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Maintenance, repair, and overhaul of aircraft with novel propulsion concepts – Analysis of environmental and economic impacts

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Abstract

Technological transitions of aircraft propulsion concepts are a key strategy for reducing the environmental impacts of air travel. Using battery-electric and fuel cell-based powertrains can avoid climate-damaging CO_2 and non-CO_2 emissions from kerosene combustion in conventional jet engines. However, the long service life of aircraft requires extensive maintenance, repair, and overhaul (MRO) processes of the powertrain. The main components of novel powertrain concepts (e.g., batteries, fuel cells, and electric motors) might require more frequent replacements than conventional powertrain components, leading to negative impacts on sustainability. Therefore, this article analyzes the environmental and economic impacts of novel powertrain concepts associated with their MRO. For this purpose, the aging behavior of the main components is analyzed, and replacement times are determined. Using life cycle assessment and life cycle costing, the MRO-related impacts of novel powertrain concepts are investigated and compared to those of conventional jet engines. The analysis shows that batteries, fuel cells, and electric motors must be replaced more often than conventional jet engines. In addition, the replacement frequency of batteries and fuel cells results in higher environmental impacts than conventional jet engines.

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Keywords: Aircraft; Maintenance, repair, and overhaul (MRO); Battery, Fuel cell; Life cycle sustainability assessment

1. Introduction

Global air traffic is increasing rapidly and has already achieved the pre-COVID-19 level [1]. Strongly positive annual growth rates of 3.2% to 3.8% are expected in the long term, leading to a doubling of air traffic every 20 years [2]. While aircraft manufacturers and airlines desire this trend, it is also associated with new environmental challenges. Especially the emission CO_2 and non-CO_2 emissions (nitrogen oxides, soot, water vapor, and sulfate aerosols) resulting from fossil kerosene combustion are associated with long-lasting harmful effects on the climate. In 2018, the aviation sector was responsible for 2.4% of the global CO_2 emissions and 5% of global anthropogenic climate forcing [3]. Even if fuel efficiency improvements of approximately 25% can be achieved per new aircraft generation, the predicted growth of air traffic would cause the aviation-induced CO_2 and non-CO_2 emissions to triple until 2050, making the aviation sector one of the main emitters in the long term [4]. This is particularly critical as the impacts of emissions at high altitudes are more severe than those at ground level [5].

While minor reductions of CO_2 and non-CO_2 emissions per passenger kilometer traveled (pkm) can be achieved by efficiency improvements of aircraft engines, radical

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technological innovations are needed to generate further progress toward sustainable aviation [6]. Promising approaches are battery-electric propulsion concepts consisting of propellers powered by electric motors and a battery system for energy storage applicable in regional and short-range aircraft [7–9] and hydrogen and fuel cell-based propulsion concepts consisting of propellers powered by electric motors, a battery system for energy storage and a fuel cell system for generating electricity from hydrogen applicable in short- and medium-range aircraft [10]. Furthermore, synthetic fuels burned in conventional jet engines are a promising solution for medium- and long-range aircraft [11]. These concepts promise a significant reduction or complete avoidance of climate-damaging CO_2 and non-CO_2 emissions during flight operations.

However, in addition to the direct emissions from flight operations, there are indirect emissions from maintenance, repair, and overhaul (MRO) activities associated with the novel propulsion concepts. These impacts are primarily due to replacing components during MRO. When components of the propulsion concept have to be replaced, the environmental impacts of their production are incurred. At the same time, the replacement of components is an important driver of the operating costs of today's aircraft, accounting for approximately 10-15% of the overall operating costs [12]. Therefore, MRO, particularly the replacement of components and assemblies, is a crucial factor of the environmental and economic impacts during the use stage of an aircraft. These negative impacts may increase further when using novel propulsion concepts with new technologies. For example, batteries usually have shorter lifetimes (10-15 years) than aircraft (20-30 years or ~60,000 operating hours) [13]. However, these aspects are barely addressed in the scientific literature, and studies focusing on MRO-related environmental and economic impacts of novel aircraft propulsion concepts are scarce [14].

