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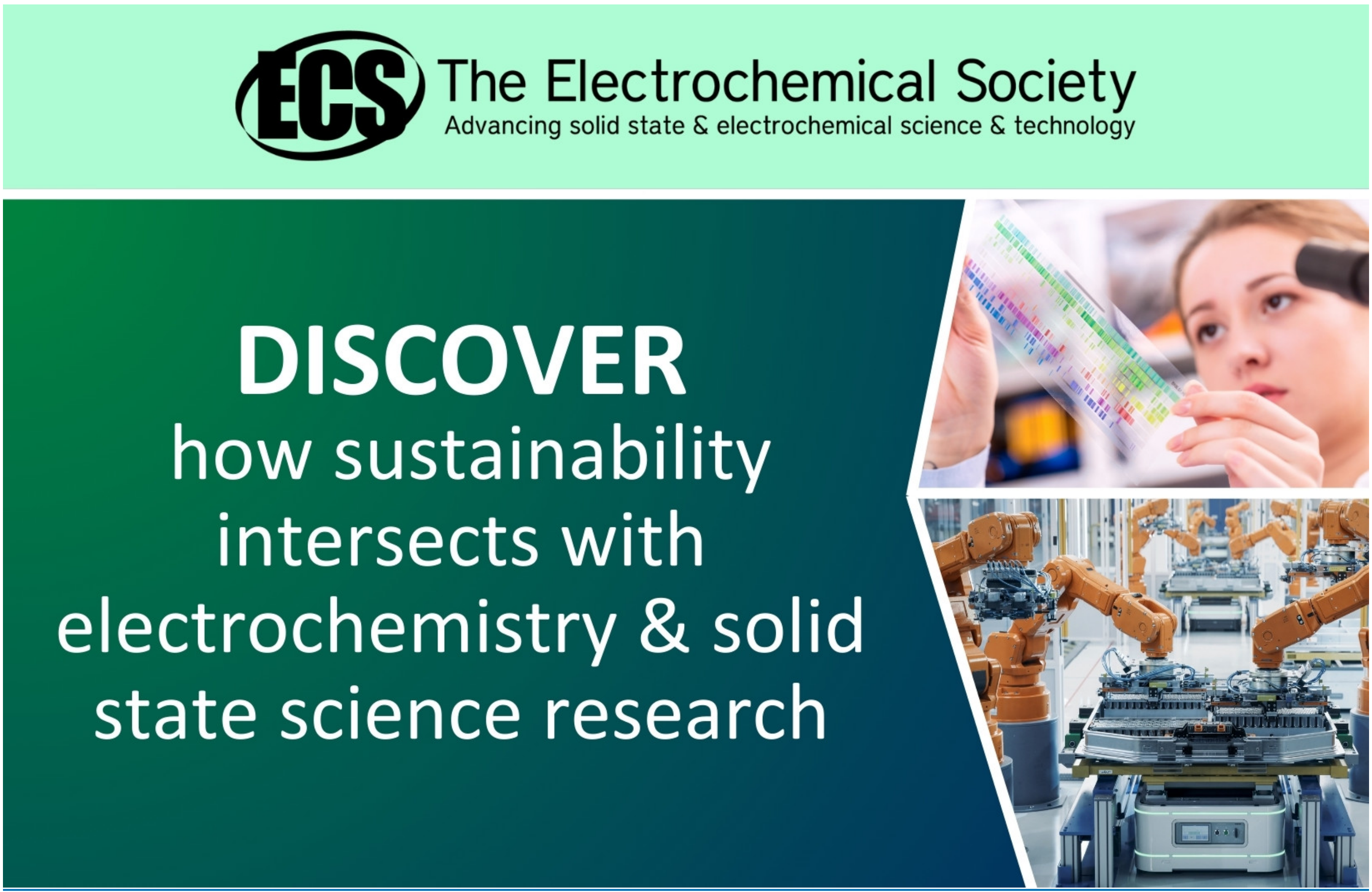

