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Hydrogen-based aircraft auxiliary power generation: Economic and ecological comparative assessment of preventive maintenance implications ⋆

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Abstract: With European governments and societies enforcing pathways towards carbon neutrality by the year 2050, the aviation industry is under pressure in its pursuit of reduced climate impacts. Thus, new revolutionary energy carrier concepts such as hydrogen-hybrid aircraft are required to decouple emissions from growing air traffic volume. However, besides technological challenges for the airborne storage of hydrogen, there are significant uncertainties associated with the overall economics and environmental sustainability of these concepts. Based on established industry standards, we will examine how the maintenance efforts, traditionally constituting up to a quarter of direct operating expenses, can be expected to change with the introduction of hydrogen. Additionally, we examine ecological implications for maintaining these new technologies so that our study helps to identify anticipated changes for the necessary maintenance and contributes to a thorough assessment of ecological implications with these energy carrier concepts.

Keywords: Hydrogen Aircraft, Aircraft Maintenance, Sustainability, Economic Analysis, Ecological Assessment, Life Cycle Assessment

1. INTRODUCTION

Having faced an existential crisis during the Covid-19 pandemic (Dube et al., 2021), the airline industry is now confronted with yet another substantial challenge – the necessity to reduce its climate impact for more sustainable operations (Amankwah-Amoah, 2020). With the traditional way of incremental efficiency gains (Edwards et al., 2016) being outweighed by annual growth rate of air traffic volume (Zhou et al., 2016) and legislation (Advisory Council for Aviation research and Innovation in Europe, 2022) demanding pathways towards climate neutrality, new revolutionary air transport concepts are required for sustainability gains and environmental footprint reductions (Goldberg et al., 2018). One of these concepts is the use of hydrogen – either liquefied or gaseous – to power aircraft. However, despite ambitions for a quick mass commercialization (Schmidtchen et al., 1997) and the existence of these concepts for several decades (Brewer, 2017), there has not been any broad adoption, yet. One factor for this slow technological adoption is the uncertainty regarding the subsequent maintenance implications[1] . These maintenance implications can be subdivided into two categories: potentially increased preventive maintenance (e.g., checks and inspections) and increased unscheduled restorative maintenance (e.g., due to higher degradation). Thus, for a quick and financially sustainable commercialization, it is essential to estimate the associated maintenance efforts and cost implications. Furthermore, with a reduction of Greenhouse Gas (GHG) emissions during flight, maintenance activities are becoming increasingly important in terms of (a) their direct environmental impact and (b) their role in enabling environmentally-friendly airline operations.

Based on these observations, our work will focus on the following aspects:

- Estimating economic and ecological preventive maintenance implications for the introduction of hydrogen-hybrid aircraft, i.e., hydrogen-based auxiliary power generation with kerosene-powered propulsion,
- Identifying contributing factors to the emissions of CO_2-equivalents of aircraft maintenance, and
- Analyzing the overall changes in maintenance execution in terms of complexity and associated logistics effort.

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[1] During an aircraft's life cycle of approximately 21.2 years (Cirium, 2022), the total maintenance-related expenditures will have equaled about 1.2 times the discounted new aircraft cost (Aircraft Commerce, 2006a,b).

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2. FUNDAMENTALS

2.1 Aircraft maintenance

The fundamental concept of scheduled aircraft maintenance is based on the idea of Reliability Centered Maintenance (RCM) (Nowlan and Heap, 1978), 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 (Dhillon, 2002). That concept has since been adapted for the needs of aircraft maintenance through the Maintenance Steering Group – 3rd Generation (MSG-3) logic (Air Transport Association of America, 2018). In its essence, the methodology consists of two parts – (a) a risk-based analysis of functional failures, their causes, and potential consequences and (b) a model of the system's reliability for the definition of appropriate maintenance intervals. With an increased technical complexity for a hydrogen-based system design philosophy, e.g., due to higher combustibility of hydrogen and its cryogenic storage temperature, there are efforts within the aviation industry to replace the MSG-3 approach of scheduled maintenance definition by automated aircraft health management technologies (Weiss, 2018; Meissner et al., 2021). However, since these efforts have unresolved challenges in terms of commercialized certification, we focus within this work on the traditional preventive maintenance definition. Therefore, in accordance with RCM, the defined preventive maintenance schedule will be examined in terms of the equipment's life cycle to determine a cost-effective program (Blanchard and Blyler, 2016) and can consist of the following tasks (Nowlan and Heap, 1978; Moubray, 1997; Rausand, 1998):