This article aims to analyze the MRO-related environmental and economic impacts of novel aircraft propulsion concepts. The focus is particularly on analyzing and comparing the main components of state-of-the-art, battery-electric, and fuel cell-based concepts. To this end, the aging behavior of the components is analyzed, and the replacement frequencies are determined. Subsequently, the associated environmental and economic impacts of the replacement activities are analyzed using life cycle assessment (LCA) and life cycle costing (LCC).

The intended contribution to the scientific literature is twofold: First, we seek to determine the replacement frequencies of the components of novel aircraft propulsion concepts. For this purpose, we analyze the degradation behavior of batteries, fuel cells, and electric motors. Second, we seek to derive insights into the environmental and economic impacts of replacing these components. Therefore, we use LCA and LCC to determine the environmental and economic impacts and compare them with those of a conventional jet engine.

The remainder of this article is structured as follows: The degradation behavior and the resulting replacement frequency for jet engines, batteries, fuel cells, and electric motors are derived in Section 2. The replacement frequency and the resulting environmental and economic impacts are analyzed in Section 3. The main findings are discussed in Section 4, and a conclusion and outlook are provided in Section 5.

2. Methods and materials

2.1. MRO strategies for aircraft propulsion concepts

In the MRO of aircraft propulsion concepts, a basic distinction is made between three strategies: *corrective*, *preventive*, and *predictive* MRO [15].

In *corrective MRO*, faults and failures are corrected after they have occurred and are noticed [16]. No intermediate inspection takes place, and possible faults and failures are accepted. After a fault occurs, the system is restored to a condition where the required functionality is ensured [16]. Corrective MRO requires the least amount of planning in advance and enables optimum use time of components.

Preventive MRO proactively attempts to avoid unplanned MRO activities [17]. It is usually based on predetermined or periodically recurring intervals, such as flight cycles or flight hours [18]. Preventive MRO is characterized by complex maintenance management compared and sometimes leads to premature removal of still functioning components.

In *predictive MRO*, the components of the propulsion concept are evaluated based on their condition and subjected to an MRO activity in good time before they fail [19]. There is the possibility to evaluate the condition of the component at regular time intervals or to continuously collect data on the condition during operation [20]. This enables the subdivision of predictive MRO into diagnostic and prognostic MRO [15]. Diagnostic MRO attempts to detect impending failures on time by assessing the affected components. In prognostic MRO, the remaining service life is determined by considering the wear and operating behavior. Predictive MRO requires the greatest effort of all maintenance strategies due to the necessary expertise and diagnostic or prognostic technology. However, it leads to the best possible service life of the components, and MRO can be planned very well [20]. Thus, predictive MRO is best suited for determining the replacement frequency.

2.2. Degradation behavior and assumptions on the usage of conventional aircraft propulsion concepts

Based on predictive MRO, data is collected during the operation of the conventional aircraft propulsion concept, which is used to infer the internal condition of the engine [21]. When critical values are reached, indicating a fault or failure, the propulsion concept is subjected to an MRO activity. Here, the engine is inspected, and the necessary parts are replaced or repaired [22]. In addition, preventive MRO is carried out on those components whose failure could lead to further damage. These components, known as life-limited parts (LLP), are replaced once they have reached the end of service life [23].

Different operating conditions, such as the flight-cycle-to-flight-hour-ratio, can determine the replacement time. The LLPs are usually subject to flight cycle limitations due to the high stress placed on components during the take-off. Another MRO reason results from the flight-hour-independent efficiency decrease associated with an increasing exhaust gas temperature. An MRO activity has to be conducted as soon as the difference between exhaust gas temperature and the maximum permissible exhaust gas temperature exceeds a threshold that operation is no longer possible. However, due to the high flight-cycle-to-flight-hour-ratio in short-range operations, the replacement of the engines is primarily based on reaching the service life limit of the LLPs [24].

The service life of LLPs differs between different engine designs and between specific components. However, it can be assumed that the service life of the LLP is approximately 20,000 flight cycles for short-range engines [24]. The flight time of a short-range flight is defined as one to three hours [25]. In this study, it is assumed that a flight cycle has a flight time of two hours and is conducted three times a day.

