Life Cycle Assessment of Aircraft Maintenance: Environmental Implications of Battery Electric Propulsion Systems

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ABSTRACT

The electrification of aircraft propulsion systems is currently being intensively investigated to reduce climate-damaging emissions during flight operations. Battery Electric Propulsion Systems (EPSs) are highly complex and require regular maintenance to ensure airworthiness. In particular, the limited lifespan of batteries necessitates frequent replacements, which can lead to significant environmental impact. This paper discusses possible maintenance activities for battery EPSs and their environmental implications. The environmental assessment is based on a Life Cycle Assessment (LCA), which considers the impact of individual maintenance tasks over the entire aircraft life cycle. The LCA results show that the environmental impact of maintenance increases significantly with the use of the electrical system compared to conventional propulsion systems. Two different battery scenarios with state-of-the-art and projected energy densities towards the year 2035 show significant potential for improvement. In our analysis, the batteries, which have to be replaced a total of eight times during the evaluated life cycle, account for the largest contribution to the environmental impact. At the same time, battery EPSs offer the potential to significantly reduce the environmental impact of flight operations, as there are no direct emissions into the atmosphere. The results highlight the need to consider maintenance-related environmental impact alongside operational improvements, providing a foundation for future strategies that minimise the impact while ensuring operational safety and efficiency. Nevertheless, implementing these systems presents significant challenges from a maintenance perspective, particularly in avoiding environmental burden shifting.

1. INTRODUCTION

The potential of electric and hybrid propulsion systems to replace fossil fuels has attracted considerable interest within the aviation sector in recent years (Hoelzen et al., 2018; Afonso et al., 2023). Such technologies include an energy storage system, power electronics, electric motors, and control systems. In particular, batteries are widely regarded as a promising solution for primary energy storage (Kumar et al., 2024), offering zero local emissions during operation and representing a key technology for the decarbonisation of the transport sector (European Commission, 2020b). However, the integration and operation of novel propulsion systems pose new challenges to the aviation industry in terms of weight, safety, and range (Schäfer et al., 2019). Numerous studies concentrate on enhancing battery capacity (Hoelzen et al., 2018), optimising the efficiency of electric motors and generators (Nagy, 2019), or modifying the airport energy infrastructure (Hou et al., 2024). Concurrently, there is a pronounced emphasis on energy production and recycling strategies, as this is a crucial aspect influencing the ecological benefits of electrical systems (Marmiroli et al., 2018).

To identify the potential of new propulsion systems, it is essential to evaluate their environmental impact across the entire life cycle and avoid burden shifting, i.e., the transfer of environmental impacts between life cycle phases or to other environmental aspects (Peters et al., 2017). In particular, the Maintenance, Repair, and Overhaul (MRO) of Electric Propulsion Systems (EPSs) and the replacement of batteries has received only limited attention thus far (Eltohamy et al., 2024; European Commission, 2020a). This is particularly relevant given that batteries often need to be replaced multiple times during an aircraft's use phase due to their limited lifespan (Arvidsson et al., 2024; Cox et al., 2018). Barke et al. (2023) addressed the MRO-related environmental and

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https://doi.org/10.36001/IJPHM.2025.v16i4.4245

economic impacts of novel aircraft concepts, showing that battery-based EPSs have the most significant impact in terms of both climate change and financial costs. However, the study did not consider other subsystems and their maintenance requirements.

To address these aspects, our study evaluates the environmental impact of all scheduled maintenance processes for an EPS designed for an Airbus A320-sized aircraft. Furthermore, the replacement of key components, such as batteries, pumps, or propellers, is incorporated into our analysis on the basis of their degradation behaviour and an average usage profile of the vehicle. For the calculation of the climate change impact, an environmental Life Cycle Assessment (LCA) is conducted in accordance with the ISO 14040/44 standard. The environmental impact of EPS maintenance is compared with those of conventional kerosene-powered engines, highlighting the trade-offs between maintenance-related effects and the operational emission savings of electrified systems. The aim of this study is to provide new insights into potential MRO strategies for reducing the environmental footprint and preventing burden shifting early in the design process.

The structure of this paper is as follows: First, we present the initial design of the EPS for an Airbus A320. Based on this layout, an analysis grounded in reliability centred maintenance principles is conducted to identify maintenance tasks for the propulsion system. These tasks are subsequently assessed through an LCA. Particular emphasis is placed on the environmental impact of spare part production, resulting from the need for replacing key components which degrade over time. A hot-spot analysis identifies the maintenance activities with the highest environmental impact. Finally, the results are compared with the climate change impact of a conventional Airbus A320.