- Scheduled on-condition, i.e., tasks that determine the condition of a system through condition-monitoring techniques,
- Scheduled overhaul, i.e., tasks that will be issued in fixed time intervals with the system to be restored to its (nearly) new condition,
- Scheduled functional test, e.g., failure-finding tasks that shall detect functional defects for hidden systems where the (in)correct function is unknown to the operating crew, and
- Run-to-Failure, i.e., the deliberate decision to run the system up to the point of failure.

Depending on the applicable degradation mechanism, the defined preventive maintenance tasks can subsequently be triggered by a flight cycle, operating hour, or calendar day counter – or by a combination of those. Ultimately, it has to be noted that the main objective of RCM is not to avoid failures per se, but to limit their consequences to an acceptable level (Ahmadi et al., 2010).

2.2 Life cycle analysis

In general, Life Cycle Assessment (LCA) is a suitable tool for the thorough analysis of an aircraft's environmental performance over its entire life cycle, i.e., from the initial conceptualization through production and operations up until the end of life. The LCA is structured in four distinct steps as follows: First, as part of the *goal and scope* phase, system boundaries for the analysis will be defined. These are required to subsequently *collect* all necessary *analysis inputs*, e.g., material resources and energy flows, as well as *outputs*, e.g., expected waste and emissions, in step two. In a third step, these in- and outputs will be assessed within different *environmental impact categories* as part of the Life Cycle Impact Assessment (LCIA). Finally, step four will focus on the *interpretation and discussion of the obtained results* on the basis of the initially defined goal and scope. (European Committee for Standardization, 2006, 2018)

Despite this well established analysis procedure, there is hardly any aviation-maintenance-related LCA thus far, since most emissions are generated during flight and maintenance has traditionally been thought to contribute only a minor environmental impact (Rahn et al., 2022). However, with decreasing in-flight emissions through new energy carrier concepts, the comparably minor emissions from Maintenance, Repair, and Overhaul (MRO) processes are becoming increasingly important, primarily due to the impact of replacement parts and the energy use during maintenance task execution. Thus, with potentially increasing maintenance efforts, e.g., due to shorter life expectancies of new technologies or more complex processes for part replacements, it is vital to consider the ecological impact of the associated maintenance efforts (Barke et al., 2020).

For this study, we adhered with our ecological assessment to the well-established LCA methods of DIN EN ISO 14040 (European Committee for Standardization, 2006) and DIN EN ISO 14044 (European Committee for Standardization, 2018).

3. ESTIMATING THE MAINTENANCE IMPLICATIONS

3.1 Identification of necessary scheduled maintenance

As described in Sec. 2.1, we use the MSG-3 methodology to derive adequate maintenance tasks. The derivation of the required scheduled maintenance is a meticulous process that requires a thorough understanding of the system design concept. Since the description of the system with its suitable maintenance tasks would exceed the limit of this paper, we kindly refer to our previous publications in (Meissner et al., 2023a,b) as well as to (Barke et al., 2023).

