ROYAL
AERONAUTICAL
SOCIETY

RESEARCH ARTICLE

Elaboration and outlook for metal hydride applications in future hydrogen-powered aviation

F. Franke ⓘ, S. Kazula ⓘ and L. Enghardt

German Aerospace Center (DLR), Institute of Electrified Aero Engines, Cottbus, Germany
Corresponding author: F. Franke; Email: florian.franke@dlr.de

Abstract
Hydrogen is a promising energy carrier to decarbonise aviation. However, many challenges regarding its storage or handling still have to be solved to successfully utilise hydrogen in aircraft and at airport infrastructures. The increasing use of hydrogen also generates opportunities for disruptive improvements, like the possibility to integrate metal hydrides (MHs) into the hydrogen powertrain and its infrastructure. Besides their ability to store hydrogen, MHs enable a wide range of potential secondary functions such as high-power thermal applications or compression. This way, MHs may contribute to achieve the goal of sustainable hydrogen-powered aviation. Hence, potential MH application options and their current state-of-the-art are presented. Based on that overview, the following seven use cases for aviation are selected for evaluation: 'hydrogen emergency storage', 'cabin air-conditioning', 'thermal management of fuel cells', 'gas gap heat switches', 'hydrogen boil-off recovery', 'onboard hydrogen compression' and 'hydrogen safety sensors'. Four of these use cases are investigated to achieve comparable degrees of detail to avoid misevaluations in the subsequent weighted point rating. The results reveal the high potential of MHs for 'hydrogen boil-off recovery', 'hydrogen safety sensors' and 'cabin air-conditioning'. For the three most promising use cases, outlooks to their potential future implementation are provided in order to outline the ability of MHs to empower sustainable aviation. These investigations highlight the huge potential of MHs for boil-off treatment.

Nomenclature

AC	air-conditioning
ACM	air cycle machine
AHX	ambient heat exchanger
CgH2	compressed gaseous hydrogen
CHX	cabin heat exchanger
FC	fuel cell
GGHS	gas gap heat switch
GH2	gaseous hydrogen
MH	metal hydride
MHR	metal hydride reactor
H2	hydrogen
HTF	heat transfer fluid
HX	heat exchanger
LH2	liquid hydrogen
PEMFC	polymer electrolyte membrane fuel cell
TMS	thermal management system

| TRL | technology readiness level |
| VCM | vapor cycle machine |

Symbols

|	
A	heat transfer area (m^2)
g	thickness of layer or gap (cm)
k	total number of criteria (-)
m	numerical measure (-)
m	mass flow (kg/s)
n	total number of applications (-)
p	pressure (Pa)
P	power (kW)
Q	heat flow (kW)
r	relative rating (-)
SE	specific energy (kWh/kg)
SP	specific power (kW/kg)
t	time (h)
T	temperature (°C)
w	weighting factor (-)
W	weight (kg)
y	system usage years (-)
ΔE_{pot}	potential energy difference of the hydrogen pressure (J)
ΔH	lower heating value (kJ/g)
ΔT	temperature difference (K)
η	efficiency (%)
λ	thermal conductivity (W/(m·K))

Recurring indices

$*_{abs}$	absorption of hydrogen
$*_{cool}$	cooling
$*_{comp}$	compressor
$*_{des}$	desorption of hydrogen
$*_i$	application number
$*_j$	criterion number
$*_{max}$	maximum
$*_x$	layer number

1.0 Introduction

Aviation connects people and delivers goods across long distances with high reliability and speed [1]. The key challenge facing future air transport is to preserve this service, while significantly decreasing its climate impact. Both the European Commission's 'Flightpath 2050' and the aviation industries 'ATAG Waypoint 2050' also emphasise the necessity for aviation to transition to electric or hybrid-electric propulsion and sustainable energy sources such as hydrogen [2].

Although hydrogen possesses a high gravimetric energy density, its volumetric energy density as a gas at ambient conditions is low. Thus, storage methods that reduce the volume of hydrogen are essential for its use in transport systems. Common methods are compressed gaseous storage at high pressures or liquid storage at cryogenic temperatures [3]. Both methods have various advantages and drawbacks, such as storage losses and required energy for compression or liquefaction [4]. For the utilisation of hydrogen as an energy carrier in future sustainable aviation, progress in the advancement of hydrogen storage systems has to be achieved [2].
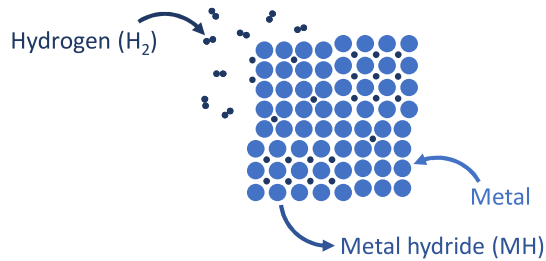
Figure 1. *Generation principle of metal hydrides according to Ref. (5).*

A third method to store hydrogen is in a solid state as a metal hydride (MH). In this method, the hydrogen reacts with metallic compounds to form a MH, as illustrated in Fig. 1. When the hydrogen gets absorbed, it is stored in atomic form in the metals lattice [5]. Although MHs offer the highest volumetric hydrogen storage densities, their gravimetric hydrogen storage capacity is insufficient to function as the primary hydrogen storage system in aviation [4, 6]. However, MHs receive ongoing research attention due to their significant potential in engineering applications beyond hydrogen storage [7]. These 'secondary' applications include hydrogen compression, purification and sensing as well as the use in optical or thermal systems [6, 7].

This paper investigates the potential for application of MHs in aviation. Firstly, an overview of MH-based applications is provided and potential options for the utilisation in aviation are selected for consideration. Secondly, the current state-of-the-art of the selected options is reviewed. To benchmark the MH applications, an evaluation methodology and the evaluation criteria are then introduced. For an objective evaluation, specific aviation use cases of these applications are elaborated and sized to achieve comparable levels of detail [8]. Subsequently, the potential of the selected use cases is assessed and illustrated. Finally, the most promising use cases are identified and outlooks for highest rankings are elaborated.

2.0 Review of metal hydride applications

The formation of MHs can be characterised with Equation (1):

$$\text{metal}_{\text{solid}} + \text{hydrogen}_{\text{gaseous}} \leftrightarrow \text{metal hydride}_{\text{solid}} + \text{heat} \tag{1}$$
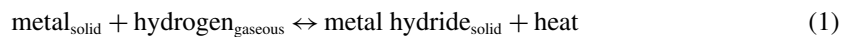
Heat is released during the absorption of hydrogen due to the exothermic nature of the reaction. For the desorption of hydrogen, which is an endothermic reaction, heat must be supplied [7]. The pressure level, at which MHs reversibly absorb or desorb major quantities of hydrogen, increases with rising temperature. This pressure-temperature-dependency is illustrated in so called Van't Hoff plots according to Fig. 2(a), which support the selection of appropriate types of metal hydrides for the operational range of a specific application. By plotting the natural logarithm of the MHs equilibrium pressure p in relation to the reciprocal of its corresponding temperature T, a straight line is obtained [5, 7]. The pressure and temperature correlation varies with the composition of the metallic alloy, which allows the tuning of the material's properties to the designated application as illustrated in Fig. 2(b) [7].

The properties of MHs enable a wide range of engineering applications. To provide an overview, these are compiled and classified in Table 1 [6, 7, 9, 10]. Not all of the listed applications offer reasonable use cases in aviation. The most promising options are selected and highlighted by means of an asterisk in Table 1. In the following subsections, their current state-of-the-art will be presented and specific use cases for aviation will be identified for the evaluation.

2.1 Hydrogen storage

Despite their limited gravimetric hydrogen storage densities, MHs offer multiple advantageous properties like compactness, low infrastructure requirements, low energy consumption, loss-free storage and

Table 1. *Classification of metal hydride applications*

Engineering field	Application options
Energy storage	Hydrogen storage* (stationary, mobile, portable), electrode material in batteries
Thermal systems	Heat storage* (heat source, heat sink), heat pumps* (heating, cooling), cryocoolers, heat switches*
Actuation and compression	Hydrogen compressors*, thermal-mechanical actuators*, thermal engines
Processing	Hydrogen purification*, hydrogen separation*, hydrogen getter, catalysis, hydrogen sensing*
Electronics	Semi-conductors
Optical systems	Smart windows
Nuclear systems	Neutron moderators, transmutation
Biomedical systems	Pre-process for implant material preparation

* Considered in this study as potential application options in aviation.
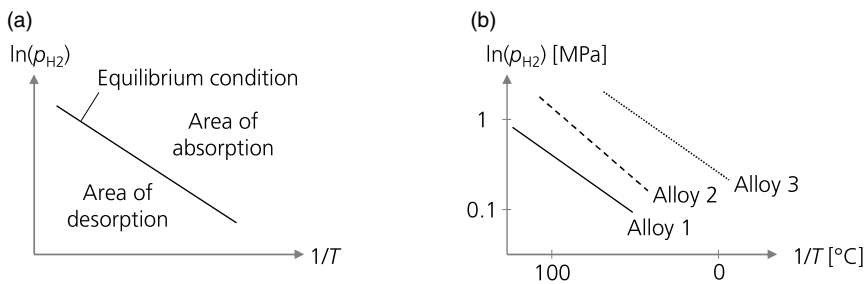
Figure 2. *Exemplary Van't Hoff plots: (a) schematic Van't Hoff plot of a single metal hydride, (b) schematic Van't Hoff plot of multiple hydrides based on different notional metal alloys.*

inherent safety due to the endothermic nature of the hydrogen release [3, 5, 11–16]. Therefore, MHs may be ideal as a secondary hydrogen source, which serves as an emergency supply. As a drawback, MH storage systems require a thermal management system for heat supply and heat rejection [4]. This can lead to a delay between the heat activation and the release of hydrogen [17].

Hybrid storage systems, which combine solid storage in MHs with compressed gaseous hydrogen (CgH2) storage at high pressures, could be a suitable compromise. These systems achieve higher volumetric storage densities compared to CgH2, while causing only moderate weight penalty [11, 18–25]. Hybrid systems also offer a fast response behaviour, which is mandatory for emergency power supply systems [24]. Disadvantages of hybrid systems include the loss of inherent leakage safety and the need for an additional containment device to avoid MH spillage in the event of a damaged vessel [22, 23]. The use of such hybrid storage systems to store reserve fuel was analysed in Ref. (26). This study presents the achievable mission ranges for a commuter aircraft, which is equipped with a dedicated tank for reserve fuel to allow a diversion to an alternative airport. The results show that an application of a hybrid storage system for this reserve is only feasible when the payload of the aircraft is reduced. Despite the improved gravimetric hydrogen storage densities compared to pure MH storage systems, the energy density of a hybrid system remains too low compared to other energy storage technologies of hydrogen.

2.2 Heat storage

According to Equation (1), the characteristic of the hydride formation allows the use of MHs in thermal applications. MHs possess high thermal storage capacities of up to 2,000kJ/kg$_{MH}$ and are therefore
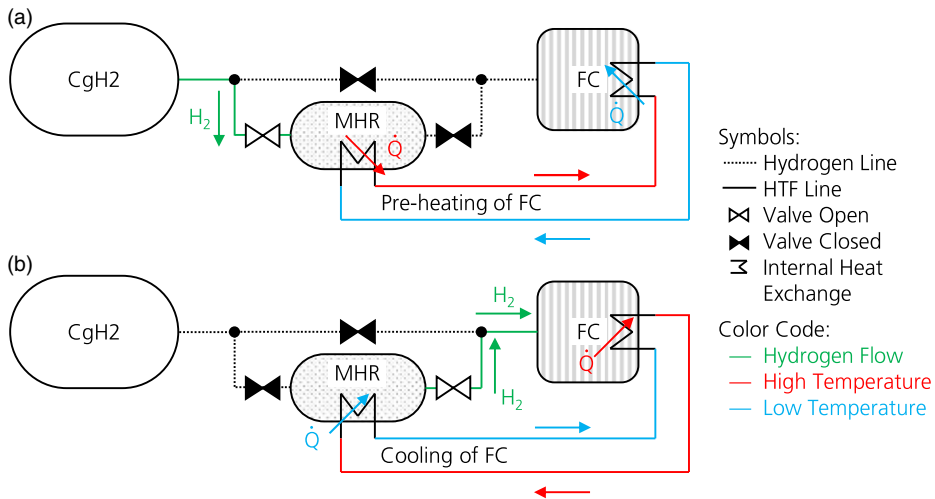
Figure 3. *Operation modes of an exemplary FC-powertrain coupled to an MHR: (a) pre-heating of the FC by the heat of absorption and (b) cooling of the FC by the desorption's heat uptake.*

ideally suited as heat sinks for cooling applications or as heat sources for pre-heating processes [6, 7, 27, 28]. Both use cases appear promising for future electric propulsion systems. The high quantity of waste heat produced at the relatively low operating temperature of the components, especially in polymer electrolyte membrane fuel cells (PEMFC), poses challenges to the thermal management system (TMS) [29–32]. In these powertrains, an MH reactor (MHR) is suitable for pre-heating a fuel cell (FC) prior to a cold start to reduce aging. Additionally, it can operate during periods of high power demand, like take-off or climb, to absorb some share of the heat generated by the PEMFC [33–35]. Both of these operation modes are illustrated in Fig. 3. While a CgH2 tank serves as the main hydrogen source for the FC, the MHR stores the hydrogen only intermediately to generate a heating or cooling effect. No hydrogen is consumed by the operation of the MHR.

The operating temperatures of PEMFCs restrict the use MH alloys to low-temperature types with lower thermal storage capacities in the range of $184 kJ/kg_{MH}$ for the example of $LaNi_{4.85}Al_{0.15}$ [28, 36, 37]. Another limiting factor occurs when the FC hydrogen intake is directly coupled to the MHR hydrogen outlet. In that case, the FC hydrogen consumption limits the achievable thermal power of the MH, as the hydrogen mass flow dictates the magnitude of the absorption and desorption heat flow [34]. In an example of direct coupling, the MH can theoretically absorb up to 35% of the FC's waste heat when the FC operates at an efficiency of 60% [37]. This proportion becomes even larger at higher FC efficiencies.

However, the duration of the cooling effect is limited by the hydrogen capacity of the MHR, since the MH material only absorbs heat during the endothermic desorption of hydrogen. The longer the desired operating time, the more MH material is required, which results in an increased system mass. This mass increase causes the specific cooling power of the MHR to decrease because the thermal power remains constant, as it is linked to the hydrogen mass flow of the FC. Therefore, the use of MHs as a heat sink for component cooling does not seem reasonable for operating times above one minute, as the specific cooling power of the total MHR drops below 1.5kW/kg [37]. Nevertheless, the utilisation of MHs as a heat source for de-icing, for pre-heating of the cabin or for warm-up of components like fuel cells, sensors or lubricants may still be reasonable use cases in aviation due to the high thermal storage capacities [28, 33, 34, 36, 38].