2. BATTERY-ELECTRIC PROPULSION SYSTEM

As there is no specific model of the EPS with batteries available for the Airbus A320, this chapter is dedicated to the development, description, and sizing of such a system.

2.1. Development of the Design Layout

The considered EPS layout is modelled on the basis of technical standards and regulatory requirements in order to create a safe, reliable, and efficient system for the Airbus A320-like aircraft. Several established analysis methods[1] are used to evaluate functions, risks, and failure conditions. The required functions of the system are first collected within a functional breakdown analysis and then classified according to the aircraft's flight phases and failure conditions (i.e., functional hazard analysis). The determination of redundancy and component requirements is then facilitated by a fault tree analysis. The final failure mode and effect analysis aims to investigate the cascading failure effects and to provide possible approaches on the detection and compensation of failure conditions. The design was gradually refined to ensure high reliability and efficiency, while conservative assumptions ensured safety in the early design phase.

2.2. Description of the Electric Propulsion System

The EPS consists of three main subsystems: an Energy Storage and Distribution System (ESDS), two Energy Drive Systems (EDSs), and a Thermal Management System (TMS). A graphical overview of the entire EPS can be found in Figure 1.

In the ESDS, rechargeable lithium-ion battery packs are supported by a Battery Management System (BMS) and a Battery Cooling System (BCS). The BMS acts as the central control unit of the storage system and monitors the charging and discharging process to ensure that no battery cell exceeds the limits specified by the manufacturer. The BCS regulates the operating conditions of the batteries, as temperatures outside the optimal range are considered to be one of the main factors for battery aging (Edge et al., 2021). For this study, a liquid cooling system is assumed, which is characterised by high cooling performance and stable temperature control (Abramushkina et al., 2021). To meet its safety requirements, the storage system is divided into several independent battery packs, with three redundant BMS and BCS units.

The two parallel EDSs are responsible for converting electrical energy into mechanical energy. Multiple inverters convert the direct current (DC) voltage of the storage system into the alternating current (AC) voltage required for the operation of the electric motors. This mechanical energy is then used to drive the propellers, which generate thrust for flight.

The produced heat of the batteries, motors, and electronics is regulated by the TMS. The TMS contains two redundant cooling circuits that flow in opposite directions through the individual subsystems of the EPS. To ensure continuous operation of both circuits, a Power Transfer Unit (PTU) provides a continuous coolant flow in case of a pump failure, e.g., due to a jammed shaft. The system is based on existing hydraulic systems from the aviation industry and uses common cooling circuits for batteries and motors.

All subsystems interact to provide safe, efficient, and reliable power and propulsion, while the centralised control systems, such as the BMSs, monitor and regulate the system. A more detailed description of the system design layout can be found in Dauer (2024b).

2.3. Configuration of the Battery

One of the key challenges in designing a fully electric aviation system is determining the optimal battery siz-

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[1] These methods are based on the Certification Specifications (CSs) 25.1309 (European Union Aviation Safety Agency, 2023) and Aerospace Recommended Practices (ARPs) 4761 (SAE International, 1996) and 4754A (SAE International, 2010).

