	160
Ice protection	10	10
Landing gear	865	865
Lights	95	95
Other systems	570	570
Total system mass	**7 180**	**6 245**

[a]Hydrogen tanks made of carbon fiber reinforced plastic [7]

As shown in table 6, the mass for cabin equipment & furnishing increases compared to the *ESBEF-RB2040* (cf. table 4) due to the adapted cabin configuration of the *ESBEF-CP1* (cf. section 3). Also, the mass of the LDG increases compared to the *ESBEF-RB2040*. This is due to the increased MLM of about 23.1 t. Since the *ESBEF-CP1* does not need integral tanks for storing kerosene in the wings anymore, the fuel system is replaced by the hydrogen storage and supply system. The hydrogen system accounts for the two liquid hydrogen tanks, the distribution network, and the peripheral systems such as electrical heaters, pumps, and ventilators. Because the hydrogen tanks cannot be integrated into the structure of the aircraft and need to be insulated for storing liquid hydrogen, the mass significantly increases compared to the fuel system of the *ESBEF-RB2040*. A potential mass improvement of hydrogen tanks for 2030-35 can be achieved by using materials such as carbon fiber reinforced plastic instead of metal [7]. Lastly, the mass of the HPSS increases by 5 kg compared to the *ESBEF-RB2040*. This is caused by the increased fuselage width of the aircraft, which requires longer hydraulic pipes.

The mass of the EPSS significantly decreases compared to the *ESBEF-RB2040*. This is mainly because generators are replaced by voltage transformers installed in each Pod since electric power is generated by the hybrid fuel cell systems. Thus, the impact of the technology functions on the total OBS mass is significantly lower compared to the *ESBEF-RB2040*. To this end, it is assumed that the rest of the EPSS architecture is not adapted. However, auxiliary and emergency power generation is neglected so far and is further discussed in section 5.3. The masses accounted for the other considered OBS do not significantly change compared to the *ESBEF-RB2040*.

5.2 Systems architecture definition of the propulsion units

Each Pod of the *ESBEF-CP1* consists of hybrid electric fuel cell systems. The hybridization is performed by using batteries and capacitors [33, 40]. Since the fuel cells of each Pod can provide a maximum output power of 400 kW, it is assumed that the fuel cells can only provide up to 360 kW for the primary and secondary power supply systems. The remaining 40 kW are used to power the peripheral systems of the fuel cells. Furthermore, it is assumed that low temperature proton-exchange membrane (LT-PEM) fuel cells are used, which operate at about 90 °C [45]. For current applications, a power-to-weight ratio of 3 kW/kg [38] is assumed for the fuel cell stacks. A projected value for 2030-35 is assumed to be 10 kW/kg [19, 28]. The buffer batteries are used to balance power peaks to create a constant output power requirement for the fuel cells to reduce degradation effects as much as possible [40]. With this approach, the capacity of the battery in a Pod is calculated to be 16.3 kWh. Furthermore, it is assumed that the batteries are operated in normal conditions between 20 % and 80 % state of charge due to degradation and life cycle effects [47]. The total electric power demand (primary and secondary power) is shown in fig. 8.

The baseline architecture of the power train consists of one permanent magnet synchronous motor (PMSM) including its motor controller, one gearbox, and a variable pitch propeller. Current power-to-weight ratios for PMSM and its controller are assumed to be 5.8 kW/kg [28] and 15 kW/kg, respectively. Projected future values for power-to-weight ratios are assumed to be 13 kW/kg and 19 kW/kg, respectively [25]. Furthermore, a cooling system is required for the fuel cells, the PMSM, and the motor controller. For LT-PEM fuel cells, it is necessary to use a liquid cooling system due to a low temperature gradient. As baseline, a one phase cooling system is integrated [34]. For future applications, the integration of a two phase cooling system is assumed [34]. Lastly, a compressor in a ram air channel in each Pod is used to supply air for the fuel cell.

The system masses of the presented Pod architecture are listed in table 7. Since in total ten Pods are installed on

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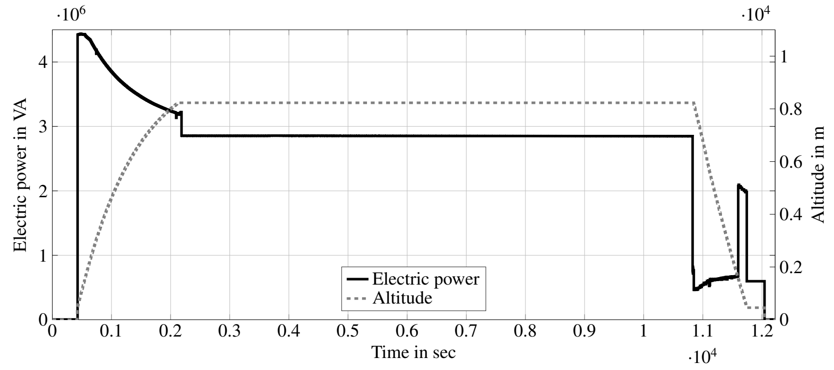