2.3 Heat pumps

In addition to thermal storage, MHRs can also operate as heat pumps [6, 7, 27]. A heat pump transfers heat from a low temperature source to a higher temperature sink [32]. MH-based heat pumps can be
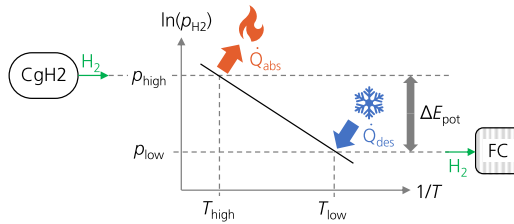
Figure 4. *Working principle of metal hydride heat pump integrated into an FC-powertrain with a compressed gaseous hydrogen (CgH2) storage according to Ref. (34).*

driven by the pressure differential between a CgH2 storage system and a consumer, such as an FC, as shown in Fig. 4. Thus, MH-based heat pumps can convert the potential energy of the high-pressure gas into thermal energy for both heating and cooling [6, 28, 39, 40]. Until now, this potential energy is throttled to the supply pressure of the consumer and thus lost [41]. When MH-based thermal devices utilise the potential energy of the tank pressure, they require only minimal additional amounts of electric energy for their operation [39].

When used for cabin air-conditioning or galley cooling, the rather low energy consumption of MH heat pumps could result in a weight advantage compared to conventional state-of-the-art aircraft systems, as less energy has to be carried during the flight. Furthermore, MH-based thermal devices are environmentally friendly, as they can operate without harmful refrigerants [39]. During cruise flight, the cabin of the aircraft usually requires cooling, even though ambient temperatures are low at high altitude [42, 43]. Presently, air-conditioning systems of aircrafts comprise air cycle machines (ACM), vapor cycle machines (VCM) or a combination of both [42, 44–48]. As VCMs are more efficient, this type serves as a benchmark for the proposed MH-based air-conditioning system in Section 4.1 [32, 42, 44, 47, 48].

In addition to air-conditioning, MH-based heat pumps have the potential to improve the heat rejection of the propulsion system's TMS. The limited temperature difference between PEMFCs and ambient air presents a significant challenge for the TMS. The implementation of an MH-based heat pump can increase the temperature difference between the heat transfer fluid (HTF) and the ambient air. Thus, the necessary heat exchanger size (HX) decreases as heat rejection temperature difference increases [29–31]. A pair of two MHRs enables the quasi-continuous operation of a heat pump through alternating hydrogen absorption and desorption, as shown in Fig. 5 [37]. Subsequent to exiting from the FC, the hot HTF flows through the first MHR, which increases the HTF temperature even further to elevate the heat rejection temperature in the HX. Prior to re-entering the FC, the second MHR removes the quantity of heat that was added by the first MHR, from the HTF. The increase in heat rejection temperature can potentially reduce the size of the HX, although the amount of heat rejected to the ambient air does not change significantly. This is particularly advantageous in hot ambient conditions, where the temperature difference between the PEMFC and the surrounding air is low. At an ambient temperature of 38°C and an FC efficiency of 60%, the integration of an MH-based heat pump could theoretically result in a 7% relative decrease in HX size. However, the additional weight caused by the pair of MHRs functioning as a heat pump exceeds the mass savings of the HX by a factor of 10 [37].

2.4 Heat switches

Heat switches are utilised in the thermal management of cryogenic applications because they can provide a thermal connection or separation [49, 50]. Gas gap heat switches (GGHS) in particular permit variable thermal conductance by adapting the gas pressure in a narrow gap between two components [49, 51, 52]. Hydrogen is the optimal operating medium for GGHSs because it has the highest thermal conductivity among all gases [7, 53]. Despite this, its conductivity remains 100–1,000 times lower than that of solid metals such as copper or titanium [54]. As a result, GGHS require large surface areas and
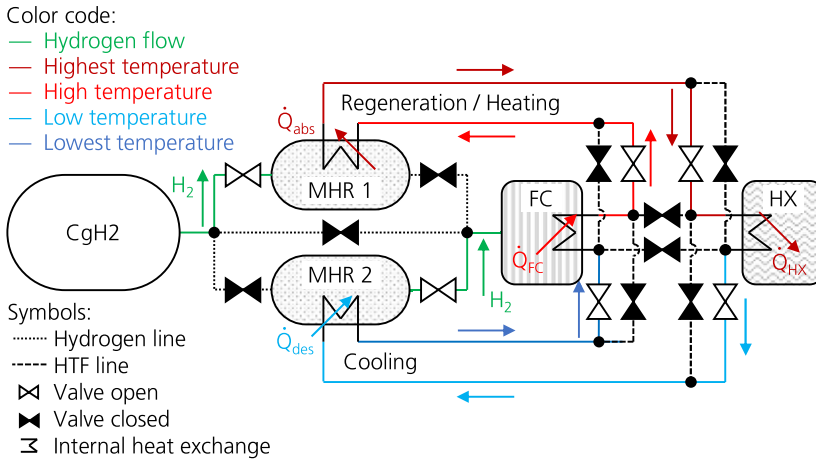
Figure 5. *Schematic of the alternating heat pump operation of two MHRs to enhance the FC's TMS by increasing the temperature difference to the ambient air in the HX.*
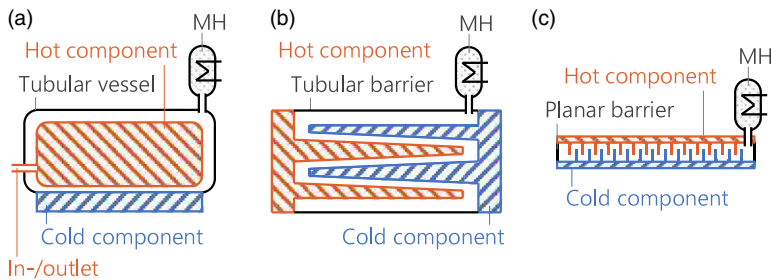

Figure 6. *Gas gap heat switch (GGHS) designs: (a) concentric vessel design acc. to Refs (55–57), (b) overlapping fin design according to Refs (54, 58–61) and (c) flat panel design acc. to Refs (62, 68).*

small gaps, as illustrated in Fig. 6 [49, 63]. In design (A), the hot component inside of a vacuum tubular vessel resembles a heat source that requires temporary cooling. A feedthrough enables the in-/outlet of operating fluids or electric wiring, depending on the interfaces required by the specific device. In design (B) and (C), the hot and cold component resemble the interfaces to an arbitrary heat source and heat sink, respectively. Although both designs possess fins to increase the area for heat transfer, they differ in their outer shape. While design (B) is framed by a tubular barrier, design (C) forms a flat panel. For all three designs, MHs can act as regulating units for the provision and removal of the hydrogen gas [6, 7, 52, 54, 62, 64].

The working principle of GGHSs may be suitable for facilitating an efficient thermal management of liquid hydrogen (LH2) tanks with vacuum insulation. Although LH2 is the most promising storage option for aircraft, its need for a TMS to supply the hydrogen and to maintain the tank pressure is a disadvantage [4, 65–67]. An MH regulating unit with the capacity to vary the vacuum insulation pressure of an LH2 tank by desorption or absorption of hydrogen can thereby affect the heat transfer through the insulation [68]. In this particular use case, the MH regulating unit acts as a heat amplifier. A small heat supply to the MH for hydrogen desorption results in a larger heat input into the LH2 tank due to the increased heat transfer in its insulation. With such an approach, 95% of the necessary evaporation energy can be drawn from the surroundings [69]. This reduces the power requirements for the LH2 tank's TMS. The described approach is similar to the GGHS design (a) from Fig. 6 but with the hot and cold components reversed. Section 4.4 will adapt all the designs from Fig. 6 to the geometry of an
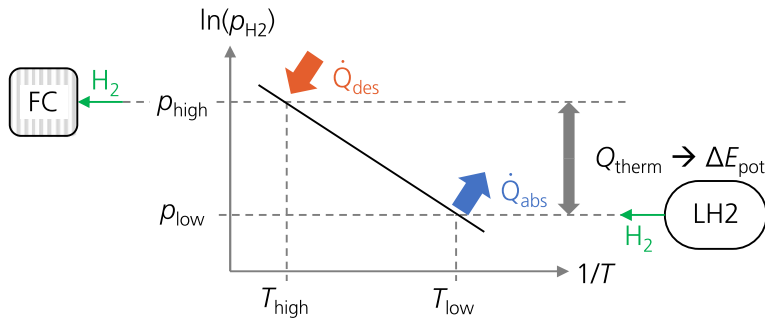
Figure 7. *Schematic Van't Hoff plot illustrating the working principle of hydrogen compression by metal hydride from low pressure liquid hydrogen (LH2) storage to the supply pressure of a fuel cell (FC).*

LH2 tank and estimate the size of an MH regulating unit to allow the evaluation of the potential of such MH-actuated GGHS for an aircraft's LH2 tank.

2.5 Hydrogen compressors and actuators

MHs enable the design of thermally driven hydrogen compressors [41, 70–72]. This allows the use of waste heat, resulting in an environmentally friendly and cost-effective hydrogen compression [6, 73]. With this ability, MHs may be used to efficiently capture, store and compress the boil-off hydrogen gas released from LH2 tanks for further utilisation, as illustrated in Fig. 7 [74–76]. While absorbing boil-off gas from a low pressure LH2 tank, the MH has to be cooled by rejecting the heat of the absorption reaction. An increase in the MH's temperature would raise its equilibrium pressure, as indicated by the black line, and thereby impede the hydrogen absorption. In turn, this characteristic behaviour is utilised after the hydrogen uptake is completed. By increasing the MH's temperature, e.g. by using the waste heat from the FC, the hydrogen is released at a higher pressure level to be directly supplied to the FC. The boil-off gas, which occurs periodically during refueling and also continuously during periods when the aircraft is not in service, could be a cost-effective fuel source for ground-based power services [77]. Recovering this hydrogen decreases the financial loss resulting from the venting of hydrogen boil-off and thereby enhances the efficiency of the LH2 supply chain [77].

Compared to the sequential process of hydrogen uptake at low pressure followed by provision at higher pressure for the boil-off recovery, a continuous compressed hydrogen supply can be achieved by utilising at least two MHRs operating in parallel [70, 72], as shown in Fig. 8. An alternating operation of this parallel process has the potential to enable an onboard compression of hydrogen, which is extracted in gaseous form from a low-pressure LH2 storage, to the supply pressure of the consumer such as an FC or a combustion engine. Therefore, the waste heat of the consumer, which is an FC in Fig. 8, is provided to one of the MHRs to drive the desorption of hydrogen on a pressure level that is desirable for the consumer. In parallel, the other MHR is refilled with hydrogen from the LH2 tank. To enable such low-pressure absorption, this MHR has to be cooled by an additional HX.

Furthermore, the compressed hydrogen could be utilised in pneumatic actuators to convert waste heat into mechanical work [7, 72, 78–82]. While hydraulic and electrical systems perform most actuation tasks in aircrafts, pneumatic devices are applied as well in minor applications [48]. Exemplary pneumatic aircraft systems, which could potentially be powered by compressed hydrogen instead of compressed air, are engine services on the one hand, like actuating variable guide vanes or the thrust reverser, and aircraft services on the other hand, like pressurising water tanks and hydraulic reservoirs or inflating flexible deicing systems [38]. Nevertheless, replacing air as an operational medium by hydrogen gas leads to additional hazards, such as material embrittlement or the accumulation of explosive gas mixtures
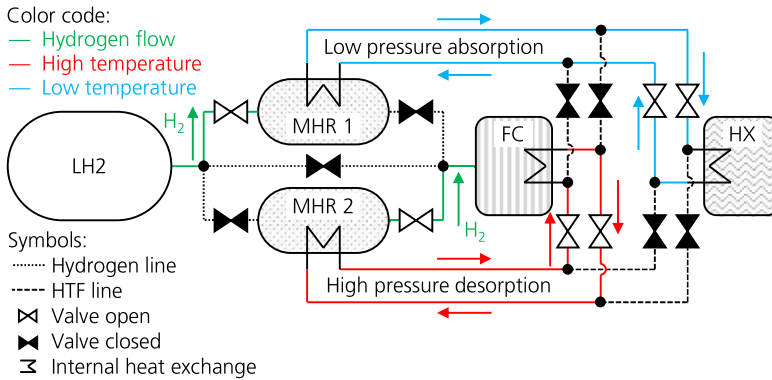
Figure 8. *Topology of a metal hydride onboard hydrogen compression system in an FC-powertrain with low pressure liquid hydrogen (LH2) storage.*
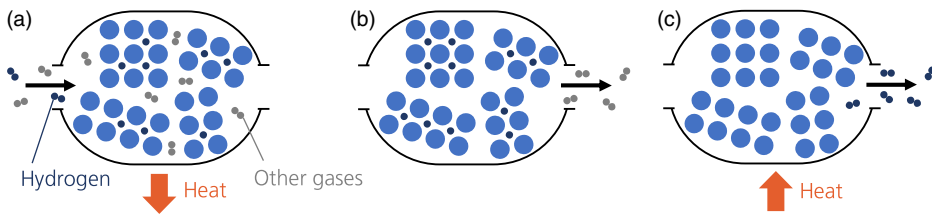
Figure 9. *Working principle of hydrogen purification by MHs according to Ref. (6): (a) filling with impure hydrogen and absorption, (b) flushing of admixtures and (c) desorption of pure hydrogen.*

[14, 66]. Due to these potential hazards and due to the minor use of pneumatic systems in aviation, only the two use cases 'boil-off recovery' and 'onboard hydrogen compression' will be further investigated in Section 4.

2.6 Hydrogen purification and separation

Although there are many methods for purifying hydrogen, MHs have received special attention in that field due to their safe, simple and cost-effective operation. MHs achieve a high-level purification of hydrogen, regardless of the input hydrogen quality [6, 9]. Figure 9 shows the procedure of hydrogen purification by MHs. When the impure gas enters the MHR, only the hydrogen is absorbed, while the other gas admixtures occupy the void space between the MH particles. After flushing out these admixtures, the MHR can provide pure hydrogen by desorption. This use of MHs may be promising in FC-powered aircrafts, since hydrogen impurities can cause rapid degradation of PEMFCs [14]. However, onboard purification is not reasonable due to the limited hydrogen exploitation rates of 75–95% and the high weight of such MH systems [7, 9, 83].

Besides purifying hydrogen gas, MHs can also separate hydrogen from gas mixtures. However, this separation method is only applicable for hydrogen contents exceeding 15% [6, 9]. Additionally, admixtures such as oxygen or water can gradually reduce the capacity and durability of the MH material [84]. Hence, use cases such as removing hydrogen from ambient air in the event of a hydrogen leak or extracting hydrogen from an exhaust gas are unfeasible. Although hydrogen purification and separation by MHs show promise in industrial applications, they are not further considered as use cases in this study due to their expected low potential for a direct use in aviation.