With these preventive maintenance tasks defined, we now need to determine the corresponding task intervals. In line with RCM's philosophy of a timely fault detection to initiate preventive maintenance measures before the actual failure occurrence, maintenance tasks that aim to determine a system's condition can be executed continuously or periodically in discrete time intervals (Hauge, 2002). While a continuous monitoring typically provides more insights into the current state of degradation, it requires an expensive sensor network to monitor the system's condition and, depending on the sensitivity of the monitoring system, can be prone to faulty, inaccurate alarms. Consequently, (manual) periodic inspection is often used as an alternative with higher cost efficiency. However, an insufficiently chosen interval may result in an increased risk of missing failure events between successive inspections (Moubray, 1997). Thus, determining an adequate inspection interval represents a significant challenge in establishing an effective maintenance task (Hauge, 2002; Jardine et al., 2006). Despite MSG-3 providing guidance to identify suitable maintenance measures for the intended operating environment, it leaves the interval determination to the engineer's expertise (Hauge, 2002). Consequently, these intervals are primarily estimated through one of the following approaches:

- Available historical data, e.g., past Maintenance Review Board Reports (MRBRs) or failure rate estimates from the component manufacturer (Moubray, 1997; Chalifoux and Baird, 1999),
- Comparison with standards or established procedures from other industries, e.g., Liquefied Natural Gas (LNG) facilities (Baker, 1982; Pelto et al., 1982), or
- Experiments-based degradation analysis and derivation of so called P-F-Intervals, i.e., time intervals between an initial detection of an existing fault until the actual failure occurrence (Moubray, 1997).

However, due to the novelty of anything related to hydrogen-hybrid-powered aircraft, there is hardly any operating experience and historical data to build upon. Furthermore, any accelerated life test will require extensive laboratory set-ups and will exceed the scope of this work. Therefore, for the definition of maintenance intervals we exclusively rely on established practices from other industries.

3.2 Estimation of ecological implications

For this study, we have based the LCA on one of our prior in-depth analyses of individual maintenance activities (Rahn et al., 2024), where we have assessed the ecological impacts based on the necessary maintenance tasks and expected efforts. These maintenance tasks are extracted from the Maintenance Planning Document (MPD) (for the reference aircraft system) and the results from Sec. 3.1 (for the developed hydrogen-hybrid system), respectively. Thus, there is a set of individual maintenance tasks for different systems that will be executed throughout the aircraft life cycle based on the defined task intervals. As of this study, we assume all maintenance activities being based in Germany - a key contributor in the European Union's push towards sustainability. Furthermore, our ecological assessment will not consider maintenance activities related to task completions in designated off-aircraft workshops as well as the recycling of decommissioned components. Additionally, the manufacturing and transport of specialized maintenance equipment are also excluded from the evaluation process.

Table 1. Ecological implications of preventive maintenance tasks

Task code	Description	Ecologic implications*
SVC	Servicing	exchange of fluids, draining of components
OPC	Operational Check	–
VCK	Visual Check	–
GVI	General Visual Inspection	–
DET	Detailed Inspection	–
SDI	Special Detailed Inspection	use of specialized equipment, transportation to workshop
FNC	Functional Check	transportation to workshop
RST	Restoration	cleaning of components, transportation to workshop
DIS	Discard	replacement of components

* Since all scheduled maintenance tasks require facility and general equipment usage, the ecological implications list only activities beyond those.

To simplify the calculation of ecological implications, all tasks were clustered based on their defined task code, providing information about the type of the maintenance activity or the used equipment and auxiliary goods. An overview of the different task codes in this study and their resulting ecological implications is shown in Tab. 1. Detailed ecological implications and a description of activities associated with each task code can be found in the study by Rahn et al. (2024).

For the LCA calculation, the open-source, Python-based brightway2 framework (Mutel, 2017) and the ecoinvent 3.9.1. database are used. Furthermore, the Environmental Footprint (EF) 3.0 method is employed for the LCIA, focusing on the impact category of climate change. The EF 3.0 method considers the global temperature change induced by greenhouse gases, capturing various gases with their Global Warming Potential (GWP). The GWP defines the time-integrated warming effect of releasing one kilogram of a specific greenhouse gas into the atmosphere compared to that of carbon dioxide. This study adopts a time horizon of 100 years.