2.3. Degradation behavior and assumptions on the usage of novel aircraft propulsion concepts

Due to uncertainties concerning the design of novel aircraft propulsion concepts, the study focuses primarily on the known main components of battery-electric and fuel cell-based concepts. These are the battery, fuel cell, and electric motor, for which the replacement time is determined based on their degradation behavior.

In the case of batteries, the current state of health and the remaining useful life are of particular interest, as they change through degradation as the operation progresses [26]. The potential remaining useful life, measured in charging cycles, is directly related to the state of health [27]. Here, degradation is based on changes in the properties of components of the battery, specifically affecting the anode and cathode. The key drivers are the state of charge, temperature, and storage conditions [28]. In particular, the environmental conditions during aircraft operation, such as low pressures, strong temperature fluctuations, and radiation, are the drivers of degradation [29]. Therefore, the current scientific literature assumes that 7,000 charging cycles can be achieved in unmanned aerial vehicles and only 2,500 in short-range electric aircraft [30]. In this study, the replacement time is determined based on the 2,500 charging cycles, where one charging cycle corresponds to a short-range flight of two hours. Due to charging times, two flights per day are assumed, and one battery system is used per aircraft.

Several potential fuel cell systems could be used in passenger aircraft. The scientific literature focuses primarily on proton-exchange membrane fuel cells (PEMs) due to their high mass-specific performance [10]. PEM degradation is primarily driven by the anode, cathode, and membrane. These are subject to mechanical, thermal, and electrochemical degradation effects, which lead to reduced performance due to restricted proton transport. This decreases the electrical voltage, which is used as a measure of wear [31]. The maximum operating life of PEMs is often defined as the period until the available power has decreased by 10%. This period is the operating life. Current scientific studies determine an operating life of 8,900 hours for using PEMs in commercial aircraft [32]. Since fuel cell-based propulsion concepts do not require charging but only hydrogen refueling, it is assumed in this study that three flights per day with a flight time of two hours each can be performed. In addition, it is assumed that a fuel cell-based short-range aircraft is equipped with only one PEM.

Electric motors are essential in all novel propulsion concepts that can potentially be used in short-range aircraft. Although they differ in terms of the power to be delivered due to the different sizes of the fan to be driven, the basic design and degradation characteristics are very similar. The degradation behavior of electric motors depends on mechanical, electrical, and thermal influences as well as environmental conditions [33]. The scientific literature estimates maximum operating life of 8,000 to 10,000 hours [33,34]. In this study, 9,000 operating hours are assumed, and two electric motors are required per aircraft.

2.4. Assessment method

The assessment carried out in this article is based on the LCA and LCC methods, and the procedure is derived from the ISO 14040/14044 standards. Explanations of the basic LCA and LCC approaches can be found in the pertinent literature (e.g., [35–37]).

This study analyzes the MRO of conventional, battery-electric, and fuel cell-based propulsion concepts for short-range aircraft. The focus is on the environmental and economic impacts associated with replacing batteries, fuel cells, and electric motors during the aircraft service life. For this purpose, the replacement frequency based on the degradation behavior is determined, which is described in subsections 2.1-2.3.

The different components of the propulsion concepts are modeled in the foreground system and are taken from our previous studies [7,9,10]. Background data from the ecoinvent 3.8 database with the system model "allocation, cut-off by classification" is used to model raw materials and supplies [38].

The functional unit is a scaled component (battery, fuel cell, and electric motor), which can be used for propulsion of a short-range aircraft with a load of 100 passengers, including luggage, over 60,000 operating hours.

The environmental impact assessment is based on three impact categories, according to the ReCiPe Midpoint v1.13 method [39]. Here, the impact category climate change is chosen due to the high amount of climate-damaging CO_2 and non-CO_2 emissions resulting from the production of the components, fossil resource depletion is chosen due to the fossil sources required for electricity generation, which is used during the production, and mineral resource depletion is chosen due to the materials needed for the components of the propulsion concepts. The economic assessment is based on the replacement costs associated with the components of the propulsion concepts [35,40]. Table 1 provides an overview of the considered impact categories within this study.

