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Towards Sustainable Aviation: End-of-Life Scenarios for Lithium-Ion Batteries used in Hybrid Electric Aircraft

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Abstract

The transition to novel aircraft concepts presents a promising way to reduce the environmental impacts of the aviation sector, with plug-in-hybrid electric aircraft emerging as a viable solution. In the short-to-medium term, these aircraft will primarily rely on lithium-ion batteries (LIBs), whose manufacturing process is energy-intensive and highly resource-demanding, leading to significant environmental burdens in terms of climate change and depletion of minerals and metals. This study explores End-of-Life (EoL) scenarios for LIBs used in short-to-medium haul commercial hybrid aircraft, employing the life cycle assessment (LCA) methodology. It focuses on the production and maintenance phases of the entire aircraft, while the EoL phase is exclusively for the LIB. Maintenance events include inspections, repair and replacement of components. Our findings demonstrate that while recycling LIBs significantly reduces raw material demand and landfill waste, the overall climate change (CC) impact remains significant, which is nearly twice as high as that of a fossil-based aircraft. This is primarily due to the substantial number of battery replacements required throughout the aircraft's lifetime. Moreover, recycling LIBs instead of using new batteries each time further decreases the impact on climate change over the aircraft's lifetime. This work highlights the critical need for advanced recycling strategies and robust regulatory frameworks to achieve the sustainability goals in the aviation sector.

Keywords: life cycle assessment; end-of-life; hybrid-electric aircraft; lithium-ion battery

1. Introduction

The increasing demand for commercial flights, along with the aviation sector's ambitious goal to meet climate targets by 2050, has paved the way for the development of new aircraft concepts [1]. These new concepts include novel propulsion systems, which aim at decreasing the greenhouse gases (GHG) emissions, especially during in-flight operation. For instance, propulsion systems based on electric batteries are expected to be included in hybrid aircraft designs as these technologies are expected to technically develop in the medium- and long-term and therefore become suitable for aviation applications [2]. However, a more comprehensive environmental assessment including the extraction of raw materials, manufacturing, and end-of-life phases is required for more informed decision-making. Therefore, it is important to further explore the impact that these on-ground phases could have in the future.

To assess the potential impacts of such emerging technologies in terms of climate change or metal depletion, the so-called prospective life cycle assessment (pLCA) methodology can be used. This methodology allows the comparison of new emerging concepts to reference technologies (e.g., fossil-based) to identify environmental hotspots during the entire life cycle of the technologies.

Past studies have conducted pLCA of electric-based propulsion concepts for aircraft, mainly focusing on the manufacturing and operation phases. For example, [3], [4], and

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[5] showed that the electricity needed for battery production has a significant effect on global warming, which could be counteracted using renewable energies in the electricity mix. Hoelzen et al. [6] emphasized the critical role of battery performance in hybrid-electric aircraft (HEA). Their findings highlighted that the environmental benefit of HEA depends on charging the batteries with renewable energy and the alignment of battery design with mission-specific profiles. Similarly, [7] identified battery charging as a major contributor to global warming, emphasizing the need for renewable energy sources. More recent studies, [8] and [9] used pLCA approaches for HEA and all-electric aircraft to explore the long-term environmental trade-offs of electrified aviation. However, these studies neglect the maintenance phase and its associated impacts, such as battery replacements over the aircraft's lifetime.

Maintenance is a critical phase in the life of an aircraft, essential for maintaining airworthiness, ensuring safe operations, and sustaining efficiency. However, the maintenance phase is often overlooked in conventional life cycle assessment (LCA) literature due to the perception that it has a relatively low environmental impact compared to the operational phase [10]. Nevertheless, maintenance practices and constraints can significantly impact the deployment and certification of novel technologies. The considerably shorter cycle life of batteries (currently estimated at 2,000 to 3,000 cycles for use in the mobility sector [11]) compared to the aircraft's lifespan may offset the positive effects on flight operations due to frequent replacements. These drawbacks can have a substantial influence on the overall assessment of environmental impacts [12], especially considering the uncertainty surrounding whether the used batteries can be recycled or reused [11].