2.7 Hydrogen sensing

Some metals and their hydrides change their electrical, mechanical or optical properties, when being exposed to hydrogen. These characteristics can be used for hydrogen sensing purposes [7, 66, 85, 86]. MH-based sensors offer selective sensing behaviour and operate without requiring oxygen. The use of MHs as hydrogen detection devices in aviation safety applications was evaluated by Ref. (87). The six investigated design principles of MH-based hydrogen sensors enable diverse sensing applications ranging from wide area monitoring to local leakage detection. While sensors based on some principles are already commercially available, other principles are still a field of research. The sensor properties depend on their design principle and can be generalised as follows:

- *Electrical resistance sensors:* wide detection range and good accuracy, but large size, high weight and high-power consumption
- *Cantilever sensors:* wide detection range, small size and inherently safe, but slow response and low maturity
- *Nanogap sensors:* fast response and high sensitivity, but poor upper detection limit and complex fabrication
- *Fiber optic sensors:* no magnetic interference, inherently safe and suitable for wide area monitoring, but low accuracy, slow response and high cost
- *Chemochromic sensors:* no infrastructure needed and low cost, but limited hydrogen quantification ability and need for periodic inspections
- *Acoustic sensors:* wide detection range, high sensitivity and fast response, but challenging manufacturing and low maturity

Despite their various advantages and disadvantages, none of the six design principles meets all the requirements to be used as a safety sensor in aviation [87]. However, with continuous growth in hydrogen-based aviation and research progress in MH technology in parallel, MH-based hydrogen sensors may evolve further. As hydrogen leakage detection is expected to be a key technology for hydrogen-fueled aircraft, MH-based sensors should be investigated due to their promising properties [88].

2.8 Use case selection for evaluation

Based on the review of possible MH applications, this study selects the following aviation-specific use cases for the evaluation:

1. Hydrogen storage systems as emergency supply
2. Cabin air-conditioning
3. TMS system enhancement for FCs
4. GGHS for thermal management of LH2 tanks
5. Hydrogen boil-off recovery
6. Onboard hydrogen compression
7. Hydrogen safety sensors

3.0 Evaluation method

Numerous methods are available to assist in evaluating technical application to provide a holistic judgement and support the decision-making in case of various potential solutions. These methods enhance the plausibility and objectivity of the decision-making-process [8, 89, 90]. For the applicability in this
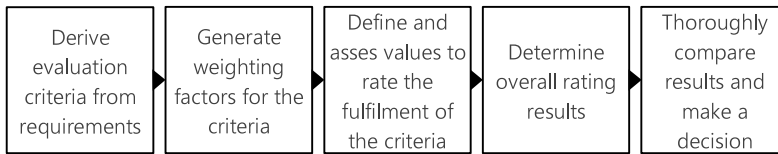
Figure 10. *General procedure of evaluation methods for decision-making.*

study with its low level of concretisation, the evaluation method should be suitable to rate qualitative criteria [8, 90, 91]. As the rating of qualitative criteria is subjective, a group of individuals from different engineering fields must be consulted to ensure a broad scope of expertise [8]. The general procedure for most of these methods is similar to Fig. 10 [8, 89, 91, 92]. The following subsections present the single process steps in detail.

3.1 Evaluation criteria

The evaluation criteria should be derived from the requirements list of a technical product, while essential minimum requirements should not be considered [90, 91]. Recommendations and checklists with general requirements from [8, 30, 90, 93, 94] serve as guidance material in this study, resulting in the following criteria for the evaluation:

1. *Performance:* The system's power and operational behaviour are covered by this criterion. Potential synergies, when multiple tasks can be performed by the same device, increase this performance rating. Additionally, the mass specific powers and energies are compared to appraise also the weight of the system. Possible weight savings in the necessary amount of energy carrier are also taken into account.

2. *Ease of integration:* This criterion contains installation space requirements and interface requirements like mountings, TMS, wiring and other necessary infrastructure. Moreover, the resilience against ambient conditions and interactions with components in the vicinity is included.

3. *Safety:* As no hazardous events should occur due to the use of novel MH systems, this criterion considers failure types and their severity and probability. The potential to store hydrogen for emergencies or the ability to perform multiple tasks and thereby increase redundancy improves the overall aircraft safety.

4. *Cost:* This criterion includes manufacturing and operational costs on the one hand and development costs on the other hand. Besides material costs, the manufacturing costs consider the producibility. Operational costs are influenced by consumables, lifetime or maintenance. The development costs are related to the technology's maturity, as a low technology readiness level (TRL) implies increased development efforts and risks.

5. *Sustainability and Efficiency:* As the mitigation of climate change is the main goal for hydrogen-powered aviation, the potential to reduce greenhouse gas emissions is considered by this criterion. This can be achieved by a high system efficiency and by improving the overall efficiency. The latter can be realised by the use of waste heat or by the use of the potential energy of compressed hydrogen. A high material utilisation in combination with recyclability is also valued by this criterion.

3.2 Criteria weighting

The significance of each criterion j is rated by weighting factors w_j. While these factors w_j are real, positive numbers in the range from 0 to 1, their sum must be equal to 1 [8, 90, 91]. The weighting factors w_j are derived in Table 2 by a pairwise comparison. In this table, the criteria are benchmarked against

Table 2. *Criteria weighting via pairwise comparison*

Criteria	P	I	S	C	E	Weighting Factor w_j
Performance (P)	–	2	0	2	2	0.30
Ease of integration (I)	0	–	0	1	2	0.15
Safety (S)	2	2	–	2	2	0.40
Cost (C)	0	1	0	–	1	0.10
Sustainability and efficiency (E)	0	0	0	1	–	0.05

Values: row criterion is more important than column criterion $= 2$, equally important $= 1$, less important $= 0$.

each other according to their importance. The importance values are allocated in the bottom line [93]. Subsequently, the weighting factors w_j are obtained by summing the importance values for each criterion and dividing by the total sum of all criteria. The pairwise comparison is suited for this study, where the majority of criteria have to be appraised qualitatively and subjectively [8, 93]. As this comparison is conducted by a group of aerospace engineers, the 'safety' criterion dominates the other criteria because the safety assessment is a fundamental part in the system development process in aviation [48, 95, 96]. Besides safety, a lightweight design is considered to be a substantial requirement for aircraft systems. As the mass of the components and also weight savings in the amount of energy carrier are covered by the 'performance', this criterion also achieves high values in the benchmark.

3.3 Value assessment

The grade of fulfilment of the criteria is appraised with numerical measures $m_{i,j}$. When characteristics and performance parameters are inadequately known, a narrow range of $m_{i,j}$ from 0 to 4 according to VDI 2225 is reasonable and therefore used in this study as follows [90, 91]:

- very good fulfilment: $m_{i,j} = 4$ points $= + +$
- good fulfilment: $m_{i,j} = 3$ points $= +$
- moderate fulfilment: $m_{i,j} = 2$ points $= o$
- bad fulfilment: $m_{i,j} = 1$ point $= -$
- very bad fulfilment: $m_{i,j} = 0$ points $= - -$

3.4 Overall rating

By multiplying the grade of fulfilment with the weighting factors w_j and dividing by the scale size m_{max}, the relative rating $r_{i,j}$ is calculated for each criterion j and each MH use case i, as shown in Equation (2) [8, 30, 90, 91]. The sum of all relative ratings $r_{i,j}$ associated with a use case i results in the use case's overall rating r_i. The variable k represents to the total number of criteria and n is the total number of possible solutions, which are the MH use cases in this evaluation.

$$r_i = \sum_{j=1}^{k} r_{i,j} = \sum_{j=1}^{k} w_j \cdot m_{i,j}/m_{max}, for\ i = 1 \ldots n \tag{2}$$

3.5 Decision making

The most promising use cases for aviation will be determined with the help of the overall ratings r_i coupled with subjective appraisement to account for uncertainties or the influence of the choice and weighting of the criteria [89].

Table 3. *Parameters of a generic commuter aircraft as reference*

Parameter	Value and Unit	Comments
Passengers	19	Derived from Ref. (97)
Service ceiling	7,620m	Derived from Ref. (5)
Empty weight	4,000kg	Derived from Ref. (5)
Take-off FC power P_{FC}	1.5MW	Derived from Ref. (5)
FC efficiency η_{FC}	50%	[14, 30, 65, 98–100]
Hydrogen fuel mass	270kg	Scaled from Ref. (129)
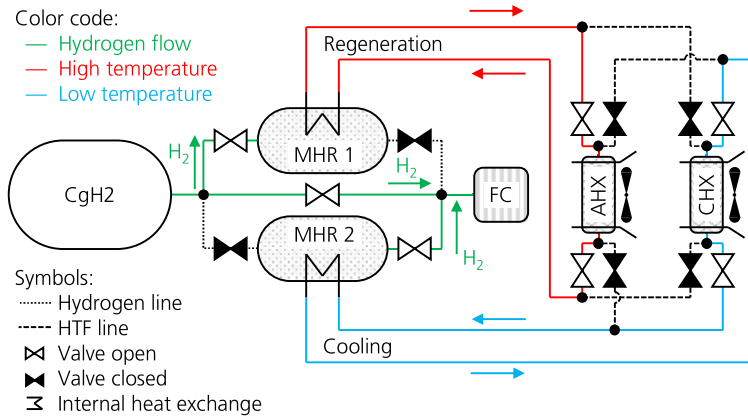
Figure 11. *Topology of an air-conditioning (AC) system with 2 MH reactors (MHR), ambient heat exchanger (AHX) for waste heat rejection and cabin heat exchanger (CHX) for cooling.*

4.0 Elaboration of dedicated aviation use cases for metal hydride applications

In order to allow a reasonable and objective evaluation, the use cases should be presented at comparable levels of detail to avoid misevaluations. Three of the selected MH use cases, the 'emergency hydrogen storage', the 'TMS system enhancement for FCs' and the 'hydrogen safety sensors', were already investigated in dedicated studies regarding their potential in aviation [26, 37, 87]. Hence, the other four use cases, the 'cabin air-conditioning', the 'boil-off recovery', the 'onboard hydrogen compression' and the 'GGHS for thermal management of LH2 tanks', will be elaborated in this section before the evaluation can be performed. Therefore, a generic FC-powered commuter aircraft according to Table 3 serves as a reference for sizing estimations.

4.1 Cabin air-conditioning

To evaluate the potential of MHs for air-conditioning (AC), this section sizes a MH-based AC system and its energy consumption and benchmarks this system against a conventional vapor cycle machine (VCM). Figure 11 shows the topology of the MH-based system. A CgH2 storage tank is considered as energy carrier, since this enables the MH-based system to beneficially convert the potential energy of the compressed hydrogen to a cooling effect, which leads to low additional power demands. In contrast to the application of hydrogen compression in Fig. 8, the refilling of the MHRs is realised in Fig. 11 by CgH2 tanks. This high absorption pressure allows the use of MH materials, e.g. alloy 3 from Fig. 2, enabling heat uptake by desorption at temperatures below 0°C to generate a cooling effect. While the desorbed hydrogen is supplied to the FC, the cooling effect is used in the cabin heat exchanger (CHX) for

Table 4. *Component weights of an MH-based AC system with a cooling power of 2kW*

Component	Weight
MH weight based on Ref. (107)	7.25kg
MHR weight based on weight ratio of 1 [33]	7.25kg
Coolant pump based on Ref. (32) plus plumbing and coolant	1.10kg
AHX and CHX based on 1kW/kg power density assumption	4.00kg
AHX and CHX blowers based on Ref. (108)	1.74kg
Peripheral devices, 10% of overall mass	2.10kg
Overall mass of MH-based AC system	23.47kg
Resulting mass-specific power of MH-based AC system	$SP_{MH} = 0.09kW/kg$

Table 5. *Power demands of the components of both AC systems*

Component	Power Demand
AHX and CHX blowers based on Ref. (108)	$P_{blower} = 2 \times 0.056kW$
Coolant pumps based on Ref. (32)	$P_{pump} = 2 \times 0.027kW$
Refrigerant compressor with COP of 1.5 based on Ref. (47)	$P_{comp} = 1.33kW$

air-conditioning. The ambient heat exchanger (AHX) rejects the heat of absorption of the MHR, which is being refilled.

With respect to Ref. (46), a power P_{cool} of 2kW is estimated to meet the heat load demands during cruise flight of the reference commuter aircraft. Even though the cooling requirements may be greater on ground [44, 101], the comparison solely pertains to cruise conditions, as the MH-based AC system necessitates a hydrogen mass flow to operate. To accomplish initial cooling on the ground, a stationary cooling system could be utilised instead. The comparison between the VCM and the MH-based AC takes into account the weight of the systems and their respective energy demand as well. The system weight of the VCM is calculated on the basis of a specific power SP_{VCM} of 0.20kW/kg, which is derived from literature sources [102–106]. Table 4 compiles the weight of the MH-based system, while Table 5 lists the energy demands of both systems' components.

While the blowers of the heat exchangers AHX and CHX generate energy demands for both AC systems, the energy consumption of the coolant pumps only needs to be considered for the MH-based system. On the other hand, the energy demand of the refrigerant compressor is only relevant for the VCM, which results in an overall higher energy consumption compared to the MH system. The total energy demand impacts the respective weight of the energy carrier and its storage system as well as means for energy conversion. According to Fig. 11, the CgH2 tank and the FC are considered to provide the energy not only for the aircraft propulsion but also for the AC system. Thus, the respective weight of the hydrogen fuel as energy carrier and the corresponding weight of the CgH2 storage tank are calculated for both AC systems. Therefore, a gravimetric storage density of 5.5 wt.% is applied for the CgH2 tank, which results in a mass-specific energy SE_{CgH2} of 1.83kWh/kg [109]. Additionally, the corresponding weight of an FC, which is needed to convert the chemical energy into electrical energy, is considered by a mass-specific power SP_{FC} of 0.15kW/kg [110]. The weight results W of the comparison are displayed in Fig. 12, which is based on the Equations (3) and (4).

$$W_{AC,MH} = \frac{P_{cool}}{SP_{MH}} + \frac{P_{pump} + P_{blower}}{SP_{FC}} + \frac{(P_{pump} + P_{blower}) \cdot t}{SE_{CgH2} \cdot \eta_{FC}} \tag{3}$$

$$W_{AC,VCM} = \frac{P_{cool}}{SP_{VCM}} + \frac{P_{comp} + P_{blower}}{SP_{FC}} + \frac{(P_{comp} + P_{blower}) \cdot t}{SE_{CgH2} \cdot \eta_{FC}} \tag{4}$$

The increased power demand of the compressor results in a higher corresponding FC weight for driving the VCM, which offsets the VCM's higher specific cooling power to some extent. However, due
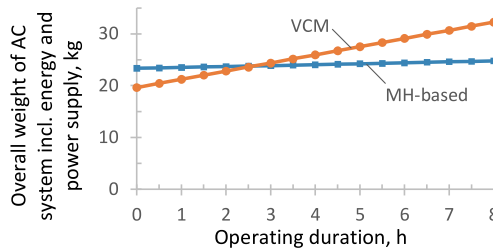
Figure 12. *Overall weight comparison of a conventional vapor cycle machine (VCM) and an MH-based cabin air-conditioning system both sized for 2kW of cooling power.*

to its lower specific cooling power, the MH-based AC system still displays greater weights for shorter cooling durations. For durations exceeding 2.5 hours, the MH-based AC system achieves an overall weight advantage over the conventional VCM owing to its lower energy requirements.
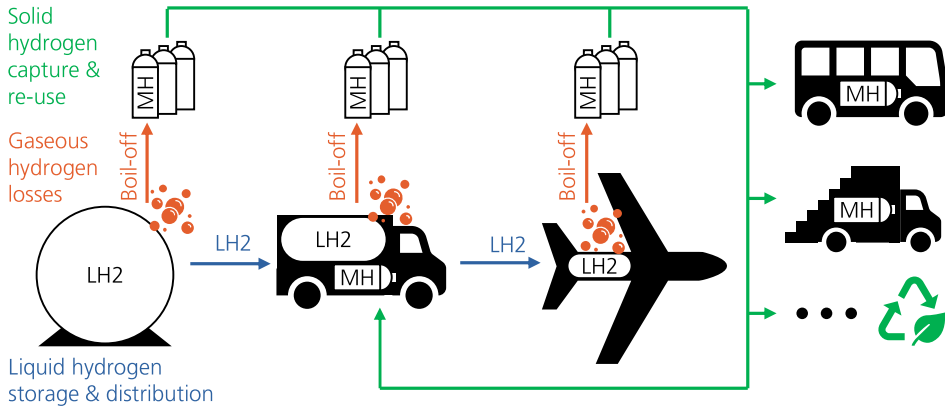
4.2 Boil-off recovery