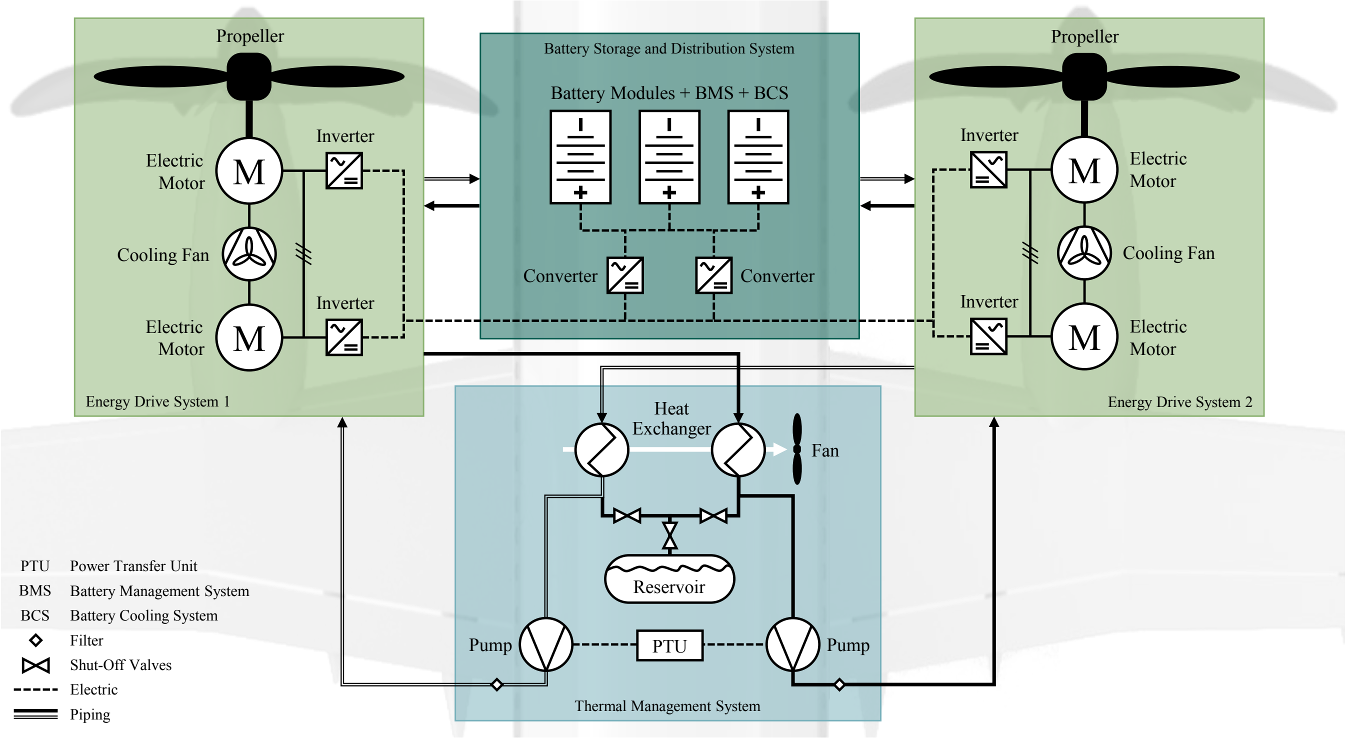


Figure 1. The EPS layout consisting of the three subsystems ESDS, EDS, and TMS. Smaller components, such as temperature sensors or circuit breakers, are not included in the figure.

ing (Avanzini et al., 2016). Unlike conventional aircraft, the system mass remains constant throughout the mission, as no fuel is consumed. As a result, the required energy is significantly higher than that of a conventional aircraft, leading to an increased total mass under identical mission conditions. This in turn requires larger batteries, which further increases the system mass. The design process thus becomes iterative, often leading to an infeasible solution unless the mission requirements are significantly constrained.

Our battery system is sized based on the study by Ng & Datta (2019) and is strongly affected by the intended flight time of the aircraft. A maximum flight time of three Flight Hours (FHs) per Flight Cycle (FC) is assumed for the EPS-powered aircraft. The battery system is dimensioned based on current Panasonic 18650PF lithium-ion cells (Chin et al., 2019) with the energy requirement of the battery being the primary sizing factor. We assume three battery modules with multiple cells arranged both in series and in parallel to determine a nominal system capacity of 15.6 MWh and an output voltage of 3 kV. A 20 % reserve is included to minimise deterioration associated with deep discharges.

Given the currently achievable energy densities of Panasonic cells of 217.5 Wh/kg and efficiencies of up to 98 %, the dimensioned battery has a weight of almost 72 t per battery module. This would result in a total battery mass which exceeds the maximum take-off weight of a conventional Airbus A320 (Airbus, 2020), thus electrification under these assumptions would not be feasible. However, to simulate the effects of future technological development, a second scenario with a projected energy density of 500 Wh/kg is considered. Due to the higher energy density, the mass per battery module could be reduced by more than 50 % to approx. 31.2 t. Although this weight still remains impractical for operation in commercial aircraft, it serves as a methodological foundation for assessing the environmental impact of battery maintenance and its dependence on weight and energy density. Table 1 gives an overview of the two battery energy density scenarios with the corresponding weight per battery module.

Table 1. Battery specifications for the state-of-the-art scenario (2024) and the projected scenario for 2035+.

Scenario	**Energy Density** [Wh/kg]	**Weight per Module** [t]
2024	217.5	71.8
2035+	500	31.2

3. ANALYSIS OF MAINTENANCE ACTIVITIES

Aircraft maintenance can be categorised into different types: routine maintenance actions, which are carried out according to predefined schedules, and degradation-based (non-routine) replacement activities. Routine maintenance tasks include all measures that are carried out according to a defined maintenance schedule (such as the Maintenance Planning Document (MPD)). This includes, for example, functional, operational, or service checks. Non-routine maintenance tasks, on the other hand, are usually not carried out according to a fixed schedule but rather in the event of unexpected failures or malfunctions.