Another important aspect related to the growing demand of lithium-ion batteries (LIBs) to cover the needs of the automobile and aviation sectors in the future, is the increased risk of critical materials supply. In this regard, research on LIBs for the automobile sector is more extensive and some efforts have been made to investigate End-of-Life (EoL) strategies to counteract this, such as recycling and recovery. These EoL measures have the potential to reduce the critical material supply risk as well as the electricity demand for manufacturing processes [13], [14], [15]. For instance, [16] determined that implementing recycling in the battery electric vehicle life cycle could reduce up to 8% of the climate change impact and up to 25% of minerals and metals depletion. In aircraft LCAs, the EoL phase is still often neglected or overlooked, as is the consideration of the number of batteries needed through the life cycle of an aircraft or fleet of aircraft.

In this study, a comparative pLCA of the ground-based impacts of a reference aircraft (fossil-based kerosene) and a hybrid-electric concept – with focus on a LIB, its lifetime and some recycling scenarios – is conducted.

The two previously mentioned research gaps are addressed by: 1) including the maintenance phase within the on-ground operations phase of the pLCA and 2) examining various recycling scenarios for LIB once they have reached the end of their service life in the aircraft. The novelty of this work lies in considering the maintenance activities required for battery use over the lifespan of an aircraft. This allows the identification of potential environmental trade-offs or critical issues.

2. Methodology

The Plug-In Hybrid Electric Propulsion (PHEP) aircraft and the reference aircraft (Airbus A321 neo) concepts analyzed and compared in this work were developed within the framework of the project "Exploration of Electric Aircraft Concepts and Technologies" (EXACT[1]) of the German Aerospace Center (DLR). The two designs only differ in their operating empty weight (44.9 t for the baseline and 77.0 t for the PHEP) and their propulsion systems. The following sections focus on the details of the PHEP concept.

2.1. Description of PHEP concept

The PHEP is a 250-passenger short-range aircraft designed to be fully battery-operated on a range of up to 500 kilometers. Additionally, it is equipped with a large gas turbine as a range-extender operated with synthetic kerosene allowing the aircraft to cover up to 2800 kilometers at a cruise speed of Mach 0.67. The design features four identical propellers, with each one including one electric motor and three of them having a nickel-manganese-cobalt (NMC) LIB, while the fourth one is the gas turbine generator as shown in Fig 1. The battery packages are designed to be placed in the nacelles; thus, the fuselage structure is not affected by the battery mass.

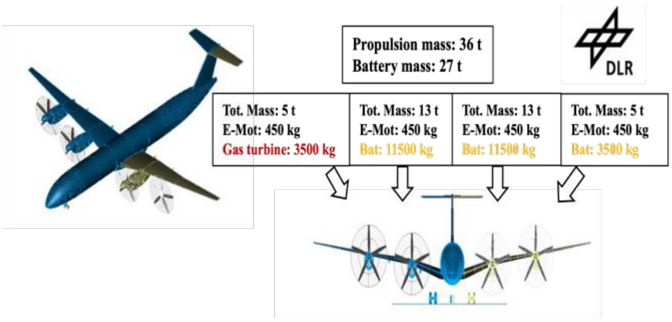

Fig 1. EXACT Plug-in hybrid electric aircraft (DLR, 2023)

2.2. Life cycle assessment of PHEP aircraft concept

2.2.1. Goal and scope

The goal of the assessment was to analyze the effect of LIBs on the PHEP aircraft concept in comparison with the reference aircraft. The life cycle phases considered include manufacturing and maintenance of the entire aircraft, and EoL exclusively for the battery. Flight operation is excluded to focus on ground-based impacts and to prevent the climate impacts of the use phase from dominating the overall results. Although aircraft electrification may reduce in-flight emissions, such benefits fall outside the scope of this study. The geographical

[1] https://exact-dlr.de/project-overview/

scope is limited to Germany, corresponding to the assumed location of manufacturing and maintenance activities. The foreground system is modeled using primary data from EXACT and secondary data from peer-reviewed literature; the background system is modeled using ecoinvent 3.9.1. The functional unit is one aircraft with an entry into service in 2030 and an assumed lifetime of 20 years. The study employs an attributional LCA methodology, applying the impact assessment method EF no LT v 3.1 and the open-source software Brightway.

