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Towards climate-neutral aviation: Assessment of maintenance requirements for airborne hydrogen storage and distribution systems

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HIGHLIGHTS

- Hydrogen in aviation requires strict safety measures to comply with regulations.
- Systems will become technically more complex and demanding towards maintenance.
- The substitution of kerosene with hydrogen is likely to increase maintenance costs.
- Without prior experience, maintenance has to be estimated across industry sectors.

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ABSTRACT

Airlines are faced with the challenge of reducing their environmental footprint in an effort to push for climate-neutral initiatives that comply with international regulations. In the past, the aviation industry has followed the approach of incremental improvement of fuel efficiency while simultaneously experiencing significant growth in annual air traffic. With the increase in air traffic negating any reduction in Greenhouse Gas (GHG) emissions, more disruptive technologies such as hydrogen-based onboard power generation are required to reduce the environmental impact of airline operations. However, despite initial euphoria and first conceptual studies for hydrogen-powered aircraft several decades ago, there still has been no mass adoption to this day. Besides the challenges of a suitable ground infrastructure, this can partly be attributed to uncertainties with the associated maintenance requirements and the expected operating costs to demonstrate the economic viability of this technology. With this study, we address this knowledge gap by estimating changes towards scheduled maintenance activities for an airborne hydrogen storage and distribution system. In particular, we develop a detailed system design for a hydrogen-powered, fuel-cell-based auxiliary power generation and perform a comparative analysis with an Airbus A320 legacy system. That analysis allows us to (a) identify changes for the expected maintenance effort to enhance subsequent techno-economic assessments, (b) identify implications of specific design assumptions with corresponding maintenance activities while ensuring regulatory compliance and (c) describe the impact on the resulting task execution. The thoroughly examined interactions between system design and subsequent maintenance requirements of this study can support practitioners in the

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development of prospective hydrogen-powered aircraft. In particular, it allows the inclusion of maintenance implications in early design stages of corresponding system architectures. Furthermore, since the presented methodology is transferable to different design solutions, it provides a blueprint for alternative operating concepts such as the complete substitution of kerosene by hydrogen to power the main engines.

Introduction

After the aviation industry has been hit by travel restrictions in the wake of the coronavirus pandemic with immense economic consequences for the industry as a whole, it is facing yet another substantial challenge in the pursuit of a cleaner and more sustainable air transport system. The European Commission, through its Green Deal initiative, has set the strict goal of a climate-neutral air mobility system by 2050 [1]. The International Air Transport Association (IATA) envisions a similar objective by committing their member airlines to a net-zero carbon emission scenario by 2050 [2]. Albeit different in their ultimate goal, the direction is clear: the aviation industry needs to quickly employ techniques to reduce their dependency on fossil fuels. Even though aircraft are constantly becoming more energy-efficient and operators are pushing to reduce their fuel consumption [3], the annual traffic growth rate for some regions prevents any reduction in Greenhouse Gas (GHG) emissions [4]. As a consequence, the aviation industry is exploring the possibility of novel propulsion and aircraft concepts that promise a drastic reduction of their associated emission levels, such as battery- or hybrid-electric flying, the use of Sustainable Aviation Fuels (SAFs) or hydrogen-powered aircraft. However, despite initial euphoria and ambitions for rapid industrialization [5] as well as the availability of these concepts for several decades already [6,7], there has not yet been any mass adoption.

While every of these concepts has its unique challenges, the large scale utilization of battery-electric aircraft arguably faces fundamental challenges. Since current battery technologies have a far inferior specific energy[1] compared to kerosene [8], a significant leap is required to allow short-range turboprop aircraft design missions [9–13]. Furthermore, even with hybrid-electric[2] concepts, the issues of thermal runaway incidents and necessary changes to the ground power infrastructure remain unsolved [7,15–17]. With these limitations in mind, it becomes obvious that, for a longer flight duration, an alternative energy carrier will need to be used. One possible solution is the use of SAFs, i.e., fuels that are made from sustainable sources [18] and release only the amount of CO_2 into the atmosphere that has previously been captured [19]. However, SAFs emit NO_x levels that are comparable to conventional fuels [20] and require extensive additional testing since they are currently only approved as a blend together with fossil fuels [21].

Therefore, for this work, we will focus on hydrogen as energy carrier with its substantial environmental benefit over the direct use of fossil fuels when produced from renewable energy sources [22]. Even though hydrogen produces water vapor through its oxidation process that can potentially form contrails, their longevity in the atmosphere is expected to be significantly shorter than for CO_2 [23] and they can be substantially reduced by adjusting flight routes [20,24]. However, hydrogen as energy carrier has two major drawbacks. First, Gaseous Hydrogen (GH_2) has a much wider range to form a combustible gas mixture than vaporized gasoline. Since it also requires less energy to initiate an ignition [25], greater safety measures are needed to prevent unwanted combustion. Second, even with a higher specific energy compared to conventional fuels, uncompressed GH_2 has a much lower volumetric energy density[3] [26,27]. Consequently, to be used in transport applications, it must be stored in a safe and efficient way, for example, under high compression or liquefied [28–30].

First concepts have been developed that use composite cylinders as wing spars to (a) store compressed hydrogen and (b) save space within the fuselage of the aircraft [31,32]. However, as discussed in Sect. 4.2.5, these design studies are incompatible with current regulatory requirements. Furthermore, compressed GH_2 will quadruple the required tank capacity for the same amount of energy compared to Liquefied Hydrogen (LH_2) [33]. Therefore, even with a higher energy demand for the liquefaction of hydrogen compared to GH_2 compression [27], the use of LH_2 appears advantageous as it allows a superior energy capacity for a given volume and subsequently reduces the weight of the airborne equipment [33,34]. Screening available literature (see Table 1) reveals that, despite first conceptual studies for an aircraft and cryogenic tank design [27,35–37], there has been no in-depth analysis of an airborne LH_2 system design with its implications on maintenance and regulatory compliance. Nonetheless, these insights are essential for an evaluation of the associated development and certification risk and for Original Equipment Manufacturers (OEMs) to invest into disruptive technologies [38].

Besides these technical aspects, multiple publications have dealt with ecological [39–43] and economic [44–46] aspects of

[1] The specific energy, also referred to as gravimetric energy density, describes the stored energy in a given system per unit mass and is typically expressed in Watt-hours per kilogram (Wh/kg) or Joules per kilogram (J/kg).

[2] In hybrid-electric system layouts, vehicles draw energy only partially from an electrical energy/power source such as a battery and combine this with conventional fuel combustion [14].

[3] The volumetric energy density puts the stored energy within a given system in relation to its volume. It is typically expressed in Watt-hours per cubic meter (Wh/m^3) or Joules per cubic meter (J/m^3).

Table 1 – Overview of selected, relevant literature and comparison with our contribution.

	Stückl et al. [9]	Gnadt et al. [11]	Zhang et al. [21]	Yilmaz et al. [27]	Mangold et al. [37]	Nicolay et al. [35]	Janić [39]	Goldberg et al. [38]	This study
Energy Carrier	Bat.	Bat.	SAF	Hyd.	Hyd.	Hyd.	Hyd.	Hyd.	Hyd.
Operating Aspects									
Maintenance	-	-	-	-	-	-	◑	◑	●
Technical Aspects									
Aircraft/System Design	●	●	-	◑	◑	◑	◑	◑	●
Regulatory Compliance	-	-	●	-	◑	-	◑	-	●

Other energy carriers (Stückl et al. [9], Gnadt et al. [11], Zhang et al. [21])

Bat. ... Battery, Hyd. ... Hydrogen, - ... not addressed, ◑ ... partially addressed, ● ... thoroughly covered

introducing hydrogen-powered aircraft concepts. These studies typically use a Direct Operating Cost (DOC) approach [47] to estimate the expected cost implications for the subsequent aircraft operation [38,44,45]. However, although this DOC approach touches on maintenance-related aspects, it was originally developed for legacy systems and uses regression-based statistics; therefore, it introduces significant inaccuracies when transferred to newer and more disruptive technologies. Since aircraft maintenance contributes between 10% and 20% to the operating cost [48–52], these inaccuracies can significantly influence the subsequent profitability of an airline and, therefore, heavily influence investment decision for and mass commercialization rates of these technologies.

In summary, to allow a thorough estimation of the profitability of a hydrogen-based fuel system and support the investments in this green technology, we will address the following aspects.

- Development of a conceptual design for airborne LH_2 storage and distribution systems to identify specific system components and define necessary design assumptions
- Definition of scheduled maintenance activities that will be required to comply with existing regulations and to keep such a system in an airworthy and safe condition
- Completion of a comparative study with a legacy fuel storage system to quantify the estimated changes in maintenance efforts by substituting a kerosene storage and distribution system with an hydrogen-based equivalent

For this work, we focus on the fuel system of an Airbus A320, an established short-/medium-haul aircraft that significantly contributes to the aviation's worldwide GHG emissions. With the results of the comparative analysis (see Sect. 5), this work will significantly contribute to and enhance existing techno-economic assessments of novel, energy-efficient aircraft concepts, e.g., as performed by Goldberg et al. [38]. Furthermore, the developed system design (see Sect. 4.1) and its influence on subsequent maintenance tasks (see Sect. 4.2) ensures regulatory compliance and provides aircraft designers with insights into necessary system requirements for a seamless introduction into current airline operations.

The remainder of this paper is organized as follows: After presenting the theoretical concept for determining maintenance tasks and their corresponding task intervals, we will provide a brief overview of the legacy fuel storage and supply system and its associated maintenance. On the basis of these insights, we will develop a system design for an onboard cryogenic system with its core components and their relevant standards. This system design will subsequently serve as our basis to derive necessary scheduled maintenance tasks. Finally, we will compare the maintenance task structure and total estimated effort with the legacy fuel system of an Airbus A320 to identify any expected changes towards scheduled maintenance for hydrogen-powered aircraft.

Fundamentals to estimate maintenance efforts

In general, aircraft maintenance is based on the idea of Reliability Centered Maintenance (RCM) [53], i.e., a generic decision process to identify measures that will allow the management of failure modes which could otherwise cause severe functional failures and operational consequences [54]. It has been adapted for the needs of aircraft maintenance through the Maintenance Steering Group - 3rd Generation (MSG-3) logic [55] and is continuously updated to incorporate changes of aircraft system design philosophies. Essentially, the MSG-3 methodology consists of two parts, (a) the risk-based analysis of functional failures, their causes, and their consequences and (b) modeling of the system's reliability to derive suitable maintenance intervals. We want to preface this section by emphasizing that neither RCM nor MSG-3 are new concepts. Thus, there are significant efforts within the aviation industry to replace scheduled maintenance activities by aircraft health monitoring technologies to save maintenance cost [56,57]. Consequently, there are ideas already to incorporate health management approaches into the next generation of aircraft maintenance schedules [58,59]. However, since these attempts have not yet been adopted for broad commercialized certification, we will focus with our work on the definition of traditional preventive scheduled maintenance tasks and neglect the possibilities for an automated sensor-based health monitoring.