3.1. Routine Maintenance Checks

To create a scheduled maintenance plan, the Maintenance Steering Group-3 logic is used to evaluate the failure scenarios for the battery-electric system layout (see Section 2). Each failure scenario is classified into a Failure Effect Category (FEC), which is used to determine whether and what kind of maintenance tasks are necessary. These FECs can be subdivided into:

- safety-critical (i.e., failures that affect the aircraft airworthiness and the requirement of a task is mandatory),
- operational (i.e., failures that impact operational performance but are not critical and a task can be considered optional), and
- economical (i.e., failures that have economic impacts for the operator and tasks are usually only carried out if they are cost-effective).

These maintenance tasks can range from simple activities, such as servicing or lubrication, to inspection tasks, or even more complex restoration and discard tasks. How often a specific maintenance task needs to be performed is calculated using intervals based on the legacy MPD of the Airbus A320 or expected degradation patterns and failure rates. Tasks with the same intervals can be grouped to minimise aircraft downtime. The duration of a task is either derived from comparable MPD tasks or estimated from literature data. A detailed description of the determination of suitable maintenance tasks for the EPS is beyond the scope of this paper. For detailed information, readers are referred to Dauer (2024a).

A total of 32 routine tasks have been defined for the EPS (see Figure 2). Nine of these 32 tasks are functional checks (FNC) that are important to ensure proper functioning of a component or system and to detect deviations from the defined operating parameters at an early stage. Five tasks are restoration checks (RST) that are carried out either in dedicated workshops or directly in the maintenance hangar. These are followed by visual checks (VCK) or discard tasks (DIS) for smaller components. An overview of the remaining routine maintenance tasks for the three subsystems can be found in the supplementary material.

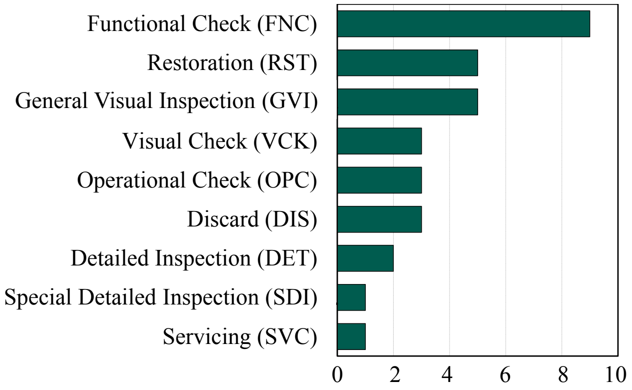


Figure 2. Frequency of maintenance task codes for the EPS.

3.2. Degradation-Based Replacement Checks

Some of the components in the EPS have complex failure behaviours. In particular, the battery is one of the most critical components in the EPS, as it is crucial for the range and efficiency of the aircraft (Arvidsson et al., 2024; Hoelzen et al., 2018). The battery capacity is highly dependent on the cyclic charging and discharging processes, as well as the operating conditions, such as the ambient temperature (Staack et al., 2021). Static failure rates from literature are not suitable for determining the replacement interval, since they do not consider external factors and mission profiles (Wolf, 2024). For this reason, we apply a semi-empirical model based on Clarke & Alonso (2021) and Schmalstieg et al. (2014), which takes into account the design parameters of the battery system. An average utilisation scenario with an FH/FC ratio of 1.8 and 1,500 FCs per year, based on Meissner et al. (2024), is assumed. Furthermore, for the sake of simplification, a constant operating temperature of 35 °C is assumed. The individual phases of the mission profile are iterated and the batteries are recharged after each flight. Due to the decreasing capacity after each flight, the amount of energy that can be stored decreases and triggers a replacement task when the remaining battery capacity falls below 80 % of its nominal new value.

The replacement interval for the battery pack and the above mentioned utilisation profile is determined based on our degradation simulations of the individual battery modules and totals approx. 4,670 FCs or 8,400 FHs. The degradation behaviour only affects the battery cells. However, the entire battery pack is regularly overhauled in workshops. During these restoration activities, it is assumed that the battery cells will be replaced, as the pack is completely disassembled and cleaned as part of the process. Other non-routine components that need to be replaced based on their degradation behaviour, as calculated by our degradation model, are the propeller unit (which needs to be replaced every 10,500 FHs (Aircraft Commerce, 2007)), the coolant pump (approx. 28,740 FCs), and the PTU (approx. 35,110 FCs).