The calculation model for the inventory analysis and impact assessment is implemented in Python using the Brightway2 framework [41].

Table 1. Environmental and economic impact categories

Dimension	Impact category	Unit
Environmental	Climate change	kg CO_2-eq.
	Fossil resource depletion	kg Oil-eq.
	Mineral resource depletion	kg Fe-eq.
Economic	Replacement costs	US-Dollar

3. Results

3.1. Replacement frequency of different components of propulsion concepts

Based on the degradation behaviors of conventional jet engines, batteries, fuel cells, and electric motors presented in sections 2.1-2.3, the replacement frequency is derived in this section. The calculation is based on the maximum operating hours of a short-range aircraft (60,000 flight hours [13]). The replacement times of the individual components were converted to the operating hours accordingly, and a full replacement of the components is always conducted. Individual parts of the components are not replaced. Furthermore, for conventional jet engines, the replacement frequency is calculated exclusively concerning the LLPs, and the increased exhaust gas temperature is neglected. The resulting replacement frequency is shown in Figure 1 and Table 2.

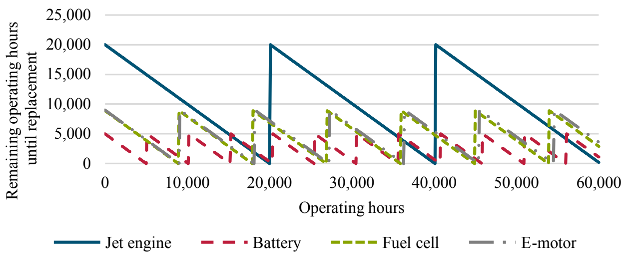

Figure 1. Replacement frequency of the investigated components

Conventional jet engines must be replaced every 20,000 operating hours. Assuming three flights per day and a flight time of two hours, as presented in section 2.2, this corresponds to a replacement of approximately every nine years. During the entire service life of a short-range aircraft, the jet engine is thus completely replaced twice and would have to be replaced a third time if the aircraft were to be used for more than 60,000 operating hours. The low replacement frequency is mainly due to the high level of development of the jet engine and the good interaction of the subcomponents.

The battery, on the other hand, as a key component of the electric propulsion concept, must be replaced every 5,000 operating hours. Based on the assumptions of two flights per day and a flight time of two hours, this corresponds to a replacement approximately every 3.5 years. Overall, with the assumed 60,000 operating hours, the battery system must be replaced a total of eleven times over the entire service life of a short-range aircraft. This significantly more frequent replacement is mainly due to low pressures, strong temperature fluctuations, and radiation during flight operations as major drivers of degradation.

Based on current forecasts, the fuel cell, an essential component of the fuel cell-based propulsion concept, must be replaced every 8,900 operating hours. Assuming three flights per day with a flight time of two hours each, the fuel cell must be replaced approximately every four years and one month. Thus, assuming 60,000 operating hours of the short-range aircraft, the fuel cell must be replaced six times. This replacement frequency results mainly from decreased electrical voltage due to degradation.

The electric motor is required in both the battery-electric and the fuel cell-based propulsion concept, and it is assumed that replacement is necessary every 9,000 operating hours. For an application in a battery-electric propulsion concept with two flights per day and a respective flight time of two hours, this corresponds to a replacement every six years and three months. In a fuel cell-based propulsion concept, the electric motor must be replaced after only four years and two months due to the more frequent flight operations (three flights per day of two hours each). Accordingly, the electric motor in a battery-electric concept can be used for almost twice as long as the battery. In contrast, the replacement of a fuel cell and electric motor in a fuel cell-based propulsion concept takes place at about the same interval. In total, the electric motor must be replaced six times during the assumed 60,000 operating hours of the short-range aircraft.

Table 2. Replacement frequencies of different propulsion components

Component	Maximum operating hours	Replacement frequency along the aircraft's lifetime
Jet engine	20,000	2 times
Battery	5,000	11 times
Fuel cell	8,900	6 times
E-Motor	9,000	6 times

3.2. Environmental and economic impacts associated with the component replacement

Based on the replacement frequencies calculated in section 3.1, the associated resulting environmental and economic impacts are analyzed. These are based on impacts related to the production of the components that are replaced. The environmental and economic assessment results associated with the component replacement are depicted in Figure 2. The analysis focuses on climate change, mineral resource depletion, fossil resource depletion, and replacement costs.