For cryogenic LH2 tanks, heat transfer from the ambient environment causes continuous boil-off losses ranging from 0.2% to 3% per day, which have to be vented to avoid overpressure. These losses depend on the size of the tank and the quality of its insulation [3, 4, 67, 111, 112]. Larger tanks experience smaller losses through heat transfer due to their lower surface-to-volume ratio [113]. In addition to continuous boil-off, up to 15% of the transferred LH2 vaporises when re-fueling the storage tank [75, 114, 115]. These transfer losses strongly depend on the filling method, the amount of delivered hydrogen, the size of the tank, the geometry of the tank, the insulation thickness and the hydrogen mass flow [114, 115]. Therefore, the design of an LH2 aircraft tank involves balancing acceptable boil-off losses on the one hand with tank weight and insulation thickness on the other hand [77]. For LH2 tanks in aircraft, a boil-off rate in the order of 0.1% per hour is acceptable [116]. As a baseline for the sizing, the reference commuter aircraft of Table 3 is considered to be equipped with an LH2 tank to store its hydrogen fuel. An exemplary loss of 2% of the total fuel mass is applied to calculate the necessary amount of MH material for boil-off recovery. Such a share is assumed to be a reasonable value for both the continuous boil-off loss per day as well as the additional loss per re-fueling. For the given tank size, this share of 2% corresponds to a loss 5.4kg of hydrogen.

Besides the quantity of boil-off losses, also the properties of the MH material and of the corresponding MHR affect the sizing results. For capturing low-pressure boil-off gas, the material $LaNi_5$ and its alloys are suited as they absorb hydrogen rapidly, reversibly and selectively even at relatively low temperatures [36, 74]. For example, the $LaNi_{4.85}Al_{0.15}$ alloy has the capability of absorbing hydrogen gas at a pressure of only 2 bar when its temperature does not exceed 30°C [36]. This ability enables the capture of boil-off from an LH2 tank, while the ambient air can carry out the heat removal of the exothermic absorption reaction. By transferring waste heat from an FC, which typically operates at a temperature level of 80°C, to the MH for the endothermic desorption, the release of hydrogen takes place up to a pressure of 4 bar. Thus, the MH can directly supply the FC with hydrogen [36]. This enables the recovery of boil-off losses from the LH2 supply chain by capturing in an MH storage and re-using the hydrogen in FC-powered vehicles, as illustrated in Fig. 13. Moreover, MH storage systems offer the potential to swiftly replace depleted MH cartridges and are therefore a viable option for emission-free mobile applications such as utility vehicles [11].

As the usable hydrogen capacity of the $LaNi_{4.85}Al_{0.15}$ alloy is approximately 1.1 wt.%, it requires 491kg of this material to capture the 2% loss of 5.4kg hydrogen. This amount of hydrogen is capable of supplying multiple utility vehicles such as forklifts, pushback tugs or towing tractors, as 2kg of hydrogen is sufficient for several hours of operation. For example, an FC-powered forklift could operate more than

Figure 13. *MH cartridge system for boil-off recovery by capturing and re-using.*

three hours with an average power of 10kW or a light duty industrial vehicle could cover a distance of 80km within 7 hours of operation [70, 117]. Therefore, it seems reasonable to locate a set of multiple cartridges near the LH2 tanks. A single cartridge with a hydrogen capacity of 2kg requires approximately 180kg of $LaNi_{4.85}Al_{0.15}$ alloy. To determine the total weight of the cartridge, a 1:1 ratio of MH material weight to empty cartridge weight is assumed for a lightweight cartridge design [33, 37]. This results in a total MH cartridge weight of approximately 360kg, which is an order of magnitude heavier compared to a CgH2 tank with a gravimetric storage density of 5.5 wt.% [109]. Since utility vehicles require a minimum weight to ensure traction or to avoid overturning, the high weight of the cartridge is advantageous [118].

4.3 Onboard hydrogen compression

Like in the previous section, the sizing of the onboard compression system bases upon a topology with an LH2 tank to store the hydrogen fuel of the FC-powered reference aircraft from Table 3. To achieve a low weight, LH2 tanks in aviation should operate at low pressures of 1.2–3.5 bar [77, 119–122]. Typical hydrogen supply pressures for FCs range from 1.1 to 10 bar [11, 12]. These pressure levels allow the use of a single-stage MH compressor as an onboard hydrogen compression system, since pressure ratios of a factor of 5 are feasible per stage [6, 70–72]. The required size of this MH compressor depends on the achievable half-cycle time and on the maximum hydrogen mass flow demand. In this study, a half-cycle time of 60s is assumed for the sizing, which is considered to be optimistic [72]. The hydrogen mass flow $\dot{m}_{H2}$ demand for an FC can be calculated with Equation (5). The variable ΔH_{H2} corresponds to the lower heating value of hydrogen [12].

$$\dot{m}_{H2} = P_{FC} / (\eta_{FC} \cdot \Delta H_{H2}) \tag{5}$$

The take-off power P_{FC} of the reference aircraft and its fuel cell efficiency η_{FC} from Table 3 result in a maximum hydrogen mass flow demand of 25g/s. Based on a usable hydrogen capacity of the MH of 1.1 wt.% in respect to the previous section, an amount of 136kg MH material will be required for the half-cycle of a single MHR. Since an MH compressor requires two MHRs for continuous operation, as shown in Fig. 8, the total amount of MH material for both reactors adds up to 272kg. Considering the same mass ratio of 1:1 to estimate the empty weight of a high-power, lightweight MHR like in the previous section, the total weight for both MHRs constitutes to 544kg. Although this appears competitive with conventional piston compressors for gaseous hydrogen, the weight far exceeds that of LH2 fuel pumps [77, 123, 124]. For instance, a centrifugal LH2 fuel pump, which achieves a hydrogen mass flow of even 350g/s at similar pressure levels, weighs less than 2kg [77]. Even when considering a potential reduction
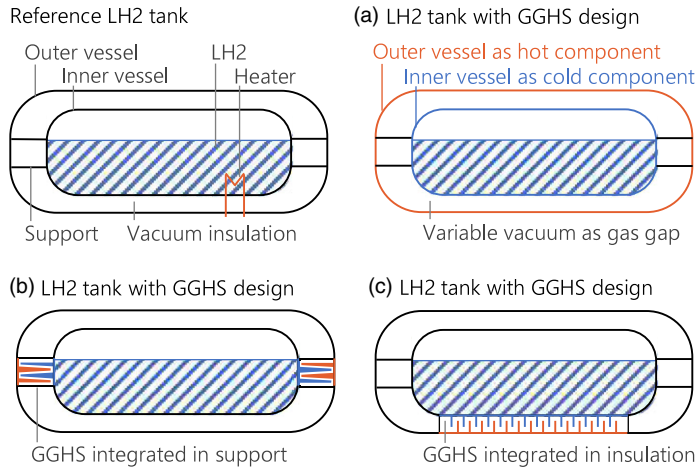
Figure 14. *Reference LH2 tank layout and proposals for GGHS integration: (a) concentric vessel design, (b) overlapping fin design in the support and (c) flat panel design in the insulation.*

of the onboard power demand for compression, the MH compressor seems not competitive to an LH2 fuel pump due to this massive system weight penalty.

4.4 GGHS for thermal management of LH2 tanks

A common form of LH2 tanks is a shape with a cylindrical mid-section and spherical end caps [67, 109, 115]. Figure 14 proposes potential layouts for the integration of the GGHS designs from Fig. 6 into the insulation of such an LH2 tank shape. The fuel mass of the reference aircraft from Table 3 results in a volume requirement of 4.1m³, when the hydrogen is stored as a cryogenic liquid [3, 17]. Exemplary dimensions of an inner vessel to realise this volume are a diameter of 1.60m and a length of the cylindrical part of 0.97m. These dimensions result in an overall surface area of the inner vessel of 12.9m². This resembles the possible heat transfer area A, which is used in the following to estimate the weight and the thermal power of GGHS design (a). Before sizing this MH-actuated GGHS, the thermal power demand for vaporisation of the LH2 fuel is calculated. The heat requirement to vaporise LH2 is 446kJ/kg$_{H2}$ [17, 120]. Multiplying this value with the hydrogen mass flow yields the thermal power which is needed for vaporisation. The take-off mass flow of the reference aircraft leads to a maximum thermal power demand of 11kW to vaporise the LH2 fuel.

The temperature difference across the GGHS determines the heat flux and thereby the thermal power. While the temperature in the inner vessel of the LH2 tank remains constant at –253°C, at least for a full tank, the ambient temperature on the outside varies depending on weather conditions and altitude [3, 120]. For the purpose of a conservative estimate, an outside temperature of –34°C is selected, which corresponds to the air temperature of the international standard atmosphere at the aircraft's service ceiling defined in Table 3 [125]. These boundary conditions lead to a temperature difference ΔT of 219K and an average temperature of –143.5°C. The calculation is based on the assumption of a multilayer insulation, that effectively reduces radiation and convection. Therefore, only the conduction is considered for heat transfer in the 'on' state, when the insulation is filled with hydrogen. The conductive heat flow $\dot{Q}$ across a wall with multiple layers x can be determined using Equation (6). The variable g denotes the thickness of the layer, which can be a solid material or a gap in this case, while the variable k represents the layer's conductivity [126].

$$\dot{Q} = A \cdot \Delta T / \left(\frac{g_1}{k_1} + \frac{g_2}{k_2} \ldots \frac{g_x}{k_x} \right) \quad (6)$$

Since the solid layers of a multilayer insulation are very thin and their conductivity is high compared to the gas gap, their impact on the achievable heat transfer in the 'on' state is assumed to be neglectable. Accordingly, only the gas gaps are considered in this state in Equation (6). The mean thermal conductivity of hydrogen at the average temperature of –143.5°C and at a selected gas pressure of 1 bar is 0.088W/(m·K) [127]. Based on an assumed total gap width of the insulation of 5cm, the achievable heat transfer reaches nearly 5kW. For comparison, a continuous boil-off loss of 2% per day as stated in Section 4.2 corresponds to a heat flow of 0.028kW. With this parasitic heat flow in the 'off' state, when no hydrogen is present in the insulation, the 'on/off' conductance ratio calculates to approximately 180. As this ratio correlates to other studies, the heat flow estimations are considered to be reasonable [49, 52, 60, 62]. Based on the gaseous density of hydrogen of 0.187kg/m^3 at –143.5°C and 1 bar, a hydrogen amount of 127g is required to fill the total gap volume [128]. To provide this amount of hydrogen by an MH alloy with a usable capacity of 1.1 wt.%, a minimum of 11.5kg of the alloy will be required.

Although the calculated heat transfer of GGHS design (a) of 5kW is not sufficient to cover the maximum hydrogen demand of the FC, this tank design may still be a viable option for generating the lower hydrogen mass flow during cruise flight [129]. Additionally, the achievable thermal power could be improved by decreasing the gap width or by adopting the GGHS designs (b) or (c) to increase the available heat transfer area. As a drawback, those actions result in a compromise as they may deteriorate the insulation quality and, consequently, lead to increased boil-off rates due to higher parasitic losses. An amplification in the applied hydrogen gas pressure to improve the thermal power is not reasonable, as the impact on the thermal conductivity would be neglectable [127]. Instead, the higher pressure would lead to an increased tank weight. However, risks and challenges induced by the cycling of the vacuum pressure and the component temperatures are considered to be major drawbacks of the GGHS integration into the LH2 tank insulation.

5.0 Evaluation results and outlooks

As the use cases are brought to comparable levels of detail, the evaluation can proceed by rating the grade of fulfilment of the criteria for each MH use case. This rating is performed in Table 6 by compiling the key aspects and by assigning appropriate numerical measures $m_{i,j}$. Based on Equation (2) and on the weighting factors w_j from Table 2, the overall ratings r_i are calculated. The evaluation results are additionally plotted as bar charts in Fig. 15. These charts visually highlight the individual advantages and drawbacks of each MH use case. Moreover, since the bar width corresponds to the weighting factors w_j, the share of the area which is covered by the bars represents the value of the overall rating r_i. These overall ratings indicate the potentials of the MH use cases in aviation. However, the results should be interpreted with care, as they are influenced to some extent by uncertainties, by subjective appraisement and by the derivation of the weighting criteria.