Overview of safety challenges associated with integration of hydrogen-based propulsion systems for climate neutral aviation

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Abstract. Electrification through hydrogen-based fuel cells as well as hydrogen combustion in gas turbines is a key strategy in aviation for achieving substantial reduction of emissions. However, this transition presents multifaceted challenges. Besides the development and improvement of technologies required for such hydrogen-fuelled aero engines, the safety of hydrogen storage and distribution systems on aircraft is paramount. Challenges associated with hydrogen in terms of its material properties, the design and selection of components for the conditioning and distribution, as well as the system design are being presented and discussed in this work. This includes the consideration of high diffusivity, flammability and reactivity of hydrogen and the consequences of these traits: hydrogen embrittlement, hydrogen-induced cracking and leakage, for instance. The challenges elaborated in this work are pertinent to both hydrogen fuel cell-based propulsion systems and hydrogen combusting gas turbines. Design considerations were derived and are being outlined in this work. These are transferable to applications in other industries such as automotive and stationary power plants. The need for novel rigorous safety protocols to enable a sustainable future in aviation is being highlighted.

1. Introduction

The severity and consequences of the greenhouse phenomenon are constantly increasing. More and more greenhouse gases (GHG) are being emitted by the power generation, manufacturing and transportation industries each year as the European Commission indicates [1]. In order to constrain the impact of climate change, new methods of power generation should be implemented to minimise and, if possible, cease to emit the GHG emissions, particularly CO_2. The utilisation of green energy sources, such as sustainable fuels, hydrogen and electrical energy storage devices, can play a pivotal role towards the ATAG Waypoints 2050 net-zero emission target [2]. Hydrogen in particular has considerable potential as its gravimetric energy density (GED) [3] is higher than that of other available fuels. Depending on its production and consumption approach, it may lead to a zero carbon footprint [4]. Therefore, the means of production ought to be based fully on green energy electricity. Different options for electrification based on hydrogen are currently being investigated [5]. However, the implementation of hydrogen and the required infrastructure impose several challenges that need to be considered and mitigated throughout the design process in order to enable a safe, reliable and efficient power system. Applying the safe design process of aviation these challenges have been derived in this work.

2. Design Process in Aviation

To attain zero-emission flight the assimilation and deployment of novel technologies is essential. Advancements at the aircraft, system and component level need to be pursued. However, the ultimate aircraft product must satisfy the necessary safety and reliability requirements common in aviation as well as comply with the certification specifications (CS) in order to obtain flight approval. For this purpose, the European Aviation Safety Agency (EASA) proposes acceptable means of compliance (AMC), ranging from calculations and analyses to tests. The overview given in this paper is the result of an investigation carried out in the DLR-internal project "H_2EAT". The authors' focus within this project is on the design of the hydrogen supply and distribution system for a solid oxide fuel cell-based propulsion system. The design process applied follows the ARP 4754A [6] described in AMC 25.1309 of CS-25 [7]. The principal approach is based on the V-model of systems engineering, as presented in the ARP 4754A [6] and consists of a top-down design and validation phase, followed by a bottom-up verification process after successful implementation. Furthermore, the process is accompanied by safety assessment methods described in ARP 4761 [8] to validate the system requirements and ensure the design is guaranteed to provide the necessary functions.

Given an initial design of the aircraft and propulsion system topology, the conceptual design of the hydrogen system begins. In order to understand and collect all necessary requirements as well as being able to make design decisions concerning the hydrogen architecture, all challenges associated with hydrogen have to be considered.

3. Challenges Associated with Hydrogen

Hydrogen is the first element of the periodic table. It is a diatomic molecule and at standard temperature and pressure (STP) it takes on a gaseous form [9]. The detection of hydrogen is more challenging than that of other gases due to its being odorless, colorless, non-toxic and non-metallic [9]. Compared to other fuels, hydrogen has a large GED, but a low volumetric energy density (VED). More specifically, kerosene has a GED of 40 MJ/kg [10], while that of hydrogen is 120 MJ/kg [3] – three times higher. However, the VED of hydrogen at STP is as low as 0.01 MJ/L [3], while that of kerosene at STP is 34 MJ/L [10]. When being compressed to 700 bar the VED of hydrogen 4.7 MJ/L [3] and in liquid form it is 8.5 MJ/L [3].