Overall, the results show that replacing the battery and the fuel cell is associated with high negative impacts concerning the environmental impact categories.

Regarding climate change and fossil resource depletion, the battery is associated with the highest negative impacts. Compared to the jet engine, these are 7.1 times higher for climate change and 9.1 times higher for fossil resource depletion. About the fuel cell, the battery is also clearly worse, with 2.6 and 2.7 times higher impacts for climate change and fossil resource depletion, respectively. Concerning the electric motor, it is even 76.9 and 107.2 times worse for climate change and fossil resource depletion. This is mainly due to the high replacement frequency and the substantial negative impacts of battery production due to the high energy demand.

Regarding mineral resource depletion, the fuel cell is associated with the highest negative impact due to replacement. They are 1.9 times higher compared to the battery, 88.6 times higher compared to the electric motor, and even 290.1 times higher compared to the jet engine. Since the replacement frequency is relatively low compared to the battery, the negative impact is mainly due to the materials used in the fuel cell. The main driver here is the platinum used in the catalyst.

The battery also has the highest replacement costs. However, the battery replacement costs are only 2.1 times higher than the jet engine, 3.4 times higher than the fuel cell, and 1.9 times higher than the electric motor. This is because energy and material costs are the main drivers for fuel cells and batteries. In contrast, labor costs are primarily relevant for the conventional turbine engine and the electric motor due to the complexity of the systems and the long manufacturing and assembly times.

4. Discussions

The analysis shows that conventional jet engines are advantageous in terms of replacement due to their high level of development. With a short-range aircraft's maximum of 60,000 operating hours, fuel cells and electric motors must be replaced three times more often and batteries five times more often.

This is associated with high environmental and economic impacts, making the MRO-related impacts between 2-290 times higher than those of the conventional jet engine. Even if novel propulsion concepts do not release direct CO_2 and non-CO_2 emissions during the use phase, these indirect emissions from MRO cannot be neglected. In addition, the associated costs can become a major determinant of aircraft operating costs. They must be considered when assessing propulsion concepts, leading to disadvantages of novel propulsion concepts in terms of environmental and economic impacts along the entire life cycle.

However, this study is subject to some uncertainties, especially concerning the novel aircraft propulsion concepts, their components, and their degradation behavior. The propulsion concepts and components were modeled in previous work and are based on multiple assumptions about energy demand, scaling, and actual composition. The sizing of the components cannot be validated since there are no field-tested passenger aircraft with battery or fuel cell-based propulsion concepts yet. These circumstances result in the fact that there is still no information on the actual degradation behavior and the resulting replacement frequency. The calculated replacement frequency is based on scientific forecasts for the components. However, if the propulsion concepts or individual components change regarding the technology used and scaling, this would significantly influence the replacement frequency and the resulting environmental and economic impacts.

Further uncertainty arises from the subject of the study. Here, only the indirect environmental and economic effects of the use phase associated with MRO were investigated. However, these need to be expanded to include the direct impacts of energy carrier consumption during flight operations in order to analyze and assess the use phase of conventional and novel aircraft propulsion concepts. To ultimately derive valid recommendations for the development of future aircraft propulsion concepts, production and end-of-life must also be integrated.

5. Conclusions and outlook

The study provides initial insights into the MRO behavior and the associated environmental and economic impacts of components of novel aircraft propulsion concepts compared with currently operated conventional jet engines. Here, the analysis shows that batteries, fuel cells, and electric motors must be replaced more frequently, leading to disadvantages of the novel propulsion concepts regarding environmental and economic impacts. The findings obtained in this study extend the literature on the analysis and assessment of novel aircraft propulsion concepts with an initial analysis of MRO-related environmental and economic impacts and can be used as a basis for future research.