Determination of maintenance tasks

RCM assumes that the inherent reliability of an item is a function of its design and the built quality [60]. According to Nowlan and Heap [53], the following factors need to be taken into account in order to develop corresponding preventive maintenance and inspection requirements of systems.

- Examination of factors leading to a functional failure,
- Consideration of the expected consequences from an occurring failure, and
- Determination of preventive measures and their implications towards a safe and reliable operation.

Subsequently, these aspects will be examined in terms of the equipment's life cycle to determine a cost-effective program for preventive, i.e., scheduled, maintenance [61]. As Ahmadi et al. [60] point out, the main objective of RCM is not to avoid failures per se, but to limit the expected operational consequences for a failure event to an acceptable level. The analysis of the RCM approach can subsequently yield the following maintenance actions [53,62–64].

Scheduled on-condition task
These kind of tasks determine the condition of a system, e.g., by using condition-monitoring techniques. For this task to be effective, a system needs to (a) allow the observation and detection of specific failure modes and (b) provide sufficient time between the identification of a potential fault and the ultimate failure. Depending on the component, this interval can vary between fractions of a second to several decades [64]. While longer intervals are favourable, as they allow more time for planning of restorative actions, the actual task interval is typically much shorter to ensure a reliable detection of upcoming failures [64].

Scheduled overhaul
These maintenance tasks will be issued in fixed time intervals and the system will be reworked to restore it to its (nearly) new condition. Thus, systems need to possess a clear age limit after which the failure rate significantly increases. This task is typically applied to emergency equipment.

Scheduled replacement
These tasks are similar to the scheduled overhaul, as they will also be executed in fixed time intervals. However, after removal, the systems will not be reworked but replaced with new parts. These maintenance tasks are usually applied to systems with high operational criticality and comparably low replacement costs.

Scheduled functional test
These tasks are also referred to as failure-finding tasks and shall detect functional defects for hidden systems, i.e., (protective) systems where the (in)correct function is unknown to the operating crew throughout normal operation. As failures may still occur, these scheduled failure-finding tasks may lead to subsequent (unscheduled) restoration tasks.

Run-to-Failure
If a system is not critical to safe operation and its economic impact on the occurrence of a malfunction is acceptable, it can be the deliberate decision to run the system up to the point of failure. However, it might be necessary to redesign a system to either minimize the criticality of possible failure modes or reduce the probability of occurrence.

Lastly, maintenance tasks that require any kind of disassembly should be limited to their absolute minimum, especially for protective functions, since reassembly can introduce human errors and cause subsequent hidden failures [64,65].

Determination of maintenance intervals

With the effective task identified, we need to determine the corresponding task intervals. Maintenance tasks that aim to determine a system's condition, i.e., scheduled on-condition and scheduled functional test tasks, seek to detect the onset of a failure [66] and can be executed continuously or periodically in discrete time intervals [67]. Their ultimate goal is to initiate preventive maintenance measures before the actual failure occurrence. Continuous monitoring typically requires a suitable sensor system that observes the system's condition and issues a warning whenever a fault is detected. However, these systems are often expensive and, depending on the sensitivity of the monitoring system, can be prone to false alarms due to noise-induced inaccuracies. Additionally, current certification standards do not necessarily allow the extensive usage of automated condition monitoring technologies (as briefly discussed in Sect. 2.1). Therefore, periodic monitoring is often used as a more cost-effective alternative. However, the use of periodic monitoring risks the possibility of missing failure events that occur between successive inspections [62]. Thus, determining the condition monitoring interval represents a significant challenge in establishing an effective maintenance task [66,67].

Even though maintenance guidelines, such as RCM or MSG-3, help to identify the best maintenance measure for a given operational situation, they often leave it to the engineering department's expertise to determine these intervals [66]. Thus, they are mainly estimated through the collection of (publicly) available data. Typically, these are legacy Maintenance Planning Documents (MPDs) and failure rate estimates for the component based on experience from the manufacturer or the operator [62,68]. However, with maintenance experts frequently lacking the methodology needed to optimize these intervals, they regularly rely on intuition, which does not necessarily work for new and unknown system architectures [66]. In the following, we will therefore review approaches for determining maintenance intervals that have been published in the past [62,66,69] and combine these with our own observations.

Comparative analysis of existing standards

The first approach is the derivation of initial maintenance interval estimates from existing standards, such as the International Organization for Standardization (ISO), or through established industry practices. Therefore, this is rather simplistic but transparent for the identification of maintenance intervals. Furthermore, through the published standards, these maintenance intervals are well established and relevant information can be accessed easily, so that no further assumptions on degradation patterns are required. However, since these standards are usually not specifically designed for aerospace applications but for ground-based industrial solutions, they do not necessarily reflect the severity of functional failure consequences and have potentially different requirements towards system reliability. In fact, comparable information for every component from previous operating experience is lacking.

Statistical analysis of historical failure rates

The second approach is to use statistical models - typically Poisson- and Weibull-distributions - with historical failure rate data for repairable and non-repairable items [70]. Through the technique of reliability analysis, it is possible to determine maintenance time intervals that will limit the probability for a system failure to a certain level. Though this time interval does not prevent a part failure per se, it ensures a timely repair without any operational interruption at the system level [70]. The main advantages here are that (a) these models primarily depend only on the historical Mean Time Between Failures (MTBF) of a system, (b) allow to incorporate the criticality of a system failure by defining a reliability threshold (see Eq. (1)) and (c) enable the consideration of installed redundancies. However, the reliance on MTBF information represents also the most significant limitation of this approach since there is no consensus on whether the use of failure rates or MTBF data will produce viable maintenance interval estimates [71,72]. Furthermore, the calculated time interval is highly sensitive towards the system's required reliability, which potentially leads to impractically short maintenance intervals for high reliability values. Thus, in this paper, we will use the statistical approach to determine Failure Finding Intervals (FFIs), i.e., repetitive time intervals to check the functionality of protective systems and restore their condition if necessary [62,65]. It can be calculated as

$$\mathrm{FFI} = \frac{2 \cdot M_{TIVE} \cdot M_{TED}}{M_{MF}} \tag{1}$$

with M_{TIVE} as the MTBF of the protective function, M_{TED} as the MTBF of the protected function, i.e., the mean time between demands of this protection, and M_{MF} as the allowable MTBF of the whole system, i.e., in what time instance does an operator allow the system to have failed completely with its protective functions.

Failure degradation models based on lifecycle experiments

The third approach is the derivation of physical models to thoroughly understand the degradation behavior of components. The goal is to identify parameters that correlate with the system's degradation as well as the corresponding diagnosis of immanent system failures. Any findings from experimental settings can subsequently be transferred to so called P–F intervals to derive effective maintenance intervals.[4] The predominant advantage of this approach is the detailed technical understanding of failure mechanisms, their consequences, and the possibilities of reliably detecting them [62]. Additionally, the experimental set-up will incorporate specific system design features as well as typical operating scenarios, enabling the definition of tailored condition monitoring techniques and maintenance intervals. However, these detailed analyses will result in significant expenditures and are time-consuming as they require designated laboratory facilities and test equipment. There is also no publicly available database that would allow the derivation of previously determined P–F intervals.

Taking these characteristics and drawbacks into account, it seems infeasible for this work to carry out extensive experimental tests to derive degradation patterns and maintenance intervals. As we also have only limited information about specific system designs (see Sect. 3.1), we will primarily rely on values from existing standards. It should further be noted that maintenance intervals, once established, are not static but often change over time, e.g., the maintenance schedule of the Airbus A320 has been updated more than 40 times since its introduction 30 years ago [73]. Thus, maintenance intervals must be considered as a product of their time and be set in context of the operating experience. Consequently, because there exists only very limited experience with airborne hydrogen systems, the maintenance intervals of this work may be subject to future changes and provide an initial estimate only.

Legacy fuel system

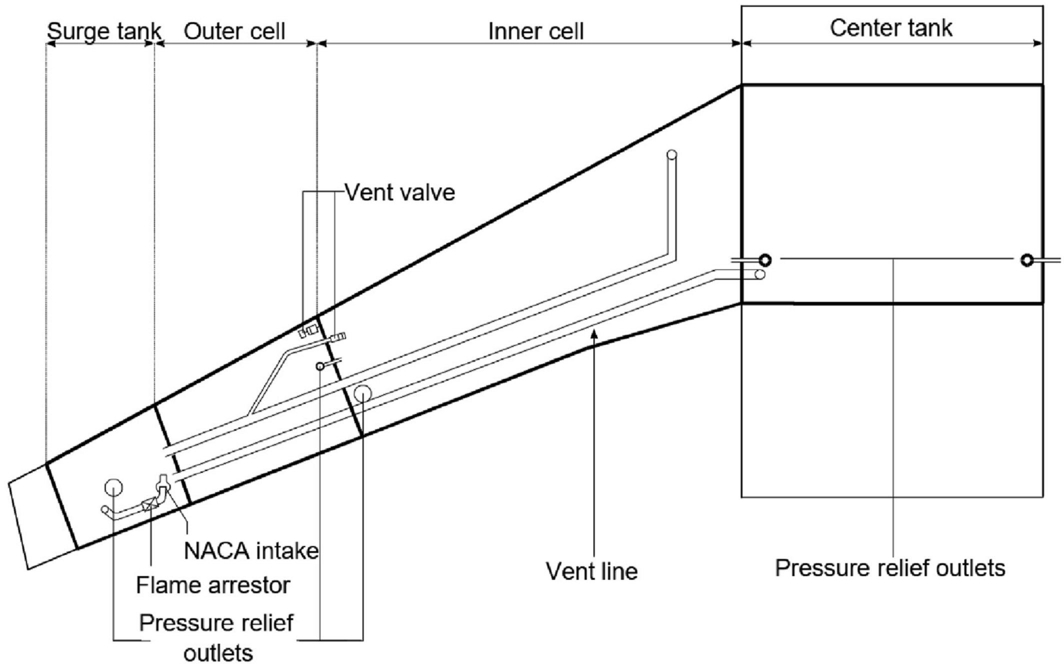
With the fundamentals of the development of aircraft maintenance tasks explained, we now want to introduce the state-of-the-art fuel system of an Airbus A320 with the current maintenance schedule. This legacy system with its maintenance implications will serve as our reference scenario for the subsequent comparative analysis in Sect. 5.