3.1. Material Challenges

The utilisation of hydrogen imposes several challenges on the materials used for storage and distribution. The physical properties of the fluid and the conditions under which it is contained must be taken into consideration at each system level throughout the entire design process.

3.1.1. Extreme Hydrogen Conditions: By compressing hydrogen to 700 bar at ambient temperature the storage vessel is subjected to extreme forces [11]. The walls ought to be strong enough to withstand the pressure and get certified as a pressure tank based on the EC79/2009 Annex III & V regulation [12]. In order to store hydrogen in a liquid state, cryogenic temperature of 20 K or less are necessary [13]. The temperature is limiting for the material selection as the material properties must possess the capability to perform effectively under these conditions [14]. It is crucial to acknowledge that the mechanical properties of materials may undergo significant alterations given cryogenic conditions [15], as indicated in Figures 1 and 2. Figure 1 shows that a ductile material may become brittle due to such low temperatures. This type of embrittlement is caused by the low temperature alone and not by the interaction with the surrounding hydrogen itself [15]. The latter type of embrittlement will be discussed in the next section. Figure 2 illustrates that the yield stress of the materials rises as the temperature drops, while the breaking stress remains constant. At temperatures lower than T_B the yield stress becomes higher than the breaking stress, meaning that the material fails before reaching its yield limit.

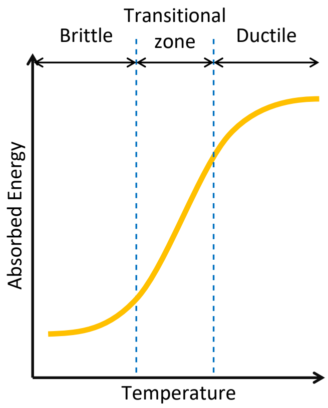

Figure 1: Characteristic dependency of the absorbed energy on temperature based on Anoop *et al.* [15].

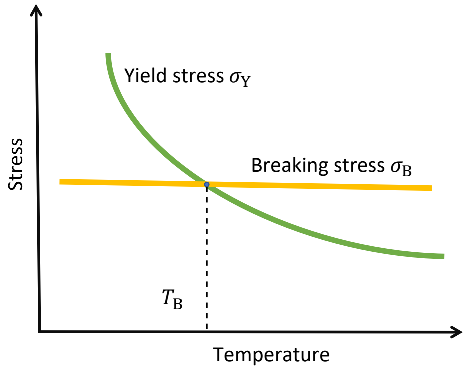

Figure 2: Characteristic dependency of the yield and breaking stress on temperature based on Anoop *et al.* [15].

3.1.2. Hydrogen Diffusion into the Material: Hydrogen molecules and atoms are smaller than all other gases in terms of volume at STP, enabling them to permeate through materials that are conventionally deemed airtight [9]. Through adsorption on the surface of the material, which is in contact with the hydrogen-rich environment, the material itself is enriched with hydrogen [16]. The molecules dissociate into hydrogen atoms, which are small enough to get absorbed into the material [16]. Due to diffusion, the atoms advance inside the core of the material [17]. Depending on many factors two possible effects may result, as shown in Figure 3: leakage or trapping. The former meaning that hydrogen atoms succeeded in diffusing through the material and, thereby, escape to the atmosphere through desorption, while in the latter case the atoms remain contained within the material [17]. These phenomena are strongly affected by pressure