Figure 8: Total load profile of primary and secondary electric power

the *ESBEF-CP1*, the mass of the propulsion units is calculated to 5 450 kg for EIS in 2040. Compared to the *ATR 72* engines with a total mass of 1 330 kg (cf. table 2), the mass of the propulsion systems increases significantly by about 4 120 kg. However, masses of the nacelle structure and the pylon are neglected in this comparison (cf. section 4.1).

Table 7: Estimation of the systems masses of a *ESBEF-CP1* propulsion unit

System	Mass in kg (2025)	Comment	Mass in kg (2040)
Propeller	25	Provided by OAD	25
Power train	120	Improv. of power-to-weight ratios [18, 25]	70
Oil and fluids	5	-	5
PMAD	40	Improv. of DC/DC conv. (cf. table 5)	10
Fuel cell stacks	135	Improv. of materials [19, 28]	40
Air supply	25	-	25
Cooling system	250	Architecture with two-phase fluid [34]	235
Batteries	450	cf. table 5	135
System mass of one Pod	**1 050**		**545**

5.3 Concept studies for the electric power supply system

In the following, the systems architecture of the EPSS is traded from a three-phase AC voltage specification to HVDC. Furthermore, emergency power system concepts are traded for the case that all Pods fail due to, for example, a failure within the hydrogen supply system. However, the provision of auxiliary power as a dedicated APU or fuel cell system is not further considered and discussed in the scope of this paper. It is assumed that ten Pods provide enough redundancy to supply flight critical systems with electric power. Also, other use cases of the APU, such as generating electric power at the airport, can be performed by the hybrid fuel cell systems in the Pods without generating carbon oxide emissions.

5.3.1 Trade between alternate current and high voltage direct current

Relevant impacts of changing the EPSS architecture from three-phase AC to HVDC are the decrease of electrical cable diameters due to lower currents, the increase of cable insulation due to higher voltage levels, replacing TRUs and inverters with DC/DC converters, and adding inverters to consumer systems that require three-phase AC [17, 24, 30]. These impacts are separately visualized in fig. 9. It is assumed that the voltage transformers are designed according to the projected values for 2030-35 as listed in table 5. Furthermore, it is assumed that inverters are required to provide three-phase AC for EHAs, for the HPP, for the compressors and fans of the ECS, for the vacuum pumps for waste water, and for the pumps and ventilators of the hydrogen supply system.

As it can be seen in fig. 9, the mass of the EPSS is reduced significantly by changing the system architecture to HVDC. In addition, the decrease of the system mass is higher when the technology functions for the ECS and IPS are not considered. Due to the high power requirements of these systems, higher mass savings for the cables are obtained. However, the absolute mass of the EPSS is still lower when the improved ECS and IPS are integrated into the systems architecture. Hence, the voltage specification of the EPSS is adapted to HVDC for the *ESBEF-CP1*, reducing the system mass to 430 kg.