4. LIFE CYCLE ASSESSMENT

The environmental impact of the derived maintenance and replacement activities are evaluated through an LCA in accordance with the standards defined in ISO 14040/44 (International Organization for Standardisation, 2020a,b). This structured approach comprises four stages: definition of the goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation.

4.1. Goal and Scope Definition

The goal of this study is to evaluate the environmental impact associated with all MRO activities of the novel EPS. The study aims to identify possible hot-spots and showstoppers regarding their climate change impacts. A comparison of the environmental impact of maintenance between the EPS and a conventional kerosene-powered propulsion system demonstrate the system's potential and possible burden shifting effects.

The study's scope includes all scheduled maintenance activities and component replacements for the EPS over the aircraft's lifetime of 25 years. With an average utilisation profile of 1.8 FHs per FC, 1,500 flights are performed per year. The system boundaries encompass all processes directly related to maintenance, including the energy consumption of maintenance facilities and equipment, as well as the production of spare parts. It is assumed that all maintenance activities and spare part production take place in Germany, with the exception of the batteries, which are manufactured in China. The environmental impact of spare parts storage and the effects on their degradation is beyond the scope of this study. The analysis is conducted using the open-source Python package Brightway2, employing the Environmental Footprint (EF) 3.1 LCIA methodology. The functional units for the analysis are defined as *per aircraft lifetime* and *per FH*.

4.2. Inventory Generation

The ecoinvent version 3.9.1 database with the cut-off model by classification was used as the background database. Foreground data for the maintenance activities were taken from Rahn et al. (2024) and adapted for the EPS. The environmental impact of the scheduled maintenance activities was assessed considering their task codes. Depending on the type, these tasks involve the use of specific equipment and/or consumables, such as lubricants like oil or grease. During restoration tasks (RST), components are thoroughly inspected and cleaned either in the maintenance hangar or in dedicated workshop facilities. In the case of discard tasks (DIS), wear components, such as filters or valves, are replaced. Here, only the production of new components is considered. The duration for individual maintenance tasks is calculated using the specified man-hours and the number of mechanics. This downtime is further used to estimate energy requirements for lighting, heating, or cooling the maintenance facilities. As it is not possible to precisely determine which maintenance activities can be performed simultaneously, we assume that all maintenance activities for the EPS are carried out sequentially.

The LCI for the non-routine tasks is created based on literature data and scaled according to the component's estimated weight. For the battery, the bill of materials from Ellingsen et al. (2014) and manufacturing energy inputs from von Drachenfels et al. (2023) are used. Each battery cell is composed of a graphite-based anode and a cathode made from lithium-nickel-cobalt-manganese-oxide and it is assumed that the batteries are manufactured in China. The construction and maintenance of the manufacturing facilities are out of scope. The inventory for the two energy density scenarios (2024 and 2035+) differs due to the different weights of the batteries. The LCI of the propeller unit is taken from Rahn et al. (2025). The propeller blades are made of a mixture of different fibre-reinforced plastic and rigid foam polyurethane, while the propeller hub is manufactured from Inconel 718. The inventory for the coolant pumps and PTU is based on datasheets of existing components (Brinkmann Pumps, 2024; Eaton Aeropace Group, 2014).

Table 2 provides an example of the inventory used to calculate the environmental impact of battery-related tasks. Two operational checks (OPC) are required for the BMS, which involve fault diagnosis and operational verification using Built-In Test Equipment (BITE). In addition, a functional check (FNC) is performed on the battery and connectors. As these tasks involve only a single mechanic reading out information from the BITE system, the calculation only takes into account the time required to operate the hangar. The towing of the aircraft into the hangar is excluded from the analysis of individual checks, as it is assumed that short tasks are typically performed as part of longer maintenance checks.

Furthermore, a restoration task (RST) has been defined for the battery packs. During the restoration process, it is assumed that the battery cells will be replaced, as the pack is completely disassembled, sent to a dedicated workshop, and cleaned as part of the process. The interval for this check has been derived from the degradation behaviour of the batteries. The inventory for this task consists of the time during which energy must be provided for hangar and equipment (e.g., to remove the old and install the new battery modules), the transport of the battery pack to the workshop, and the cleaning of individual components. As the batteries can no longer be used in aviation when they reach 80 % of their remaining capacity, the production of new battery cells has to be taken into account here.