2.2.2. Inventory modeling

Manufacturing

The inventory for the baseline aircraft is based on [17] and adjusted according to the mass breakdown. The inventory for the PHEP aircraft was similarly constructed for the airframe and combustion-based propulsion system. The electric propulsion system, excluding the batteries, was modeled in a simplified manner using the ecoinvent database.

As detailed inventories for aircraft batteries are not currently available in the literature, the battery model was initially based on an NMC111 inventory for automobile applications developed by [18]. To represent an NMC811 battery and meet the PHEP design requirements in mass and effective energy density, the inventory was adapted using the Battery Cell Energy and Cost Model (CellEst) [19] and additional bill-of-materials data from [20]. Further sizing assumptions are described in Table 1:

Table 1. Assumptions on the technical specifications of the LIB for the PHEP

Parameter	Assumption
Cell energy density (Wh/kg)	500
Battery pack energy density (Wh/kg)	400
State of Charge (SoC) at the start of the mission	90%
State of Charge (SoC) at the end of the mission	20%
Total battery mass (t)	27
Total battery energy capacity (Q_max) (kWh)	13247

Maintenance

The maintenance plan for both aircraft configurations is based on [10] and is assumed to be identical. To capture the effects of battery integration, particular attention was given to battery-specific maintenance, which was incorporated into the overall analysis. Due to the lack of experience with batteries as part of the propulsion system, maintenance activities were modeled based on the already implemented Nickel-Cadmium (Ni/Cd) aircraft batteries used for engine starting, auxiliary power units, and emergency systems [21]. These activities are categorized into monthly, quarterly, and annual maintenance tasks for regular inspections. They consist solely of visual inspections for damage and capacity checks. As these procedures can be easily incorporated into existing line maintenance routines, they are expected to contribute significantly to the overall ecological impact.

The battery replacement at the end of its life is performed in a separate maintenance event. It involves removing the old battery and installing a newly produced battery. The electricity required to produce a new battery is assumed to be 16.8 kWh/kg as estimated in [18]. The electricity required to recycle an old battery was calculated based on the dataset "used Li-ion battery" from ecoinvent 3.9.1, which assumes a value of 0.14 kWh/kg via hydrometallurgical treatment and 0.8 kWh/kg via pyrometallurgical treatment. The estimated duration for this maintenance task is 10 hours and it is assumed to be carried out in a hangar. The inventory for this check is based on [10] and includes the towing of the aircraft into the hangar, the operation of the hangar, and the operation of a diesel-powered ground power unit, as shown in Table 2:

Table 2. Inventory list of the maintenance check for the LIB replacement

Activity	Dataset	Quantity
Aircraft towing	Electricity	10 kW
Hangar operation	Electricity	76.7 kWh
Ground power unit	Diesel	30 l/h
Recycling of old battery (50% hydrometallurgical+ 50% pyrometallurgical)	Electricity	12.7 MWh
Production of new battery	Electricity	454 MWh

2.2.3. Prospective aspects/scenarios

Since the electricity mix used to manufacture and charge the batteries plays a crucial role in the assessment, some prospective aspects were included in the background system. A green electricity mix for Germany for 2050 was generated based on long-term normative scenarios for renewable energy deployment to manually modify the ecoinvent dataset [22].