DOI: 10.13009/EUCASS2023-602

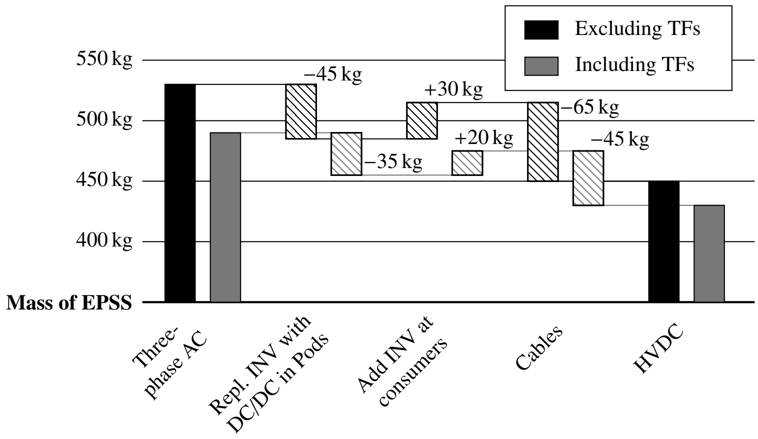
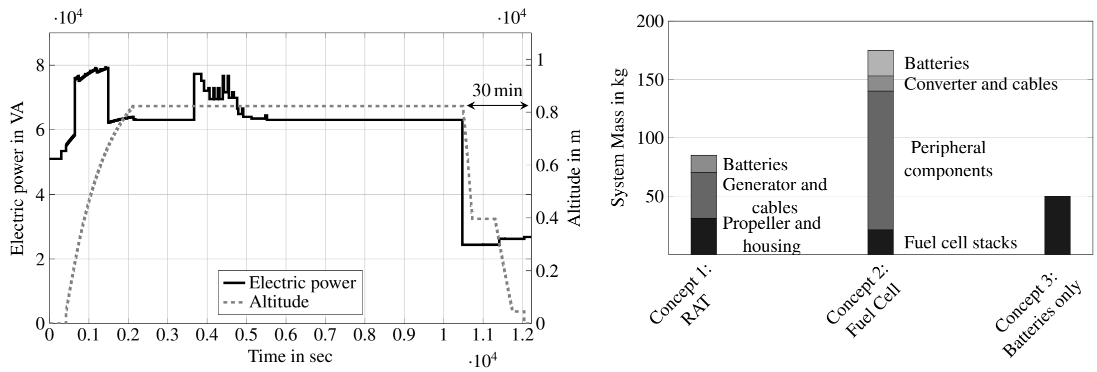


Figure 9: Impact on components masses of the EPSS due to integration of a HVDC architecture

5.3.2 Concepts for emergency power supply

Emergency power supply is required for the *ESBEF-CP1* in case the hydrogen supply to the Pods fails. This scenario is comparable to a total engine flame-out of a conventional kerosene-powered aircraft. It is assumed that primary power cannot be generated by solely using the batteries in the Pods. In addition, emergency power needs to be generated due to the electrified FCS to be able to further control the aircraft in such an emergency case. It is assumed that the emergency power demand is 30 kW and the emergency power supply system needs to be able to supply this power for a maximum remaining flight time of 30 minutes, as shown in fig. 10(a). Relevant boundary conditions and requirements for emergency power supply concepts are given in the certification specification [8].



(a) Load profile for emergency operations

(b) Analysis of emergency power sources

Figure 10: Aspects for emergency power for the *ESBEF-CP1*

An architecture trade for relevant emergency power supply concepts is performed for the *ESBEF-CP1*. The comparison is visualized in fig. 10(b). First, a conventional RAT is integrated, which automatically deploys when the normal secondary power supply fails. The RAT is connected to a generator and a voltage transformer, so it can also supply the HVDC system. However, it is required to integrate batteries into the system architecture to compensate for the decrease of generated power by the RAT at lower flight speeds (cf. section 4.2). With respect to the second option, a hybrid fuel cell system is integrated. The hybridization is necessary because the fuel cell system needs to perform a cold start if required [40]. To compensate for the required power during the starting process of the fuel cell, batteries are again integrated for hybridization. A dedicated (gaseous) hydrogen tank is required as a separate energy source to supply the fuel cell. Third, since the first two options require batteries for hybridization, only batteries are integrated into the systems architecture for emergency power supply. As shown in fig. 10(b), this variant has the lowest mass, assuming an energy density of 500 Wh/kg (cf. table 5).

Last, it is also considered using the batteries in the Pods for emergency power supply. Due to the high redundancy of Pods in the *ESBEF-CP1*, it may be extremely improbable that all integrated batteries fail. Hence, this concept may be considered for this aircraft [8]. For example, it is defined that the batteries can have a minimum state of charge of

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20 % during normal operations. In case of an emergency, this limit may be reduced. If this limit is reduced to, for example, 10 %, emergency power can be supplied for about 33 minutes. It is assumed that the latter concept is used for the *ESBEF-CP1*, avoiding adding additional mass to the systems architecture for emergency power supply.

5.4 Summary of the derived systems architecture

In conclusion, the integration of the OBS architecture into the *ESBEF-CP1* is feasible. A visualization of the systems topology based on the information from the OSD framework is presented in fig. 11.