System design

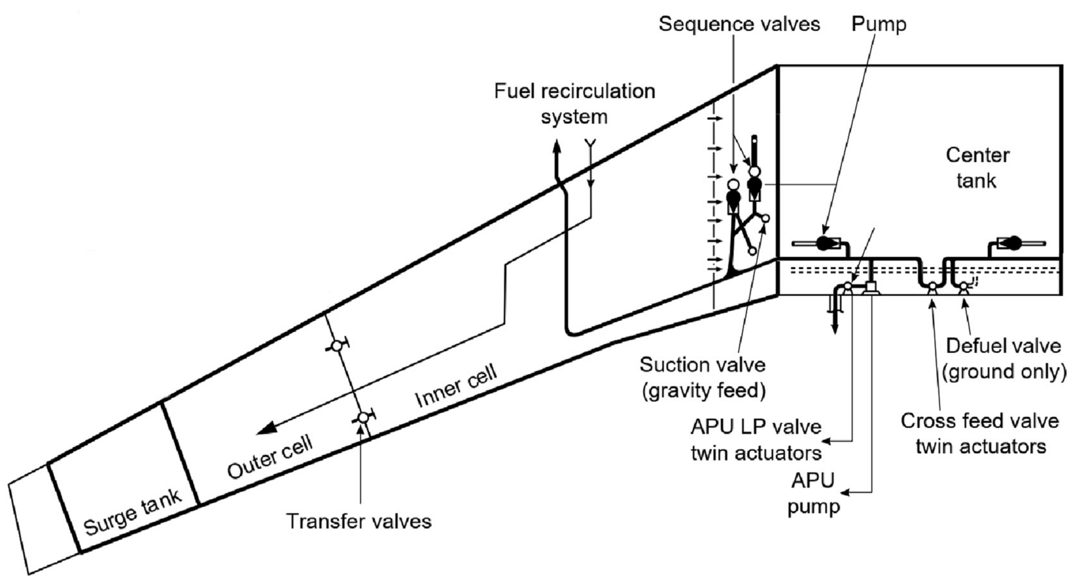
The following information on an A320 fuel system is based on publicly available training documents from Airbus [74]. The structurally-integrated fuel tank system is composed of two essential parts: the tank venting system (see Fig. 1a) and the fuel supply system (see Fig. 1b). The fuel supply system has the following functions.

- To keep fuel in the main fuel tanks and the center (transfer) tank, which are open to atmosphere through the vent surge tanks,
- To control and supply fuel in the correct quantities to the fuel tanks during refuel operations,
- To supply the fuel to the engines,

[4] Interested readers are kindly referred to the work from Moubray [62], who provides an in-depth explanation of P–F intervals and how they can be used to derive corresponding maintenance intervals.



(a) Current tank venting system



(b) Current fuel system

Fig. 1 – Current fuel supply system [74].

- To supply the fuel to the Auxiliary Power Unit (APU),
- To use the stored fuel to cool the oil of the engine-mounted Integrated Drive Generators (IDGs), and
- To provide indications to the cockpit crew on the current state of the system.

Additionally, the tank venting system has the primary purpose to prevent excessive structural loads being applied by keeping the air pressure in the fuel tanks close to the ambient air pressure; thus, no large pressure differences can accumulate which ultimately have the potential to cause damage to the fuel tank/aircraft structure. While each tank within the wings is ventilated through surge tanks at each wing tip, the center tank is ventilated via the left hand wing surge tank. This venting process is primarily necessary during refueling (or defueling) and during the aircraft's climb or descend flight phases. Furthermore, if a fuel tank is inadvertently overfilled during the refueling process or through a fuel transfer, the venting system can contain a certain amount of this fuel in their surge tanks to avoid any spillage. During flight, any accumulated fuel in these tanks is transferred into the outer cell by a scavenge jet pump. However, if the quantity of fuel exceeds the capacity of the venting system, this excess fuel can also be drained. To prevent the occurrence of critical internal pressure levels, the tanks are additionally equipped with pressure relief devices [74].

As shown in Fig. 1, the current fuel system consists of one center tank, two inner wing tanks, and two outer wing tanks. There is also no distinction made for the fuel supply of the main engines of the aircraft and the APU. Although there is an option for installation of an additional center tank for range extension, we will not consider this particular configuration as of this work. The fuel is supplied to the engines by booster pumps, with center tank and each wing being equipped with two redundant pumps. Fuel will usually be supplied by the center tank first; however, the pumps within the wing also operate continuously, although at a lower pressure than their center tank counterparts. Therefore, even with the center tank pumps shutting down, a steady supply of fuel to the engines can be ensured. Additionally, there are two electrical transfer valves are installed on each wing to transport fuel from the outer to the inner cells whenever the fuel level drops below a certain threshold. Furthermore, the fuel is also continuously recirculated to cool the IDG and the engine oil for a IAE V2500 engine configuration. Lastly, to avoid water accumulation in the tank, a scavenge system is installed and each tank is equipped with corresponding water drain valves [74].

System maintenance

After we have presented the basic system layout for the legacy A320 fuel supply and storage system, we will now introduce the associated scheduled maintenance efforts. The MPD [75] will serve as our baseline for the following study, as it incorporates established scheduled maintenance tasks that operators currently use to ensure compliance with regulatory requirements. In addition to the MPD, operators can define scheduled maintenance tasks on their own if they consider them beneficial according to their experience. Regarding the legacy fuel system, and according to a recommendation of International Air Transport Association [76], operators typically take a fuel sample once a year to test for microbiological contamination that could, for example, subsequently lead to corrosion of the internal tank structure or blocked fuel filters [77].

As of this work, we will exclusively focus on tasks related to the onboard fuel systems, i.e., Air Transport Association (ATA) chapter 28. Keeping with the system design previously presented, this ATA chapter is subdivided into three sections for (a) the fuel storage system (ATA 28-10), (b) the distribution system (ATA 28-20), and (c) the indication system (ATA 28–40). In addition, some maintenance tasks may only be applicable to specific aircraft configurations, e.g., only if equipped with a certain engine type or if an additional center tank has been installed. For a correct comparison, we will focus on the most common aircraft configuration, i.e., an A320 with CFM-56 engines installed. Furthermore, to estimate the required workload for each task, the MPD provides three categories of the so called Maintenance Man Hours (MMH).

- MMH_{prep} for preparatory work, e.g., removal of structural items to allow access to the unit,
- MMH_{access} to access the location within the aircraft, e.g., by removing panels or opening doors, and
- MMH_{task} for the completion of the actual maintenance task.

However, since the system design is currently in its conceptual state and the exact layout is yet to be determined, any estimate of access and preparatory MMH would introduce high levels of uncertainty. Thus, in order to simplify the subsequent analysis, we will only use the MMH information to perform the actual task itself and compare the resulting maintenance workload in Sect. 5. It should also be noted that the time information provided by MPD does not incorporate waiting times, such as drying a sealant or defueling the aircraft. Furthermore, Airbus [75] states that these times are mere indications of expected workload and do not necessarily need to reflect actual times needed to complete the maintenance task. This is in line with reports by Aircraft Commerce [78] who state that the true MMH can exceed the estimate of the MPD up to a factor of three.

Since maintenance tasks can be triggered based on the aircraft's Flight Hours (FHs), Flight Cycles (FlCs), calendar days, or a combination of them, we need to use conversion factors based on an A320's typical annual utilization. Table 2 provides an overview of typical utilization rates for different operating scenarios. The annual average utilization of a representative A320 passenger aircraft, without any distortions due to extended ground times during the coronavirus lockdown, is 1500 FlCs and 2750 FHs, respectively, which results in an average flight duration, i.e., FH-to-FlC ration, of 1.8 [79].

Taking this average utilization, an A320 will require 8.26 MMH per 1000 FHs of scheduled maintenance work for the fuel system alone (see Table 2). As can be seen in Table 3, most of the workload is associated with the fuel storage system while the indication system is virtually free of any scheduled maintenance tasks.

Furthermore, we examined the total scheduled maintenance efforts for the legacy fuel supply system, depending on different aircraft utilization rates. For an aircraft with a high utilization rate (HUR), i.e., an annual utilization within the 95% percentile of the worldwide A320 fleet, the total maintenance effort will decrease to 6.03 MMH per 1000 FHs. In contrast, for an aircraft with a low utilization rate, that is, within the 5% percentile of the worldwide A320 fleet, this maintenance effort will increase to 13.33 MMH per 1000 FHs. To examine the dependency of scheduled maintenance tasks on the average

Table 2 – Total scheduled maintenance effort for different A320 utilization rates.

Dimension	AVG	LUR	HUR	SFS
FH per YR	2750	1650	3900	2750
FlC per YR	1500	900	2100	2750
FH per FlC	1.8	1.8	1.9	1
MMH per 1000 FHs	8.26	13.33	6.03	8.28

AVG: Average utilization.
LUR: Low utilization rate.
HUR: High utilization rate.
SFS: Average utilization with short flight segments.

Table 3 – Distribution of scheduled maintenance tasks within ATA chapter 28.

Chapter	Sub-System	MMH per 1000 FHs	Share
ATA 28-10	Total	7.0	85.0%
	Tank Structure	4.3	51.4%
	Tank Drain	0.3	3.7%
	Tank Venting System	0.3	3.3%
	Intercell Transfer System	0.01	0.1%
	Fuel Recirculation	0.02	0.2%
	Ignition Prevention	2.2	26.3%
ATA 28-20	Total	0.33	4.0%
	Fuel Pump	0.3	3.4%
	Shut-Off Valve	0.02	0.2%
	Crossfeed System	0.01	0.1%
	Refuel Coupling	0.02	0.3%
ATA 28-40	–	0	0%
–	Fuel Sample	0.9	11.0%

flight duration, we have also examined the effect of average utilization with short flight segments (SFS), i.e., a FH-to-FlC-ratio of one. As indicated in Table 2, the resulting scheduled maintenance efforts barely change, from 8.26 to 8.28 MMH per 1000 FHs since most tasks are triggered on a calendar basis; thus, they are more influenced by the total annual utilization as the baseline for comparison rather than different flight segment lengths.

Besides that workload estimate, we also examined the structure of the necessary maintenance tasks. The MPD defines, in accordance with the MSG-3 logic (see Sect. 2.1), six different task categories. The respective shares of these task categories are shown in Fig. 2.

In total, there are 63 maintenance tasks at distinct units for the chosen aircraft configuration. A significant share of these tasks are Operational Checks (OPCs) that ensure a unit's performance of its intended function without determining any

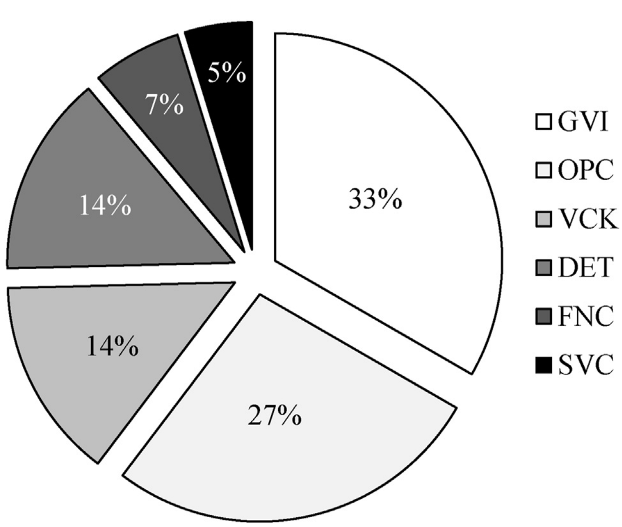


Fig. 2 – Distribution of scheduled maintenance task categories for the legacy fuel storage and distribution system.

quantitative tolerances [55]. Therefore, this type of task serves as a Failure Finding Task (FFT). Together with Visual Check (VCK) tasks, i.e., an observation without quantitative measurements to ensure that an item is in its intended state [55], FFTs account for 41% of the routine maintenance activities. 54% of maintenance tasks are associated with different forms of quantitative inspection tasks. These are.