In order to draw comparisons between the EPS-powered aircraft and a kerosene-powered equivalent, the LCI of the maintenance activities for a conventional turbofan aircraft and its

Table 2. Overview of maintenance tasks and associated inventory for battery-related maintenance checks.

Task Description	Units	Interval	Task Code	Environmental Implications	Inventory
Battery Management System perform fault diagnosis for sensor via BITE	3	1,000 FH	OPC	hangar and equipment	207 kWh
Battery Management System perform operational check via BITE	3	350 FH	OPC	hangar and equipment	207 kWh
Battery perform functional check of battery and connectors	1	200 FC	FNC	hangar and equipment	115 kWh
Battery Pack* remove battery pack for in-shop restoration of cells and cooling	3	4,670 FC	RST	hangar and equipment transport to workshop cleaning of components replacement of battery cells	2,761 kWh 236,993 tkm 3 m^3 -

*The detailed inventory of the battery cells can be found in the supplementary material.

engines from Rahn et al. (2025) is used. For the conventional propulsion system, this comprises all engine shop visits and maintenance tasks related to the power plant, the auxiliary power unit, and the fuel distribution system. The maintenance implications are then compared with the in-flight impacts. For the conventional aircraft, the environmental impact of flight operations is derived using the ecoinvent dataset *market for transport, passenger aircraft, short haul*, while for the EPS the German energy mix (*market for electricity, medium voltage*) is used. For flight operations, the same 25-year average flight schedule is assumed. The full LCI for maintenance and flights can be found in the supplementary material.

4.3. Life Cycle Impact Assessment

In the LCIA stage, the data in the LCI is analysed and linked to the environmental impact. The EF 3.1 impact assessment methodology focuses on the impact category climate change with the Global Warming Potential (GWP) indicator. The GWP is a measure of the integrated warming effect caused by the release of one kilogram of a particular greenhouse gas into the atmosphere, relative to carbon dioxide (CO_2). The calculation is based on a time horizon of 100 years.

5. RESULTS

The results of the environmental impact of all EPS maintenance tasks are shown below. The climate impact of EPS maintenance amounts to 306.5 $kgCO_2$-eq. for the 2024 scenario and 171.0 $kgCO_2$-eq. for the 2035+ scenario per FH, as shown in Figure 3. In both cases, the majority of the environmental impact is attributed to the ESDS subsystem due to the battery replacement. With a weight of more than 71.8 t (or 31.2 t, respectively) of a single battery module, the production of the replacement batteries accounts for about 95 % of the environmental impact, mainly due to the use of rare raw materials. Based on the utilisation profile of the aircraft and the calculations of the battery degradation model, the battery will need to be replaced eight times over the entire service life of the aircraft. Both the EDS and TMS subsystems contribute only a small share of the total climate impact. Although the TMS has the highest number of components and maintenance tasks, the environmental impact of TMS maintenance is only 0.2 $kgCO_2$-eq. per FH, as it consists mainly of shorter functional and inspection tasks with no further environmental aspects. By comparison, the maintenance activities for conventional engines are about 3.4 $kgCO_2$-eq. per FH (Rahn et al., 2024). This means that the maintenance of EPS exceeds that of conventional systems by a factor of almost one hundred. After 25 years of operation, the total climate change impact is approx. 20.688 tCO_2-eq. for the 2024 battery scenario and 11.541 tCO_2-eq. for the 2035+ battery scenario.

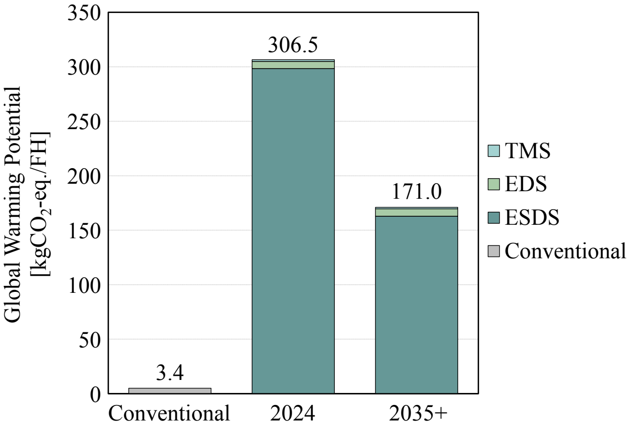
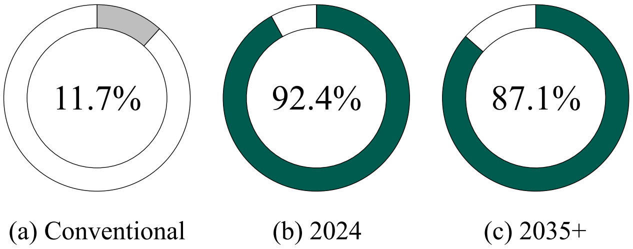


Figure 3. GWP per FH for the maintenance activities of conventional propulsion system and the EPS with both battery scenarios (2024 and 2035+).