4. COMPARATIVE ANALYSIS

After the underlying method has been described, we now want to discuss the detailed maintenance implications for the introduction of fuel-cell-based, hydrogen-hybrid aircraft.

Table 2. Examined operating scenarios

Dimension	AVG	LUR	HUR	SFS	LFS
FH per YEAR	2,750	1,650	3,900	2,750	2,750
FC per YEAR	1,500	900	2,100	2,750	917
FH per FC	1.8	1.8	1.9	1	3

AVG ... Average annual utilization, LUR ... Low utilization rate, HUR ... High utilization rate, SFS ... Short flight segments, LFS ... Long flight segments, FH ... Flight hours, FC ... Flight cycles

4.1 Economic and ecological implications

First, we want to examine how the overall maintenance effort, expressed as required Maintenance Man Hours (MMH) per 1,000 Flight Hours (FHs) indicating the economic implications, and ecological footprint, expressed in terms of CO_2-equivalents per 1,000 FHs, can be expected to change when replacing a purely kerosene-powered system with a hydrogen-hybrid. To account for different operating strategies, we have analyzed different scenarios (see Tab. 2) and their subsequent effects on the scheduled maintenance effort and the CO_2-equivalent emissions.

Table 3. Comparison of total maintenance efforts

Evaluation dimension	**Unit**	**System**	**Operating scenario**				
			AVG	LUR	HUR	SFS	LFS
Economic	$\frac{\text{MMH}}{1{,}000\,\text{FH}}$	conventional	9.1	14.4	6.8	9.1	9.3
		hydrogen-hybrid	12.1	18.3	9.4	13.6	11.5
		relative change	+ 32%	+ 27%	+ 38%	+ 49%	+ 24%
Ecological	$\frac{\text{kg CO}_2\text{eq}}{1{,}000\,\text{FH}}$	conventional	338.9	533.9	252.8	338.9	342.9
		hydrogen-hybrid	448.0	678.9	347.7	503.6	424.9
		relative change	+ 32%	+ 27%	+ 38%	+ 49%	+ 24%

AVG ... Average annual utilization, LUR ... Low utilization rate, HUR ... High utilization rate, SFS ... Short flight segments, LFS ... Long flight segments, MMH ... Maintenance Man Hours

The resulting changes can be seen in Tab. 3. Comparing these values, it becomes apparent that the overall maintenance efforts and emissions can be expected to increase when introducing a hydrogen-hybrid system. Furthermore, we can identify that – from a pure MRO perspective – it seems advantageous to operate hydrogen-hybrid aircraft with low annual utilization rates and on comparably long flight segments – as these two operating strategies will yield the lowest percentage increase in maintenance costs and CO_2-equivalents. However, comparing the absolute numbers in relation to the current world average utilization (see Fig. 1), hydrogen-hybrid aircraft should still be operated on a long-distance flight network but with a high annual utilization rate.

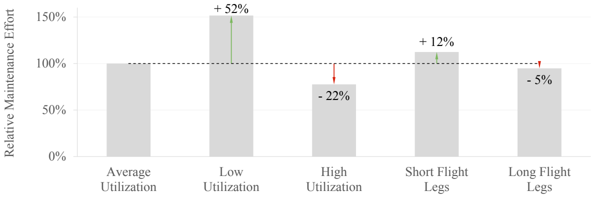
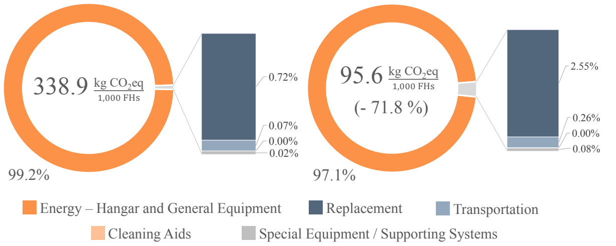


Fig. 1. Comparison of maintenance effort changes under different operating scenarios