- General Visual Inspections (GVIs), i.e., examinations of areas within touching distance under normal lighting conditions to detect obvious damages,
- Detailed Inspections (DETs), i.e., intensive examinations of a specific installation normally supported with supplemental lighting to detect damages and check for tightness and security, and
- Functional Checks (FNCs), i.e., quantitative checks to determine if one or more functions of an item performs within specified limits [55].

There are also few Servicing (SVC) tasks necessary to ensure that the system is within its proper operating condition. For the legacy fuel tank system, these are associated with the repetitive drainage of excessive water from the fuel tanks.

Lastly, it should be noted that all these scheduled maintenance tasks can be performed on the aircraft itself; thus, no unit needs to be removed and shipped to a designated shop maintenance facility for further inspection or overhaul. This simplifies the supply chain necessities since no spare units need to be provided for a quick return into service of the aircraft. Additionally, it reduces labor and material costs by avoiding any disassembly and in-depth examination of removed items.

Hydrogen fuel system

With these theoretical fundamentals explained, we will now present a conceptual system design layout for an airborne cryogenic tank system of a hydrogen-powered APU substitute, including its maintenance requirements and possible implications on aircraft operations. We want to emphasize that the presented system design has been defined as detailed as necessary to estimate the implications towards maintenance; thus, we did not perform any extensive Failure Mode and Effects Analysis (FMEA) to determine the system's reliability and any possible redundancy configurations. The general performance characteristics of the system are show in Table 4. The system has been specified to deliver an equivalent power output of a conventional APU [80] with the electrical power demand of a conventional A320 [81].

System design

The basic schematic outline of the design of the cryogenic hydrogen storage and supply system is shown in Fig. 3. It has been developed in alignment with the recommendation of SAE's standard J2579 [82]. As shown here, all the associated cryogenic onboard infrastructure is assumed to be installed outside of the pressurized passenger cabin in the rear of the aircraft's main body. In general, the considered system can be

Table 4 – General system performance characteristics.

Parameter	Value
LH_2 Tank	
Volume	15 kg
Pressure	max. 7 bar
GH_2 Tank	
Volume	12.5 kg
Pressure	300 bar
Fuel Cell	
Electrical Power Output	15 kW–100 kW
Voltage	250 VDC - 500 VDC
Current	45 A–420 A
Gross Output (@ 20 kW)	365 VDC/55 A
Mass Flow H_2	60 NLPM - 1500 NLPM
Temperature H_2	5 °C–70 °C
Pressure H_2	3 bar–5 bar
Mass Flow Air	900 NLPM - 6800 NLPM
Temperature Air	−30 °C - 45 °C

Table 5 – Cryogenic hydrogen storage and supply sub-systems.

Sub-System	Main Functions
Cryogenic tank	– Storage of LH_2 – Minimizing heat influx to limit boil-off rate
Cryogenic refueling line	– Refueling of the tank with LH_2 – Prevention of unwanted and uncontrolled hydrogen flow out of the refueling nozzle – Controlled return of boiled-off hydrogen to a suitable ground receptacle
Fuel cell supply line	– Vaporization of LH_2 – Heating of GH_2 to keep the fuel cell within its most efficient operating range
GH_2 pressurization system	– Enabling supply of LH_2 through tank pressurization – Ensuring constant supply of hydrogen
Gaseous refueling line	– Controlled repressurization of GH_2 storage cylinder – Prevention of contamination

subdivided as shown in Table 5 and will serve as our foundation for the subsequent maintenance requirements analysis.

As this study mainly focuses on maintenance-related aspects, we limit this section to central design assumptions that are necessary to subsequently derive maintenance requirements. As a consequence, we are focusing here on the general system layout that would need to be followed with information provided through public standards and operator experience. All associated technical assumptions of the intended components are summarized in Table 6.

Cryogenic hydrogen storage tank

The cryogenic hydrogen will be stored in a designated tank that has been designed according to ISO standards 21029-1 [83] and 21029-2 [84]. The tank will feature a double-wall construction to hold a suitable vacuum insulation. Even though the manufacturing costs are expected to be higher than for single-wall constructions [85], this design can significantly reduce the loss of hydrogen due to evaporation and venting [86]. This is in line with multiple studies that recommend vacuum insulated Multi-Layer Insulation (MLI) against radiation heat transfer for cryogenic aerospace applications [85,87]. With the performance also heavily depending on the integrity of the vacuum, any degradation will significantly increase the hydrogen evaporation rate [87,88], potentially leading to mission failures [85]. Thus, the tank's vacuum will be continuously monitored.

The tank material should ideally possess high-strength properties while being lightweight, i.e., having a low density [85]. Although these requirements naturally point to composite materials, with potential weight savings of 25%

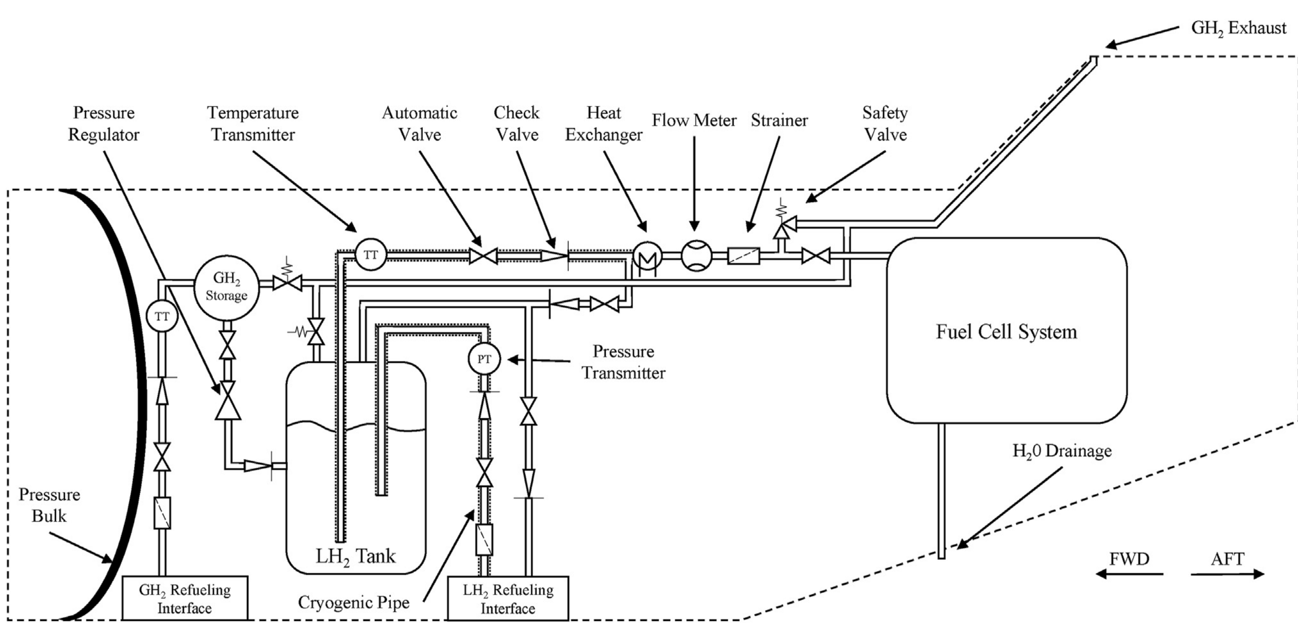


Fig. 3 – Schematic hydrogen system layout.

Table 6 – Assumptions on system design and characteristics.

System unit	Sub-components	System design assumptions	Applicable standard
Cryogenic Tank Unit	Aluminium Tank	– Sensor-monitored vacuum insulation to detect leakage and observe the insulation performance – Three fuel quantity probes for continuous monitoring of hydrogen level and to ensure system redundancy	ISO 21029-1 ISO 21029-2
	Tank Fixtures	– Made of metal	–
Pressure Relief Unit	Resealable Safety Valve (Cat. A)	– Emergency relief valve for sudden, high rates of evaporating hydrogen	ISO 21013-1
	Burst Disc	– Standby redundancy for resealable safety valve (Cat. A) – Complies with Safety Integrity Level (SIL) 4 standard	ISO 21013-2 IEC 61511
	Resealable Safety Valve (Cat. B)	– Continuous venting of minor boil-off gases	ISO 21013-1
Vaporizer	–	– Electrically powered – Self-monitored to adjust power so that generated GH_2 has a constant output temperature	ISO 15547
Cryogenic Hydrogen Supply	Check Valve	– Valve to prevent any uncontrolled flow of LH_2 and GH_2	ISO 21011
	Automatic Valve	– Valve to control the mass flow of LH_2 into the tank – Redundant system of installed check valves – Capability to control hydrogen flow to or from the tank and to the Fuel Cell (FC)	ISO 21011
	Cryogenic Pipe	– Vacuum insulated – Equipped with sensors to detect any abnormal gas concentration that could indicate (a) a breach of the insulation or (b) hydrogen leakage from the pipe	ISO 21012
	Hydrogen strainers	– Made of metal – Can be cleaned and reused	–
Gaseous Tank Unit	Composite material tank	– Metallic liner – Tank fully wrapped with composite (Type III) – With surface protection	ISO 11119-3

compared to aluminium [89], the structure also needs to provide resistance to hydrogen embrittlement and low hydrogen permeability. However, non-metallic, composite materials suffer significant permeation which can subsequently compromise the vacuum insulation performance [90]. While different composite materials with protective metal foils have been examined [90] and can potentially offer optimal performance at a minimum weight, there are still significant unsolved challenges, e.g., their long-term resistance to hydrogen permeation under cryogenic conditions and their associated reliability [85,90]. Therefore, in this study, we assume that the tank will be made of a lightweight metal such as aluminium.

Pressure relief system

Because of the unique properties of (liquefied) hydrogen, it requires specific measures to ensure safe operations and explosion prevention. Comparing the density of gaseous and liquefied hydrogen reveals that during the hydrogen boiling process, the associated volume will increase by a factor of more than 840 [91]. Thus, the system will require a reliable venting capability to maintain the internal pressure of the system within its design specifications. However, since hydrogen has a broad range to form a combustible gas mixture, any release into the atmosphere needs to ensure no explosive environment is created. In alignment with a proven design by BMW [92], we have chosen a venting design with an exhaust through the tail fin so any lighter-than-air GH_2 will exit at the highest point of the aircraft.

As briefly mentioned in Sect. 4.1.2, resealable safety valves are distinguished in Cat. A and Cat. B valves, depending on their typical annual utilization. While Cat. A valves are designed to operate continuously, i.e., with more than 20 opening and closing cycles per year, Cat. B valves will only work sporadically, i.e., with less than these 20 cycles [93].

Normal operation. A certain (small) amount of boil-off hydrogen gas is inevitable due to heat influx. With the FC operating, this evaporated hydrogen will be directly used for electricity generation; therefore, the system pressure will be kept constant without any venting. However, if the system is shut down completely, e.g., during overnight stops, there will be no consumption of gaseous hydrogen; as a consequence, these hydrogen gases will need to be vented safely. To get an idea of the frequency of these venting requirements, BMW [92] states that for their tank design only after the system has been shut down for at least 17 h, the evaporated hydrogen will need to be vented - given that the tank pressure was at its lowest operating limit right before.[5] Therefore, the pressure relief device must be designed for continuous operations, as described for Cat. A valves in ISO 21013-1 [94].