The 'boil-off recovery' receives top marks for its ability to provide inherently safe storage and sustainable capture and re-use of hydrogen losses. Since such system does not necessarily have to be installed in the aircraft, its high weight will not lead to a devaluation of the 'performance' criterion. Following closely behind are the MH-based 'safety sensors', which now need to be implemented into aviation since commercial applications are already available. Because of their diverse design principles, MH-based 'safety sensors' offer potential in manifold hydrogen detection scenarios. However, the properties of MH-based hydrogen sensors still have to improve and these sensors have to compete against other sensing mechanisms. MH heat pumps for 'air-conditioning' come third. Despite their heavier component weight, these systems can still reduce the overall aircraft weight during longer operations due to their lower energy consumption compared to conventional systems. As a drawback, the use of MH heat pumps is limited to powertrain topologies with a CgH2 storage, which narrows the applicability in future hydrogen-powered aviation. The 'emergency storage', the 'TMS of FCs' and the 'onboard compression' receive low ratings, as these three use cases result in severe weight penalties for the aircraft. The 'GGHS for LH2 tanks' implies risks by adapting the vacuum pressure of the insulation and by altering the temperatures of the tank's components. Nevertheless, this use case is still promising due to the

Table 6. *Evaluation of metal hydride use cases in aviation*

	Performance (P)	Ease of Integration (I)	Safety (S)	Cost (C)	Sustainability and Efficiency (E)	Relative rating r_i
Emergency storage	slow response, high weight, thermal storage (hybrid: fast response, moderate weight)	most compact H_2 storage, TMS required (hybrid: reduced TMS requirements)	inherently safe, leakage free (hybrid: retaining device necessary)	high MH material costs, commercially available (hybrid: TRL 6)	recyclable material, lower energy demand compared to CgH2 and LH2	
	−	o	+	o	+	0.54
Cabin air-conditioning	low specific power, but still weight benefit achievable, pre-heating possible	H_2 mass flow needed for operation, high weight requires adequate mounting	low severity in case of failure, possible emergency H_2 supply, suitable for de-icing	high MH material costs, lower fuel consumption, TRL 4	re-use of the potential energy of CgH2, no refrigerants needed	
	o	−	++	o	++	0.69
TMS for FCs	heat sink and heat pump operation, accurate temp. control, weight penalty	system complexity increased, high weight requires adequate mounting	possible emergency H_2 supply, cooling depends on H_2 flow, heat sink for peak loads	high MH material costs, increased number of components, TRL 3	high amount of MH material compared to small savings in HX material	
	−	−	+	−	−	0.45
GGHS for LH2 tanks	slow response behaviour, low system weight, low energy carrier weight possible	no feed through into inner tank needed, high surface area needed	risks of altering pressure and temperatures, ambient temperature dependence	TRL 9 for GGHS in general, TRL 1 for LH2 tank integration	evaporation energy is drawn from surroundings	
	o	o	−	o	+	0.41

Table 6. *(Continued)*

	Performance (P)	Ease of Integration (I)	Safety (S)	Cost (C)	Sustainability and Efficiency (E)	Relative rating r_i
Boil-off recovery	manifold use cases possible, weight is less critical for heavy duty applications	operation at ambient pressure and temperature, no integration in aircraft needed	inherently safe, leakage free, boil-off capture can prevent hazardous H_2 concentrations	increased H_2 supply chain efficiency, high MH material costs, TRL 3	recycling of H_2 losses, compression work by using waste heat	
	+	+	++	+	++	0.86
Onboard compression	high purity H_2 compression, low dynamics, heavier than LH2 pumps	TMS required, more compact as gaseous H_2 piston pumps, but bigger as LH2 pumps	thermal energy needed for fuel supply, fuel supply is critical	high MH material costs, low operational costs, TRL 9	efficient H_2 compression, energy savings may be consumed by weight penalty	
	−	−	−	+	+	0.33
Safety sensors	wide property range, high weight of currently available sensors	small design space feasible, optical sensors: no magnetic interference, no O_2 required	multiple mechanisms available, optical sensors: no source for ignition	costs depend on type: from low to high, commercially available (no aviation use)	low power demand sensors available, use of palladium	
	o	++	++	+	o	0.80
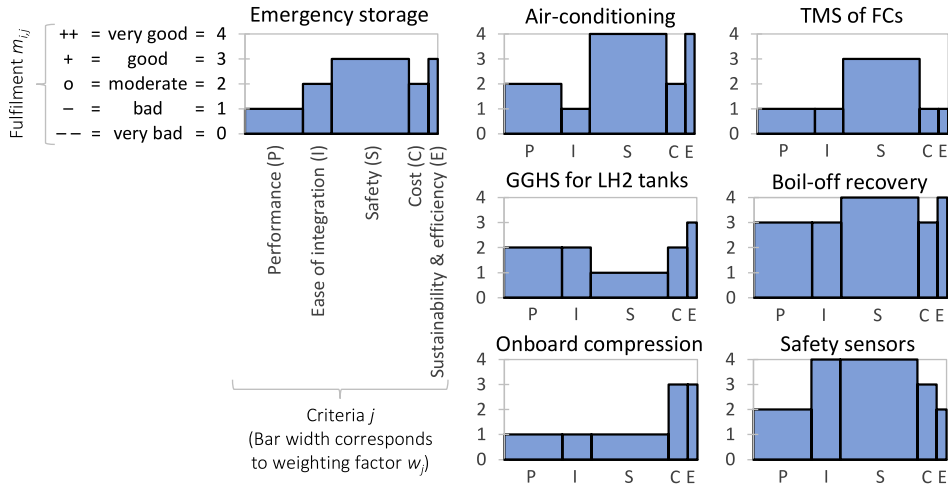
Figure 15. *Illustration of evaluation results of MH use cases in aviation.*
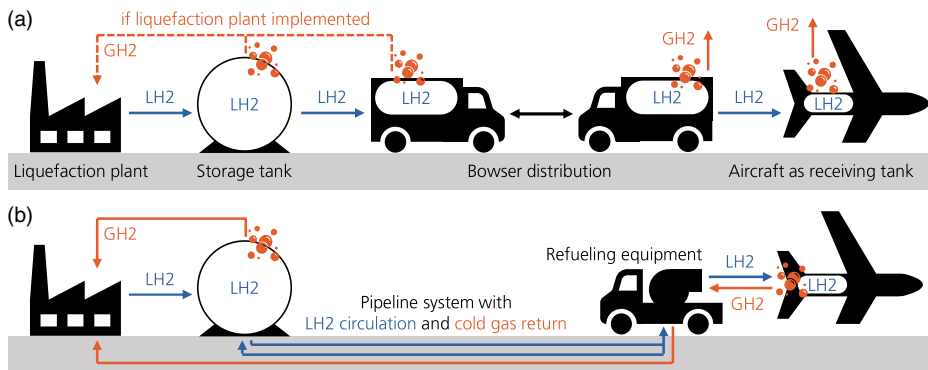

Figure 16. *Hydrogen distribution scenarios at airports: (a) bowser distribution and (b) pipeline dispenser system.*

simplicity of realising the thermal management by adjusting the insulation. For further investigations, a more detailed study regarding the assumed input parameters and their sensitivities is recommended. In the following subsections, outlooks for the potential future application of the three most promising use cases 'boil-off recovery', 'safety sensors' and 'air-conditioning' are elaborated.

5.1 Outlook for boil-off recovery

Since the capture and re-use of boil-off losses with MHs is generally plausible, as shown in Section 4.2, this section investigates the losses along the LH2 pathway and projects an initial economic estimation of such MH-based hydrogen recycling. The illustration of Fig. 13 is a simplified schematic, as the occurrence of boil-off losses depend on the specific means of hydrogen transfer and distribution. Two different hydrogen distribution methods, a distribution by bowser trucks and a pipeline dispenser system, are illustrated in Fig. 16.

In the upcoming initial years of hydrogen usage at airports, the bowser distribution from Fig. 16(a) is likely the preferred scenario due to its lower capital costs [130]. For LH2 transfer from the bowser to a receiving vessel, the bowser is generally pressurised by an onboard vaporiser [69, 131]. During transfer,

Table 7. *Sources of boil-off gas for both hydrogen distribution scenarios*

Scenario	Location	Source of Boil-off Hydrogen Gas	Recovery/Mitigation
(a) Bowser	Storage tank	heat transfer from ambient	possible*
		depressurisation after transfer	possible*
	Bowser	heat transfer from ambient	possible*
		cool-down of LH2 pump**	no
		cool-down of hoses	no
		depressurisation after transfer	depends on regulations
		inerting of hoses	no
		displaced gas during re-filling	possible**
	Aircraft	depressurisation before transfer	no
		displaced gas during re-filling	only means of reduction
		heat transfer from ambient	depends on dormancy time
		de-fueling for maintenance	no
(b) Pipeline	Storage tank &pipeline	heat transfer from ambient	yes
		depressurisation after transfer	yes
		warmed-up, circulated liquid	yes
	Refueling equipment	cool-down of LH2 pump**	yes
		cool-down of hoses	yes
		depressurisation of equipment	yes
		inerting of hoses	yes
	Aircraft	depressurisation before transfer	yes
		displaced gas during re-filling	yes
		heat transfer from ambient	yes
		de-fueling for maintenance	yes

* If liquefaction plant is implemented at airport.
** If LH2 transfer is realised by LH2 pump instead of tank pressurisation.

the displaced gaseous hydrogen in the receiving vessel is typically vented and not recovered. Neither is the gaseous hydrogen from the bowser after transfer, when the bowser is de-pressurised again. Those venting losses increase for higher tank pressures and lower tank filling levels, as more hydrogen vapor is present [131]. The venting losses from the receiving vessel are likely the most significant along the LH2 pathway [114]. The venting losses from the bowser are not significant, when the applicable regulations allow to postpone the de-pressurisation to the time of arrival at the liquefaction plant [114, 131].

With increased use of LH2 at the airport, a cryogenic pipeline system according to Fig. 16(b) may become beneficial [130]. Besides the pipe network with hydrants, such scenario will require refueling equipment to connect and disconnect the hose to the aircraft, to purge the aircraft tank and the hoses and to transfer LH2 by pressurisation or by pumping [77, 130]. The implementation of a hydrogen liquefaction plant and of a cold gas return system allows to recover the vented boil-off gas and thereby limits the losses to the re-condensation energy of the cold gas [67, 77, 130].

Table 7 provides an overview of the boil-off gas sources of both scenarios [77, 114, 115, 121, 131]. Although the bowser scenario is disadvantageous in terms of boil-off recovery and mitigation, it has the potential to allow re-fueling without generating significant hydrogen losses [121]. Therefore, the bowsers require additional devices like an extra gas storage with a compressor or like the proposed MH cartridge system from Fig. 13.

Depending on the size of the airport, a cryogenic hydrogen pipeline infrastructure with cold boil-off gas return may not be reasonable [130]. Especially in the near future up to 2040, bowsers will presumably distribute the LH2 to the aircrafts at all airports. While a pipeline infrastructure is expected to be beneficial for medium and large airports after 2045, smaller airports of 10 million passengers per year and below will still rely on bowsers for distribution of LH2 at the airport and even for the delivery of LH2 to the airport, if no liquefaction plant is implemented. In addition, the way of hydrogen delivery to the aircraft may also depend on its parking position, as it may not be reasonable to install cryogenic pipelines to remote positions of the airport apron. Thus, an infrastructure-independent solution for boil-off recycling remains reasonable in the future.

The release of hydrogen to the ambient should not only be prevented because of economic reasons but also because of ecologic reasons and safety issues. Hydrogen indirectly influences global warming and its emission would partially offset the climate benefit of savings in CO_2 emissions [132]. As released hydrogen is also a potential hazard, the gas is typically burnt by flare stacks, which implies siting issues on an airfield [77]. To evaluate the economic motivation for hydrogen recycling, the prospect of hydrogen costs as well as the composition of hydrogen recycling system costs are assessed in the following.

The current cost of green hydrogen, which is produced with renewable energies by electrolysis, is in the range of 5 \$/kg_{H2} [133, 134]. Studies estimate green hydrogen prices of 3–4 \$/kg_{H2} in 2030 and of 2 to 3 \$/kg_{H2} in 2050 [133, 135]. Liquefaction consumes 30–40% of the hydrogen's chemical energy and adds 1 \$/kg_{H2} [4, 65, 109, 112, 133]. Although this cost of liquefaction of 1 \$/kg_{H2} may be applied for benchmarking a boil-off recycling system against a cold gas recovery pipeline according to Fig. 16(b), an overall cost estimation of such scenario is difficult, as the cost of the cryogenic infrastructure is interlaced with the airport infrastructure and operation procedures. Therefore, this study focuses on the comparison of the two infrastructure-independent approaches, the MH-based hydrogen recovery and hydrogen recycling by compression, and compares these two approaches to external venting of hydrogen by burning. As the latter results in a complete loss of the vented boil-off gas, the hydrogen cost of 5 \$/kg_{H2} is applied for the estimation of today's economic break-even-point of the boil-off recycling. A price of 2 \$/kg_{H2} is applied as an outlook for the future.

As a baseline for benchmarking the economic reasonability of MH-based hydrogen recycling, the costs for hydrogen compression are assessed first. Therefore, the cost for the high-pressure hydrogen storage tank is considered with 500 \$/kg_{H2} [4, 109, 112, 134, 136]. While the process of compressing hydrogen to a high pressure level is already energy intensive, the capital costs for the required components contribute to a significant share to the costs of the compression process [134, 137]. This study estimates the costs for the high-pressure compression process with 1.50 \$/kg_{H2} [137].

The cost estimation for MH hydrogen storage systems is difficult because of the lack of commercial, large-scale applications of such systems [138]. The cost of the MH material strongly depends on the composition of the alloy and affect the overall capital cost of the system significantly [70, 134, 139]. Earlier studies reported a wide range of MH hydrogen storage system costs from 500to 22,000 \$/kg_{H2} [138, 139]. To estimate the cost of an MH material, which is able to desorb the hydrogen by using the waste heat of a low-temperature PEMFC, this study scales the data from Heung et al. [117] to an equivalent of US dollar in 2023. This results in MH material cost of 1,500 \$/kg_{H2} as a lower estimate and of 4,900 \$/kg_{H2} as a higher estimate. The cost for the empty MHR are assessed with 1,500 \$/kg_{H2} [134]. Although the capital costs of the MH recycling system are higher compared to the recycling of the boil-off gas by compression, the use of waste heat saves operational costs and can lead to an overall economic benefit [6, 72, 73]. Figure 17 compares the overall costs of both hydrogen recycling systems in relation to their usage in years *y*. The graphs are derived from the Equations (7)–(11), which assume a recycling system size with a capacity of 2kg_{H2} and a charging and discharging frequency of two cycles per day or 730 cycles per year, respectively. The costs include the capital costs as well as an estimation for the operational costs. As the MH system is driven by waste heat, only minor amounts of electrical energy are required to control the system [70]. The chosen MH material should exhibit a high-cyclic stability to allow lifetime operation without the need to replace or regenerate the MH material to keep
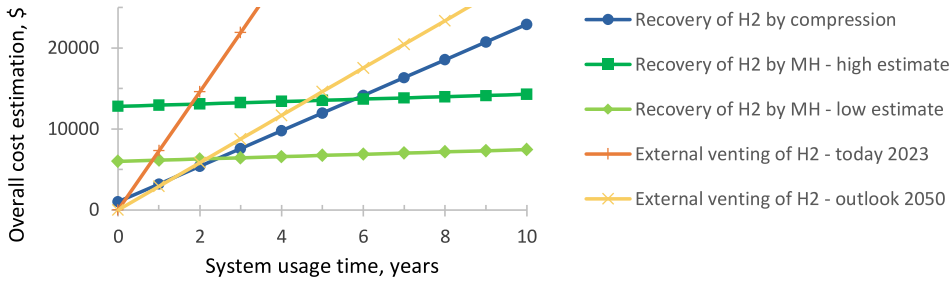
Figure 17. *Overall costs of boil-off gas recycling systems with 2kg of hydrogen capacity based on 2 charging and discharging cycles per day in comparison to the costs of external hydrogen venting.*

the maintenance costs at a minimum. Hence, the operational costs of the MH system are assumed with $0.10 \, \$/\text{kg}_{H2}$.

$$Cost_{\text{compression}} = 2\text{kg}_{H2} \cdot (500 \, \$/\text{kg}_{H2} + 730 \cdot y \cdot 1.5 \, \$/\text{kg}_{H2}) \tag{7}$$

$$Cost_{\text{MH,high}} = 2\text{kg}_{H2} \cdot ((4,900 + 1,500) \, \$/\text{kg}_{H2} + 730 \cdot y \cdot 0.1 \, \$/\text{kg}_{H2}) \tag{8}$$

$$Cost_{\text{MH,low}} = 2\text{kg}_{H2} \cdot ((1,500 + 1,500) \, \$/\text{kg}_{H2} + 730 \cdot y \cdot 0.1 \, \$/\text{kg}_{H2}) \tag{9}$$

$$Cost_{\text{venting,today}} = 2\text{kg}_{H2} \cdot (730 \cdot y \cdot 5.0 \, \$/\text{kg}_{H2}) \tag{10}$$

$$Cost_{\text{venting,2050}} = 2\text{kg}_{H2} \cdot (730 \cdot y \cdot 2.0 \, \$/\text{kg}_{H2}) \tag{11}$$

Figure 17 shows a general economic advantage of boil-off recycling compared to today's cost of hydrogen losses by external venting. For the lower hydrogen cost of the future, the payback of the hydrogen recycling relies on system lifetimes of 2 years and above. Furthermore, the graphs predict an economic benefit of an MH-based hydrogen recycling system compared to recycling by compression, when the usage time exceeds a duration of 2.5 years for the low estimate and 6 years for the high estimate. This implies that the use of MHs for hydrogen recycling is still plausible. Nevertheless, since the cost for the MH material strongly impacts the overall MH system cost, further studies should prospect for a suited MH material with low cost, flat plateau slope, low hysteresis, high cyclic stability, fast kinetics of hydrogen exchange and appropriate low temperature behaviour [6, 72]. In addition, a detailed balance-of-plant investigation of the MH system should be performed to precise the forecast of the capital costs and the operational costs.