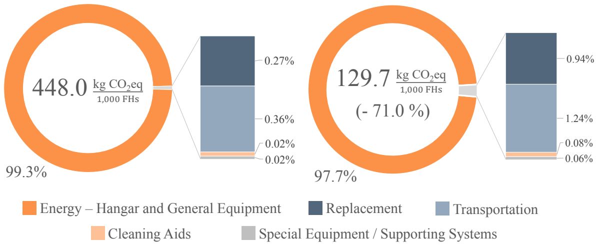
4.2 *Ecological implications and contributing factors*

With the results in Tab. 3 showing a strong relationship between the economic and ecological implications, we examine the main contributors to the maintenance-related emissions. Fig. 2 depicts the emissions of CO_2-equivalents per 1,000 FHs for the conventional (Fig. 2a) and the hydrogen-hybrid system (Fig. 2b), respectively. Furthermore, both figures depict the ecologic implications for two different energy supply scenarios: (a) the current energy mix for Germany on the left and (b) a fully renewable energy mix scenario in 2050 on the right. Analyzing these graphs, the following key messages can be extracting:

- The needed energy for the hangar facilities and general equipment is the predominant environmental contributor, regardless of the underlying energy mix [2].
- By switching to a fully renewable energy mix, the emissions of CO_2-equivalents related to scheduled maintenance can be reduced by about 70%.
- While the emissions for scheduled part replacements can be reduced for a hydrogen-powered system, the logistics-related ecological impact will increase significantly with the expected additional transportation effort.



(a) Conventional system (left: current energy mix, right: sustainable energy mix)



(b) Hydrogen-hybrid system (left: current energy mix, right: sustainable energy mix)

Fig. 2. Environmental assessment for different system layouts in comparison of underlying electricity mixes

4.3 *Percentage of off-aircraft maintenance*

In line with the observation of contributing ecological factors, we have further examined how the share of maintenance tasks performed at designated facilities is expected to change. With a higher degree of technical complexity and a larger share of movable parts, the hydrogen-hybrid system design will require significantly more tasks to be performed off-aircraft (see Fig. 4). Subsequently, this will require additional spare materials to replace those parts and keep the aircraft in an airworthy state as well as extra logistics efforts for the transport.

4.4 *Task complexity*

Lastly, we analyze how the complexity of the associated maintenance tasks is expected to change. Based on the

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[2] With this energy being linked to the length of an individual maintenance task, it comes to no surprise that the overall economic and ecological implications (see Tab. 3) are correlating strongly.

(a) Conventional system (b) Hydrogen-hybrid system

Fig. 4. Percentage of off-aircraft maintenance tasks

tasks listed in Tab. 1, we have examined their relative share for the conventional, kerosene-based system and the hydrogen-hybrid design, as illustrated in Fig. 3. In general, the implications for each task, e.g., the required down time, level of skills, or necessary repair material, increases from left to right in Fig. 3. Thus, the tasks with the least effort are servicing, visual check, and inspection tasks, whereas restoration and discard tasks require removal of the component, spare materials, and often a transport to designated, qualified repair facilities. Consequently, if technical feasible, it is desirable to limit preventive maintenance to mere visual inspections and avoid more complicated functional check or restoration tasks. However, the hydrogen system will likely be composed of more movable parts with higher technical complexity, e.g., valves, pressure regulators, and sensors, than kerosene-powered designs that (a) cannot be maintained by mere visual inspections and (b) will require designated equipment to check and restore their condition (Kranich et al., 2024); therefore, the associated maintenance tasks will become more complex with additional skills required.