[5] With new materials, the tank insulation performance, and subsequently this vent-free time period, can be expected to increase.

Emergency situation. Since only Cat. B valves are equipped with a redundant non-resealable pressure relief device, the following information applies only to these valves and not to Cat. A valves. In case the hydrogen tank experiences any structural defect, e.g., a breach of its insulation, excessive amounts of liquid hydrogen could rapidly evaporate and rapidly increase the system pressure beyond its safe design limits. However, the pressure relief valve for continuous venting is not designed to release these large amounts of hydrogen gas. Therefore, the system will need to be equipped with a backup pressure relief system, consisting of a resealable pressure relief device, as described for Cat. B valve in ISO 21013-1 [94], and a redundant burst disc, as described in ISO 21013-2 [95]. Furthermore, we designed the system so that excess hydrogen gas will be vented through the exhaust pipes in the tail fin of the aircraft.

Due to the double-wall design of the tank structure, the vacuum insulation of the cryogenic tank will also be equipped with a pressure relief device to avoid any adversarial situations, e.g., in case of a defective inner tank structure [82].

Cryogenic hydrogen supply

The system is designed to transport LH_2 through differential pressure from the tank to the heat exchange unit and the fuel cell. With this design assumption, we can reduce the technical complexity and increase the reliability, since the system does not require any pumps to transport liquid hydrogen to the vaporizer. Thus, we can eliminate any kind of associated pump maintenance and reduce loss of hydrogen due to boil-off during the pumping process as described by Petitpas and Aceves [96]. Furthermore, a continuous pressurization of the tank will help keeping cryogenic hydrogen in its liquid state [85]. However, as Reynolds [97] points out, the pressurization shall be limited to its minimum since an increase in fuel tank pressure will result in increased structural weight; in addition, the tank may expand as well based on the internal pressure. In accordance with Mital et al. [85], the system will be pressurized with GH_2 that is stored in a designated GH_2 tank. Through a suitable pressure regulating device, sufficient GH_2 will constantly be provided to transport LH_2 to the vaporizing unit.

Regarding the insulation of the cryogenic hydrogen pipes, SAE states that an ageing foam-based insulation will gradually allow diffusion of the ambient atmosphere into the insulation. As a consequence, this can lead to a decreased insulation performance and can potentially also support the phenomenon of Corrosion Under Insulation (CUI) [65,98]. With this degradation typically occurring within one year from the first signs of an imminent fault to the ultimate failure (P–F interval) [65], Moubray [62] recommends suitable maintenance tasks to be performed at half of these interval times, i.e., a visual inspection every 6 months. With this maintenance interval being impractical for normal operations and vacuum insulated pipes not requiring these frequent inspections, we define the supply pipes for cryogenic hydrogen as being vacuum insulated. Although SAE states that any loss of insulation performance can be detected by accumulation of ice on the cryogenic pipe [65], we assume that the vacuum insulated pipes will be equipped with suitable sensors for a continuous monitoring of the vacuum's integrity. To avoid the contamination of the system during refueling and prevent damages, there are cryogenic filters installed.

GH_2 storage tank

As Mital et al. [85] state, a continuous pressurization of the tank is beneficial to keep hydrogen in a liquid state and will also aid the transportation of the fluid to the vaporizer unit. Thus, we will use a designated GH_2 storage reservoir to continuously pressurize the cryogenic system. For the tank material specifications, we found that Toyota is using composite GH_2 tanks (Type IV[6]) for their model Mirai for quite some time already [100]. They have shown their durability and are rated for service pressures of 700 bars. This aligns with the work from Bensadoun [101] who states that Type III and IV tanks may potentially be suitable for aerospace applications. However, as Morrin [102] emphasizes, Type III cylinders might be advantageous, compared to Type I and II cylinders [103], for aerospace applications as they offer significant weight saving due to their composite parts while also providing greater resistance to permeability than Type IV cylinders due to its metal liner. Therefore, as of this paper, we assume the GH_2 tank to be compliant with the specification of ISO 11119-3 [104] and Type III specifications.

For the pressurization of the LH_2 tank, the pressure shall be selected as low as possible to reduce stresses on the tank structure and to limit the requirement for additional structural weight. Simultaneously, the FC needs to be supplied with sufficient pressure in order to produce the required power output. Thus, in order to maintain the desired constant system pressure of about 3 bar and to avoid overpressurization events, a pressure regulator will need to be installed between the GH_2 and LH_2 tanks.

Vaporizer

Besides the correct pressure, the FC also requires GH_2 that is well within a certain temperature range in order to provide the intended power output. Therefore, the stored LH_2 needs to be evaporated and heated before being supplied to the FC. This evaporation will be performed by an electrically-powered heat exchange unit. While there are more energy-efficient alternatives, e.g., by using the FC's exhaust heat, they would increase the system's technical complexity and will require mechanisms during start-up or flight phases when the FCs exhaust heat is insufficient for the hydrogen heating process. The vaporizer will be designed in accordance with ISO standard 15547-1 [105], which has been developed for heat exchangers in the natural gas industry; thus, the technical specifications shall be transferable to the application of hydrogen evaporation. Since the vaporizer is electrically-powered, it can not only control the condition of the GH_2 output but also allow a constant monitoring of its condition, e.g., through observation of electrical resistance as a sign of degradation or imminent failure.

[6] Barthelemy et al. [99] provide a detailed overview of the different hydrogen gas cylinders with their key characteristics and specifications.

(a) (b)

Fig. 4 – ECAM panel comparison. (a) Current APU system panel [106]. (b) Proposed H_2 system panel.

System monitoring

Ultimately, the flight crew needs to be provided with suitable system data to obtain an overview of the current system's working status and possible malfunctions. This update is also important to select the correct failure mode according to the MSG-3 logic. Therefore, we adapted the Electronic Centralized Aircraft Monitor (ECAM) display to handle different (additional) information. The proposed hydrogen information screen (see Fig. 4b) is derived from the Airbus A320 legacy APU monitoring system (see Fig. 4a); thus, the system status information presented is closely related to previous status displays. The following parameters have been altered or added.

- the quantity of LH_2 onboard (HOB),
- the temperature of LH_2 and GH_2,
- the fuel flow (FF) per second towards the FC, and
- the current system pressure P.

The flight crew will also be alerted if hydrogen - LH_2 or GH_2 - is being refueled or an excessive amount of GH_2 is being vented. If hydrogen is detected in dangerous, i.e., combustible, concentrations by any of the system sensors, a warning will be displayed to the flight crew as the system potentially experiences a fundamental functional failure.

System maintenance

After we have presented the necessary system design adjustments to enable a hydrogen-powered FC operation, we will now discuss the corresponding (scheduled) regular maintenance necessities. To this day, there are hardly any in-depth insights into maintenance implications for hydrogen-powered aircraft and the few existing studies [38,39,46] are lacking details on the specific tasks and their appropriate intervals. However, these information are important to estimate the subsequent economic profitability of such a technology. Nevertheless, there are studies for other applications of cryogenic gases, e.g., Liquefied Natural Gas (LNG) facilities [107–109], as well as standards that address the associated maintenance requirements. Despite their focus on non-aerospace applications and their age, these standards will serve as the foundation of our analysis because of their meticulous documentation of failure data for all kinds of tank and supply equipment.

In the following sections, we will present a thorough analysis of the necessary maintenance tasks for each subsystem. The corresponding maintenance tasks and intervals are summarized in Table 9. We want to emphasize that we primarily focus on the effects of a hydrogen-powered FC on routine, scheduled tasks. However, if information is available, we will also describe qualitatively some implications on non-routine tasks.

Cryogenic hydrogen storage tank

A well known phenomenon of materials that are in continuous contact with hydrogen is their tendency to embrittlement [110,111] which leads to a significantly increased susceptibility to cracking and possible tank ruptures. While there are techniques during manufacturing that can reduce the risk of hydrogen embrittlement, e.g., the selection of certain materials or corrosion-preventing coatings, regular visual inspections of the tank structure European Industrial Gases Association [112] are vital to avoid sudden mechanical failures with potentially catastrophic consequences [113].

A general regulatory guideline for the repetitive maintenance of transportable pressure vessels is provided in Title 49 U.S. Code of Federal Regulations (CFR) §180.209[7] [114]. Here, a distinction between cryogenic and pressurized storage cylinders needs to be made. While pressurized cylinders will need to be requalified within certain intervals (see Sect. 4.2.5), cryogenic storage devices (Type DOT 4L) have a less restrictive testing cycle and usually do not require regular retests. However, the ISO standard 21029-2 [84] recommends to perform an extensive visual inspection for the inner tank at

[7] Although this regulation applies for receptacles that shall be operated within the United States or by US carriers, it has been established as guideline to comply with the MSG-3 standard.

least every ten years for these types of vessel. Additionally, ISO 21029-1 [83] specifies that each cylinder design must withstand 10,000 pressure cycles, which are equivalent to 10,000 FlCs, during production tests without any signs of compromised structural integrity. Thus, a visual inspection of the external tank structure will have to be performed in that interval accordingly. Furthermore, whenever the external tank is visually inspected, the tank fixtures are also subject to a Special Detailed Inspection (SDI), similar to the inspection of the engine mount pylon bolts that ensure a secure attachment to the aircraft and avoid any involuntary separation. With the task interval varying from 7500 FlC or 15,000 FH for an A320 [75] to 15,000 FlC or 30,000 FH for an A320, we define a task interval of 10,000 FlC or 20,000 FH, respectively, to harmonize the interval with the external task inspection.

Since any tank opening will need to be kept as small as possible to reduce pressure-induced stresses, it will likely not provide sufficient space for a mechanic to enter the tank. Therefore, an internal inspection needs to be carried out with a borescope inspection and will require the disassembly of the accessories to open the tank. We estimate the corresponding task execution time to be 1.0 MMH[8] which is in line with information from the MPD for a compatible engine borescope inspection of similar area and comparable safety requirements. The external tank inspection is similar to the visual inspection task of an additional center tank, so that we estimate an associated maintenance effort of 0.58 MMH. Finally, we assume that the completion of the SDI task requires 0.4 MMH for each fixture which is equivalent to the average task time for current engine bolt inspections.

If a structural repair is necessary as a result of these inspections, the tank needs to undergo a subsequent testing routine that is identical to the one after manufacturing and typically includes a visual inspection, a radiography analysis of welds, and a pressure test [83,84]. With these non-routine tests requiring the tank's removal from the aircraft, suitable access points will have to be considered in the aircraft's design phase.

Cryogenic hydrogen supply

After we have examined the maintenance requirements for the cryogenic tank, we will now focus on items related to cryogenic hydrogen supply.

Cryogenic valves. Cryogenic hydrogen valves consist of numerous elements that are subject to aging and constant degradation as they need to provide a reliable sealing capability under extreme adverse conditions. Thus, they require regular inspections and replacements of sensitive elements which can typically only be performed once the system has been warmed and depressurized. Therefore, maintenance intervals need to be carefully defined to minimize downtimes and temperature-induced thermal stresses on the system [115].