2.3. Implementation of maintenance events through discrete event simulation (LYFE)

The life cycle of both aircraft is analyzed using the discrete-event simulation framework LYFE, which breaks down the life cycle of an aircraft into individual events and analyzes them from both economic and ecological perspectives [8,19]. For the sake of simplicity in comparison, it is assumed that both aircraft are operated on the same flight schedule. The additional battery replacement event is included as input in the life cycle simulation as a condition-based event depending on the battery capacity, which varies with the flight events. Since the PHEP aircraft uses the battery only during the cruise phase, the battery capacity depends on the flight plan and operational conditions. LYFE identifies when the battery is in use and checks the remaining capacity before each flight. The replacement event is triggered when the battery's remaining capacity falls below a critical threshold of 5%. After the replacement, the new battery is assumed to have full capacity.

All events in the life cycle are evaluated ecologically using an LCA and the individual results are aggregated. Since the scope of this study focuses on ground-based impacts, in-flight impacts are not considered further.

2.4. End of life scenarios for battery recycling

The EoL phase focuses exclusively on the LIB used in the PHEP aircraft. Based on the energy capacity outlined in Table 1, the PHEP aircraft requires eleven battery replacements over a 20-year operational lifetime, which serves as the reference scenario. Additional recycling scenarios were developed to evaluate the environmental benefits of reducing dependence on raw materials through the recovery and reuse of materials from spent batteries. These scenarios are modeled using the "used Li-ion battery" dataset from ecoinvent 3.9.1, which represents a 50:50 mix of hydrometallurgical and pyrometallurgical treatment processes. The dataset includes avoided production impacts by accounting for the recovery of materials such as cobalt, lithium, and plastics, which are reintegrated in subsequent production processes. These avoided impacts are reflected as negative emissions (carbon credits) in the LCI. Four recycling rates were considered: 25%, 50%, 75%, and 100%. For example, in the 25% recycling rate scenario, 25% of the battery mass is modeled as "used Li-ion battery", while the remaining 75% is represented as new battery production, as illustrated in Fig 2.

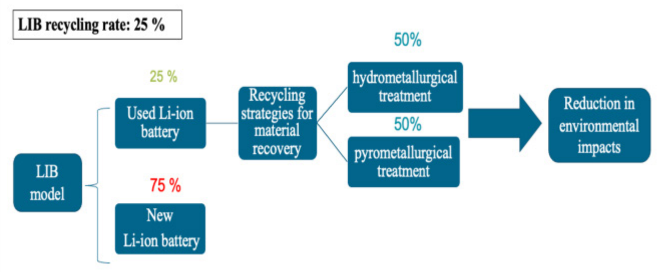

Fig 2. Proposed approach to include LIB recycling scenarios (own figure)

3. Results

3.1. Comparative results with fossil-based kerosene reference aircraft

Fig 3. illustrates the comparative analysis of the impact on climate change (CC) for the reference aircraft versus the PHEP concept, broken down into manufacturing, maintenance, and the production of 11 replacement battery packs. The PHEP aircraft exhibits a higher overall CC impact, primarily due to emissions associated with battery replacements over its lifetime. For the reference aircraft, manufacturing impacts are driven by the production of combustion engines and the airframe. In contrast, the higher manufacturing emissions of the PHEP concept stem from the production of battery systems, electric motors, and power electronics. Maintenance-related impacts are slightly higher for the PHEP concept due to additional requirements such as battery diagnostics, power electronics servicing, and battery swap or recharge protocols. However, emissions in this phase remain relatively low overall. The dominant contributor to the PHEP's CC is the cumulative impact of producing replacement batteries. The extraction and processing of raw materials such as lithium, cobalt, and nickel for LIBs result in a more resource-intensive process.