Considering EPS maintenance in the broader context of overall aircraft maintenance (Figure 4), it becomes evident that their share in overall maintenance efforts increases significantly compared to conventional systems. While the maintenance of the propulsion system in conventional aircraft only accounts for about 11.7 % of the total aircraft maintenance, this share increases to 92.4 % in the 2024 battery scenario. The higher energy density in the 2035+ scenario leads to a lower battery mass, yet the climate impact still accounts for 87.1 %. This is due to the fact that, even in the 2035+ scenario, the batteries still have a significant mass and need to be replaced regularly due to degradation and limited lifespan.



(a) Conventional (b) 2024 (c) 2035+

Figure 4. Contribution of propulsion system maintenance for the conventional scenario (a) as well as for the 2024 scenario (b) and 2035+ scenario (c) to the total aircraft maintenance effort in terms of climate change impact. All three scenarios have been calculated for a 25-year aircraft lifetime.

Figure 5 shows the main factors influencing the environmental impact of the EPS, broken down by the environmental implication for each subsystem. For the entire EPS (a) and for the ESDS subsystem (b), the replacement of batteries and their transport to special workshops has the largest environmental share with almost 98 %. For the EDS subsystem (c), the production of spare parts also accounts for the largest ecological share of 94 %. This is mainly due to the replacement of the propeller, which has to be replaced six times in our life cycle simulation. The remaining climate change impact from EDS maintenance is attributed to the electricity used for the hangar and equipment. The maintenance of the TMS subsystem (d) is dominated by electricity as the main contributor, as it's maintenance mainly consists of functional checks and inspection tasks. This is in line with other studies on the environmental impact of maintenance (Meissner et al., 2024; Rahn et al., 2024), where both the production of spare parts and energy consumption are the most critical aspects.

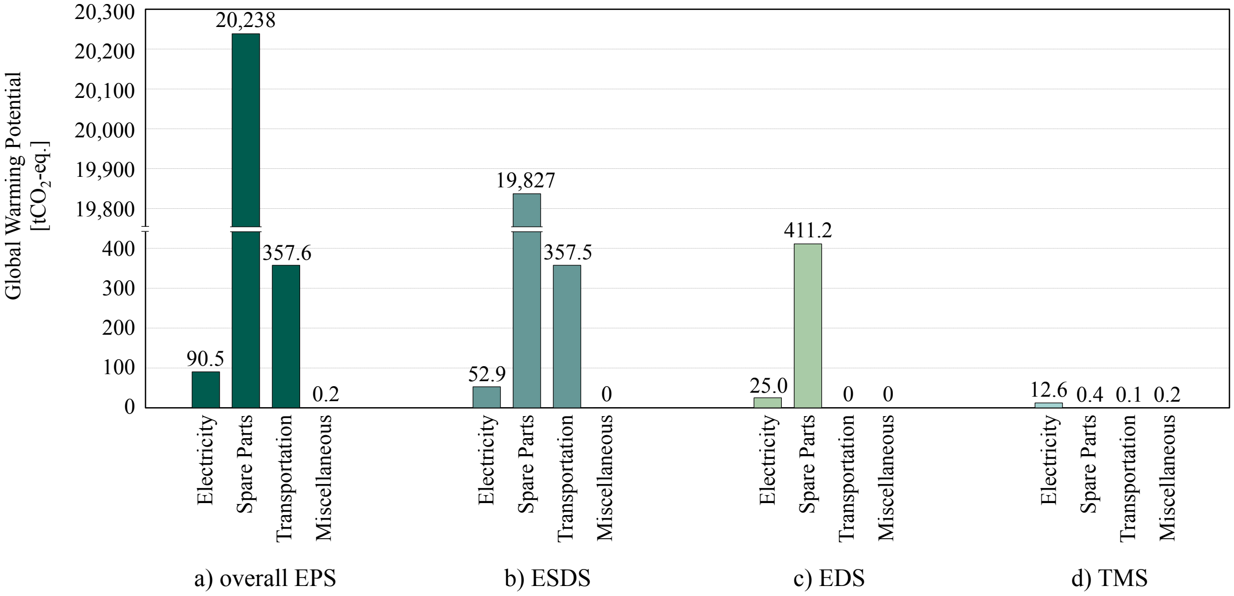
While the environmental impact of maintenance activities for the EPS is significantly higher than for conventional propulsion systems, a comparison should also be made with the impact during flight operations. The EPS-powered aircraft has the potential to significantly reduce the climate impact during flight, as no direct emissions are released into the atmosphere. The utilisation of the *aircraft transportation* dataset in ecoinvent facilitates the estimation of the climate impact associated with conventional propulsion systems during flight operations. The climate change impact is calculated assuming a flight distance of 800 km and a passenger capacity of 180, which leads to approx. 10.6 tCO_2-eq. per FH. In contrast, according to our mission calculations, the EPS consumes a total of about 17.1 MWh per flight, which corresponds to an average consumption of 9.5 MWh per FH. The calculated climate change impact, based on the German energy dataset from ecoinvent, is about 4.5 tCO_2-eq. per FH. With a renewable energy mix, this impact can be reduced even further. This highlights the trade-offs between increased maintenance requirements and operational emission reductions.