In future research, four aspects should be focused on: 1.) the integration of further components of the propulsion concepts into the analysis of the replacement frequency, 2.) the consideration of the replacement of individual subcomponents, 3.) the development of further measures for replacement and degradation, and 4.) the integration of the MRO analysis into a life-cycle oriented sustainability assessment of the propulsion concepts.

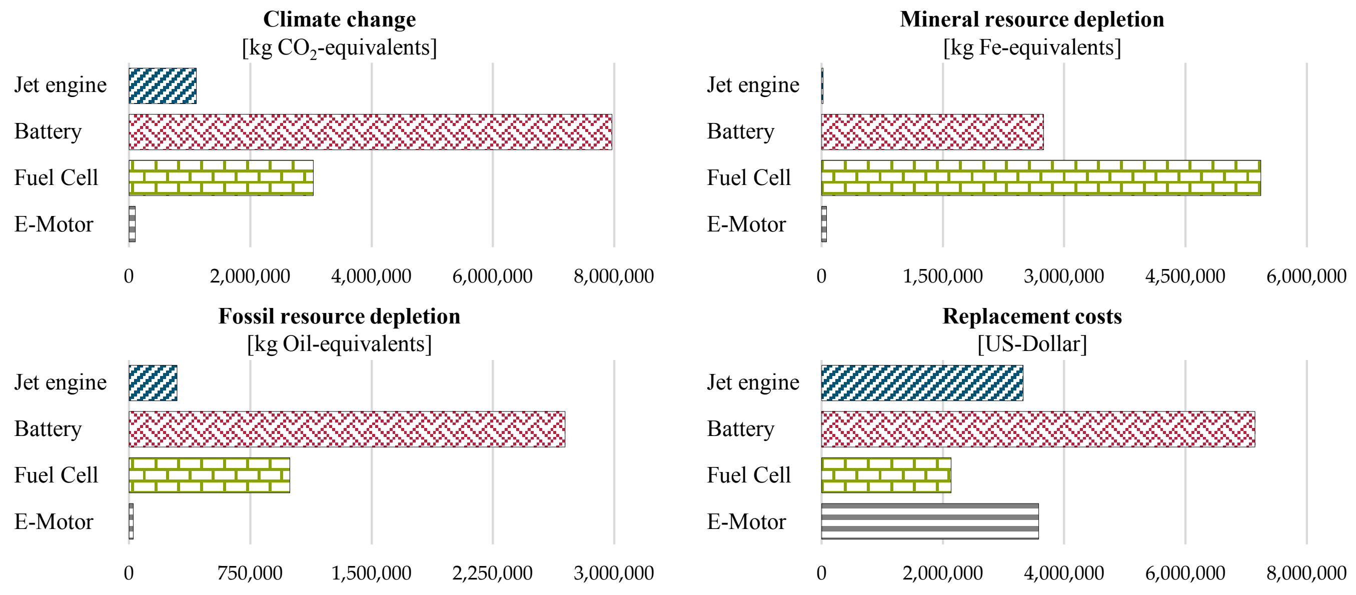

Figure 2. Environmental and economic assessment results associated with the component replacement along the aircraft lifetime of 60,000 operating hours