According to ISO 21029-2 [84], it is recommended to perform an inspection of all cryogenic accessories within ten years of operation to detect early signs of damage or possible leakages. As this standard is primarily focused on the cryogenic tank and on pressure relief applications with intermittent utilization, a suitable inspection cycle for frequently used cryogenic valves may be significantly shorter. Thus, we assume a safety factor of 2 for this inspection task, resulting in a maintenance task interval of 60 months. Furthermore, cryogenic tank accessories that have been manufactured in accordance with ISO norm 13985 [116] are required to withstand 20,000 open-close-cycles as part of their production tests. As the exact conversion of these operating cycles to an FlC equivalent is difficult to determine and the true degradation pattern in aerospace applications is yet to be determined, we will use a more conservative estimation by using the average annual utilization of an A320 with 1500 FlC (see Table 2) and aligning the removal of the component with the inspection task interval above. Therefore, we define a maintenance interval of 15,000 FlC, corresponding to ten years of average operation, for the removal of these cryogenic valves and a subsequent thorough inspection in a maintenance shop.

Due to the lack of information on possible MMH for the execution of these tasks, we adopt the information provided by the MPD for gaseous applications (see Sect. 4.2.5).

Cryogenic pipes. Pipes are subject to constant vibration and acceleration as well as deceleration forces during aircraft (ground) movement. Thus, after time, they may experience signs of fatigue to the piping structure itself or its insulation. Therefore, these systems must be subjected to regular visual inspections for any signs of physical damage, leaks, or other signs of excessive degradation, especially when operating with hydrogen [64,117,118]. However, most recommendations leave the determination of appropriate intervals to the operator's experience, with the only exception from SAE [64] who emphasize in their Aerospace Recommended Practice that cryogenic duct coupling systems must withstand 100,000 cyclic bending loads without failure during production tests. As these loads typically occur during taxiing, any inspection task should be primarily driven by experienced loads during ground operation and be equivalent to the aircraft's FlCs. Since there is a lack of experience on the conversion of these cyclic bending loads to a suitable FlC equivalent, we assume that for every minute of taxiing, one corresponding cyclic bending load will be applied to the piping structure. Based on pre-pandemic taxi data from Eurocontrol [119] and an average taxi duration for each flight segment of 18 min, we define a visual inspection task interval of about 5500 FlCs. Although this conversion is already a conservative estimate, there will also be a redundant mode of condition monitoring, as the vacuum insulation of the cryogenic pipes is continuously sensor-monitored and able to timely detect any leakage. Thus, there is no need for regular inspection tasks to ensure the functional integrity of the pipe's insulation which reduces system interference that can adversely affect the subsequent insulation performance [120]. It is imperative for this periodic maintenance task that the system will be thoroughly purged to avoid any contamination of the system with other fluids which otherwise could result in an inadvertent ignition or further damages [64].

We estimate the completion of the inspection task to require 1.0 MMH which aligns with the inspection task for the

[8] Any internal tank inspection will also require the complete evacuation of hydrogen residue to avoid the risk of explosive gas mixtures and the subsequent thawing of the tank to ambient temperatures. However, to ensure comparability to the conventional fuel storage system, we will neglect this tank preparation.

distribution pipes of the engine fire extinguishing system. Despite being different applications, both systems require meticulous inspection as they need to comply with comparable safety standards. Although the exact length of the pipelines in our system layout has not yet been determined, we assume that the workload is equivalent even with the different areas to be inspected.

Similar to the cryogenic tank, any non-routine structural repair on a pipe joint needs to be followed by a hydrostatic leakage test [121].

Cryogenic filter. As there is no standard available for suitable filter inspection and cleaning intervals, we will define the applicable maintenance task in accordance with the legacy MPD's task of the fuel filter maintenance since the safety criticality and the likelihood of any contamination can be considered equivalent. For an A320, the conventional fuel filter needs to be removed (and discarded) every 6 years or 8500 FHs with an estimated maintenance effort of 0.15 MMH for the removal. The only difference is that the cryogenic filter will be checked for contamination and cleaned instead of being discarded.

Pressure safety devices

The safety devices against excessive pressure events consist of resealable and non-resealable units, so that the maintenance tasks will need to be defined accordingly. Similar to the cryogenic hydrogen supply parts (see Sect. 4.2.2), any impurities in the liquid need to be avoided as blocking of the valves by solidified gas contamination and material aging are the main reasons for cryogenic valve failures [115].

Resealable pressure relief devices. Based on the distinction in Cat. A and Cat. B valves (see Sect. 4.1.2), ISO 21011 [93] states that these vales need to withstand 2000 and 100 opening-closing cycles, respectively, during production tests. Furthermore, safety valves shall undergo regular visual inspections to check for any signs of corrosion, damage, or leakage. Since ice accretion from leaks at the valve's outlet can potentially block the outlet and prevent it's normal function [120].

With Cat. B pressure relief devices being typical items for failure-finding tasks to ensure their protective function [66], we will calculate the necessary maintenance intervals according to Eq. (1) (see Sect. 4.1.2). For this calculation, we assume the following:

A_1 Since the situation of an excessive system pressure without any operable protective functions can have catastrophic consequences, the CS-25 regulations requires its probability to be limited to 10^{-9} per hour; therefore, M_{MF} needs to be at least 10^9 h.

$A_2 M_{TED}$ describes the expected time intervals between events with excess hydrogen vaporization, i.e., with the need for GH_2 venting through Cat. B valves. As these events do not occur during normal operations but only with damage to the tank insulation and subsequent rapid increase in temperature, protective devices are expected to be required only with a tank failure. There are different failure rates λ for cryogenic tanks in the literature, ranging from $1 \cdot 10^{-9}$ per hour [108] to an upper limit estimate of $1.6 \cdot 10^{-6}$ per hour [122]. We will use the more conservative estimate for our further calculations; thus, M_{TED} - as the inverse of λ - will equal $1/1.6 \cdot 10^{-6} \approx 6.3 \cdot 10^5$ h.

A_3 Since the pressure relief unit is composed of a resealable pressure relief valve and a (redundant) burst disk (see Sect. 4.1), the MTBF of the protective function M_{TIVE} needs to be calculated from their corresponding failure rates. With failure rates for the SIL-4-compliant burst disk of at most $1 \cdot 10^{-8}$ per hour [123] and for the resealable pressure valve of $6.1 \cdot 10^{-8}$ per hour [124], we use the higher failure rate for a conservative estimation of the corresponding MTBF for the pressure relief unit. Therefore, M_{TIVE} can be estimated with $1/6.1 \cdot 10^{-8} \approx 1.6 \cdot 10^7$ h.

Using these values, we can determine a suitable FFI of Cat. B valves as

$$\mathrm{FFI} = \frac{2 \text{ x } 1.6 \cdot 10^7 \text{ x } 6.3 \cdot 10^5}{10^9}$$
$$\mathrm{FFI} = 20,160 \text{ hours} \sim 27 \text{ months.} \tag{2}$$

For Cat. A valves, we will use the information given by ISO 21029-2 [84] which recommends a time-based check of operability at intervals of 60 months. The required MMH for this task can be estimated based on a functional check of a comparable safety valve of the air conditioning system; thus, we assume a necessary maintenance effort of 0.83 MMH per valve [75].

In addition to these functional check intervals, ISO 21029-2 [84] recommends a time-based replacement or restoration interval of 120 months for pressure relief devices. We estimate the corresponding maintenance effort to equal 0.65 MMH which is in line with the legacy removal task of the air conditioning safety valve [75].

Non-resealable pressure relief devices. For non-resealable pressure relief devices, i.e., burst discs, visual inspections are not effective to determine their current state of degradation as (a) they do not reveal any insights of the disc's remaining lifetime and (b) would require interference with their holding devices which is strongly discouraged [125]. Thus, there is a consensus that burst discs shall be regularly replaced; however the corresponding interval recommendations vary widely from 3 years [125] for severe operating conditions (e.g., cyclic pressure conditions) to 5 years [126] up to 10 years [84]. Therefore, we will define a task interval of 60 months for the removal of the burst disc which corresponds to the task interval for the vacuum vessel of the International Thermonuclear Experimental Reactor (ITER) [126]. Since burst discs should not be separated from their holding devices, the whole safety valve unit will need to be replaced. Thus, the removal interval of Cat. B pressure relief units will need to be triggered by the burst disc limitation of 60 months, instead of 120 months as stated in the previous section (see Task No. 12 in Table 9). The associated maintenance effort will remain unchanged with 0.65 MMH.

Vaporizer

The vaporizer unit will allow a continuous monitoring of its electrical resistance to quickly identify imminent failures. However, periodic maintenance of the vaporizer unit shall be performed to assure the structural integrity of the exhaust, especially due to effect of hydrogen embrittlement, and to identify any potential blocking from ice accumulation [127]. Therefore, for the conventional heat exchange section, we define a removal interval of 108 months or 12,000 FHs, respectively, which corresponds to the maintenance requirements of an A320 legacy air conditioning heat exchanger

[75]. Although hydrogen may pose a more severe condition to the material in terms of hydrogen embrittlement (see Sect. 4.2.1), this interval is comparable to the interval suggested by the ISO norms 21029-1 [83] and 21029-2 [84] for the cryogenic tank. The removal of the legacy air conditioning heat exchange section takes an average 1.3 MMH [75] and will serve as our task duration estimate.

Gaseous hydrogen supply

In the following, we examine the necessary maintenance activities for all parts that are related to the onboard storage and distribution of pressurized GH_2.

GH_2 storage tank. The transport of highly pressurized receptacles onboard an aircraft presents a potentially hazardous situation and requires meticulous safety procedures. The consequences of a failure of one of these pressure vessels could be observed in the aftermath of the infamous Qantas Boeing 747 incident in 2008, when a pressurized oxygen cylinder suddenly ruptured during flight and pierced the aircraft's hull [128]. According to Title 49 CFR §180.207(c) and §180.209, composite pressure vessels need to be periodically tested, visually inspected for any signs of micro-crack formation or corrosion [112] and requalified in accordance with ISO 11623 [129] and the C-6 testing procedure series by the Compressed Gas Association (CGA). Since requalification requires the measurement of volumetric expansions of the receptacle through hydrostatic testing, the cylinder needs to be able to expand freely in all directions which can realistically only be performed with the pressure cylinder removed from the aircraft. Title 49 CFR specifically determines a maximum maintenance interval for this removal of 60 months. Additionally, ISO 11119-3 [104] specifies that cylinders with an unlimited service life must be able to withstand production tests of at least 12,000 pressure cycles [130], with one pressure cycle translating to one FlC. Furthermore, a recommendation by a United Nation's expert committee [131] as well as Title 49 CFR §178.71(l)(1) [132] requires the restoration and re-approval of composite pressure receptacles that have been manufactured in accordance with ISO 11119 specifications after 15 years of service, even if they have an unlimited service life. We estimate the maintenance effort for the removal of the GH_2 receptacle to be similar to the removal task of the crew oxygen cylinder, taking 0.2 MMH [75].