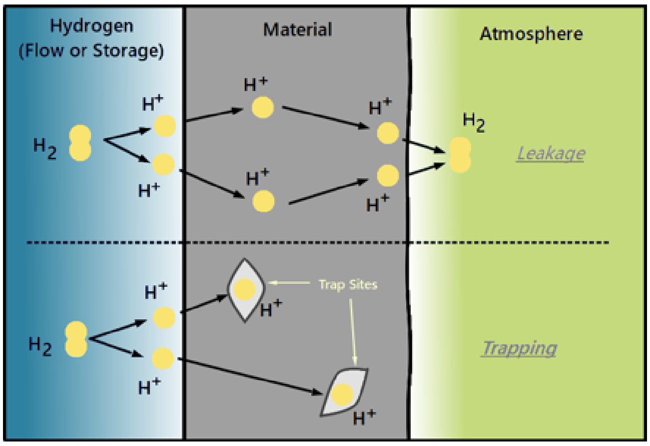

Figure 3: Schematic of permeation of hydrogen.

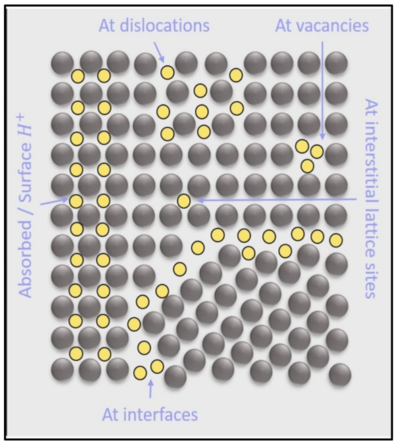

Figure 4: Most common trap sites.

and temperature conditions. If the solubility of the material decreases while hydrogen permeates through it, hydrogen is highly likely to get trapped [17]. Increased temperature and pressure may lead to the leakage of trapped hydrogen atoms [17]. Traps are also referred commonly to as wells [18], where hydrogen is bound within the crystalline structure of the material. The most common trap sites are in between phases and grains or interfaces of precipitates, but also voids, dislocations and any type of vacancies or imperfections in the material [16], as illustrated in Figure 4. If the trap sites and local conditions allow it, hydrogen atoms can re-associate into molecules inside the material as well.

3.1.3. Hydrogen Damage Mechanisms: Hydrogen can be either trapped inside the crystalline grid structure of the material during operation or during the manufacturing process [19]. It can accumulate in the grain or phase interfaces and cause decohesion of the structure leading to hydrogen embrittlement [18, 20]. This damage mechanism is responsible for the degradation of the mechanical properties of the material, as well as loss of ductility and tensile strength [21]. The latter leads to a decrease in fracture resistance and sub-critical cracking – even at stresses lower than the yield stress of the material [19]. Many embrittlement mechanisms have been identified in literature [16]. Another damage mechanism is caused by formation of hydrogen bubbles inside the material. If multiple atoms are trapped in the same void, H_2 molecules are formed, which tend to expand and create a stress field inside the material independent of external stresses being applied [22]. Finally, an additional damage mechanism is the high temperature hydrogen attack. Here, the chemical reaction of hydrogen – both as atoms and molecules – with the carbon contained in the material enables the formation of methane. This phenomenon leads to a deterioration of the mechanical properties of the material due to decarburisation and the formation of defects caused by methane bubbles entering the lattice. It takes place at high operational temperatures ($> 600^oC$) and its severity corresponds with the duration of the exposure of the material to the hydrogen-rich environment [17].

3.2. Component Challenges

In order to implement hydrogen technologies into an aircraft, novel components have to be developed to store, condition and deliver the fuel. In addition to the aforementioned material considerations, the components ought to be designed taking into account not only the prevention of hydrogen damage and means of mitigating the challenges of hydrogen, but also efficiency, compactness and reliability play an important role. For operational and economical reasons maximising their power-to-weight ratio and component life while lowering the cost of maintenance, must be achieved by detailed analysis of their design and off-design characteristics.