5.2 Outlook for hydrogen safety sensor installation in aviation

To mitigate the risks of hydrogen exposure in future aviation, a rigorous surveillance should be applied for aircraft and at airports. The use of various sensing principles in parallel is not only reasonable to enhance reliability through redundancy but also to exploit their specific properties [66, 140]. Besides MH-based hydrogen sensors, all other kinds of sensing principles should be considered during sensor selection. An exemplary hydrogen safety sensor installation is illustrated in Fig. 18. Fiber optic sensors can be advantageous for aircrafts because of their inherent safety by optical sensing and their installation flexibility [87]. Difficult design spaces and hardly accessible components can be monitored for hydrogen leakage with a single evaluation unit and various sensing elements along an optical wire. After triggering an alarm threshold by an arbitrary sensor, additional chemochromic sensors can help to localise the leakage during repair and maintenance operations. Those sensing elements can be beneficially applied
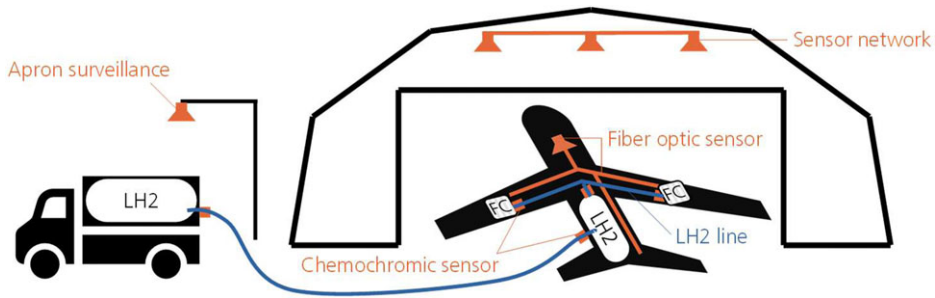
Figure 18. *Exemplary hydrogen safety sensor installation on an airport.*

to hydrogen lines, fittings, flanges and connectors to deliver visual awareness of any hydrogen leak [141]. For monitoring the vast spaces of the airport's aprons, optical open path sensors or ultrasonic gas leak detectors are suited, as they enable wide area monitoring [66]. Hydrogen leak localisation methods based on sensor networks and machine learning can assist first responders in identifying small leak zones in large confined spaces like hangars [142].

5.3 Further thermal use cases of metal hydride heat pumps

Although a MH-based cabin AC system can already be competitive to a conventional VCM system as shown in Section 4.1, potential synergies and multiple use cases should be considered to further improve the overall aircraft weight specific performance by replacing other dedicated systems. For example, the MHRs of an AC system can also serve as a heat source for pre-heating during a cold start scenario as well as for de- and anti-icing of components like fuel cells, sensors, valves, lubricants, intake ducts or the leading edges of the wings [48]. The latter is especially beneficial, if the wing surfaces are used as the AHX of the AC anyway. Current state-of-the-art anti-icing devices for wings either deposit a freezing point depressant fluid on the wing surface or heat the leading edge by the engine bleed air or by electric power [38, 48, 88]. As bleed air will not be available in various electrified propulsion system topologies and as electrical heating is energy demanding, MH-based pre-heating can be an appealing alternative [48, 88].

To provide the desired heating effect by hydrogen absorption, the MH material needs to be charged with hydrogen from one of the aircraft's hydrogen storage tanks. Therefore, at least some share of the MH material has to offer free capacity for hydrogen absorption. This is guaranteed, when the MHRs were operating as an AC system at the end of the previous flight mission. During this continuous alternating heat pump operation, only half of the MH hydrogen capacity is occupied with hydrogen. When the MH material is fully charged with hydrogen after a pre-heating application, it needs to be regenerated to its half-charged state before being able to operate as a heat pump again. This regeneration can be performed by desorbing hydrogen to the FC and by providing its waste heat to the MH. When the operator already expects an upcoming cold start scenario for the next scheduled flight of an aircraft, it is reasonable to fully discharge the hydrogen capacity of the MHR at the end of the previous flight mission. Thereby, the maximum amount of heat is stored in the MH material to be provided as thermal energy for pre-heating.

The application of MH heat pumps to enhance the TMS of FCs achieved a low rating as a stand-alone use case mainly because of its high weight penalty. However, an MH-based AC system can also serve as a heat sink. Although the heat storage capacity would be much lower compared to a dedicated system for the 'TMS of FCs', it can still be reasonable to use the MH-based AC system as a short time cooling booster in an emergency situation. In addition, the MH-based AC system can even serve as an emergency hydrogen supply, as half of the MH hydrogen capacity is always occupied by hydrogen during its continuous alternating operation.

Besides air-conditioning of the cabin, also the cooling of the galley by an MH heat pump should be investigated in further studies. However, as the potential energy of the compressed hydrogen is necessary to drive the heat pump operation, the application of such systems is limited to aircraft with CgH2 storage systems. This narrows the applicability in the aerospace industry, as LH2 is the most promising storage type for hydrogen in aviation [4, 67].

6.0 Conclusions

MHs offer various potential applications for future hydrogen-powered aviation. In this study, seven aviation-specific use cases of MHs are presented and evaluated. Due to different levels of detail in the literature review, four of these use cases had to be elaborated and sizing estimations were performed for a generic commuter aircraft as a reference. The use cases 'boil-off recovery', 'hydrogen safety sensors' and 'cabin air-conditioning' show large potential as they achieved the highest rankings in the weighted point rating. As these three use cases should be further investigated, initial outlooks for their future application are given and open research topics are indicated. The 'boil-off recovery' for capturing and re-using the boil-off losses becomes particularly promising with globally increasing utilisation of liquid hydrogen, as such systems are also applicable to filling stations for road vehicles or to maritime harbor infrastructures. Hence, the boil-off losses of these diverse hydrogen sectors have to be analysed and quantified in detail. For the use in aviation, operating scenarios should be investigated from the airliner's and airport's point of view. Additionally, a more profound cost estimation must be established and low-cost hydrides, which are suitable for hydrogen desorption at ambient conditions, have to be investigated. Subsequently, the MH-based 'boil-off recovery' should be benchmarked to other means for boil-off recycling, like re-liquefaction or the conversion into electricity by a fuel cell. In summary, MH technologies can become additional enablers for a sustainable hydrogen-based industry due to their manifold potential applications.

Competing interests. The authors declare none.

References

[1] Darecki, M. et al. Flightpath 2050: Europe's Vision for Aviation; Maintaining Global Leadership and Serving Society's Needs; Report of the High-level Group on Aviation Research, European Commission, Luxembourg, 2011. Accessed: Aug. 15 2022. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/296a9bd7-fef9-4ae8-82c4-a21ff48be673

[2] ATAG - Air Transportation Action Group, Waypoint 2050: An Air Transport Action Group Project, Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency., ATAG - Air Transportation Action Group, online, 2020. Accessed: Nov. 23 2022. [Online]. Available: https://aviationbenefits.org/media/167187/w2050_full.pdf

[3] Züttel, A., Remhof, A., Borgschulte, A. and Friedrichs, O. Hydrogen: The future energy carrier, *Phil. Trans. R. Soc. A*, 2010, **368**, (1923), pp. **3329–3342**, doi: 10.1098/rsta.2010.0113

[4] Baroutaji, A., Wilberforce, T., Ramadan, M. and Olabi, A.G. Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors, *Renew. Sust. Energ. Rev.*, 2019, **106**, pp 31–40.

[5] Dornheim, M. and Moreno-pirajàn, J.C., EDS., Thermodynamics - Interaction Studies - Solids, Liquids and Gases: Interaction Studies - Solids, Liquids, Gases. Thermodynamics of Metal Hydrides: Tailoring Reaction Enthalpies of Hydrogen Storage Materials: IntechOpen, 2011.

[6] Muthukumar, P., Kumar, A., Raju, N.N., Malleswararao, K. and Rahman, M.M. A critical review on design aspects and developmental status of metal hydride based thermal machines, *Int. J. Hydrog. Energy*, 2018, **43**, (37), pp 17753–17779, doi: 10.1016/j.ijhydene.2018.07.157

[7] Bhuiya, M.M.H., Kumar, A. and Kim, K.J. Metal hydrides in engineering systems, processes, and devices: A review of non-storage applications, *Int. J. Hydrog. Energy*, 2015, **40**, (5), pp 2231–2247, doi: 10.1016/j.ijhydene.2014.12.009

[8] Feldhusen, J. and Grote, K.-H. *Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung*, 8th ed, Springer Vieweg, 2013, Berlin, Heidelberg.

[9] Chen, X.Y., Wei, L.X., Deng, L., Yang, F.S. and Zhang, Z.X. A review on the metal hydride based hydrogen purification and separation technology, in *AMM*, vol. **448-453**, 2013, pp 3027–3036, doi: 10.4028/www.scientific.net/AMM.448-453.3027

[10] Röntzsch, L. and Heubner, F. Metal Hydride Technology, Fraunhofer IFAM, Jan. 2022. Accessed: Jan. 4 2022. [Online]. Available: https://www.ifam.fraunhofer.de/content/dam/ifam/de/documents/dd/Infobl%C3%A4tter/metal_hydride_technology_fraunhofer_ifam_dresden.pdf

[11] Lototskyy, M.V., Tolj, I., Pickering, L., Sita, C., Barbir, F. and Yartys, V. The use of metal hydrides in fuel cell applications, *Prog. Natural Sci. Mater. Int.*, 2017, **27**, (1), pp 3–20, doi: 10.1016/j.pnsc.2017.01.008

[12] Weckerle, C., Nasri, M., Hegner, R., Bürger, I. and Linder, M. A metal hydride air-conditioning system for fuel cell vehicles – functional demonstration, *Appl. Energy*, 2020, **259**, pp 1–14, doi: 10.1016/j.apenergy.2019.114187

[13] Röntzsch, L. and Heubner, F. Hydride zur H2-Speicherung. [Online]. Available: https://www.ifam.fraunhofer.de/de/Ueberuns/Standorte/Dresden/Wasserstofftechnologie/hydride/hydride-zur-h2-speicherung.html (accessed: Apr. 11 2022).

[14] U.S. Department of Transportation, Ed. Energy Supply Device Aviation Rulemaking Committee: Final Report, Federal Aviation Administration, Springfield, Virginia 22161 DOT/FAA/TC-19/16, Dec. 2017. Accessed: Jun. 28 2022. [Online]. Available: https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/Energy%20Supply%20Device%20ARC%20Recommendation%20Report.pdf

[15] Depken, J. Hydrogen Applications in Shipping: An Overview, Mar. 25 2022.

[16] Kazula, S., De graaf, S. and Enghardt, L. Preliminary safety assessment of PEM fuel cell systems for electrified propulsion systems in commercial aviation, 32nd European Safety and Reliability Conference (ESREL 2022), Dublin, 2022.

[17] Colozza, A.J. and Kohout, L. Hydrogen Storage for Aircraft Applications Overview, NASA, Brook Park, Ohio 20020085127, Sep. 2002. Accessed: Jun. 28 2022. [Online]. Available: https://ntrs.nasa.gov/citations/20020085127

[18] Puszkiel, J. et al. Designing an AB2-type alloy (TiZr-CrMnMo) for the hybrid hydrogen storage concept, *Energies*, 2020, **13**, (11), p 2751, doi: 10.3390/en13112751

[19] Song, C. et al. Using metal hydride H2 storage in mobile fuel cell equipment: Design and predicted performance of a metal hydride fuel cell mobile light, *Int. J. Hydrog. Energy*, 2014, **39**, (27), pp 14896–14911, doi: 10.1016/j.ijhydene.2014.07.069

[20] Mori, D. et al. High-pressure Metal Hydride Tank for Fuel Cell Vehicles, SAE International SAE 2007-01-2011, 2007.

[21] Komiya, K. et al. High-Pressure Hydrogen-Absorbing Alloy Tank for Fuel Cell Vehicles, SAE International 2010-01-0851, 2010.

[22] Takeichi, N. et al. Hybrid hydrogen storage vessel: A novel high-pressure hydrogen storage vessel combined with hydrogen storage material, *Int. J. Hydrog. Energy*, 2003, **28**, pp 1121–1129, doi: 10.1016/S0360-3199(02)00216-1

[23] Yokota, T. et al. Hybrid Hydrogen Storage Container and Method of Storing Hydrogen in Container, US 7,681,753 B2 10/501,810.

[24] Schulz, R., Liang, G., Hout, J. and Larochelle, P. Method for Storing Hydrogen in Hybrid Form, WO 2005/064227 A1.

[25] Zhang, Y., Li, C., Yuan, Z., Qi, Y., Guo, S. and Zhao, D. Research progress of TiFe-based hydrogen storage alloys, *J. Iron Steel Res. Int.*, 2022, doi: 10.1007/s42243-022-00756-w

[26] Bahrs, V., Franke, F., Kazula, S. and De graaf, S., Potential of metal hydride-based range extenders for commuter aircraft, DLRK 2023, Stuttgart, 2024 in print.

[27] Yang, F.S., Wang, G.X., Zhang, Z.X., Meng, X.Y. and Rudolph, V. Design of the metal hydride reactors – a review on the key technical issues, *Int. J. Hydrog. Energy*, 2010, **35**, (8), pp 3832–3840, doi: 10.1016/j.ijhydene.2010.01.053

[28] Kölbig, M., Bürgers, I. and Linder, M. Thermal applications in vehicles using hydralloy C5 in single and coupled metal hydride systems, *Appl. Energy*, 2021, **287**.