On a final note, as a result of the Qantas incident, the International Maintenance Review Board Policy Board has proposed in its Issue Paper IP 185 [133] to deem hydrostatic tests no longer an effective maintenance task as part of the MSG-3 logic. However, since the maintenance procedure for requalification is not within the scope of this work, CFR Title 49 still applies and the defined removal tasks remain unaffected.

Pressure regulator. To estimate the pressure regulator's maintenance requirements for a fault-free operation, we use the maintenance tasks for the legacy emergency oxygen pressure regulator. Although different in the operating medium, both systems have comparable levels of safety that need to be achieved. According to the MPD, conventional oxygen pressure regulators shall be removed for in-shop functional checks every 72 month or 8000 FHs, respectively [75]. Furthermore, we estimate a maintenance effort of 2.0 MMH for the removal of each unit which is in line with the task duration for the legacy oxygen pressure regulator [75].

System monitoring sensors. According to the MPD and the legacy pressure transmitter for the oxygen system, the pressure transducer unit will be removed for an in-shop functional test every 72 month [75]. Since the legacy removal task takes 0.92 MMH for each transmitter [75], we will adhere to this value for our task duration estimate. With the temperature transducer unit being similar in its function and criticality, we assume that the maintenance interval and task effort will be equivalent as well.

To define suitable maintenance tasks for the flow meter, we use the work of Liao et al. [134] who examined industry flow-meters to derive optimized age-based preventive maintenance policies. They determined replacement intervals of about 15 years for safety critical flow meters operating under adverse conditions, e.g., with acidic fluids. Since the requirements for the different applications are comparable, we adopt this maintenance task and interval for our system. Due to a lack of information in the legacy MPD, we estimate the maintenance effort based on the removal of the pressure transducer, i.e., 0.92 MMH for each unit.

Valves and filter. Similar to the cryogenic section of the system, there are check and automatic valves installed on the GH_2 section as well. According to ISO 19880 [135], which has been developed for GH_2 refueling station applications, check valves shall withstand 102,000 pressure cycles without any signs of damage or excessive leakage. However, an exact conversion of this pressure cycle limit to a FH equivalent is difficult without any operating experience. Fortunately, a legacy A320 has check valves for the passenger oxygen system that are scheduled to be removed for an in-shop functional check in intervals of 180 months and require 1.49 MMH for each valve [75]. Thus, with an annual utilization of 2750 FH (see Table 2) and the given interval of 180 month, we can define a maintenance interval for a removal task of roughly 40,000 FHs. A comparison with ISO 19880 [135] reveals a resulting safety factor for the system of three. In addition to these removal tasks, the MPD also defines a regular operational check for these valves of the legacy oxygen system. The corresponding task is scheduled every 72 months and requires an equivalent 0.2 MMH to complete [75].

Finally, the maintenance needs for the GH_2 filter elements would naturally point towards the A320's air supply systems. However, the corresponding intervals for the various filter elements vary widely due to the vastly different operating conditions and the ambient air's adversity. Thus, we adopt the maintenance interval from the cryogenic filter element. Albeit being different in their respective operating temperature range, both systems experience the same likelihood of contamination and require comparable levels of safety. Additionally, this alignment offers the advantage of performing maintenance tasks on the whole system, as the cryogenic part will already have been purged and warmed for the maintenance task.

Operational implications

With the scheduled maintenance tasks defined, we want to emphasize central aspects for future aircraft (ground) operations with this system design and its maintenance implications.

First, a certain rate of hydrogen boil-off cannot be avoided due to heat influx during longer non-operating periods, i.e., times without hydrogen consumption by the FC. While the formation of a combustible gas mixture by venting excess hydrogen through the tail fin is unlikely during flight, it may be necessary to establish a secondary venting port through the LH_2 refueling access during ground operations or extended maintenance downtimes. Thus, any excess GH_2 can be safely extracted and the risk of explosions that could potentially harm the safety of passengers or crew is limited.

Besides the continuous venting requirement, the tank structure will experience significant thermal stress during a freeze-thaw-cycle, i.e., the cooling from ambient temperature to the cryogenic temperature of hydrogen or vice versa. Subsequently, in order to maximize the tank's life expectation, these thermal cycles need to be kept at their minimum. Consequently, maintenance tasks shall be scheduled in a way to avoid frequent thermal cycling. Furthermore, especially during extended ground times, we recommend to ensure that a certain level of cryogenic hydrogen remains within the system to cool all the exposed structures and accessories. This constant cooling by LH_2 also has the advantage of significantly reducing the necessary preparatory ground times for refueling [37,45]. Thus, it should be considered to include the preparation of the cryogenic hydrogen tank in the standardized parking procedure, with regular checks for the remaining fuel levels at suitable intervals.

Lastly, as a result of the low boiling temperature of hydrogen, any contamination with other gases and their potential solidification could damage the system or prevent the correct working of safety devices. Therefore, after any maintenance work in or at the cryogenic sections of the system, they will need to be thoroughly purged to ensure the absence of any contamination.

Results

After we have defined the cryogenic onboard storage system and its associated maintenance, we will now quantitatively examine the implications towards maintenance execution and compare these with the legacy, kerosene-based auxiliary power generation system.

Total scheduled maintenance effort

First, we want to compare the total scheduled maintenance effort of the two systems. Since the aircraft's main engines will still be powered by kerosene and require a suitable fuel storage and distribution system, the maintenance effort for the cryogenic hydrogen system will be in addition to that legacy maintenance effort. As shown in Table 7 for the different aircraft utilization scenarios, the scheduled maintenance effort for the onboard fuel storage system can be expected to increase by at least 21.5% up to 31.8%. Furthermore, in terms of the percentage change of the required scheduled maintenance effort, it appears that a cryogenic hydrogen storage system should ideally be operated with low utilization rates (LUR), i.e., with few annual FlC and FH rates. With a low annual utilization, maintenance tasks will - if applicable - (a) primarily be issued based on their calendar limit and (b) be postponed if they are triggered by FH and/or FlC limits. However, in terms of absolute values, the lowest scheduled maintenance effort per operating hour is still associated with a high utilization rate (HUR). Lastly, comparing different flight segment lengths for the average utilization (AVG vs. SFS), it appears that cryogenic hydrogen applications are beneficial in terms of maintenance when operating within a network of flight segments with a longer duration. By reducing the average flight segment from 1.8 FHs to 1.0 FHs, the additional scheduled maintenance effort required for the hydrogen system increases by more than 6% points.

With these insights on the expected changes in scheduled maintenance, we want to emphasize that this analysis focuses solely on the labor aspect for the task execution itself. Thus, neither any necessary preparatory work, e.g., for the removal of items to access the unit that shall be maintained, nor necessary repair material or spare parts have not been accounted for. Consequently, for a complete investigation of these maintenance implications, these factors will need to be examined as well.

Maintenance task distribution

After we have compared the expected changes of the total maintenance effort, we will now examine the distribution of the individual maintenance task codes, i.e., the type of maintenance work that shall be performed. The maintenance task distribution of the legacy system has been shown in Fig. 2, the corresponding maintenance task distribution for the hydrogen system can be seen in Fig. 5. Additionally, Fig. 5 also shows the change in percentage points for each task category from the conventional kerosene-based to the hydrogen-based system. Comparing these two distributions reveals a shift towards tasks with a higher complexity for their respective execution for the hydrogen system. For the kerosene-based legacy system, GVIs, OPCs, and VCKs dominate, i.e., tasks that typically require neither special support equipment nor any quantitative determination of the system condition.

Table 7 – Comparison of total scheduled maintenance effort.

Description	AVG	LUR	HUR	SFS
Kerosene system[a]	8.26	13.33	6.03	8.28
Hydrogen system[a]	2.12	2.87	1.83	2.63
Total[a]	10.38	16.2	7.86	10.91
Change	+25.6%	+21.5%	+30.3%	+31.8%

AVG: Average utilization.
LUR: Low utilization rate.
HUR: High utilization rate.
SFS: Average utilization with short flight segments.
[a] All values given in MMH per 1000 FH.

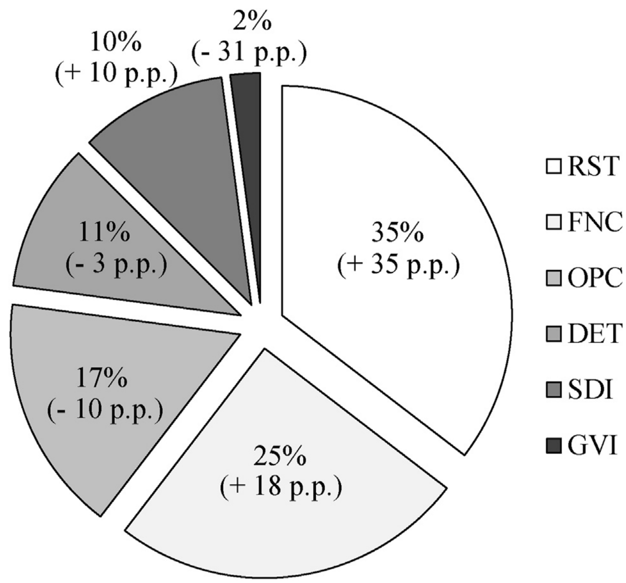


Fig. 5 – Distribution of scheduled maintenance task categories for the hydrogen storage and distribution system. Changes in percentage points from the conventional kerosene-based systems are shown in brackets.

However, 60% of scheduled maintenance tasks for the hydrogen system require either a Restoration (RST) of the unit's condition, e.g., by replacing worn out items, or a FNC, i.e., a quantitative determination of the system condition, typically needing suitable support equipment. Thus, in general, the task distribution indicates that the scheduled maintenance costs for the hydrogen system can be expected to further increase due to this additional material and equipment need. However, since many tasks of the legacy fuel system occur within the kerosene tank and require mechanics to enter the tank, the tasks for the hydrogen system can be expected to be performed in a less potentially toxic environment. It should also be noted that additional personal protection may be required due to the extreme low temperatures of LH_2 to avoid injuries from cryogenic burns.

At this point, we also want to emphasize that, similar to changes in maintenance intervals (see Sect. 2.2), the individual tasks may be subject to change with additional operating experience and are not intended to be considered static.

In-shop maintenance

After discussing the implications for the maintenance task distribution, we now want to examine how the percentage of in-shop maintenance tasks changes. In-shop maintenance describes all sets of tasks that do not take place on the aircraft itself but within a designated shop facility to quickly return the aircraft into service. Typically, this includes the replacement of an aircraft component for subsequent thorough investigation of its condition and the completion of necessary repairs. As shown in Table 8, the kerosene storage and distribution system does not require any removal of components with subsequent in-shop maintenance. However, for the hydrogen system, almost half of the tasks require this kind of maintenance execution.

Therefore, since the actual scheduled maintenance task only incorporates the removal of the component from the aircraft, any subsequent logistic effort, e.g., due to the shipment and the management of a spare unit inventory, and maintenance effort within the shop facility can have a significant influence on the overall economic performance. According to Scholz [136], these shop maintenance expenditures represent about 70% of the total spending; thus, the results of this paper only represent 30% of the expected total maintenance effort. For a complete picture, it can be expected that about 0.7/0.3 ≈ 2.3 times of the on-wing scheduled maintenance efforts for the hydrogen system in Table 7 will need to be added to account for this in-shop maintenance efforts.