5. CONCLUSION

With this study, we have examined how preventive maintenance can be expected to change when substituting kerosene-powered aircraft systems by hydrogen-hybrid aircraft designs. Thus, we contribute to a better understanding of the maintenance-driven operating cost changes and support to reduce any uncertainties regarding the economical and ecological viability for hydrogen-hybrid design concepts. During our analysis, we have identified the following key findings:

- F_1 The necessary preventive maintenance measures for hydrogen-hybrid systems are likely to increase the overall maintenance effort and will result in additional emissions of CO_2-equivalents.
- F_2 The emissions associated with electrical energy production for maintenance facilities are the biggest ecological contributors. By switching to fully renewable energy sources, the environmental footprint of aircraft maintenance can be reduced by about 70%.
- F_3 With the introduction of a hydrogen-hybrid system and its higher technical complexity, preventive maintenance can be expected to become more demanding requiring not only additional maintenance efforts but also higher skilled labor.
- F_4 Since a significant number of items cannot be effectively maintained while installed on the aircraft, additional logistics efforts will be necessary to supply required spare parts and transport the items to designated maintenance facilities for component services.

However, with the selected scope of this study, the results are subject to the following limitations:

- L_1 As we have focused in this work exclusively on scheduled on-aircraft maintenance, the associated, additional maintenance effort necessary in those designated maintenance facilities (other than transportation effort) are not represented in the results.
- L_2 The underlying new system is designed to operate as a hybrid with conventional kerosene-powered main engines and a hydrogen-based fuel cell for auxiliary power generation. A fully hydrogen-based system may result in a different system criticality, leading to additional maintenance and safety needs.
- L_3 The estimated changes for the maintenance effort and environmental footprint focuses exclusively on the system parts that are subject to change. Therefore, for an overall estimation of the expected percentage changes, the whole aircraft will need to be analyzed (Meissner et al., 2023a).

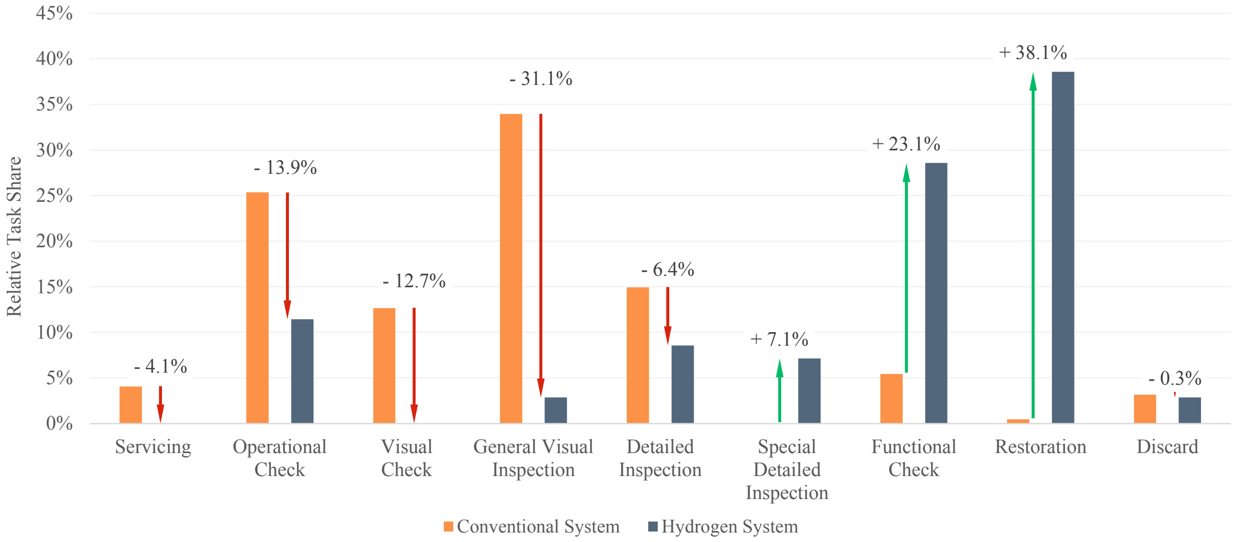

Fig. 3. Comparison of maintenance task distribution between a conventional and a hydrogen-hybrid system design

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