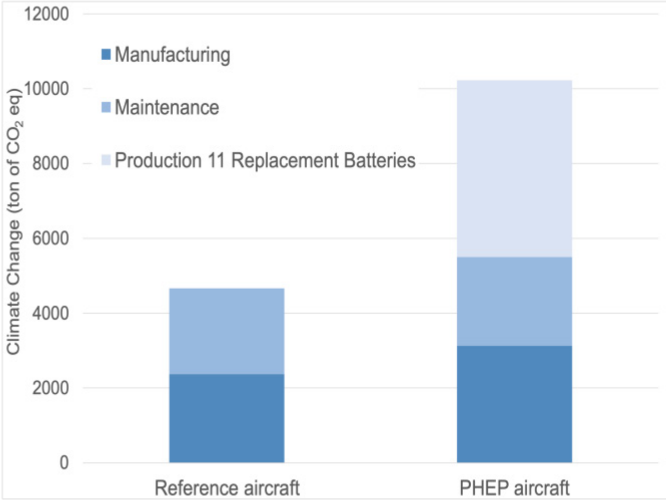

Fig 3. Relative contribution of manufacturing and maintenance phases for the plug-in hybrid electric concept

3.2. Contribution analysis to identify hotspots

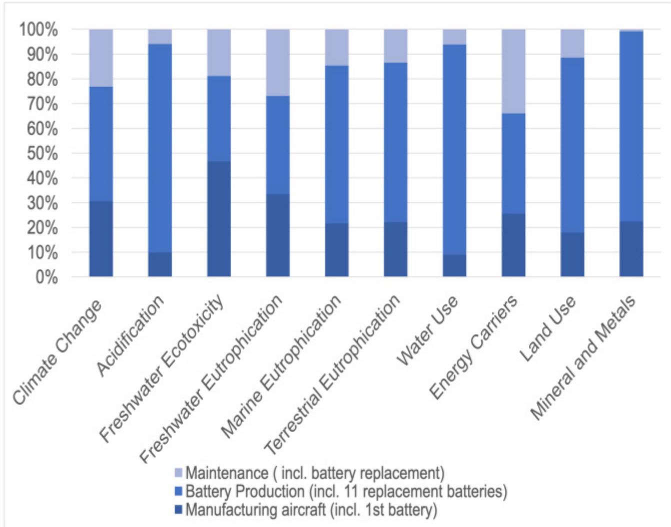

Fig 4. Relative contribution of manufacturing and maintenance phases for the plug-in hybrid electric concept

Fig 4. presents the contribution of the different life cycle phases to selected environmental impact categories. Battery production is the primary contributor in most categories, including climate change, mineral resource depletion, water use, and land use. This is largely due to energy-intensive manufacturing and the extraction of raw materials. An exception is observed in freshwater ecotoxicity, where the manufacturing phase of other aircraft components plays a more significant role. The hybrid propulsion system also leads to additional environmental burdens from increased maintenance requirements, including more frequent diagnostics, e-motor inspections, and thermal management checks for power electronics. These factors further contribute to the overall impact of the PHEP concept.

3.3. LIB recycling scenarios in the PHEP concept

Fig 5. introduces multiple battery recycling scenarios for the PHEP aircraft, depicting how varying recycling rates affect the overall CC impact. In the 0% recycling scenario, the CC impact is very high, due to the requirement of eleven battery replacements over the aircraft's lifecycle. In the 50% recycling scenario, the CC impact is substantially reduced, as 50% of each battery is recovered through metallurgical and pyrometallurgical treatments. Although significant reductions are achieved through recycling, the 100% LIB recycling scenario results in a CC impact during the maintenance phase that is only slightly lower than that of the reference aircraft. This is attributed to the slightly higher maintenance demands of the PHEP concept, which employs four turboprop engines instead of two turbofan engines. Nevertheless, under this ideal scenario, a reduction of approximately 91% in CC emissions can be attained.