3.2.1. Liquid Hydrogen Tank: The liquid hydrogen tanks operate under cryogenic conditions. They need to be well insulated in order to prevent heat leakage to the environment. If not treated properly, the liquid hydrogen vaporises and the pressure inside the closed vessel increases. Therefore, the excess gaseous hydrogen must to be used or vented-off in order to prevent a pressure build-up resulting in catastrophic failure [13, 23]. Venting-off is not desirable as it leads to loss of fuel but could be combined with means of boil-off capture. Moreover, it is crucial to avoid complete depletion of fuel, as this would subject the materials to extreme thermal cycling, resulting in shortened life for the structure. As a result not only extra fuel ought to be carried but also the vessel itself is oversized without increasing the potential range of the vehicle.

3.2.2. Heat Exchanger: Hydrogen at STP has a much higher specific heat coefficient c_p of $14\,\mathrm{kJ/kg}$ than that of air with $1\,\mathrm{kJ/kg}$ [24], making the heat transfer more challenging. High air flow is needed to counteract the difference in c_p of the two media, which leads to larger component structures, air inlets and compressor power requirements. The design is therefore significantly different than that of an air-air heat exchanger. Moreover, the temperature difference results in considerable changes in density. In Table 1 the density of hydrogen at different thermodynamic states is presented to indicate the scale of the expansion phenomenon that needs to be considered.

3.2.3. Piping: If hydrogen is delivered at cryogenic temperature, the distribution pipes need to be insulated [25]. This is necessary to prevent heat transfer as well as the condensation of water in the surrounding air. The higher the temperature of the fuel the lower its density is. Hence, due to the leakage of heat uncontrollable acceleration might occur, as a result of mass conservation, or pressure will build up. Higher density fluid can be maintained with a high

Table 1: Density of hydrogen at different thermodynamic states, as per NIST [24].

Temperature [K]	20	20	300	300	600	600
Pressure [MPa]	0.1	0.1	0.1	5	0.1	5
Phase	liquid[1]	vapor[1]	vapor	SCF[2]	vapor	SCF[2]
Density $[kg/m^3]$	71.3	1.2	0.08	3.92	0.04	1.98

[1] Saturated, [2] SCF = Supercritical fluid

pressure hydrogen delivery strategy, but this results in thicker and, therefore, heavier pipe walls. Finally, at ambient temperature and pressure hydrogen has the lowest density, leading to a large cross-sectional area of the pipe. This too, in the extreme, will lead to making the component heavier and bulkier. Therefore, a trade-off study needs to be conducted in order to optimise the delivery in terms of sizing, operation, maintenance and safety requirements.

3.3. System-level Challenges

Designing systems in aviation presents unique challenges and stringent requirements that demand high reliability and high precision in controls. These requirements are related to addressing the environmental conditions, to enabling operational strategies and to maximising efficiency. Moreover, hydrogen imposes dangers, that ought to be considered during system designing. Although it has many advantages, it may also cause catastrophic failures if not handled appropriately.

3.3.1. Extraction Method: If hydrogen is stored in a compressed gaseous form, then by opening the extraction valve, pressure forces the fuel into the distribution system. Hydrogen has a negative *Joule-Thompson* coefficient in contrast to most gases. Therefore, its temperature increases when it is depressurised [9]. When using liquid hydrogen, a pressure gradient needs to be established in order for flow to occur. This is usually done either by vaporising hydrogen in the closed tank to increase the pressure in the tank [26] or with the use of a cryogenic pump [27], which is responsible for creating the extraction pressure needed. Both of these options are illustrated in Figures 5 and 6, respectively.

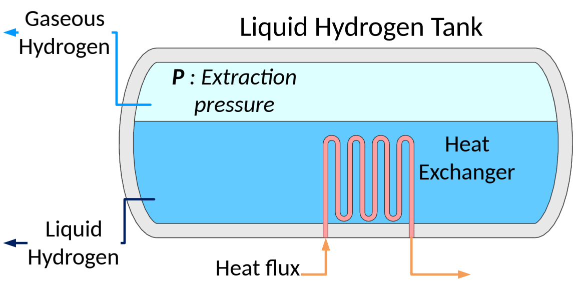

Figure 5: Extraction from a liquid hydrogen tank using the self pressurisation method.