Summary

After we have discussed the various aspects of changes towards scheduled maintenance for hydrogen systems and compared them with the legacy, kerosene-based aircraft, we now want to summarize the central observation (O) of our study. Under the assumptions made for the hydrogen system design, these would be.

- O1 By installing an onboard LH_2 storage and distribution system in addition to the conventional kerosene tank, the necessary scheduled maintenance effort can be expected to increase from 22% to 32%, depending on the scenario of aircraft utilization.
- O2 The complexity of the tasks can be expected to increase for a hydrogen-based system, as they require more thorough inspections of the individual units with measuring instruments for a quantitative determination of the condition. However, maintenance work can be performed in a less hostile environment, but personal protective equipment is still required to avoid potential cryogenic burns.
- O3 A significant share of maintenance tasks require the removal of units from the aircraft with subsequent inspection and repairs in a designated maintenance shop. Thus, the overall costs are likely to increase due to this additional maintenance effort for the component off the aircraft, as well as for logistics services, such as the shipment of components and the management of spare unit inventories.
- O4 As a result of the thermal stresses that occur in the cryogenic section of the system during the freezing and thawing cycles of the system, the system will need to be kept in its cold condition as much as possible. For extended ground times, e.g., due to extensive maintenance work, this can require active cooling by

Table 8 – Comparison of the percentage of in-shop maintenance tasks.

System	In-shop maintenance share
Kerosene system	0%
Hydrogen system	48.1%

Table 9 – Scheduled maintenance tasks for an onboard, cryogenic hydrogen storage system.

Task no.	Task description	Task code	Interval	No. of units installed	MMH (each unit)	MMH (total)	Interval References
01	Borescope inspection of inner hydrogen tank	SDI	120 MO or 10,000 FlC	1	1.0	1.0	ISO 21029-1 [83, p. 32] ISO 21029-2 [84, p. 18]
02	General visual inspection of hydrogen tank's structural integrity	GVI	10,000 FlC	1	0.58	0.58	ISO 21029-1 [83, p. 32]
03	Detailed inspection of refuel/defuel connectors	DET	72 MO or 5000 FlC	3	0.1	0.3	Legacy MPD [75]
04	Special detailed inspection of the tank fixtures	SDI	10,000 FlC or 20,000 FH	4	0.4	1.6	Legacy MPD [75]
05	Detailed inspection of cryogenic piping system	DET	5500 FlC	1	1.0	1.0	SAE [64]
06	Detailed inspection of GH_2 piping system	DET	5500 FlC	1	1.0	1.0	SAE [64]
07	Operational check of cryogenic check valve	OPC	60 MO	2	0.2	0.4	ISO 21029-2 [84, p. 18] Lu et al. [139]
08	Removal of cryogenic check valve for in-shop restoration	RST	15,000 FlC	2	1.49	2.98	ISO 13985 [116]
09	Operational check of cryogenic automatic valves	OPC	60 MO	2	0.2	0.4	ISO 21029-2 [84, p. 18] Lu et al. [139]
10	Removal of cryogenic automatic valve for in-shop restoration	RST	15,000 FlC	2	1.49	2.98	ISO 13985 [116]
11	Functional check of the safety valve unit (Cat. B)	FNC	27 MO	2	0.83	1.66	Own calculation acc. Eq. 2
12	Removal of safety valve unit for in-shop restoration (Cat. B)	RST	60 MO	2	0.65	1.3	ISO 21029-2 [84, p. 18] Miller [125] Keogh et al. [126]
13	Functional check of the safety valve unit (Cat. A)	FNC	60 MO	3	0.83	2.49	ISO 21029-2 [84, p. 17]
14	Removal of safety valve unit for in-shop restoration (Cat. A)	RST	120 MO	3	0.65	1.95	ISO 21029-2 [84, p. 18]
15	Removal of pressure regulator for in-shop restoration	RST	180 MO or 8000 FH	1	2.0	2.0	Legacy MPD [75]
16	Operational check of GH_2 automatic valve	OPC	72 MO	2	0.2	0.4	Legacy MPD [75]
17	Removal of GH_2 automatic valve for in-shop restoration	RST	180 MO or 40,000 FH	2	1.49	2.98	Legacy MPD [75] ISO 19880-3 [135]
18	Operational check of GH_2 check valve	OPC	72 MO	2	0.2	0.4	Legacy MPD [75]
19	Removal of GH_2 check valve for in-shop restoration	RST	180 MO or 40,000 FH	2	1.49	2.98	Legacy MPD [75] ISO 19880-3 [135]
20	Removal of vaporizer for in-shop inspection	FNC	108 MO or 12,000 FH	1	1.3	1.3	Legacy MPD [75]
21	Inspection and cleaning of cryogenic filter	RST	72 MO or 8500 FH	1	0.15	0.15	Legacy MPD [75]
22	Inspection and cleaning of GH_2 filter	RST	72 MO or 8500 FH	2	0.15	0.3	Legacy MPD [75]
23	Removal of mass flow meter unit for in-shop functional check	FNC	180 MO	1	0.92	0.92	Liao et al. [134]
24	Removal of pressure transducer unit for in-shop functional check	FNC	72 MO	1	0.92	0.92	Legacy MPD [75]
25	Removal of temperature transducer unit for in-shop functional check	FNC	72 MO	2	0.92	1.84	Legacy MPD [75]
26	Removal of GH_2 tank for in-shop inspection	FNC	60 MO or 12,000 FlC	1	0.2	0.2	ISO 11119-3 [104] DIN EN 12245 [130] Title 49 CFR §180.207
27	Removal of GH_2 tank for in-shop restoration	RST	180 MO	1	0.2	0.2	United Nations [131] Title 49 CFR §178.71(l)(1)

circulation of the cooled LH_2 through the storage and distribution system.

O5 A certain rate of hydrogen boil-off and venting is inevitable due to the heat influx into the tank. While unproblematic during flight, this evaporated hydrogen may accumulate in maintenance facilities, e.g., during hangar maintenance activities. Thus, the maintenance infrastructure must be equipped to detect potentially combustible or explosive gas mixtures and allow adequate air circulation.

In addition to these observations, there are also some limitations (L) to this study.

- L1 As of this work, we have focused solely on the aspect of scheduled maintenance. However, as Heisey [137] and Suwondo [138] each point out, scheduled maintenance represents with about 20% only a fraction of the total maintenance expenditures. Costs of tasks that are out of scope of regular checks and require rectification after a diagnosed defect can triple the costs of scheduled maintenance.
- L2 We only compared the actual task times, i.e., the time it takes for the execution of the maintenance task without consideration of any preparatory work that is necessary. However, additional times for the removal of components can be significant, depending on the eventual system's maintainability. Furthermore, we have neglected all aspects that are not related to the required labor for the task execution. Therefore, to have a more complete estimation of maintenance changes, additional aspects must be examined, such as material costs.
- L3 Maintenance tasks and intervals are subject to constant reevaluation and modification. As this study has primarily been performed with information from other industries and available standards, it is likely that the scheduled maintenance plan (see Table 9) will be adjusted with increasing operating experience.
- L4 There has been no optimization towards maintenance packaging, i.e., aligning task intervals for certain systems to trigger them simultaneously or at major maintenance downtimes.

Conclusion and outlook

In this work, we examined how scheduled maintenance can be expected to change when installing an onboard cryogenic hydrogen storage and distribution system for auxiliary power generation. By screening through available literature and other research work, we have demonstrated the need for an in-depth analysis of possible maintenance changes with the introduction of hydrogen-based auxiliary power generation. The generated results will significantly enhance existing techno-economic assessments as they allow the thorough investigation of maintenance impacts on the subsequent airline operations. Thus, these insights are essential for an evaluation of the associated development and certification risk and for OEMs to invest into such a disruptive technology. Furthermore, we developed a conceptual system design that not only enables an estimation of corresponding maintenance efforts but also addresses aspects of regulatory compliance by strictly adhering to established standards and international law.

As the core of this study was a comparative analysis of scheduled maintenance between a kerosene-based system and its hydrogen counterpart, we have examined the key characteristics of the legacy system design and key aspects of its conventional maintenance. Additionally, the concept of MSG-3 has been presented with its strengths and limitations. In particular, we have discussed various approaches to determine suitable maintenance intervals, their individual prerequisites, and why we have chosen to rely primarily on published information of international standards.

The hydrogen system design has schematically been developed in order to demonstrate key design assumptions and their subsequent implications on the maintenance task definition. With this design, we have defined necessary scheduled maintenance tasks to keep the hydrogen storage and distribution system in a safe and airworthy condition. Based on the developed maintenance schedule, we performed a comparative analysis to estimate the expected changes compared to conventional, kerosene-based auxiliary power generation. It was shown that the resulting total scheduled maintenance effort depends on the aircraft's utilization scenario and is likely to increase by 22%–32%. Furthermore, we could identify how the task complexity changes to estimate what their implications towards the maintenance execution are.

Since we have only focused on the hydrogen storage and distribution system, future studies should also focus on the expected maintenance for the FC as possible APU substitute. For a more complete view of the expected maintenance changes, aspects that are not directly related to the required labor, such as the material cost or spare part need, have to be addressed as well. In addition, since a significant portion of maintenance activities can be expected to occur off the aircraft at designated maintenance shop facilities, their associated efforts must also be examined and estimated for a holistic view of the expected maintenance-related changes. Finally, with cryogenic systems potentially requiring extended preparatory times before any task execution, it will be necessary to include these additional maintenance times in future analysis in order to calculate the expected maintenance-related system downtime.

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Acronyms

APU	Auxiliary Power Unit
ATA	Air Transport Association
CFR	U.S. Code of Federal Regulations
CGA	Compressed Gas Association
CUI	Corrosion Under Insulation
DET	Detailed Inspection
DOC	Direct Operating Cost
ECAM	Electronic Centralized Aircraft Monitor

FC	Fuel Cell
FFI	Failure Finding Interval
FFT	Failure Finding Task
FH	Flight Hour
FlC	Flight Cycle
FMEA	Failure Mode and Effects Analysis
FNC	Functional Check
GH_2	Gaseous Hydrogen
GHG	Greenhouse Gas
GVI	General Visual Inspection
IATA	International Air Transport Association
IDG	Integrated Drive Generator
ISO	International Organization for Standardization
ITER	International Thermonuclear Experimental Reactor
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
MLI	Multi-Layer Insulation
MMH	Maintenance Man Hours
MPD	Maintenance Planning Document
MSG-3	Maintenance Steering Group - 3rd Generation
MTBF	Mean Time Between Failures
OEM	Original Equipment Manufacturer
OPC	Operational Check
RCM	Reliability Centered Maintenance
RST	Restoration
SAF	Sustainable Aviation Fuel
SDI	Special Detailed Inspection
SIL	Safety Integrity Level
SVC	Servicing
VCK	Visual Check

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