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References

[1] Gössling S, Humpe A, Fichert F, Creutzig F. COVID-19 and pathways to low-carbon air transport until 2050. Environ Res Lett 2021;16:034063. https://doi.org/10.1088/1748-9326/abe90b.
[2] Boeing. Commercial Market Outlook. Seattle, USA: 2022.
[3] Lee DS, Fahey DW, Skowron A, Allen MR, Burkhardt U, Chen Q, et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmos Environ 2021;244. https://doi.org/10.1016/J.ATMOSENV.2020.117834.
[4] Gnadt AR, Speth RL, Sabnis JS, Barrett SRH. Technical and environmental assessment of all-electric 180-passenger commercial aircraft. Prog Aerosp Sci 2019;105:1–30. https://doi.org/10.1016/j.paerosci.2018.11.002.
[5] Jungbluth N, Meili C. Recommendations for calculation of the global warming potential of aviation including the radiative forcing index. Int J Life Cycle Assess 2019;24:404–11. https://doi.org/10.1007/s11367-018-1556-3.
[6] ICAO. Electric, Hybrid, and Hydrogen Aircraft – State of Play. Montréal, Canada: 2019.
[7] Barke A, Thies C, Melo SP, Cerdas F, Herrmann C, Spengler TS. Comparison of conventional and electric passenger aircraft for short-haul flights – A life cycle sustainability assessment. Procedia CIRP, vol. 105, 2022, p. 464–9. https://doi.org/10.1016/j.procir.2022.02.077.
[8] Barke A, Thies C, Popien J-L, Melo SP, Cerdas F, Herrmann C, et al. Life cycle sustainability assessment of potential battery systems for electric aircraft. Procedia CIRP, vol. 98, 2021, p. 660–5. https://doi.org/10.1016/j.procir.2021.01.171.
[9] Barke A, Cistjakov W, Steckermeier D, Thies C, Popien J-L, Michalowski P, et al. Green batteries for clean skies: Sustainability assessment of lithium-sulfur all-solid-state batteries for electric aircraft. J Ind Ecol 2022:in press. https://doi.org/10.1111/jiec.13345.
[10] Melo SP, Toghyani S, Cerdas F, Liu X, Gao X, Lindner L, et al. Model-based assessment of the environmental impacts of fuel cell systems designed for eVTOLs. Int J Hydrogen Energy 2022:in press. https://doi.org/10.1016/J.IJHYDENE.2022.10.083.
[11] Barke A, Bley T, Thies C, Weckenborg C, Spengler TS. Are Sustainable Aviation Fuels a Viable Option for Decarbonizing Air Transport in Europe? An Environmental and Economic Sustainability Assessment. Appl Sci 2022;12:597. https://doi.org/10.3390/APP12020597.
[12] International Civil Aviation Organization (ICAO). Airline Operating Costs and Productivity. Tehran, Iran: 2017.
[13] Porzio J, Scown CD. Life-Cycle Assessment Considerations for Batteries and Battery Materials. Adv Energy Mater 2021;11. https://doi.org/10.1002/AENM.202100771.
[14] Melo SP, Barke A, Cerdas F, Thies C, Mennenga M, Spengler TS, et al. Sustainability Assessment and Engineering of Emerging Aircraft Technologies - Challenges, Methods and Tools. Sustainability 2020;12:5663. https://doi.org/10.3390/su12145663.
[15] U.S. Department of Defense. Condition Based Maintenance Plus DoD Guidebook. Washington, D.C.: 2008.
[16] Endig M, Freund C, Götze J, Hänsch K, Kumetz S, Ryll F, et al. Instandhaltung technischer Systeme. Michael Sc. Springer Heidelberg Dordrecht London New York; 2010. https://doi.org/10.1007/978-3-642-03949-2.
[17] Gerdes M, Scholz D, Galar D. Effects of condition-based maintenance on costs caused by unscheduled maintenance of aircraft. J Qual Maint Eng 2016;22:394–417. https://doi.org/10.1108/JQME-12-2015-0062.
[18] Hinsch M. Industrielles Luftfahrtmanagement. Springer Vieweg; 2019. https://doi.org/10.1007/978-3-662-58804-8.
[19] Deutsches Institut für Normung e.V. DIN EN 13306: Instandhaltung - Begriffe Der Instandhaltung. 2017.
[20] Hölzel NB. Ein Bewertungsansatz zur Analyse von Zustandsmanagementsystemen in Verkehrsflugzeugen unter Berücksichtigung neuer Instandhaltungskonzepte. Technische Universität Hamburg, 2018. https://doi.org/10.15480/882.2543.