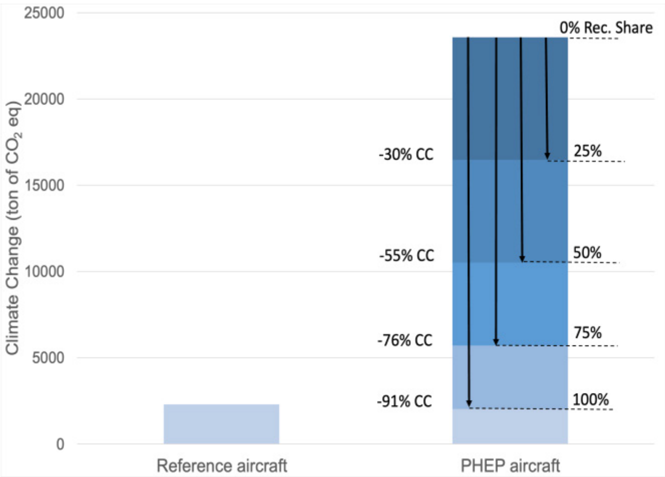

Fig 5. Maintenance phase – Impact of LIB recycling scenarios on climate change for the reference and plug-in hybrid electric aircraft

It is important to emphasize that achieving a 100% recycling rate represents an ideal theoretical scenario designed to explore potential environmental benefits. Current challenges remain in recovering all battery materials, as lithium and manganese are not so easily recoverable due to economic and technical barriers [24], [25]. Additionally, the quality of recycled materials must meet stringent requirements for aviation applications. In principle, remanufacturing of spent LIBs for aviation could be feasible, analogous to recent advancements in the automobile sector [25], [26], [27].

3.4. Sensitivity analysis on the battery capacity cycles and battery replacement frequency

The number of batteries required during the PHEP aircraft's lifetime depends on the battery energy capacity (as shown in Table 1) and its cycle life, calculated with the LYFE tool. With higher capacities, the batteries last longer, resulting in fewer replacements. Conversely, smaller capacities will require more frequent replacements, increasing the overall CC impact, as shown in Fig 6. The lowest impact on CC occurs when large batteries require fewer replacements, particularly under 100% recycling scenarios.

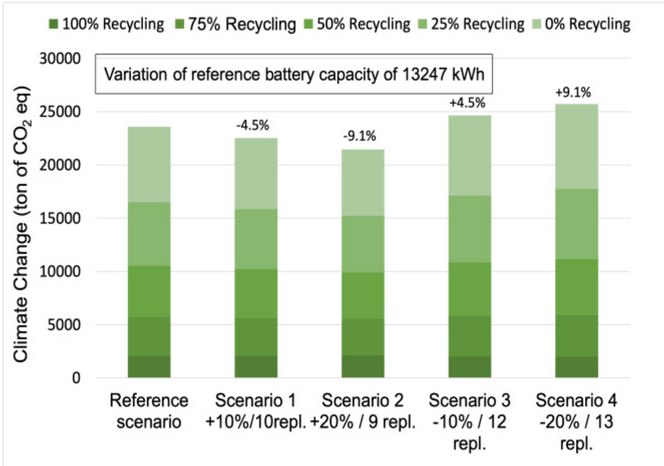

Fig 6. Sensitivity analysis on climate change based on the LIB energy capacity and number of replaced batteries

4. Discussion

In line with previous research, this study confirms that the integration of electrified propulsion systems, such as plug-in hybrid electric propulsion aircraft, can offer environmental benefits, particularly through the reduction of in-flight emissions. However, the present work focuses specifically on the ground-based impacts associated with the maintenance phase, especially related to battery life cycles.

While numerous studies have highlighted the in-flight environmental advantages of hybrid-electric propulsion, relatively few have addressed the life cycle impacts of battery maintenance, replacement, and recycling [10], [20]. This study, the first of its kind for short- and short/medium-range aircraft, demonstrates that incorporating battery recycling can significantly reduce the environmental burden associated with maintenance phase. These findings support the growing consensus that battery recycling is essential for minimizing the environmental footprint of electric aviation technologies.