[29] Webber, H., Llambrich, J. and Davoudi, H. FlyZero: Thermal-Management-Roadmap-Report, Aerospace Technology Institute FZO-PPN-COM-0019, Mar. 2022. Accessed: Jul. 25 2022. [Online]. Available: https://www.ati.org.uk/flyzero-reports/

[30] Kazula, S., De graaf, S. and Enghardt, L. Review of fuel cell technologies and evaluation of their potential and challenges for electrified propulsion systems in commercial aviation, GPPS 2022 European Technical Conference, Chania, 2022. [Online]. Available: https://gpps.global/wp-content/uploads/2022/09/GPPS-TC-2022_paper_5.pdf

[31] Hadnum, L., Pacey, M. and Milne, K. FlyZero: Technology-Roadmaps, Aerospace Technology Institute FZO-IST-MAP-0012, Mar. 2022. Accessed: Jul. 25 2022. [Online]. Available: https://www.ati.org.uk/flyzero-reports/

[32] Haran, K., Madavan, N. and O'connell, T.C. *Electrified Aircraft Propulsion: Powering the Future of Air Transportation*, Cambridge University Press, 2022, Cambridge.

[33] Bürger, I., Sourmelis terzopoulos, V.E., Kretschmer, C., Kölbig, M., Brack, C. and Linder, M. Lightweight reactor design by additive manufacturing for preheating applications using metal hydrides, *Int. J. Hydrog. Energy*, 2021, **46**, (56), pp 28686–28699, doi: 10.1016/j.ijhydene.2021.06.091

[34] Kölbig, M., Weckerle, C., Linder, M. and Bürger, I. Review on thermal applications for metal hydrides in fuel cell vehicles: Operation modes, recent developments and crucial design aspects, *Renewable Sustainable Energy Rev.*, 2022, **162**, p 112385, doi: 10.1016/j.rser.2022.112385

[35] Boll, M. et al. A holistic system approach for short range passenger aircraft with cryogenic propulsion system, *Supercond. Sci. Technol.*, 2020, **33**, (4), p 44014, doi: 10.1088/1361-6668/ab7779

[36] Kölbig, M., Bürger, I. and Linder, M. Characterization of metal hydrides for thermal applications in vehicles below 0°C, *Int. J. Hydrog. Energy*, 2019, **44**, (10), pp 4878–4888, doi: 10.1016/j.ijhydene.2018.12.116

[37] Franke, F., Link, A. and Kazula, S. Assessment of metal hydride reactors as thermal management enhancement of hydrogen fuel cells in electric aircraft, AIAA Aviation Forum, San Diego, 2023.

[38] Moir, I. and Seabridge, A. Aircraft pneumatic subsystems, in *Encyclopedia of Aerospace Engineering*, John Wiley & Sons Ltd, 2013, pp 1–18.

[39] Hegner, R. and Weckerle, C. Klimatisierungsaggregat auf Metallhydridbasis für Elektrofahrzeuge mit Batterie oder Brennstoffzelle, *ATZ Automobiltech Z*, 2020, **122**, (1), pp 82–86, doi: 10.1007/s35148-019-0161-5

[40] Weckerle, C., Bürger, I. and Linder, M. Numerical optimization of a plate reactor for a metal hydride open cooling system, *Int. J. Hydrog. Energy*, 2019, **44**, (31), pp 16862–16876, doi: 10.1016/j.ijhydene.2019.04.260

[41] Weckerle, C., Bürger, I. and Linder, M. Novel reactor design for metal hydride cooling systems, *Int. J. Hydrog. Energy*, 2017, **42**, (12), pp 8063–8074, doi: 10.1016/j.ijhydene.2017.01.066

[42] Scholz, D. Flugzeugsysteme Skript: Kapitel 2 - Klimaanlage: Air Conditioning, ATA 21, HAW Hamburg, Fakultät Elektrotechnik und Informatik, Department Fahrzeugtechnik und Flugzeugbau, Dec. 2013. Accessed: May 3 2022. [Online]. Available: https://www.fzt.haw-hamburg.de/pers/Scholz/materialFS/FS_Skript_2-Klimaanlagen.pdf

[43] Herzog, J. Electrification of the environmental control system, ICAS 2006: International Congress of Aeronautical Sciences, 2006. Accessed: Feb. 27 2023. [Online]. Available: https://www.icas.org/ICAS_ARCHIVE/ICAS2006/PAPERS/344.PDF

[44] Burschyk, T. Entwicklung und Bewertung eines brennstoffzellenbasierten Klimatisierungssystems für luftfahrttechnische Anwendungen, Masterthesis, Institut für Technische Thermodynamik, Technische Universität Hamburg, Hamburg, 2020.

[45] Santos, A., Andrade, C.R. and Zaparoli, E.L. A thermodynamic study of air cycle machine for aeronautical applications, *Int. J. Therm.*, 2014, **17**, (3), p 117, doi: 10.5541/ijot.538

[46] Jiang, H., Dong, S. and Zhang, H. Energy efficiency analysis of electric and conventional environmental control system on commercial aircraft, pp 973–978, doi: 10.1109/AUS.2016.7748195

[47] Aerothermodynamic Systems Engineering and Design, AIR1168, SAE.

[48] Moir, I. and Seabridge, A. *Aircraft Systems: Mechanical, Electrical, and Avionics Subsystems Integration,* 3rd ed, John Wiley & Sons Ltd, 2008, Chichester.

[49] Shu, Q.S., Demko, J.A. and Fesmire, J.E. Heat switch technology for cryogenic thermal management, *IOP Conf. Ser. Mater. Sci. Eng.*, 2017, **278**, p 12133, doi: 10.1088/1757-899X/278/1/012133

[50] Jahromi, A.E. and Sullivan, D.F. A piezoelectric cryogenic heat switch, *Rev. Sci. Inst.*, 2014, **85**, (6), p 65118, doi: 10.1063/1.4876483

[51] Prina, M., Bhandari, P., Bowman, R.C., Paine, C. and Wade, L.A. Development of Gas Gap Heat Switch Actuator for the Planck Sorption Cryocooler, 1999. Accessed: Feb. 21 2023. [Online]. Available: https://trs.jpl.nasa.gov/bitstream/handle/2014/17732/99-1170.pdf?sequence=1

[52] Prina, M., Bowman, R.C. and Kulleck, J.G. Degradation study of ZrNiH1.5 for use as actuators in gas gap heat switches, *J. Alloys Compd.*, 2004, **373**, (1–2), pp 104–114, doi: 10.1016/j.jallcom.2003.10.053

[53] Manjavacas, G. and Nieto, B., "Hydrogen Senors and Detectors," Compendium of Hydrogen Energy, vol. 4, pp. 215–234, 2016. [Online]. Available: https://doi.org/10.1016/B978-1-78242-364-5.00010-5

[54] Chan, C.K. and Ross, R.G., JR. Design and Application of Gas-Gap Heat Switches: Final Report of Phase II," Jet Propulsion Lab. 19910000909, Mar. 1990. [Online]. Available: https://ntrs.nasa.gov/citations/19910000909

[55] Bowman, R.C. Metal hydride compressors with gas-gap heat switches: Concept, development, testing, and space flight operation for the planck sorption cryocoolers, *Inorganics*, 2019, **7**, (12), p 139, doi: 10.3390/inorganics7120139

[56] Reiter, J.W., Karlmann, P.B., Bowman, R.C. and Prina, M. Performance and degradation of gas-gap heat switches in hydride compressor beds, *J. Alloys Compd.*, 2007, **446-447**, pp 713–717, doi: 10.1016/j.jallcom.2007.04.072

[57] Wade, L.A. et al. Hydrogen sorption cryocoolers for the planck mission, *Adv. Cryog. Eng.*, 2000, **45**, pp 499–506. [Online]. Available: https://www2.jpl.nasa.gov/adv_tech/coolers/Cool_ppr/CEC1999%20Planck%20Sorp%20Coolers.pdf

[58] Kimball, M.O. et al., "Passive gas-gap heat switches for use in low-temperature cryogenic systems, *IOP Conf. Ser. Mater. Sci. Eng.*, 2017, **278**, p 12010, doi: 10.1088/1757-899X/278/1/012010

[59] Kimball, M.O., Shirron, P.J., James, B.L., Muench, T.T., Sampson, M.A. and Letmate, R.V. Low-power, fast-response active gas-gap heat switches for low temperature applications, *IOP Conf. Ser. Mater. Sci. Eng.*, 2015, **101**, p 12157, doi: 10.1088/1757-899X/101/1/012157

[60] Martins, D. et al. Customizable gas gap heat switch, AIP Conference Proceedings, 2010, pp 1652–1660, doi: 10.1063/1.3422349

[61] Bywaters, R.P. and Griffin, R.A. A gas-gap thermal switch for cryogenic applications, Cryogenics, 1973, pp 344–349.

[62] Vanapalli, S., Keijzer, R., Buitelaar, P. and Ter brake, H. Cryogenic flat-panel gas-gap heat switch, *Cryogenics*, 2016, **78**, pp 83–88, doi: 10.1016/j.cryogenics.2016.07.006

[63] Franco, J., Martins, D., Catarino, I. and Bonfait, G. Narrow gas gap in cryogenic heat switch, *Applied Thermal Eng.*, 2014, **70**, (1), pp 115–121, doi: 10.1016/j.applthermaleng.2014.04.062

[64] Bowman, R.C. Development of metal hydride beds for sorption cryocoolers in space applications, *J. Alloys Compd.*, 2003, **356-357**, pp 789–793, doi: 10.1016/S0925-8388(03)00089-6

[65] Gong, A. and Verstraete, D. Fuel cell propulsion in small fixed-wing unmanned aerial vehicles: Current status and research needs, *Int. J. Hydrog. Energy*, 2017, **42**, (33), pp 21311–21333, doi: 10.1016/j.ijhydene.2017.06.148

[66] Hübert, T., Boon-brett, L. and Buttner, W.J. *Sensors for Safety and Process Control in Hydrogen Technologies*, CRC Press Taylor & Francis Group, 2015, Boca Raton, London, New York.

[67] Colpan, C.O. and Kovač, A., EDS. *Fuel Cell and Hydrogen Technologies in Aviation*, Springer International Publishing, 2022, Cham.

[68] Krielaart, M.A.R., Vermeer, C.H. and Vanapalli, S. Compact flat-panel gas-gap heat switch operating at 295 K, *Rev. Sci. Inst.*, 2015, **86**, (11), p 115116, doi: 10.1063/1.4936356

[69] Michel, F., Fieseler, H., Meyer, G. and Theißen, F. On-board equipment for liquid hydrogen vehicles, *Int. J. Hydrogen Energy*, 1998, **23**, (3), pp 191–199, doi: 10.1016/S0360-3199(97)00044-X

[70] Von colbe, J.B. et al. Application of hydrides in hydrogen storage and compression: Achievements, outlook and perspectives, *Int. J. Hydrog. Energy*, 2019, **44**, (15), pp 7780–7808, doi: 10.1016/j.ijhydene.2019.01.104

[71] Tarasov, B.P. et al. Metal hydride hydrogen storage and compression systems for energy storage technologies, *Int. J. Hydrog. Energy*, 2021, **46**, (25), pp 13647–13657, doi: 10.1016/j.ijhydene.2020.07.085

[72] Lototskyy, M.V., Yartys, V.A., Pollet, B.G. and Bowman, R.C. Metal hydride hydrogen compressors: A review, *Int. J. Hydrog. Energy*, 2014, **39**, (11), pp 5818–5851, doi: 10.1016/j.ijhydene.2014.01.158

[73] Yartys, V.A. et al. Metal hydride hydrogen compression: recent advances and future prospects, *Appl. Phys. A*, 2016, **122**, (4), doi: 10.1007/s00339-016-9863-7

[74] University of Central Florida, FSEC Energy Research Center, Metal Hydrides for Hydrogen Separation, Recovery and Purification. [Online]. Available: https://energyresearch.ucf.edu/research/hydrogen/hydrogen-storage-and-purification/metal-hydrides-for-hydrogen-separation-recovery-and-purification/ (accessed: Apr. 20 2022).

[75] Fujitani, S., Nishimura, K., Nishio, K., Sato, K. and Yonezu, I. US000005728483A_System-for-Storing-and-Utilizing-Hydrogen, US 5,728,483 822,065.

[76] Rosso, M.J. and Golben, P.M. Capture of Liquid Hydrogen Boiloff with Metal Hydride Absorbers, NASA; Ergenics Inc, 1984.

[77] Brewer, G.D. *Hydrogen Aircraft Technology*, 1st ed, CRC Press LLC, 1991.

[78] Ino, S., Sato, M., Hosono, M. and Izumi, T. Development of a soft metal hydride actuator using a laminate bellows for rehabilitation systems, *Sens. Actuators B Chem.*, 2009, **136**, (1), pp 86–91, doi: 10.1016/j.snb.2008.10.054

[79] Lloyd, G. and Kim, K. Smart hydrogen/metal hydride actuator, *Int. J. Hydrog. Energy*, 2007, **32**, (2), pp 247–255, doi: 10.1016/j.ijhydene.2006.03.014

[80] Sasaki, T., Kawashima, T., Aoyama, H., Ogawa, T. and Ifukube, T. Development of an actuator using a metal hydride and its application to a lifter for the disabled, *Adv. Robot.*, 1987, **2**, (3), pp 277–286, doi: 10.1163/156855387X00228

[81] Shimizu, S. et al. A basic study of a force display using a metal hydride actuator, pp. 211–215, doi: 10.1109/ROMAN.1993.367720

[82] Vanderhoff, A. and Kim, K.J. Experimental study of a metal hydride driven braided artificial pneumatic muscle, *Smart Mater. Struct.*, 2009, **18**, (12), p 125014, doi: 10.1088/0964-1726/18/12/125014

[83] Borzenko, V.I., Blinov, D.V., Dunikov, D.O. and Malyshenko, S.P. Reversible Solid State Hydrogen Storage System Integrated with PEM Fuel Cell, WHEC 2010, Essen, 2010. Accessed: Mar. 29 2023. [Online]. Available: https://www.osti.gov/etdeweb/servlets/purl/21400914

[84] Dunikov, D.O., Romanov, I.A., and Mitrokhin, S.V. Development of intermetallic compounds for hydrogen supply system integrated with PEM fuel cell, WHEC 2010, Essen, 2010, pp 133–137.

[85] Hübert, T., Boon-brett, L., Black, G. and Banach, U. Hydrogen sensors – A review, *Sens. Actuators B Chem.*, 2011, **157**, (2), pp 329–352, doi: 10.1016/j.snb.2011.04.070

[86] Yoshimura, K. et al. New hydrogen sensor based on sputtered Mg–Ni alloy thin film, *Vacuum*, 2008, **83**, (3), pp 699–702, doi: 10.1016/j.vacuum.2008.04.047

[87] Franke, F., Kazula, S. and Enghardt, L. Review and evaluation of metal-hydride-based hydrogen sensors as safety devices for future sustainable aviation, *J. Phys. Conf. Ser.*, 2023, **2454**, doi: 10.1088/1742-6596/2454/1/012001

[88] Bray, R., Burrows, E. and Hadnum, L. FlyZero: Aircraft-Systems, Aerospace Technology Institute FZO-AIR-REP-0013, Mar. 2022. Accessed: Jul. 25 2022. [Online]. Available: https://www.ati.org.uk/flyzero-reports/

[89] Ehrlenspiel, K., Kiewert, A., Lindemann, U. and Mörtl, M. *Kostengünstig Entwickeln und Konstruieren: Kostenmanagement bei der integrierten Produktentwicklung*, 7th ed, Springer Vieweg, 2014, Berlin [Online]. Available: https://doi.org/10.1007/978-3-642-41959-1

[90] Feldhusen, J. and Grote, K.-H. *Dubbel: Taschenbuch Für Den Maschinenbau: F - Grundlagen der Konstruktionstechnik. F1 - Grundlagen technischer Systeme und des methodischen Vorgehens*, 24th ed, Springer, 2015, Berlin, Heidelberg.