[21] Volponi AJ. Gas turbine engine health management: Past, present, and future trends. J Eng Gas Turbines Power 2014;136:1–20. https://doi.org/10.1115/1.4026126.
[22] Mensen H. Handbuch der Luftfahrt. 2nd ed. Berlin, Heidelberg: Springer Vieweg; 2013. https://doi.org/10.1007/978-3-642-34402-2.
[23] Stojiljković B, Vasov L, Čokorilo O, Vorotović G. An analytical model of the replacement costs of aircraft engine life-limited parts. Aircr Eng Aerosp Technol 2021;93:776–82. https://doi.org/10.1108/AEAT-12-2020-0297.
[24] Ackert S. Engine Maintenance Concepts for Financiers. 2011.
[25] Wilkerson JT, Jacobson MZ, Malwitz A, Balasubramanian S, Wayson RL, Fleming G, et al. Analysis of emission data from global commercial aviation: 2004 and 2006. Atmos Chem Phys 2010;10:6391–408. https://doi.org/10.5194/acp-10-6391-2010.
[26] Penna JAM, Nascimento CL, Rodrigues LR. Health monitoring and remaining useful life estimation of lithium-ion aeronautical batteries. IEEE Aerosp Conf Proc 2012:1–12. https://doi.org/10.1109/AERO.2012.6187375.
[27] Ungurean L, Cârstoiu G, Micea M V., Groza V. Battery state of health estimation: a structured review of models, methods and commercial devices. Int J Energy Res 2017;41:151–81. https://doi.org/10.1002/er.3598.
[28] Keil P, Schuster SF, Wilhelm J, Travi J, Hauser A, Karl RC, et al. Calendar Aging of Lithium-Ion Batteries. J Electrochem Soc 2016;163:A1872–80. https://doi.org/10.1149/2.0411609jes.
[29] Schefer H, Fauth L, Kopp TH, Mallwitz R, Friebe J, Kurrat M. Discussion on Electric Power Supply Systems for All Electric Aircraft. IEEE Access 2020;8:84188–216. https://doi.org/10.1109/ACCESS.2020.2991804.
[30] Paek SW, Kim S, Raj RV. Optimal endurance and range of electric aircraft with battery degradation. Trans Jpn Soc Aeronaut Space Sci 2020;63:62–5. https://doi.org/10.2322/tjsass.63.62.
[31] Schmittinger W, Vahidi A. A review of the main parameters influencing long-term performance and durability of PEM fuel cells. J Power Sources 2008;180:1–14. https://doi.org/10.1016/j.jpowsour.2008.01.070.
[32] Kösters L, Gao X. Safety considerations and time constant determined extended operations for fuel cell-powered aircrafts. CEAS Aeronaut J 2021;12:767–75. https://doi.org/10.1007/s13272-021-00533-7.
[33] Rothe R, Hameyer K. Life expectancy calculation for electric vehicle traction motors regarding dynamic temperature and driving cycles. 2011 IEEE Int Electr Mach Drives Conf IEMDC 2011 2011:1306–9. https://doi.org/10.1109/IEMDC.2011.5994793.
[34] Mancinelli P, Stagnitta S, Cavallini A. Lifetime analysis of an automotive electrical motor with hairpin wound stator. Annu Rep - Conf Electr Insul Dielectr Phenomena, CEIDP 2016;2016-Decem:877–80. https://doi.org/10.1109/CEIDP.2016.7785538.
[35] Hunkeler D, Lichtenvort K, Rebitzer G. Environmental life cycle costing. Boca Raton, Fla.: CRC Press; 2008.
[36] Swarr T, Hunkeler D, Klöpffer W, Personen H-L, Ciroth A, Brent A, et al. Environmental Life-Cycle Costing: A Code of Practice. Int J Life Cycle Assess 2011:389–91.
[37] Barke A, Thies C, Melo SP, Cerdas F, Herrmann C, Spengler TS. Socio-economic life cycle assessment of future aircraft systems. Procedia CIRP, vol. 90, 2020, p. 262–7. https://doi.org/10.1016/j.procir.2020.01.096.
[38] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 2016;21:1218–30. https://doi.org/10.1007/S11367-016-1087-8.
[39] Goedkoop M, Heijungs R, Huijbregts M, Schryver, Struijs J, van Zelm R. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First edit. Den Haag, Netherlands: 2013.
[40] Moreau V, Weidema BP. The computational structure of environmental life cycle costing. Int J Life Cycle Assess 2015;20:1359–63. https://doi.org/10.1007/s11367-015-0952-1.
[41] Mutel C. Brightway: An open source framework for Life Cycle Assessment. J Open Source Softw 2017;2:236. https://doi.org/10.21105/joss.00236.