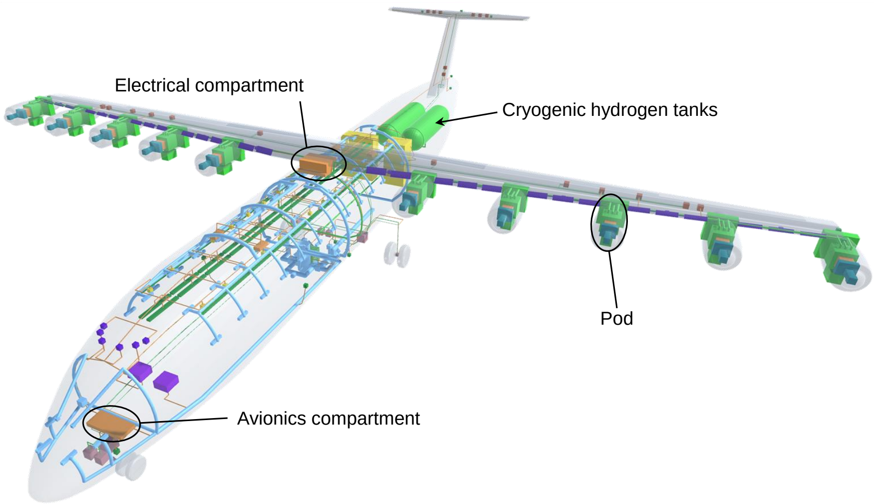

Figure 11: Systems topology of the *ESBEF-CP1*

As listed in table 8, the defined systems architecture of the *ESBEF-CP1* is significantly heavier than the systems architecture of a conventional aircraft with gas turbines, such as the *ESBEF-RB2040*. However, this finding is expected due to the increased mass of the hydrogen tanks and the propulsion systems. Nevertheless, an increased mass enables an aircraft with no in-flight carbon oxide emissions.

Table 8: Comparison of the *ESBEF-CP1* to the *ESBEF-RB2040*

	ESBEF-RB2040	***ESBEF-CP1***	**Rel. deviation**
OBS mass in kg	5 910	6 185[a]	+5 %
Propulsion system mass in kg[b]	1 330[c]	5 450	+410 %
Total system mass in kg	**7 240**	**11 635**	**+61 %**

[a]Including −60 kg for the EPSS (cf. fig. 9)
[b]No consideration of possible structural mass savings on aircraft level
[c]Assuming the same mass as for the *ATR 72*-like aircraft model

6. Conclusion

The overall parametric systems design of the hydrogen-powered regional concept aircraft, the *ESBEF-CP1*, with a defined entry into service in 2040 has been presented in this paper. To this end, several relevant steps were conducted to define the systems architecture on different aircraft models. First, an *ATR 72*-like aircraft model is used for verification of the system sizing results. Second, a state-of-the-art on-board systems architecture is defined on the *ESBEF-SOA2025* aircraft, which is derived from an *ATR 72*-like aircraft model. Third, this state-of-the-art systems architecture is electrified and projected to the year 2040, leading to the *ESBEF-RB2040*. Hence, technology functions for, among others, voltage transformers and batteries are introduced. Also, possible improvements of the electrified environmental control system and ice protection system are considered, potentially reducing the electric power demands significantly. Last, the defined systems architecture is integrated into the *ESBEF-CP1*.

DOI: 10.13009/EUCASS2023-602

In addition, further improvements of the systems architecture were conducted. Since electric power is generated by hybrid electric fuel cell systems in the *ESBEF-CP1*, high voltage direct current is introduced as a trade for the electric power supply system, decreasing its mass significantly by about 12 % compared to an architecture using three-phase alternating current. Furthermore, a trade for emergency power supply concepts has been presented, which may not be needed due to the high redundancy of ten propulsion units.

Despite of these improvements of the systems architecture, the mass of the consumer and power supply systems of the *ESBEF-CP1* increases by 275 kg compared to a similar, kerosene-powered research baseline (*ESBEF-RB2040*). The mass of the propulsion units of the *ESBEF-CP1* increases by 4 120 kg compared to the gas turbines of this research baseline. However, it is expected that the mass of a hydrogen aircraft increases compared to a similar conventional aircraft due to the fact that, among others, separate cryogenic hydrogen tanks for storing liquid hydrogen are needed. In return, carbon oxide emissions are eliminated during flight.

However, the definition of the systems architecture presented in this paper is a first design step for a hydrogen aircraft. Next, iterations with overall aircraft design are required to update the initial assumptions of the aircraft masses, allowing a holistic evaluation of the aircraft design. Also, more evaluation criteria need to be assessed on aircraft level, such as, among others, installation space requirements, costs, maintainability, and degradation and life cycle effects. Moreover, other technologies may be considered for the on-board systems to reduce the systems mass and thus further increase the potential feasibility of a hydrogen aircraft. For example, modern and lighter materials can be considered for cabin equipment & furnishing.

7. Acknowledgments

The results of the presented paper are part of the work in the research project development of systems and components for electrified flight (ESBEF), which is supported by the Federal Ministry of Economic Affairs and Climate Action in the national LuFo VI program. Any opinions, findings and conclusions expressed in this document are those of the authors and do not necessarily reflect the views of the other project partners.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

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