[91] Pahl, G., Beitz, W., Blessing, L., Feldhusen, J., Grote, K.-H. and Wallace, K. *Engineering Design: A Systematic Approach*, 3rd ed, Springer London Limited, 2007, London [Online]. Available: http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10230457

[92] Kazula, S. *Variable Pitot-Triebwerkseinlässe für kommerzielle überschallflugzeuge: Konzeptstudie mittels eines Entwicklungsansatzes für sichere Produkte*, Springer Vieweg, 2022, Wiesbaden.

[93] Lindemann, U. *Methodische Entwicklung technischer Produkte: Methoden flexibel und situationsgerecht anwenden*, 3rd ed, Springer, 2009, Berlin, Heidelberg. Accessed: Sep. 11 2017.

[94] Sadraey, M.H., *Aircraft Design: A Systems Engineering Approach*, 1st ed, John Wiley & Sons Ltd, 2013, Chichester.

[95] Guidelines for Development of Civil Aircraft and Systems, ARP4754A, SAE, 2010.

[96] Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment, ARP4761, SAE, 1996.

[97] Gkoutzamanis, V. HECARRUS Project Hybrid Electric Small Commuter Aircraft Conceptual Design: State-of-the-art technologies on research and developments underway in the field of alternative propulsion architectures, Aristotle University of Theassaloniki, Mar. 2020. Accessed: 2020.

[98] Bhatti, W., Wu, W., Doyle, F., Llambrich, J., Webber, H. and Town, N. FlyZero: Fuel-Cells-Roadmap-Report, Aerospace Technology Institute FZO-PPN-COM-0033, Mar. 2022. Accessed: Jul. 25 2022. [Online]. Available: https://www.ati.org.uk/flyzero-reports/

[99] Bargal, M.H., Abdelkareem, M.A., Tao, Q., Li, J., Shi, J. and Wang, Y. Liquid cooling techniques in proton exchange membrane fuel cell stacks: A detailed survey, *Alexandria Eng. J.*, 2020, **59**, (2), pp 635–655, doi: 10.1016/j.aej.2020.02.005

[100] Yiotis, A.G., Kainourgiakis, M.E., Charalambopoulou, G.C. and Stubos, A.K. A generic physical model for a thermally integrated high-temperature PEM fuel cell and sodium alanate tank system, *Int. J. Hydrogen Energy*, 2015, **40**, (42), pp 14551–14561, doi: 10.1016/j.ijhydene.2015.05.186

[101] Martínez, I. Aircraft Environmental Control, Escuela Técnica Superior de Ingeniería Aeronáutica y del Espacio, Madrid, 2023. Accessed: Jan. 17 2023. [Online]. Available: http://imartinez.etsiae.upm.es/~isidoro/tc3/Aircraft%20ECS.pdf

[102] Kelly Aerospace Thermal Systems. Thermacool: Electric Air Conditioning, Mooney M20-R, -S, -TN, -U, -V. Accessed: Feb. 9 2023. [Online]. Available: https://www.kellythermal.com/_files/ugd/4c74f6_25e8000447f24410a707deba514c1546.pdf

[103] Kelly Aerospace Thermal Systems. Thermacool: Electric Air Conditioning, FAA/STC Certified for the Cessna 182T - Turbo 182T. Accessed: Feb. 9 2023. [Online]. Available: https://www.kellythermal.com/_files/ugd/4c74f6_549520b8f838446ba0faa1a02d37b8c0.pdf

[104] Kelly Aerospace Thermal Systems. Thermacool: Electric Air Conditioning, Cirrus SR20/SR22. Accessed: Feb. 9 2023. [Online]. Available: https://www.kellythermal.com/_files/ugd/4c74f6_976e4d43c1e94269aad8862ad5c27336.pdf

[105] Aircenter, Inc. Cool Air Systems for DA42 Twin Star. [Online]. Available: https://aircenterinc.com/coolair_da42.php (accessed: Feb. 9 2023).

[106] Aircenter, Inc. Cool Air Systems for Twin Commanders. [Online]. Available: https://aircenterinc.com/coolair_commander.php (accessed: Feb. 9 2023).

[107] Weckerle, C., Nasri, M., Hegner, R., Linder, M. and Bürger, I. A metal hydride air-conditioning system for fuel cell vehicles – performance investigations, *Appl. Energy*, 2019, **256**, p 113957, doi: 10.1016/j.apenergy.2019.113957

[108] ebm-papst St. Georgen GmbH & Co KG. DC-Radialventilator: RER 190-39/18/2TDMLO, ebm-papst St. Georgen GmbH & Co. KG, Jun. 2016. Accessed: Feb. 27 2023. [Online]. Available: https://img.ebmpapst.com/products/datasheets/DC-Radialventilator-RER19039182TDMLO-GER.pdf

[109] Durbin, D.J. and Malardier-jugroot, C. Review of hydrogen storage techniques for on board vehicle applications, *Int. J. Hydrog. Energy*, 2013, **38**, (34), pp 14595–14617, doi: 10.1016/j.ijhydene.2013.07.058

[110] Apeland, J. Fuel Cell Powered Drone: Use of Fuel Cells to Extend Multirotor Drone Endurance, Dissertation, Faculty of Science and Technology, Department of Mechanical and Structural Engineering, University of Stavanger, Stavanger, 2021. Accessed: May 11 2022. [Online]. Available: https://uis.brage.unit.no/uis-xmlui/bitstream/handle/11250/2787738/PhD_Apeland_Joergen.pdf?sequence=1

[111] Ahluwalia, R.K., Hua, T.Q. and Peng, J.-K. Fuel cycle efficiencies of different automotive on-board hydrogen storage options, *Int. J. Hydrogen Energy*, 2007, **32**, (15), pp 3592–3602, doi: 10.1016/j.ijhydene.2007.03.021

[112] Zhang, F., Zhao, P., Niu, M. and Maddy, J. The survey of key technologies in hydrogen energy storage, *Int. J. Hydrog. Energy*, 2016, **41**, (33), pp 14535–14552, doi: 10.1016/j.ijhydene.2016.05.293

[113] Schlapbach, L. and Züttel, A. Hydrogen-storage materials for mobile applications, *Nature*, **2002**, (414). [Online]. Available: https://doc.rero.ch/record/6025/files/zuttel_hsm.pdf

[114] Petitpas, G. Boil-off losses along LH2 pathway, Lawrence Livermore National Laboratory, Livermore LLNL-TR-750685, 2018. Accessed: May 9 2023. [Online]. Available: https://www.osti.gov/servlets/purl/1466121

[115] Ghaffari-tabrizi, F., Haemisch, J. and Lindner, D. Reducing hydrogen boil-off losses during fuelling by pre-cooling cryogenic tank, *Hydrogen*, 2022, **3**, (2), pp 255–269, doi: 10.3390/hydrogen3020015

[116] Mital, S.K., Gyekenyesi, J.Z., Arnold, S.M., Sullivan, R.M., Manderscheid, J.M. and Murthy, P.L. Review of Current State of the Art and Key Design Issues With Potential Solutions for Liquid Hydrogen Cryogenic Storage Tank Structures for Aircraft Applications, NASA NASA/TM—2006-214346, 2006. Accessed: Mar. 24 2023. [Online]. Available: https://ntrs.nasa.gov/api/citations/20060056194/downloads/20060056194.pdf

[117] Heung, L.K., Motyka, T. and Summers, W.A. Hydrogen Storage Development for Utility Vehicles, Savannah River Technology Center; Westinghouse Savannah River Company WSRC-MS-2001-00025 TRN: AH200127%%227, 2001. Accessed: Dec. 23 2022. [Online]. Available: https://www.osti.gov/biblio/783387

[118] Lototskyy, M., Tolj, I., Klochko, Y., Davids, M.W., Swanepoel, D. and Linkov, V. Metal hydride hydrogen storage tank for fuel cell utility vehicles, *Int. J. Hydrog. Energy*, 2020, **45**, (14), pp 7958–7967, doi: 10.1016/j.ijhydene.2019.04.124

[119] Gomez, A. and Smith, H. Liquid hydrogen fuel tanks for commercial aviation: Structural sizing and stress analysis, *Aerospace Sci. Technol.*, 2019, **95**, p 105438, doi: 10.1016/j.ast.2019.105438

[120] Arat, H.T. and Sürer, M.G. State of art of hydrogen usage as a fuel on aviation, *Eur. Mech. Sci.*, 2017, **2**, (1), pp 20–30, doi: 10.26701/ems.364286

[121] Mangold, J. et al. Refueling of LH2 aircraft—assessment of turnaround procedures and aircraft design implication, *Energies*, 2022, **15**, (7), p 2475, doi: 10.3390/en15072475

[122] Khandelwal, B., Karakurt, A., Sekaran, P.R., Sethi, V. and Singh, R. Hydrogen powered aircraft: The future of air transport, *Prog. Aerospace Sci.*, 2013, **60**, pp 45–59, doi: 10.1016/j.paerosci.2012.12.002

[123] Lenhardt & Wagner GmbH. EX-proof Plants: Natural Gas, Biogas and Hydrogen, 2022. Accessed: Mar. 23 2023. [Online]. Available: https://www.lw-compressors.com/sites/default/files/product-files/Ex_proof_plants_en.pdf

[124] Lenhardt & Wagner GmbH. LW 720 E Data Sheet, Accessed: Mar. 23 2023. [Online]. Available: https://lw-compressors.com/sites/default/files/product-files/LW720E_e.pdf

[125] Matthews, C. Aeronautical Engineer's Data Book, Butterworth-Heineman, 2002, Oxford.

[126] Wagner, W. Wärmeübertragung: Grundlagen, 7th ed, Vogel Buchverlag, 2011, Würzburg.

[127] Engineering ToolBox. Hydrogen - Thermal Conductivity vs. Temperature and Pressure: Online calculator, figures and table showing thermal conductivity of hydrogen, H2, at varying temperature and pressure - Imperial and SI Units. [Online]. Available: https://www.engineeringtoolbox.com/hydrogen-H2-thermal-conductivity-temperature-pressure-d_2106.html (accessed: Mar. 27 2023).

[128] Engineering ToolBox. Hydrogen - Density and Specific Weight vs. Temperature and Pressure: Online calculator, figures and tables showing density and specific weight of hydrogen, H2, at temperatures ranging from -260 to 325 °C (-435 to 620 °F) at atmospheric and higher pressure - Imperial and SI Units. [Online]. Available: https://www.engineeringtoolbox.com/hydrogen-H2-density-specific-weight-temperature-pressure-d_2044.html (accessed: Mar. 27 2023).

[129] Vietze, M. and Weiland, S. System analysis and requirements derivation of a hydrogen-electric aircraft powertrain, *Int. J. Hydrog. Energy*, 2022, **47**, (91), pp 38793–38810, doi: 10.1016/j.ijhydene.2022.09.052

[130] Postma-kurlanc, A., Leadbetter, H. and Pickard, C. Hydrogen Infrastructure and Operations: Airports, Airlines and Airspace, Aerospace Technology Institute FZO-CST-POS-0035, 2022. Accessed: Jul. 5 2023.

[131] Petitpas, G. Simulation of boil-off losses during transfer at a LH2 based hydrogen refueling station, *Int. J. Hydrog. Energy*, 2018, **43**, (46), pp 21451–21463, doi: 10.1016/j.ijhydene.2018.09.132

[132] Warwick, N., Griffiths, P., Keeble, J., Archibald, A., Pyle, J. and Shine, K. Atmospheric Implications of Increased Hydrogen Use, Department for Business, Energy and Industrial Strategy, Apr. 2022. Accessed: Apr. 27 2022. [Online]. Available: https://www.gov.uk/government/publications/atmospheric-implications-of-increased-hydrogen-use

[133] Deutscher Bundestag. Kosten der Produktion von grünem Wasserstoff, Wissenschaftliche Dienste WD 5-3000 - 029/20, 2020. Accessed: Jul. 19 2023. [Online]. Available: https://www.bundestag.de/resource/blob/691748/01a954b2b2d7c70259b19662ae37a575/WD-5-029-20-pdf-data.pdf

[134] Amica, G., Arneodo larochette, P. and Gennari, F.C. Light metal hydride-based hydrogen storage system: Economic assessment in Argentina, *Int. J. Hydrogen Energy*, 2020, **45**, (38), pp 18789–18801, doi: 10.1016/j.ijhydene.2020.05.036

[135] Menn, A. Deutschlands Verlangen nach Wasserstoff: Kann nur Nordafrika es stillen?, Wirtschaftswoche, 14 Dec., 2020. https://www.wiwo.de/technologie/mobilitaet/analyse-deutschlands-verlangen-nach-wasserstoff-kann-nur-nordafrika-es-stillen/26687168.html (accessed: Jul. 19 2023).

[136] Houchins, C., James, B.D., Huya-kouadio, J., Desantis, D. and Habibzadeh, B. Hydrogen Storage Cost Analysis, Department of Energy (DOE), 2019. Accessed: Jul. 25 2023. [Online]. Available: https://www.hydrogen.energy.gov/pdfs/progress19/h2f_st100_houchins_2019.pdf

[137] Parks, G., Boyd, R., Cornish, J. and Remick, R. Hydrogen Station Compression, Storage and Dispensing: Technical Status and Costs, National Renewable Energy Laboratory (NREL) NREL/BK-6A10-58564, 2014. Accessed: Jul. 27 2023. [Online]. Available: https://www.nrel.gov/docs/fy14osti/58564.pdf

[138] Grégoire Padró, C.E. and Putsche, V. Survey of the Economics of Hydrogen Technologies, National Renewable Energy Laboratory (NREL), 1999. Accessed: Jul. 25 2023. Online]. Available: https://www.nrel.gov/docs/fy99osti/27079.pdf

[139] Ni, M. An overview of hydrogen storage technologies, *Energy Explor. Exploit.*, 2006, **24**, (3), pp 197–209, doi: 10.1260/014459806779367455

[140] Hübert, T., Boon-brett, L., Palmisano, V. and Bader, M.A. Developments in gas sensor technology for hydrogen safety, *Int. J. Hydrog. Energy*, 2014, **39**, (35), pp 20474–20483, doi: 10.1016/j.ijhydene.2014.05.042

[141] Roberson, L.B., Williams, M., Captain, J.E., Mohajeri, N. and Raissi, A. Color Changing Hydrogen Sensors, NASA; HySense; University of Central Florida, 2015. Accessed: May 18 2022. [Online]. Available: https://ntrs.nasa.gov/citations/20150023595

[142] Zhao, M. et al. Leak localization using distributed sensors and machine learning for hydrogen releases from a fuel cell vehicle in a parking garage, *Int. J. Hydrog. Energy*, 2021, **46**, (1), pp 1420–1433, doi: 10.1016/j.ijhydene.2020.09.218