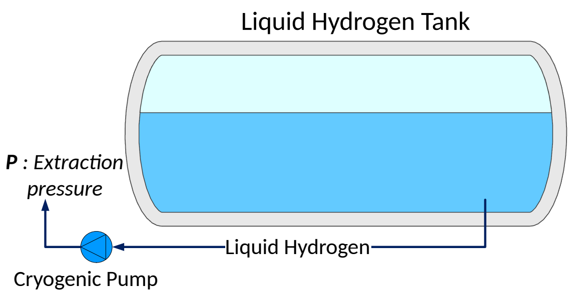

Figure 6: Extraction from a liquid hydrogen tank using a cryogenic pump.

The self-pressurisation method requires the delivery of heat to the liquid. This heat may come from other components of the system creating a synergy and improving the overall efficiency. However, the strength requirement for the tank structure increases and the extraction response time might be too long, as the vaporisation phenomenon does not occur instantaneously. The use of a liquid hydrogen pump offers better controllability, but it requires parasitic power and has yet to be developed for aviation applications. The pump needs to operate at 20 K with minimum losses in order not to produce heat or to trigger liquid hydrogen vaporisation or even cause cavitation. Moreover, since hydrogen is always consumed in a gaseous form, the need for vaporising liquid hydrogen somewhere in the delivery and distribution system arises.

3.3.2. Flammability: Hydrogen in concentrations between 4 vol% and 75 vol% in air is flammable and the ignition energy at STP is as low as 0.02 mJ [9]. Hence, leakage might impose catastrophic effects on the aircraft level. Hydrogen is lighter than air and can accumulate in enclosed spaces, which leads to the potential of local concentrations within the flammability range. Moreover, a hydrogen flame is barely visible in daylight, has low heat dissipation, creates no fumes and the laminar flame speed is eight times higher than the flame speed of hydrocarbon-based gases [28]. Furthermore, the stoichiometric flame temperature is greater than 2000 °C and has a high ultraviolet index. Ventilation is very important to maintain hydrogen concentrations below critical thresholds. There is an advantage to the character of such a fast-burning diffusion flame, however. If a fire occurs, it is much more localised and therefore more predictable in terms of effects on the vicinity of the flame as well as easier to control.

3.3.3. Operational considerations: Besides the design mission requirements, the propulsion system of an aircraft ought to be fit to handle emergency situations. A rejected take-off, the need for reverse thrust or a reactive manoeuvre will require high gradients in power demand. This needs to be considered for the design of the hydrogen supply system as well as the aero engine. In particular, the extraction method and conditioning architecture of the hydrogen supply to the engine are affected by the requirements stemming from these operational considerations. Moreover, a supplementary extraction system can be added for such occasions or even a battery for peak power demand. However, in that case the mass, volume and complexity of the system increase. Therefore, the design of the hydrogen system is highly linked to the overall propulsion system architecture design and power management strategy. Finally, hydrogen might remain in the pipes after an unexpected steep decrease of power and under conditions, which will not allow to return it to the tank. For such occasions the addition of an intermediary tank can be beneficial. Moreover, it may cover the requirements of the transition from one power level to another. Being near the engines and keeping the hydrogen at the appropriate conditions, it can be designed to provide fuel immediately for a short period of time, until the rest of the system reaches the new operational point.

4. Design Considerations

While hydrogen holds considerable potential as a fuel source and can enable net-zero emission flight, its practical implementation requires numerous innovations. Hydrogen introduces multiple challenges that demand careful consideration and means of mitigation. Traditional components and systems are often not suitable to meet the requirements of hydrogen-powered aviation. The demand for novel approaches and technologies to overcome these hurdles arises.

First and foremost, the material selection is one of great importance [29]. Components must demonstrate the capability to function effectively in the harsh operating conditions imposed by hydrogen throughout their life. These conditions may include extreme temperature and pressure as well as hydrogen permeability and consequent effects on material properties or even irreversible damage. It is likely that new materials as well as manufacturing and treatment methods ought to be developed in order to realise sustainable, reliable and efficient component designs. Moreover, different sets of test and experiments ought to be conducted throughout the design process in order to fully understand the dangers of hydrogen, set safety mechanisms and create the appropriate certification standards for such applications.