6. CONCLUSION

The aim of this study was to assess the environmental impact associated with the maintenance of a battery-based EPS. Compared to conventional drive systems, the maintenance of the EPS results in significantly higher environmental impact, mainly due to battery replacements. While the maintenance of conventional propulsion systems is largely influenced by the production of spare parts (i.e., life limited parts) and the engine run-up checks after maintenance (Oestreicher et al., 2024), its climate impact, at approx. 3.4 kgCO_2-eq. per FH, represents only a fraction of the environmental impact of the EPS maintenance activities (306.5 kgCO_2-eq./FH).

The production of spare batteries, as one of the most crucial aspects of the environmental impact, carries considerable significance due to the high capacity restrictions and the safety requirements in aviation. Our analysis, which assumes higher energy densities for batteries in the year 2035 and beyond, shows the reduction potential of climate change impact for the EPS from a maintenance perspective. Despite the predicted achievable energy densities, the mass of the required battery modules exceeds the maximum acceptable aircraft weights. The electrification of conventional commercial aircraft in the size of an Airbus A320 therefore remains a major challenge in general. For this reason, current research on all-electric aircraft focuses on the commuter segment (Afonso et al., 2023; Gnadt et al., 2019).

In addition to these technical requirements, operational factors also play a crucial role in the electrification of aircraft. As noted by Balack et al. (2023), operational aspects, such as turnaround times for charging and cooling, as well as battery storage solutions, are important considerations for the technical feasibility. There are already approaches to meeting these challenges, such as the exchange of fully charged battery packs between flights. However, this would drastically increase the demand for batteries and their infrastructure, resulting in greater consumption of scarce materials and increased climate impact. Whether the production and replacement of batteries is then attributed to maintenance or flight operations in environmental (or economic) assessments



a) overall EPS b) ESDS c) EDS d) TMS

Figure 5. Environmental hot-spot identification of the overall EPS (a) and the three subsystems (b-d). The vertical axis has been truncated for visualisation purposes.

varies widely in the literature, which makes comparability with other studies difficult.

The present study does not take into account the environmental impact associated with battery storage and the necessary infrastructure. However, this may be an additional factor contributing to the overall environmental impact of maintenance activities. Furthermore, the degradation model utilised in this analysis is predicated on a simplified average utilisation profile of the aircraft. While this approach provides useful insights, it does not capture the variability of real-world flight schedules and operational use cases. A comparative analysis of scheduled versus condition-based maintenance approaches, as well as the expansion of the degradation model to encompass more complex life cycles and realistic operational patterns is a critical area for future research.

Despite the considerable increase in maintenance costs and their environmental impact, battery-electric drive systems have the significant advantage that the environmental impact of flight operations can be diminished, since no climate-damaging emissions are released into the troposphere and lower stratosphere. By transitioning to renewable energies in the forthcoming decades, the electricity generation process is expected to support the reduction of the climate impact of aviation. However, the findings of our study demonstrate that the integration of novel technologies can result in the introduction of additional maintenance requirements. This underlines the necessity of considering potential burden shifting to other life cycle phases or sectors - a critical aspect that must be carefully addressed in the design of future aircraft systems.

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