Compared to automotive battery systems, this study reveals distinct challenges in the aviation sector. These include the need for larger battery systems, stringent weight constraints, and more demanding operational conditions. As a result, factors such as maintenance strategies, battery lifespan, and degradation behavior are particularly critical to the sustainability of HEA and may differ substantially from those in ground-based transport systems.

Several limitations of this study must be acknowledged. Material selection, flight schedules, and maintenance requirements for both aircraft configurations are assumed to be nearly identical in order to isolate battery-related effects. However, these assumptions may not fully capture the realworld differences from alternative propulsion systems. Moreover, the flight phase was excluded to enable a focused analysis of ground-based impacts, allowing for a clearer and more detailed analysis of battery-related impacts. Including in-flight emissions in future research would allow for a more comprehensive assessment.

Significant uncertainties remain regarding large-scale batteries for aviation, as such systems are not yet operational. Assumptions related to material composition, mass breakdown, capacities, and lifetimes were based on the most detailed inventory available at the time of analysis [18]. This was adapted for NMC811 chemistry using additional modeling tools and project-specific data. Although more recent datasets such as [29] have since been published, they are derived from [18]. The results of this study might vary slightly with these newer datasets, but the overall conclusions are expected to remain the same.

The EoL phase focused exclusively on the battery, identified as a major contributor to the overall impact. A 100% recycling scenario was included to explore the theoretical environmental benefits, although this assumption represents an idealized condition rather than current industry capabilities. Achieving such high recycling rates is challenging, particularly in recovering materials of sufficient quality for aviation-grade applications. Further research is needed to assess the technical and economic feasibility of high-yield recycling processes and the integration of recycled materials into aviation-grade batteries. Additionally, the analysis did not include certain EoL processes, like battery discharge and disassembly, which could introduce additional environmental impacts. Other components, such as the airframe or electric motors, were also excluded from the EoL analysis; their recycling or reuse could further reduce the overall environmental impact.

Lastly, the use of ecoinvent datasets introduce uncertainties, as the data may be outdated, generalized data, or aggregated and not fully representative of aviation batteries. In this study, it was assumed that the "used Li-ion battery" dataset could be applied to the same application. In practice, batteries from mobile applications are often repurposed for stationary applications as a second life. However, this approach was employed to depict the avoided impacts from manufacturing new batteries and can be used as a preliminary exploration in this direction.

5. Conclusions and Outlook

This study demonstrates that, while electrified propulsion systems offer promising environmental benefits-particularly in terms of operational emissions-challenges remain in other life cycle phases. In particular, the environmental trade-offs associated with battery maintenance and EoL processes must be addressed. The lifetime of battery systems and the implementation of effective recycling strategies are crucial to realizing the ecological advantages of hybrid-electric aviation. Maintenance activities, especially those related to batteries, can act as barriers to the adoption of certain configurations but may also serve as enablers for the safe sustainable implementation of new technologies. As such, they should not be overlooked in LCAs.

The frequency of battery replacements is closely linked to the technological advancements in battery chemistry and degradation behavior. A thorough understanding of the performance and degradation characteristics of different battery chemistries and emerging batteries such as lithium-sulfur and solid-state, is essential. A recent study [30] suggests that these next-generation batteries have the potential to reduce environmental impacts and advance electrified aviation. Improvements in degradation resistance, energy density, and recyclability may reduce replacement needs and the associated environmental burden, further enhancing the sustainability of hybrid-electric aircraft over their lifetime.

This study also reinforces the pivotal role of recycling in the broader sustainability framework, highlighting the need for comprehensive pLCA of future aviation technologies to incorporate recycling strategies. Future research should advance more detailed EoL approaches aligned with the LCA methodology in [26], while incorporating circular economy principles, such as second-life applications, alternative recycling methods, and extending these strategies to components like the airframe and power electronics [27]. Furthermore, uncertainty analyses are needed to better assess the impact of battery degradation on replacement frequency. Incorporating such analyses will improve the robustness and reliability of future maintenance models and support more informed decisions in the development of sustainable aviation.

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