At the system level, a comprehensive approach encompassing prevention, detection and mitigation of potential hazards is essential. Effective zoning should be implemented to isolate hydrogen from any potential ignition sources. For instance, high-voltage cables must undergo proper insulation, regular inspection and appropriate placement within the aircraft. Furthermore, given the difficulty in the detection of hydrogen, the integration of smart monitoring systems is crucial. The incorporation of shut-off and check valves capable of preventing non-favourable conditions is recommended along with a ventilation systems to maintain hydrogen concentrations below the flammability limit. In zones of high risk of fire, means of fire proofing certain areas and the selection of fire resistant materials may be necessary for integration. The integration concept must be developed considering also the dissipation of hydrogen and accumulation associated with leakage. Different scenarios of hydrogen release into the atmosphere or a closed space based on the conditions of the fluid, the surroundings and ventilation system are illustrated in Figure 7. Hydrogen is lighter than air and immediately dissipates upwards, as per scenario I. However, if the upwards path is blocked, it accumulates in the highest point and potentially diffuses to all other directions, including downwards, as shown in scenarios IV and III respectively. Finally, if liquid hydrogen is spilled, a puddle of liquid hydrogen forms mixed with condensed water and air, which is heavier than air itself. Then it starts vaporising and the gas diffuses again, according to scenario II.

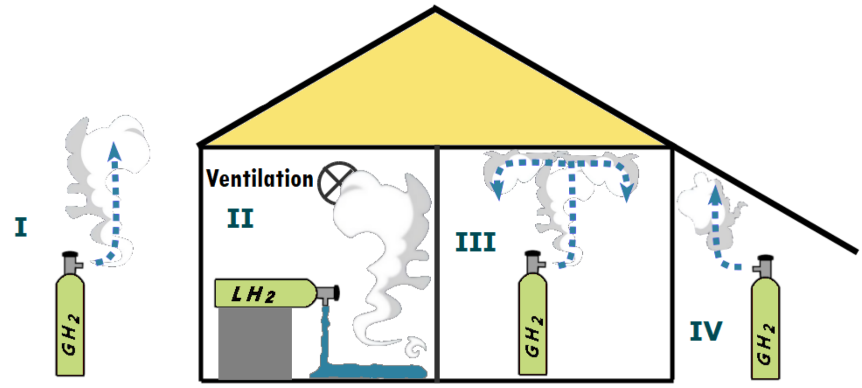

Figure 7: Considerations for hydrogen system integration concept.

As described in Section 2 the design process includes the application of safety analysis methods described in ARP4761 [8] such as Zonal Safety Analysis (ZSA) and Common Cause Analysis (CCA), which are of high importance for the design and validation of the integration concept. Moreover, with the scope of increasing the overall system efficiency the utilisation of synergies between components may be considered. However, functional dependencies can lead to safety hazards and therefore careful examination is required.

5. Conclusions and Outlook

In conclusion, hydrogen as energy carrier is a promising candidate for achieving zero-emission aviation and could enable groundbreaking solutions in the quest for sustainable flight. Its inherent properties, including high gravimetric energy density, clean combustion and suitability for use in fuel cells, are the key arguments for considering it to decarbonise the aviation sector. However, it is crucial to acknowledge the many challenges, which need to be addressed to establish a robust and reliable hydrogen aviation fleet. These concern hydrogen storage, delivery, conditioning and handling inside an aircraft and on the ground. The pursuit of zero-emission flight through hydrogen-based propulsion demands collaborative efforts from researchers, industry and policymakers to navigate these challenges successfully. With innovative solutions and groundbreaking designs the challenges can be surpassed to reduce the GHG emissions of the aviation industry to a minimum or even potentially eliminate them altogether.

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